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Optimization of drying process for better quality retention of dried potato

Dissertation zur Erlangung des akademischen Grades einer
Doktorin der Agrarwissenschaften (Dr. agr.)

von

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aus Äthiopien

Witzenhausen 2018

Die vorliegende Arbeit wurde am 1.03.2018 vom Fachbereich für Ökologische Agrarwissenschaften, Fachgebiet Agrartechnik der Universität Kassel als Dissertation zur Erlangung des Grades einer Doktorin der Agrarwissenschaften angenommen.

Tag der mündlichen Prüfung: 08.05.2018

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Im Selbstverlag: Addisalem Hailu Taye

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Acknowledgements

I would like to express my heartfelt appreciation and special gratitude to everyone who, in one way or the other, contributed in the accomplishment of this study. Great deal of gratefulness goes to the German Federal Ministry of Education and Research for the financial support within the RELOAD project. I would also like to thank the coordinator of RELOAD project, Mr. Michael Hesse, for his great job.

My special appreciation and deepest thanks extend to my supervisor, Prof. Dr. Ing. Werner Hofacker, for his continuous support, guidance, inspiration, and invaluable input. My special gratitude also goes to my primary supervisor Prof. Dr. Oliver Hensel for his diligent guidance and support. Without the expertise and assistance of my supervisors, this study would have not successfully advanced the way it did. I would like to thank Dr. Ing. Albert Esper, and the student Ahmad Dib for their great efforts on review and proofreading my research papers, respectively.

From the side of HTWG Konstanz, I would like to thank Mr. Frank Vespermann, Mr. Philip Lohrer, Mr. Kuma Gowwomsa, Mrs. Simona Weszolovsky, Dr. Anna-Maria Nunez Vega, Mrs. Geraldine Kortmann, Mrs. Marcelle Einsidler, Mrs. Petra Ballance, Ms. Katrin Joedicke, and Ms. Saskia Arendt for creating such a convenient environment during my research work and my stay in Konstanz; and from the side of Jimma University, Dr. Yetenayet Bekele, Prof. Dr. Ali Mohmmed, Prof. Dr. Debela Hunde, Mr. Kumela Dibaba, Mr. Tizazu Yirga, and Mr. Tilahun Abera for their contribution and encouragements during my research work.

I would also like to thank my brothers (Fekadu Hailu and his family, Bayu Hailu, and Yared Hailu) as well as my sister (Senait Hailu and her family) for their consistent motivation. Another special appreciation goes to my sister Bekelu Hailu for taking care of my daughter, for her support, and her encouragement. She has always had a great contribution in my life and my studies. I would like to thank my husband Habtamu Tadese for his encouragement and patience, and my daughter Tsion Habtamu for waiting so long for me. I felt a greater deal of responsibility being away from my most beloved ones, this has made me; however, more focused during my work.

Above all, I would like to thank God and St. Marry for their guidance and for standing behind me at all time

Parts of this thesis have already been published as follows

Taye A. H., Hofacker, W. and Hensel, O. (2017). Modeling and the role of water activity, desorption isotherm and glass transition in drying of potatoes quality and shelf life stability, *International Journal of Scientific & Engineering Research* Volume 8, Issue 6, June-2017, 1143-1152.

Taye A. H. and Hofacker, W. (2017). Application of the concept of glass transition temperature for better color retention and less shrinkage of dried potato slices, *International Journal of Scientific & Engineering* Research Volume 8, Issue 5, May-2017 , 1427-1432.

Taye A. H, Hofacker, W. (2017). Optimizing the drying parameters for hot air dried potato slices, *1st International Conference of ESPHM, Addis Ababa, Ethiopia*, Jan 26-27, 2018**.**

Taye A. H, Arendt, S. and Hofacker, W. (2017). Influence of processing condition on ascorbic acid retention of hot air dried potato slices, *6th European Drying Conference Liège, Belgium, 19-21 June 2017.*

Taye A. H, Hofacker, W. (2017). Effect of processing condition on drying kinetics, shrinkage and mechanical properties of hot air dried potato slices, *6th European Drying Conference Liège, Belgium, 19-21 June 2017*

Taye A. H and Hofacker, W. (2016). New method for glass transition temperature determination of potatoes. 20th International drying symposium, P2-32. Gifu, Japan

Erko, K.E., Taye A. H and Hofacker, W. (2016). Numerical modeling of coupled heat and mass transfer with moving boundary during convective drying of potato slices, *International Journal of Scientific & Engineering* Research Volume 8, Issue 11, November -2017 , ISSN 2229-5518, P 71-78

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NOMENCLATURE

Symbol	Unit	Meaning
a_w	-	Water activity
A	-	Number of pixels
ANOVA	-	Analysis of variance
A, B, C and K	-	Constants in sorption isotherm models
DPT	°C	Dew point temperature
DSC	-	Differential scanning calorimeter
ΔL	-	Change in Lightness
Δa	–	Change in redness
Δb	–	Change in yellowness
dX / dt	kg/(kgs)	Drying rate
EMC	kg/kg,dry basis	Equilibrium moisture content
HMI	-	Human-machine interface
MAE	-	Mean absolute error
MR	-	Moisture ratio
M_i	kg/kg, dry basis	Experimental values of moisture content
M_o	kg/kg, dry basis	Monolayer moisture content
PLC	-	Programmable Logic control
R	J/mol K	Universal gas constant
R^2	-	Determination coefficient

Symbol	Unit	Meaning
RSM	-	Response surface methodology
S	-	Shrinkage
t	min	Time
T	°C	Temperature
TCD	-	Total color difference
TMA	-	Thermo mechanical analysis
T_g	°C	Glass transition temperature of the binary mixture
T_{gw}	°C	Glass transition temperature of the water
T_{gs}	°C	Glass transition temperature of the dry matter
V	m/s	Velocity
W_s	-	Weight fraction of dry matter
W_w	-	Weight fraction of water

Subscripts

i i^{th} experimental observation

N number of experimental observation

o at the beginning of the drying, the initial state

1. Introduction

Potatoes are the most consumed vegetable crop in the world after rice, wheat and corn. It is a fat-free food containing, carbohydrate, protein, vitamins and minerals (FAO, 2001). Africa produces approximately one-third of the worldwide production of potato (FAO, 2001). A systematic assessment of physical losses worldwide by FAO suggests that losses of root and tuber crops are in the range of 30% to 60% (FAOSTAT, 2004). Root and tuber have high moisture content, susceptible to physical damage and have a high metabolic rate. Their higher moisture content, greater susceptibility to physical damage and higher metabolic activity have a high contribution to the loss. Currently, reduction of post - harvest loss is the major issue of the world. Therefore, in order to reduce the loss, preservation of roots and tubers is required. Drying is one of the techniques used to preserve root and tubers by removing water up to a certain level at which microbial and chemical reaction be minimized. Many research were done on drying. Some of the authors did on drying roots, tubers, fruits and vegetable are ; Krokida et al. (1998); Zu & Moyano,(2007) ; Yan, Sousa-gallagher, & Oliveira (2008) ; Abasi et al.(2009); Kawongolo, (2013). They report the sensitiveness of food products by drying processing condition, which can cause quality deterioration of products through oxidation, color change, shrinkage, loss of texture and nutritional functional properties. According to many authors, drying processes also end when the graph of mass of the samples versus time became almost constant. This method does not have a clear ending point of the drying process. One process may end with a long constant line whereas the other one may stop at the short constant line. The former may result in loss of time, quality and energy when the samples dried over required water activity (a_w) and the latter may result in the less stable product when the samples dried under required a_w. The drying process should stop at moisture content equivalent to at product's stable water activity. On another hand, Rahman (2012) reports the stability of foods in the glassy state since in the state compounds involved in the deterioration reactions take times to diffuse over molecular distances and approach each other to react. Even though many authors suggest, processing starchy product in a glassy state for better quality retention of the product, there is no work done on relating glass transition temperature and its effect on quality of drying potato slices. Therefore, it is necessary to investigate the influencing factors of drying quality and to set optimum processing condition in order to produce stable, safe and good quality product. The objective of this thesis is to increase the knowledge about the optimization of the dried product quality-influencing factors for production of stable, safe and good quality product, and proof the utilization of the product.

Approaches to the optimization of the drying process for good product quality, the residual moisture content of the product, the influence of drying process parameters, the state of the product during processing and prove of utilization of the product should be taken into consideration.

1.1. Statement of the problem

1.1.1 Background

There is a high loss of roots and tubers in the world. Water is an important component of roots and tubers and plays a major role in the degradation of the physical, microbial, chemical and biochemical properties of the root and tuber crop(Figura & Teixeira, 2007). Water in any food material exists in bound and unbound forms. At higher moisture ratio the water in roots and tubers are active chemically as pure water. As moisture content is lowered until a certain point further, a point will be reached at which the water becomes less active in that it cannot act physically or chemically as pure water. Currently, reduction of postharvest loss became a major issue in the world. In order to reduce the postharvest loss of root and tubers, preservation is required. Drying is one of the techniques used to preserve foods by removing water up to a certain level at which microbial and chemical reaction be minimized(Akpinar & Bicer, 2005). In developed countries dried potatoes used to prepare potato granules, flakes, diced potatoes and potato flour(Stearns et al., 1994). Improving the quality the product is one of the main factors for the attraction of consumer to sell the product to them. In developing country like Ethiopia, drying of root and tubers in industry, medium and small enterprise was not started. For industries, to start production of dried root and tubers, knowing influencing factors and optimum condition are the main factors taken into consideration. For the medium and small enterprise, to enter into the production of the dried root and tubers, in addition to knowing the influencing factors and optimum condition of the drying process, the affordability of the dryer also taken into consideration. For the production of dried product in developing countries, using hot air dryer for industry and solar dryer for both small and medium enterprise are feasible (Tiwari, 2016). A fundamental understanding of the quality influencing factors and using optimal processing condition can certainly help improve the overall quality of dried products. Therefore, drying process must meet the following requirements:

- The residual moisture content of the product must be reduced to an optimum level at which microbial and chemical reaction be minimized.
- The deterioration of qualities and nutritional values of dried potato slices must be minimized.
- The dried potato slices must have long shelf life and maintain the quality during storage
- The dried potato slices have to be changed to utilized form

Problem definition

Many problems exist in pre-drying, during drying and after drying of potatoes. Lack of appropriate storage and handling method contribute to high loss of potato tubers. In Ethiopia, potatoes are stored for ware and seed in different traditional potato storage material: underground storage, floor storage, raised beds and sacks. According to Ayalew *et al. (*2014), potato yield loss in Ethiopia reached 30% to 50% due to improper storage systems and post- harvest handling problems.

According to many authors, drying processes end when the graph of mass of the samples versus time became almost constant. This method does not have a clear ending point of the drying process. One drying process may end with a long constant line whereas the other one may stop at a short constant line. The former may result in loss of time, quality of the product and energy when the samples dried over required a_w and the latter may result in the less stable product when the samples dried under required a_w. To stop the drying process at optimum residual moisture content (equivalent to at stable a_w) of the sample a determination of desorption isotherm is required.

The optimum moisture content of the dried sample, at which microbial and chemical reaction be minimized, can be obtained by using the concept of water activity and desorption isotherm. Desorption isotherm of potato determination and fitting the experimental data to models were studied by Wang & Brennan (1991), McLaughlin & Magee (1998), Mcminn & Magee (2003), Chemkhi et al. (2011). However, the equilibrium moisture content of potato, at a specific temperature and water activity, by using the same model, is not similar. Dissimilarity in result may be due to the difference in variety and method.

Water activity(a_w) used to describe the stability of the product. However, a_w concept has a limitation in indicating exactly when the molecular mobility of the product starts(Sablani, 2007). The glass transition temperature (Tg) concept can fill the gap of the molecular mobility starting point. When the sample exists in the rubbery state the molecular mobility in the matrix is high whereas the samples change their state from rubbery to glassy the molecular mobility of the reacting components in the matrix is low thus diffusion of the reactants through the system to take part in reactions is very slow and stability is achieved(Rahman, 2012). Even though, glass transition temperature of food products has been pointed out to be responsible for the deterioration mechanisms during processing, and an indicator of food stability. According to Ratti (2001), quantifiable expressions between quality parameters and glass transition have not been fount yet. The limitation of studies quantifiable expressions between quality parameters and glass transition is may be due to the lack of an appropriate method for glass transition temperature (T_g) determination of real food. Determination of T_g of polymers in almost all cases, Differential scanning calorimeter (DSC) is by far the most commonly used method, However, DSC said to be not sensitive enough to detect glass transition in materials such as starch containing products(Liu et al., 2009).

Reducing quality deterioration by optimizing processing parameters is the aim of many industries to produce the competitive products. The drying process parameters can be the cause of quality deterioration of the drying samples through oxidation, color change, shrinkage, loss of texture, and nutritional functional properties(Vega-Galvez et al., 2009). The quality change during drying is due to chemical and biochemical reactions(Chen, 2008). As reported by Chen (2008) the rates of both reactions depend strongly on the processing parameters. These reactions are fast when the samples are processed above its glass transition temperature. Since the increase in temperature of a product above its glass transition temperature increases molecular mobility and also affects diffusion of the matrix and results in an increase in rates of deterioration: enzymatic reaction, non-enzymatic browning and oxidation(Roos, 1992).

Ending with the dried product of root and tubers is not an indicator of the acceptability of the product. It has to be changed to a usable form. As indicated in literature the flour of dried roots and tubers is used as partial replacement of wheat for bread baking. According to (Istva et.al, 2008) the developed must meet the consumer's requirements in terms of appearance, taste and texture.

Table.1 The cause and effect of general aspects considered in the problem definition

Cause of problems	Effect
Lack of appropriate storage	• Loss of tubers
Under drying	• quality deterioration
Over drying	• quality deterioration • high energy consumption • high labor time utilization
Appling non-optimum processing parameters	• loss of material, energy and labor resource • deterioration of quality
Drying the sample for a long time in rubbery state, and at higher temperature than glass transition temperature in glassy state	• quality deterioration
Lack of appropriate method for determination of glass transition temperature of potato	• limitation in applying the concept glass transition temperature to the process • indirectly lead to deterioration in quality
Limitation of applying the concept of glass transition temperature	• Deterioration in quality
Production of the product without proofing the acceptance	• May result in unaccepted in utilization of product

In order to solve the listed problems, the following considerations are required

- To preserve the product
- To avoid over and under drying
- To know the influence of processing parameters
- To include the concept of glass transition temperature during drying process
- To develop a new method for determination of glass transition temperature of potato
- To know optimal drying condition
- To develop product from dried samples
- To evaluate the acceptance of the product

1.1.2 Research objectives

Taking into account consideration required to solve the problem listed above the following research objective are proposed:

- To determine the optimum residual moisture content of the drying product to decide the end of drying.
- To determine the influence of processing condition on drying kinetics and the quality of dried product at optimum residual moisture content of the drying product
- To optimize drying process
- To develop a new method for glass transition temperature determination of potatoes
- To determine glass transition temperature of potatoes
- To reduce the product quality deterioration by drying the samples using the concept of glass transition temperature
- To investigate the influence of variety, position and slice thickness on quality of solar tunnel dried potatoes
- To develop a product (Bread) by using solar tunnel dried potatoes as an ingredient and evaluating the acceptability of the product

The final goal of this research was to produce product of a good quality. The schematic diagram showing the input, the output, and the interrelationship between the research objectives to produce a product of good quality is presented in Figure 1.1. The structure of this thesis is discussed in details under Section 1.2.

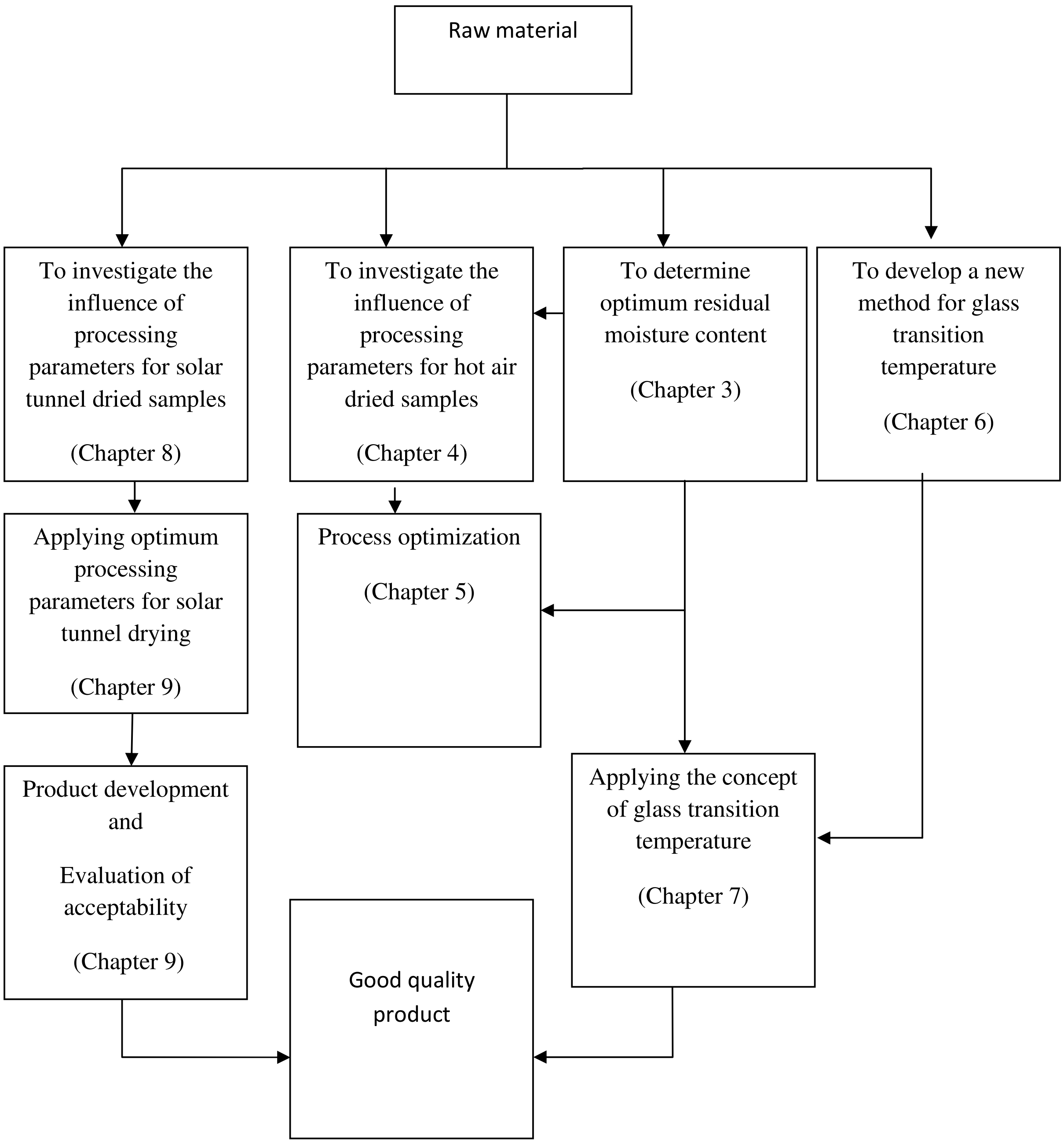


Figure 1.1. The schematic diagram showing the input, the output and the interrelationship between the objectives

Methodology

The following methodologies were used for achieving the proposed objective:

- In chapter 3, to decide the end of the drying process with an optimum residual moisture content of the drying samples, the value of the optimum water activity of the sample at which minimum reaction takes place taken from literature. To get optimum residual moisture content of the sample at optimum water activity, desorption isotherm of potatoes was determined using the standard static gravimetric method indicated in European Cooperative Project COST 90 (Wolf et al., 1985). The experimental data fitted to different models. The model with minimum mean relative percentage deviation modulus was selected as the best model. The optimum residual moisture content of the drying samples was calculated by substituting the optimum water activity of the sample into the selected model.
- In chapter 4, to determine the influence of processing condition on quality of dried potato, non-linear regression analysis of drying kinetics and kinetics of total color difference, linear regression analysis of the kinetics of the shrinkage were used.
- In chapter 5, to optimize processing parameters for drying potato slices, the RSM (Response surface methodology) was used to design the drying experiments. The desirability index is a multi-criteria optimization approach used to show how the various responses are desirable. The desired goal for each independent and dependent variables was chosen. The solution for optimum processing condition of drying of potato slices was selected for total color difference, shrinkage, hardness, work, deformation and ascorbic acid.
- In chapter 6, to develop a new method for glass transition temperature, the mechanical property of the samples were analyzed by compression test using a texture analyzer (CT3-1500, USA). Hardness, deformation and work data were recorded. The moisture ratio at a constant temperature, from the graph of hardness and work versus moisture ratio of the samples, at which minimum value of work and hardness was observed, used as a transition point from rubbery to a glassy state.

Finally, the graph of the glass transition temperature versus the moisture ratio was plotted.

- In chapter 7, to determine the quality parameter by using the concept of glass transition temperature, reduction of processing time at which the sample pass in the rubbery state took place. One way ANOVA was used to analyze the quality of the end products (lightness, redness, yellowness, total color difference, shrinkage, hardness, work and deformation). The basic third order polynomial equation was used to develop models for quality parameters: lightness, redness, yellowness, total color difference and shrinkage.
- In chapter 8, to determine the effect of drying parameters of the solar tunnel on the total color difference, hardness, shrinkage, phenolic content, ascorbic acid, the design of experiments techniques were applied. Three factorial ANOVA was used to analyze the quality parameters at $P<0.05$ significant level. The phenolic compound of potato was extracted according to Rumbaoa et al.(2009) method, and the extracted phenolic content of the potatoes was determined with Folin-Ciocalteu reagent according to the method of Slinkard and Singleton (1997). For Ascorbic acid extraction and determination, A certain amount of fresh, semi-dried and dried potatoes were prepared as explained in the European Standard EN 14130 (2003). Diluted meta-phosphoric acid was used to extract the fresh, semi-dried and dried samples. The suspension was filtered. An appropriate amount of the filtrate was diluted with an L-cysteine solution and adjusted to a pH value between 7.0 and 7.2. Then, the solution was stirred and then set to a pH value between 2.5 and 2.8. Prior to injection to the HPLC, the solution was diluted with ultrapure water. Hardness, work and deformation were analyzed by compression test using a texture analyzer (CT3-1500, USA) using Moreno-Perez et al. (1996) methods.
- In chapter 9, to bake bread, the solar dried potato and anchote slices were used, both ground separately, the flour of potato and anchote used as a partial replacement of wheat flour. The blend was designed using mixture design. The bread was baked using the straight-dough method

as described in the AACC(2000) methods. The sensory attributes; color, flavor, texture, and overall acceptability of the bread were evaluated using a five-point hedonic scale. Bread volume was measured by rapeseed displacement method.

1.2 The structure of the thesis

In Chapter 1, the general introduction, the statement of the problem, the objective and methodology were presented. In chapter 2, Potato production, the use, and handling system and the cause for the loss of potato tuber before and during storage were highlighted. In order to reduce the loss, the methods of drying and drier were suggested. The criteria of the dried product: such as optical, mechanical, physical, microbial and nutritional properties were discussed. The quality evaluating factors such as residual moisture content, glass transition temperature and drying processing condition were reviewed.

Chapter 3 is focus on optimum residual moisture content determination of dried potato. To determine the optimum residual moisture content of the dried product: the optimal water activity of the product reviewed. moreover, the experimental determination of desorption isotherm for potato, the corresponding mathematical evaluation for best fitting to different models, selection of the best model were investigated. The optimum residual moisture content of the product for three drying air temperatures was evaluated.

In Chapter 4 the optimum residual moisture content of drying potato slices, evaluated in chapter 3, were used as an input to stop the drying process. Moreover, the influence of processing parameters such as temperature, dew point temperature and air velocity on dying kinetics, kinetics of optical, and physical quality of dried potato slices were studied. In Chapter 5 optimization of the drying processing parameters such as temperature, dew point temperature and air velocity for optical, mechanical, and physical and nutritional quality product is evaluated.

To apply the concept of glass transition temperature to the drying process, there is a lack of an appropriate method for glass transition determination of real food. Therefore, Chapter 6 shifted to development and evaluation of a new method for glass transition temperature of potato. In chapter 7, the concept of glass transition temperature was applied to the drying process parameters for drying the product, and drying kinetics, optical, mechanical and physical quality parameters of dried potato are evaluated. Regression models for each quality attribute were developed.

In Chapter 8, the effect of variety, the thickness of the slices and position of the tray on quality parameters were observed. By applying potato in a solar tunnel drier. Drying kinetics, change in color, shrinkage, hardness, Vitamin C, total phenolic content were evaluated. In chapter 9 proof of utilization of the product was observed. In this chapter, the design and baking method for bread prepared from a blend of potato, Anchote and wheat flour were presented. The panelist evaluated the acceptance of the product. Finally, in chapter 10 Conclusion and recommendation regarding drying process optimization for drying potato were given.

2. State of the Art

2.1. Preservation

Preservation is a science, which deals with the process of inhibition of decay or spoilage of food thus it allowing it to be stored in a fit condition for future use(Brown, 2000). Preservation involved in inhibiting the growth of bacteria, fungi, and discoloration and ensures that the quality and the nutritive value of the food not damaged. Drying is one of food preservation methods that reduce water activity to which prevents bacterial growth. Starting from many centuries ago, fruits and vegetables were preserved through sun drying technique. The poor quality of the dried product and product contamination lead to the development of alternate drying technologies(Sagar & Suresh Kumar, 2010). Some of the applicable methods of drying include solar and cabinet or try (Sagar & Suresh Kumar, 2010). If adequately dried and properly stored, dried roots and tubers are shelf stable, and safe.

2.2. Drying methods and drier

There are numerous methods to dry food materials, and their advantage can be judged by the product quality obtained, energy utilization and safety depending on the market requirement (drying technology in food processing). Conventional drying process includes from the range natural sun drying to industrial drying. Some of the drying methods are sun drying, solar drying, and hot air drying; these methods use the direct sun, solar energy, hot air as drying mechanisms for drying the products respectively. Sun and solar drying are the most widely practiced method of drying.

The advantage of using sun drying is almost with no cost and ideal for products where little or no value is added. In sun drying method, there are uncertainties like rain and cloudiness, the product is exposed to dust contamination, the drying rate is very slow with the slow danger of mold growth, and it may not be possible to reduce to a required level of the moisture content of the product. This method is not suitable for drying product sensitive to oxidation reaction like a potato.

Solar drying method uses a simple dryer construction for more effectively make use of the sun heat. Under the correct climatic conditions, solar drying can provide many advantages over Sun drying at higher drying temperatures, which result in shorter drying times, the ability to dry to a lower final moisture content, Protection from dust contamination and from rain, low cost, and simple to construct in local workshops. The solar dryer has the disadvantage of being easily damaged by strong winds.

A hot air drying provides many advantages over sun drying and solar drying. It is possible to control the processing parameters, not dependent on weather condition, shorter drying time and the ability to dry to lower final moisture content. The disadvantage of hot air drying over sun drying and solar drying it needs high capital cost and high-energy consumption.

Using hot air dryers in commercial countries are found to be economically feasible. In Africa, only industries afford hot air dryer, but it is not affordable by small scale and medium entrepreneurs because of high cost(Tiwari, 2016). In the tropical region, solar tunnel dryer may become a more convenient alternative for rural sector and small-scale industry, and other areas in which electricity is scarce. In addition, it preserves crops, reduces the quality deterioration of dried product significantly and is economically beneficial compared to sun drying method(Sacilik, 2007). In the industrial level, using hot air drier is recommended based on its merit compared to sun drying and solar tunnel drier.

2.3. Tuber utilization

On the global basis, the potato is an important commercial crop with multiple uses(Stearns et al., 1994). Potatoes serve as a raw material for food and industrial products such as Potato soup, canned potato salad, beef stew, canned French fries, Potato chip, French fries, confections and etc. Dehydrated potato used for preparing product like potato granules, potato flakes, diced potatoes and potato flour. Potato flour is used as an ingredient for baking bread and snack-type crackers (soda and graham). Potato also used as a source of starch and Alcohol production. The potato starch has been used as a thickener in soups, gravies, and matzoth in the food industry. Potato peel and products derived from processing wastes used for animal feed. It is used as seed tubers for growing the next season's crop. In Ethiopia, potato mostly used as a stew, consumed after boiling, roasting and frying. The use of potato tuber as a household consumption is increasing rapidly in Ethiopia more than any other major food crops (Ayalew *et al.*,2014). Although, some food processing industries exist in Ethiopia; none of them are involved in the processing of potatoes(Tekalign, 2011).

Anchote (*Coccina abyssinica*) is high calcium content tuber crop and indigenous to Ethiopia (Yosef and Tileye, 2013). According to Gemede & Fekadu (2014), the raw anchote is a good source of calcium and protein as compared to others root and tubers. It also contains magnesium, iron, carbohydrate, crude protein and crude fiber. Traditionally farmers used as medicinal food for the fast mending of broken and displaced joints, as it contains high calcium and proteins than other common and widespread root and tuber crops. They also believed that Anchote makes lactating mothers healthier and stronger. The mode of consumption of anchote is rarely eaten raw and traditionally after boiling without peeling or by peeling the tuber(Gemede & Fekadu, 2014).

2.4. Potato handling

Potato has superior dietary fiber with a small amount of fat (0.1%) with the majority being the unsaturated fatty acid (linoleic acid). It is also nutritionally superior, rich in potassium, and a good source of phosphorus, antioxidant (phenolic compound) and vitamin C, and provides important Vitamins B plus minerals like potassium, copper, magnesium, and antioxidants(Brown, 2005). Potato is a starchy, tuberous and fourth-largest food crop in the world, next to rice, wheat and maize (Spooner 2005). It is originated in the high Andes of South America and grown throughout the world(Gedif and Yigzaw, 2014). This crop was introduced to Ethiopia in 1858 by the German botanist known as Shimpe(Gedif & Yigzaw, 2014). In Ethiopia, production of Potato has increased from 509,716 tonnes in 2014/2015 to 921,832 tonnes in 2015/6(Gebru, et.al., 2017).

After harvest, potatoes should be selected free of cracks, cuts and contusions. The humid potatoes need to be dried, stored in a cool and shady place after harvested. Fast transportation of potatoes (from farm to storage) is suggested, in order to prevent potato damage that can result from sun, heat and wind. Potatoes dedicated to direct consumption should not remain exposed to light for many hours after harvest because they acquire a green color, unpleasant flavor and can become toxic(formation of solanine) (FAO). Improper handling and transportation contribute to loss of tubers.

Storage of tuber is the action of putting for future use with the objective of maintaining the quality and minimizing the losses of the tubers weight. Potato should be stored in dark atmospheres with good ventilation, low temperatures (6 to 8 centigrade degrees) and high relative humidity (85 to 90 percent). In Ethiopia, Farmers use different traditional potato storage methods such as leaving the tubers in the soil un-harvested (postponed harvesting), light place in the house, dark place in the house, raised beds and in sacks (Adane *et al.*, 2010). These storage methods are very critical in affecting the tubers quality. Due to the lack of appropriate storage for preservation of potatoes, most producers are forced to sell their products immediately after harvest, losing their profits with rising economic liability. As stated in the introduction part, the losses of root and tuber crops in the world in the range of 30% to 60% (FAOSTAT, 2004). According to Ayalew *et al. (*2014), potato yield loss in Ethiopia reached 30% to 50% due to improper storage systems and post- harvest handling problems.

2.5. Quality

Quality of dried product

Consumer demand has increased for dried products that maintain more of their original characteristics. The most common properties of dried products can be classified:

- Optical properties: color, appearance
- Mechanical properties: texture
- Physical properties: shrinkage, specific volume, density, porosity
- Nutritional characteristics: vitamins, proteins and
- Rehydration properties: rehydration rate, rehydration capacity and
- Microbial properties: safety, stability

2.5.1. Optical properties

Color, flavor, taste and shape are the four important factors affecting people's choice of foods, and they are the basis for selection or rejection of the product. Color can change during drying due to chemical and biochemical reactions. The rates of both reactions depend strongly on the processing parameters and drying methods (Tsotsas and Mujumdar, 2011). These reactions are fast when the samples are processed above its glass transition temperature. Since the increase in temperature of a product above its glass transition temperature increases molecular mobility and also affects diffusion of the matrix and results in an increase in rates of deterioration: enzymatic reaction, non-enzymatic browning and oxidation(Roos, 1992). Karmas et al.(1992) studied the effect of glass transition on rates of non-enzymatic browning in food systems and reported the presence of very slow browning below glass transition temperature. Rahman (2012) also reports the stability of foods in the glassy state since in the state compounds involved in the deterioration reactions take times to diffuse over molecular distances and approach each other to react. Even though glass transition temperature of food products has been pointed out to be responsible for the deterioration mechanisms during processing, and an indicator of food stability, quantifiable expressions between quality parameters and glass transition have not been fount yet(Ratti, 2001).

2.5.2. Physical properties

Shrinkage is the physical property among the most important factors affecting people's choice of foods, and it is a base for selection or rejection of the product. According to Mayor & Sereno (2004) during drying, when moisture is removed from tubers, there is a pressure imbalance between inside and outside of the potato slices. The pressure imbalance between inside and outside of the potato slices generate contracting stresses leading to samples shrinkage or collapse. Shrinkage is a phenomenon, which is expected during drying of potatoes. High shrinkage in many cases resulted in a decrease of rehydration and a negative impression to customers(Mayor & Sereno, 2004). According to Bonazzi and Dumoulin, (2011), at lower drying temperatures a more uniform moisture distribution exists, inducing less internal stresses that allow the sample to continue to shrink until the last stages of drying. On the contrary, at higher air temperatures, case hardening of the surface may occur, and the volume of the sample becomes fixed at an earlier stage, inducing less shrinkage and a more intensive pore formation. Bonazzi and Dumoulin, (2011) report a significant change in volume can only be noticed if the solids remain in the rubbery state, at a temperature above Tg for the particular moisture content. Above Tg, the viscosity of the material drops considerably, to a level that facilitates deformation.

2.5.3. Mechanical properties

Texture plays a subsequent after color, flavor, taste and shape, but also an important role, once the foods are consumed. During drying, change in moisture content of high moisture materials like potatoes induces the structure of the material, its composition and the spatial conformation of biopolymers. Because of water removal, destruction of natural structures and loss of semipermeable of the membranes occurs hence rheological properties also change. The outer layers of drying material become rigid and acquire considerable mechanical strength(Lewicki & Jakubczyk, 2004).Texture is a quality of brittle materials that rapidly fracture under stress at small strains and has been studied both by instrumental and sensory techniques(Miranda et al., 2006). A brittle object will exhibit a large hardness, low work to fracture and a sudden drop in force as the crack propagates rapidly(Miranda et al., 2006).

2.5.4. Nutrition value

The retention of nutrition of the tubers should be considered during drying. According to Mclaughlin & Magee (1998), one of the main quality aspect associated with the drying of potatoes is the retention of vitamin C. Vitamin C (ascorbic acid) is usually selected as an index of the nutrient quality due to its easily reactive nature as compared to the other nutrients in foods (Lee and Kadir, 2000). During the drying process, the ascorbic acid degradation was found to be more dependent on the drying condition (especially temperature, moisture and time)(Santos & Silva, 2008). Phenolic compound is one of the important antioxidants found in potatoes (Rumbaoa et al., 2009). The presence of antioxidants in our food can increase cellular defense, and help to prevent oxidation damage to a cellular component of our bodies. It is used to maintain health and prevent diseases such as cancer and coronary heart (El-Far & Taie, 2009).

2.5.5. Microbial quality

Dried root and tubers are considered safe with respect to the microbial hazard. According to Odoli (2015), the undesirable effects of microbial activities in food are the development of sour flavor, discoloration, and undesirable texture, reduction in the content of protein and vitamin, development of food born infection and toxicity. Water activity, moisture sorption isotherm and glass transition temperature (Tg) are essential evaluating criteria in determining microbial quality during drying. The concept of water activity has been used as a reliable assessment of the microbial growth, lipid oxidation, non-enzymatic and enzymatic activities(Sablani, 2007). It helps to decide a_w of the drying sample at which the sample is stable. Once a_w of the samples at which the sample could be stable is known. From moisture sorption isotherm data it is possible to predict the corresponding optimum residual moisture content of the drying sample to decide the end-point of drying process(Kiranoudis, 1993). Whereas the glass transition temperature can be taken as a reference parameter to characteristic properties of safety, stability, and quality(Emy, Dupas, & Jin, 2012).

2.6. Quality influencing factors

2.6.1. Raw material

It is clear that the drying process reduces both the quality and nutritional content of the product. Therefore, a high quality of dried food must come from a high-quality raw material keeping others factor constant. Different varieties have a different composition. This resulted in the different quality of the products. Even different cultivars of the same variety can produce dried products of very different qualities may due to differences in composition. The composition of the tubers depends on agronomic, storage condition and so on. During the drying processes, dry matter and reducing sugars contents are the most important interferers, since tuber characteristics are variable, due to environmental and cultivar-intrinsic factors. Thus, specific gravity can indirectly provide a dry matter content estimate and is also related to industrial yield final product quality. Specific gravity studies have revealed that a negative correlation exists with reducing sugars content and a positive correlation exists between dry matter content(Feltran et al., 2004).

2.6.2. Water activity

Water activity is an important quality evaluation parameter as can influence the color, texture, shape, shelf life and nutritional property of a drying product. The basic objective of drying potato is the reduction of moisture in the product up to a certain level, at which microbial spoilage and deterioration chemical reactions are greatly retarded (Doyamaz and Pala, 2003). The chemical, physical and microbiological stability of drying sample highly depends on the water content and its interaction with food ingredients(Sablani, 2007). As for drying precede, the moisture content of the samples decreases with a decrease in water activity (Fig 2.1).

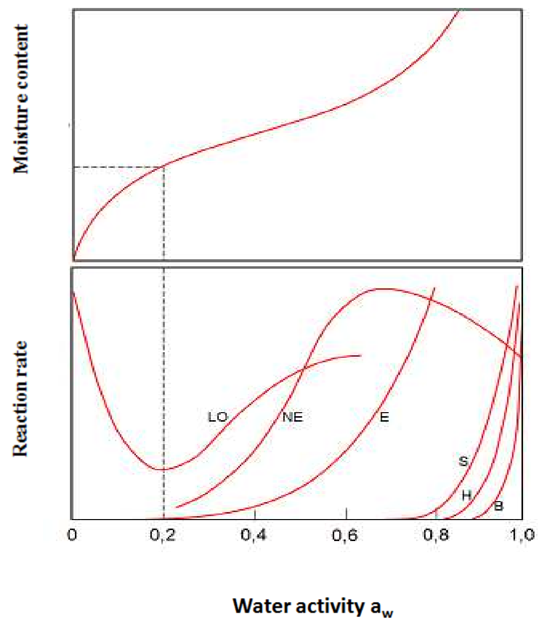


Fig 2.1. Stability diagram. LO lipid oxidation, NE non-enzymatic browning, E enzymatic reactions, S, H, B spoilage by mold fungi, yeasts, bacteria [Labuza et al., 1972 modified by Sturm et al., 2010] (The language is translated from German to English version)

In Fig 2.1, the trends of microbial growth and bio-chemical reactions are presented as a function of water activity. From a_w map, it is clearly observed that, above aw greater than 0.7, stability can be decreased with increasing water activity due to mold fungi, yeasts and bacteria growth. In a range of a_w between 0.2 and 0.7 stability can be decreased with increase in a_w due to lipid oxidation, non-enzymatic browning and enzymatic reactions. In a range below a_w less than 0.2, stability can be decreased with a decrease in a_w due to lipid oxidation. With a_w at 0.2, the product is most stable with respect to non-enzymatic browning, enzyme activity, lipid oxidation, and of course, the various microbial parameters. Rahman (2012) also reported most stability of a dried product at its monolayer moisture content and its instability above or below monolayer. Therefore, ending the drying processes both above and under optimal residual moisture content (at a_w=0.2) have a negative impact on quality of the product.

2.6.3. Desorption isotherms

At a given temperature, the relationship between a_w and corresponding moisture content is characterized by the moisture sorption isotherm(Sablani, 2007). An increase in a_w is always accompanied by an increase in the water content in a nonlinear fashion. It is necessary, to fit the experimental data into an appropriate model in order to predict or calculate the equilibrium moisture content of the drying sample at specific $a_{w.}$ Wang & Brennan (1991), McLaughlin & Magee (1998), McMinn & Magee (2003), Chemkhi & Zagrouba (2011) fit the experimental date of desorption isotherm of potato to different models. All of them reported the suitability of GAB model (equation 1) for representing the relationship between the a_w and the equilibrium moisture content of potatoes. However, the equilibrium moisture content values obtained at a specific water activity by different authors for the same product (potatoes) using the same model (GAB) are not similar as shown in Table 2.1. Therefore, Determination of desorption isotherm of potatoes was preferred to get the accurate value of optimum residual moisture content.

$$M = \frac{M_o C K a_w}{(1 - k a_w)(1 - K a_w + C K a_w)} \quad (1)$$

Table.2.1: Constant values of GAB model of desorption isotherm of potatoes at temperature of 50, 60 and 70 °C

Xm	K	C	E%	T (°C)	M (kg/kg, dry base) at $a_{w=0.2}$	Authors
0.209	0.976	4.416	0.538	50	0.26	Chemkhi & Zagrouba 2011
0.061	0.82	8.89	6.74	50	0.13	Wang & Brennan, 1991
0.053	0.84	8.57	4.59	60	0.11	Wang and Brennan, 1991
4.620	0.84	19.99	3.13	60	11.59	McLaughlin & Magee, 1998
0.042	0.738	4.68	5.58	60	0.04	McMinn & Magee, 2003
0.086	0.993	3.316	0.143	70	0.09	Chemkhi et al., 2011
0.057	0.800	4.37	9.15	70	0.06	Wang and Brennan, 1991

2.6.4. Glass transition temperature

Glass transition temperature (Tg) represents the pattern of change in the state of a material as a function of decreasing the levels of moisture content(Rahman,2009). Glass transition temperature (Tg) indicates the molecular mobility starting point of the solid matrix. In the glassy state, molecular mobility is extremely slow, due to the high viscosity of the matrix. The increase in temperature of a product above its Tg increases molecular mobility and also affects diffusion of the matrix and results in an increase in rates of deterioration:

enzymatic reaction, non enzymatic browning and oxidation(Roos, 1992). Thus, the Tg value can be taken as a reference parameter to characterize properties like quality, stability and safety of food systems(Emy et al., 2012). Foods can be considered as stable in the glassy state since in the state compounds involved in the deterioration reactions take times to diffuse over molecular distances and approach each other to react(Rahman, 2012). Sablani (2007) pointed out that certain physicochemical and structural processes such as stickiness, crispness, collapse, amorphous-to-crystalline transformations and the rates of non-enzymatic browning are better correlated to the glass transition temperature through plasticization by water or temperature than water activity.

2.6.5. Processing parameters

During drying, besides water activity and glass transition temperature, many factors having positive and negative effects on quality of dried root and tubers must be considered: such as the temperature, the air velocity, and humidity conditions during processing.

In hot air-drying, the samples gain heat due to the temperature gradient between the air and the samples. The application of heat to root and tubers at a high temperature for an adequate length of time will inactivate enzymes present. Several problems may arise through the use of heat. According to Chen, (2008), low-temperature drying processes are favorable for keeping the high bioactivity of desired bio-components, and high loss of quality in the final product. Therefore, a minimal change in nutritional values is targeted during low-temperature processes. Nevertheless, the unwanted microbial activity could also be preserved in the food material. In another hand, high-temperature thermal treatments, although highly effective in deactivating unwanted bacterial activity, also severely degrades other essential food ingredients. Keeping a good balance between these two aspects of inactivation can certainly help improve the overall quality of dried products (Chen, 2008). Marcel et al., (2014) studied the influence of air temperature and two drying principles namely: parallel airflow and traversing airflow on the color loss of pineapple slices. Finally, they concluded the pineapple slices dried at high temperature resulted in more deterioration in color.

During drying, using low dew point temperature and high air velocity has a positive effect on quality of the product. Drying took place due to heat and mass transfer. The temperature gradient between potato slices and the air is the driving force for heat transfer from air to the potato slice. The driving force for mass transfer (moisture removal) from potato slices to the air is vapor pressure difference between the sample and the air. As the heat is conducted through the potato slice, the temperature within the slices rises. Since this process involves a simultaneous heat and mass transfer phenomenon, heat gained from air increases the water vapor pressure of the moisture present within the food matrix. when the medium used for drying the potato slices has a low value of water vapor pressure at high temperatures; this creates a high vapor pressure gradient between the moisture present in the potato slices and the moisture in the air, which is responsible for fast the moisture migration or the mass transfer phenomenon. Fast moisture migration due to a low dew point temperature and high speed of air velocity reduces the drying time of the product. Reduction in drying time of the product reduce different the reaction took place in potato slice and positive influence on the quality of the product. Sturm et al. (2007) studied the influence of air velocity on drying kinetics, color changes, shrinkage and rehydration of dried apples. They report an Increasing air velocity had a positive influence on drying kinetics as well as the development of quality parameters throughout the investigated parameter space.

2.7. Proof of utilization

Finally, the dried product needs to be checked for proof of utilization. Dehydrated potato used for preparing product like potato granules, potato flakes, diced potatoes and potato flour. Potato flour is used as an ingredient for baking bread and snack-type crackers (soda and graham) (Stearns et al., 1994). Potato flour as partial replacement of wheat flour in bread: baking and nutritional value of bread containing graded levels of potato flour were studied by (Trejo et al., 1981) and report the feasibility of the incorporation of potato flour in bread making. Bread made from composite wheat -sweet potato flours was evaluated by (Yanez et al., 2014). Based on sensory properties, wheat flour replacement with 10% sweet potato flour yielded good quality bread. The success of product development of bread will depend on the consumers' acceptance of the developed product.

As mentioned in the literature review, there is a limitation to the method used for the determination of the glass transition temperature of real starchy products. In this research, a new method for determining the glass transition temperature of potato was developed. Appropriate methods were used for the determination of the quality parameters of dried potato slices and bread. The descriptions and testing methods used for determination of the quality parameters of dried Potato slices and Bread is presented in Table 2.2.

Table 2.2: Determination of the quality parameters and evaluating criteria of the products

Description	Testing method
Moisture content	using a laboratory convection oven for 48 h at a a constant temperature of 70 °C
Desorption isotherm	European Cooperative Project COST 90, Wolf *et al.* (1985)
Optimum moisture content	Fit to GAB model at a_w=0.2
Vitamin C	HPLC and Redox titration
Color	CIELAB system and Sturm and Hofacker (2009)
Shrinkage	Sturm and Hofacker (2009)
Texture	Compression test
Specific gravity	Wisler and Free (1968)
Total phenolic content	Slinkard and Singleton (1997)
Drying kinetics	Fit to Midilli et al. (2002) model
Glass transition temperature	Change in mechanical properties (new method developed)
Bread baking	AACC(2000)
Color, Flavor, Texture and overall acceptability of the bread	5 point hedonic scale
Specific volume	rapeseed displacement method (Chopin, 2000)

3 Optimum Residual Moisture Content

To avoid excessive or insufficient drying of the potato slices, the optimum residual moisture content of drying potato slices at optimum water activity was determined. The equilibrium moisture content at a_w of 0.2 is an optimal residual moisture content of the product to produce a safe and stable product(Figure 2.1). It is necessary to know the water activity and moisture content relationship in the drying samples to end the drying process at its optimal moisture content. In this chapter, In order to get the accurate value of optimum residual moisture content of the product, the desorption isotherm of potato slices was first determined. Then, desorption isotherm models were evaluated. Finally, the optimum water activity of the samples was substituted to the best model.

3.1 Desorption Isotherm

The relationship between a_w and moisture content at a given temperature is called the moisture sorption isotherm. Once a_w of the potato at which the sample could be stable is known, and by using the moisture sorption isotherm data, it is possible to predict the corresponding optimum residual moisture content of the drying potato slices to decide the end-point of the drying process.

3.1.1 Materials and Methods

3.1.1.1 Preparation of Samples

Potato of Belena variety was purchased from a local farmer (Lake Constance Region, Germany) and was stored at a temperature of 4°C. Prior to conducting each experiment, the potatoes were washed, carefully selected free of any damages like bruises, and then thinly cut into slices of 2 mm thickness using an electric food slicer (Graff, Germany).

3.1.1.2 Determination of Desorption Isotherms

The standard static gravimetric method indicated in European Cooperative Project COST 90, Wolf et al. (1985) was used to determine desorption isotherms of potatoes. Eight saturated salt solutions were selected to get different relative humidity. The salt solutions were prepared according to COST-90 Project (Table 3.1). The relationship between water activity (a_w) and high temperature of saturated salt solutions was calculated using Equation 3.1 as reported in Labuza (1985). In order to prevent fungal activity, a small quantity of thymol was placed in a glass jar (Wolf *et al.,* 1985). Triplicate samples of 3 g ± 0.00 1 g were used to determine desorption isotherms at temperatures of 60 °C, 70 °C and

80 °C. The samples were weighed in an interval of 24 h, and were allowed to equilibrate until there was no significant weight change, as evidenced by the difference between two consecutive measurements of weight values equal to ±0.001 g.

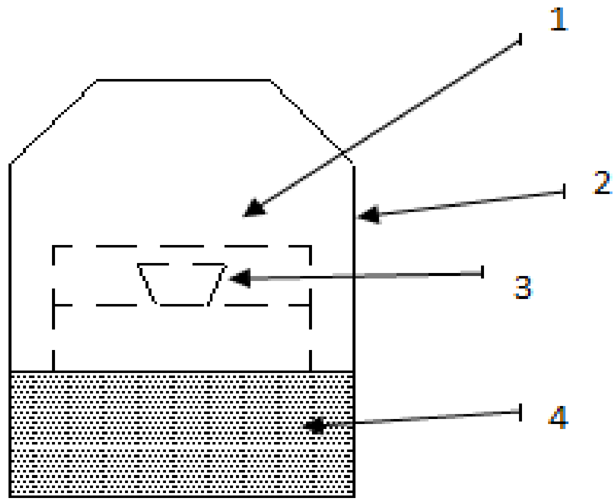


Figure 3.1: schematic diagram of the equipment for determination of equilibrium moisture content (1= Samples, 2= glass jar, 3= thymol 4= salt solution)

Table 3.1: Quantities of salt and distilled water used in the preparation of saturated salt solutions (Wolf et al., 1985) according to COST-90 Project

	Salt (g)	H_2O	60 °C a_w	70 °C a_w	80 °C a_w
LiCl	75	42	0.096	0.092	0.088
CH_3COOK	200	75	0.175	0.162	0.151
K_2CO_3	200	90	0.421	0.416	0.411
$Mg(NO_3)_2$	150	23	0.473	0.458	0.454
NaBr	200	80	0.490	0.471	0.454
NaCl	200	60	0.703	0.689	0.676
$(NH_4)_2SO_4$	200	60	0.788	0.783	0.778
KCl	200	80	0.751	0.727	0.705

$$\ln(a_w) = \frac{K_1}{T} - K2 \tag{3.1}$$

where: K_1 and K_2 are the constants for each of the different salts; T is the temperature in Kelvin. Table 3.2 gives the values for a range of salts based on experimental data reported in Labuza (1985)

Table.3.2 : Constant values of different salts(Labuza, 1985)

Salt	K_1	K_2
Lithium chloride (LiCl)	500.95	3.85
Magnesium nitrate ($MgNO_3$)	356.6	1.82
Potassium acetate ($KC_2H_3O_2$)	861.39	4.33
Potassium carbonate (K_2CO_3)	145.00	1.3
Potassium chloride (KCl)	367.58	1.39
Sodium chloride (NaCl)	228.92	1.04
Sodium bromide (NaBr)	447.81	2.06
Ammonium sulfate $(NH_4)_2SO_4$	76.8191	0.469

3.1.1.3: comparison of desorption Isotherm models

The values obtained from the experiment were fit to GAB, Oswin, BET and Halsey models. The non-linear regression was used to fit the experimental data to the models.

Table 3. 3: Models fitted to determine desorption

Name of models	Models
GAB(Van Den Berg and Bruin, 1981)	$EMC= CKX_m a_w/[(1 - Ka_w) \quad (1 - Ka_w, + CKa_w)]$
Oswin (Oswin, 1946)	$EMC= A(a_w/(1 - a_w))^B$
Halsey(Halsey, 1948)	$aw = \exp(-A/EMC^B)$
BET(Brunauer *et al.,* 1938)	$EMC= CX_m a_w/[(1 - a_w)+(C-1)(1-a_w) a_w]$

A, B, C and *K* = constants in sorption isotherm models; a_w=water activity; *EMC* = equilibrium moisture content (dry basis); X_m = monolayer moisture content (dry basis)

3.1.1.4 Evaluation of Models

To evaluate how good the fit of each equation is, the mean relative percentage deviation modulus (E) was used (Aguerre *et al.,* 1989) and defined as indicated in Equation 3.2:

$$E(\%) = \frac{100}{N}\sum_{i=1}^{N}\frac{M_i - MP_i}{M_i} \qquad (3.2)$$

where M_i and M_{Pi} are the experimented and predicted values, respectively, and N is the number of experimental data.

3.1.2. Results and Discussion

3.1.2.1 Equilibrium Moisture Content and Water activity

The equilibrium moisture content of potatoes versus a_w at different temperature levels (60 °C, 70 °C, and 80 °C) are presented in Figure 3.2. From this graph, an increase in equilibrium moisture content with increasing water activity at constant temperature can be clearly seen. This change in the equilibrium moisture content is due to difference in vapor pressure gradient between the samples and the water activities of the solution (atmospheric humidity). At a constant water activity, equilibrium moisture contents increase with decreasing temperature. McLaughlin & Magee (1998) report that an increase in temperature will decrease the binding energy between molecules due to an increase in state of excitation; thus, the molecule's mutual distances increase and the attractive forces decrease. Quirijns et al.(2005) also reports that an increase in temperature induces a reduction in the equilibrium moisture content at a specific water activity since the molecules become less stable and break away from the water binding site of the food materials.

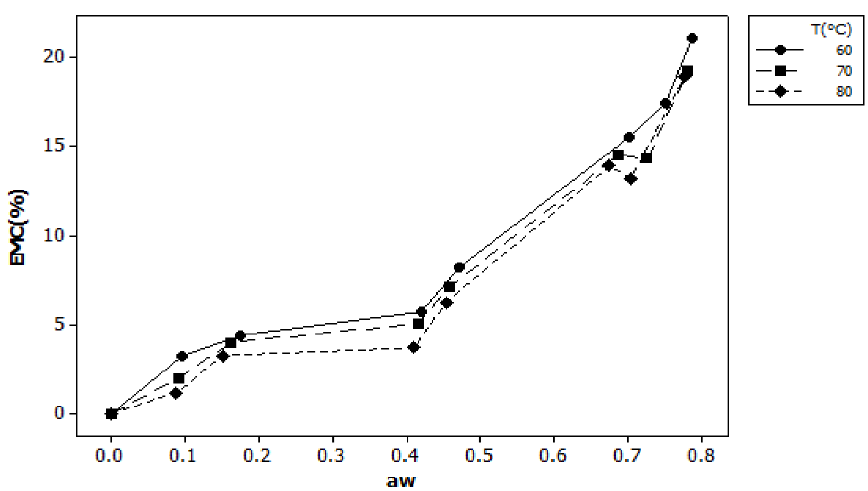


Figure 3.2: Desorption isotherms of potatoes at different temperatures.

3.1.2.2 Fitting of Models to Isotherm Graphs

The parameters shown in Table 3.4 were estimated by fitting the mathematical model to the experimental data, using the method of direct nonlinear regression. The mean relative deviation modulus (E) and the estimated constants for the models in Table 3.3 are presented in Table 3.4. A model is considered to be suitable if its E value is less than 10% (McMinn & Magee, 2003).

As indicated in Table 3.4, all models, except Hasely, showed a smaller mean relative percentage deviation (E<10%); therefore, they were suitable for fitting experimental data. However, among all models, the smallest mean relative percentage deviation was obtained for the GAB model. This shows that the GAB model gave the best fit for desorption isotherm of potatoes. This agrees with the results reported in Wang & Brennan (1991) and Kaymak-ertekin & Gedik (2004). Figure 3.3, Figure 3.4, and Figure 3.5 depict comparisons of data between experimental and predicted values of desorption isotherm at 60 °C for GAB, BET, and Oswin models, respectively. The figures show a reasonable agreement between experimental and predicted values. However, a model following Halsey's concept (Halsey, 1948) showed a poor fit over the entire range of equilibrium moisture contents. As shown in Figure 3.6, the theoretically predicted isotherm lies below the experimentally determined isotherm and large mean relative percentage deviations (greater than 10%) were obtained. The result also agrees with the result of Wang & Brennan (1991).

Table 3.4: parameter values for all models in desorption

Models	Parameters	Temperature (°C)		
		60	70	80
GAB	Xm	6.569	6.564	6.136
	C	5.517	4.311	4.158
	K	0.860	0.840	0.820
	E%	**3.022**	**1.052**	**0.887**
Oswin	A	8.997	7.990	7.279
	B	0.626	0.668	0.758
	E%	**3.495**	**2.787**	**3.803**
Halsey	A	0.019	4.14E+027	2.688
	B	0.006	1.55E+027	1.152
	E%	**48.92**	**48.43**	**50.57**
BET	Xm	0.290	0.346	0.521
	C	16.941	13.699	9.674
	E%	**4.987**	**4.048**	**4.017**

As shown in Table 3.4, the monolayer moisture content values of constant K and C of the GAB model decrease as the temperatures increase. The decrease in monolayer moisture contents might be due to structural modification in starch polymers with an increase in temperature (McLaughlin & Magee, 1998). An increase in temperature results in the reduction in the degree of hydrogen bonding in the polymers, thereby decreasing the availability of active sites for water binding and, thus, the monolayer moisture content(McLaughlin & Magee, 1998).

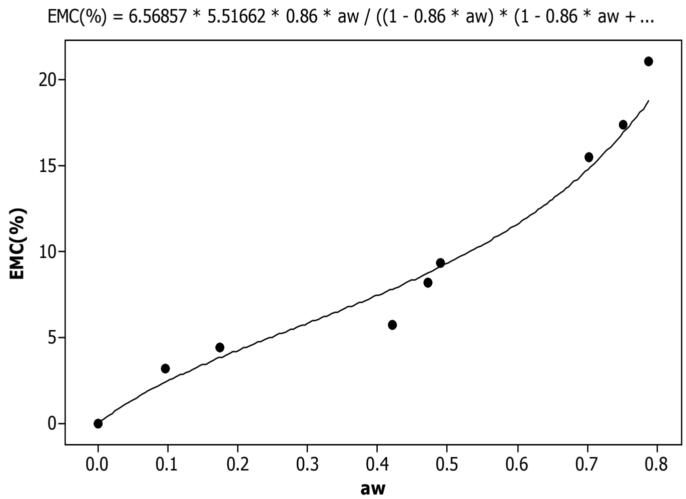


Figure 3.3: Comparison between experimental and predicted values of the desorption isotherm using the GAB equation at a temperature of 60°C.

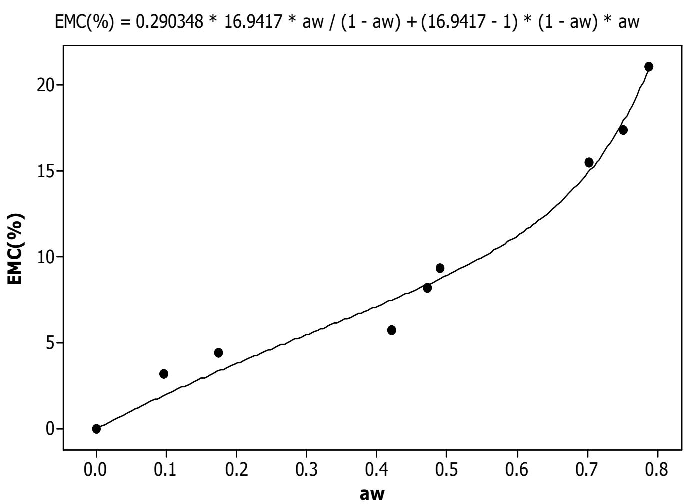


Figure 3.4: Comparison between experimental and predicted values of the desorption isotherm using the BET equation at a temperature of 60 °C

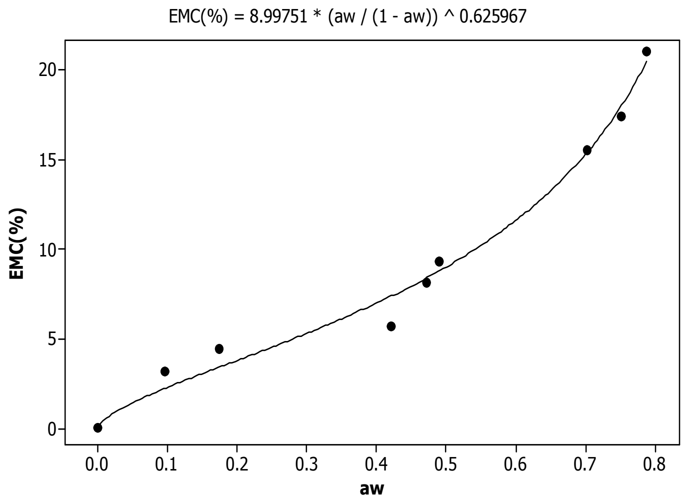


Figure 3.5: Comparison between experimental and predicted values of the desorption isotherm using the Oswin equation at a temperature of 60°C.

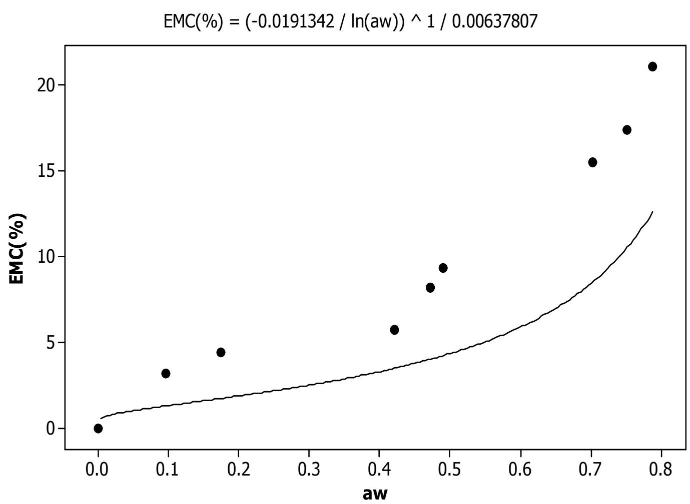


Figure 3.6: Comparison between experimental and predicted values of the desorption isotherm using the Halsey equation at a temperature of 60 °C

3.2. Optimum Residual Moisture Content Calculation

To determine the residual moisture content of the sample during drying, GAB model was used since this model is a best fit for the experimental data. The corresponding equilibrium moisture content of the samples was calculated by substituting the water optimum activity in GAB model as indicated in Table 3.5. The result shows that the equilibrium moisture ratio of the sample at water activity of 0.2 recorded 0.042, 0.036 and 0.0.3 (dry bases) for sample's dried at temperatures of 60 °C, 70 °C and 80 °C, respectively. This shows that the samples of potato slices have to be dried until the moisture ratio of the samples reached 0.042, 0.036 and 0.033 in dry base for temperatures of 60 °C, 70 °C and 80 °C, respectively.

Table 3.5: Optimum residual moisture content at a water activity of 0.2

GAB model equation	T (°C)	X_m	C	K	MR
EMC= $CKX_m a_w/[(1 - Ka_w)\ (1 - Ka_w, + CKa_w)]$	60	6.569	5.517	0.860	0.042
	70	6.564	4.311	0.840	0.036
	80	6.136	4.158	0.820	0.033

3.3. Conclusions

It has been shown that the GAB model can be very well applied to represent the relationship between the water activity and the equilibrium moisture content of potatoes. Optimum residual moisture contents (MR) of dried potato slices at a water activity of 0.2 were 0.042, 0.036 and 0.033 in (db) at temperatures of 60 °C, 70 °C and 80 °C, respectively. Therefore, according to the water activity concept, in order to have stable dried potato slices to stop the drying process, moisture ratio of 0.042, 0.036 and 0.033 were recommended for the samples dried at a temperatures of 60 °C, 70 °C and 80 °C respectively.

4. Processing Parameters on Drying Kinetics and Quality Attributes

The optimum residual moisture content of the potato slices was taken in to consideration for ending the kinetics result of quality parameters of the dried product. Knowing the behavior of the product might be an indication for the need of optimizing the processing parameters as well as for taking any action for best product production of the potato slices. By investigating the influence of processing parameters on quality of the product, the behavior of the product in response to the processing parameters is attained. The objective of this section is to determine the influence of processing parameters on drying kinetics and quality of hot air dried potato slices.

4.1. Material and Methods

Belana variety of potatoes was purchased from a farmer of Lake Konstanz and stored in the fridge at 4°C. Prior to starting each experiment, the potatoes were washed, selected free of mechanical damage and then sliced into chips of 3.5 mm thickness using an electric food slicer (Graff, Germany). Seven slices from the same tuber were taken for each experimental run to minimize the error caused by heterogeneity in raw material.

The drying device comprises of three main parts: the humidifier, the air heater, and the drying chamber. Ambient air is sucked into the humidifier by a radial fan. The humidifier consists of spray nozzles, a packed bed, a water bath (50 l), a heater (31 kW) and a refrigerating unit (8 kW). Three Pt-100 sensors were inserted into the humidifier (one for controlling water bath temperature, and the other two for monitoring the dew point and dry bulb temperature of the air). The air passes the packed bed in counter flow to the water. The water needed for humidifying the air is taken from the tap. The air heater includes four heating units (40kW). After passing the heater, the air is led into the drying chamber in the through flow. Air temperature is measured using Pt-100 sensors placed at the respective inlets. Air velocity is measured using a hot wire anemometer. A precision pyrometer (Heitronics KT15II) is installed on the top of the drying chamber for non-invasive determination of surface temperature. The system is controlled using a programmable logic control (Siemens S7=300). Programming of the PLC and data acquisition is carried out using the human-machine interface (HMI) software WinCC. Data is saved in the CSV format and processed in Microsoft Office Excel. The schematic diagram of the drier is presented in Figure 4.1.

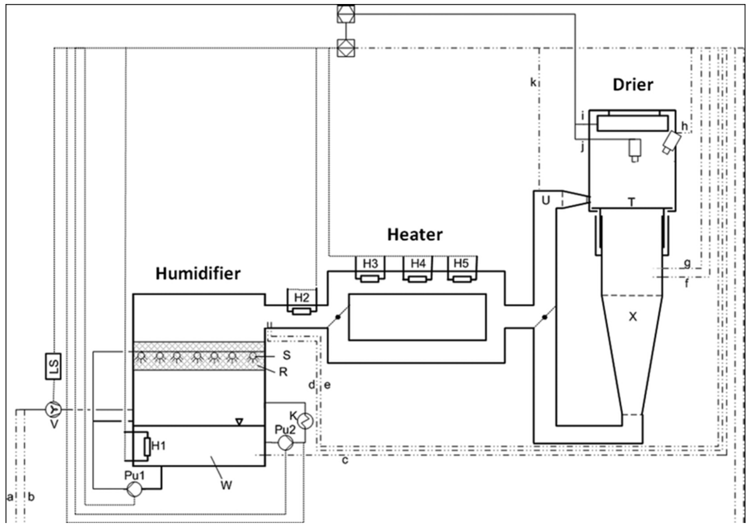


Figure 4.1: Experimental set-up: where, a: ambient temperature (Pt-100); b: air velocity (hot wire anemometer); c: water bath temperature (Pt-100); d: dry bulb temperature (Pt-100); e: wet bulb temperature (Pt-100); f:temperature trough flow unit (Pt-100); g: pressure difference measurement device; h: product temperature (pyrometer); i: weight (balance); j: CCD camera; k: temperature over flow unit (Pt-100). H1: water heating unit; H2-H5: air heating unit; K: water chiller; LS: power controller; Pu1: pump primary circuit; Pu2: pump secondary circuit; R: packed bed; S: spray nozzles; T: drying chamber; U: Overflow Unit; V: fan; W: water bath;X: through flow unit(Sturm et al.,2012).

The dry mass of the product was determined by the gravimetric method using a laboratory convection oven (Heraeus UT 12) over 48 h at a constant temperature of 70 °C. The moisture content (MR) at each measurement time was calculated as a ratio of current moisture content to the initial moisture content of the samples. Drying rates for each treatment were calculated based on the weight of water removed per unit time per gram of dry matter. The drying kinetics experimental data fit to the model of Midilli et al. (2002) are represented in Equation 4.1. To determine the quality of the fit of drying kinetics model, root mean square error (RMSE), chi-square(x^2), R-square(R^2) and mean absolute error (MAE) were used. Higher values for R^2 and lower values for x^2, MAE, and RMSE indicate a better model fit. These can be calculated as follows in Equation. 4.2 - 4.5

$$MR=a\exp(-kt^n)+bt \qquad (4.1)$$

$$R^2 = 1 - \frac{\sum_i^N (MRexp_i - MRpre,_{i)})^2}{\sum_i^N (\overline{\text{MRexp}} - MRpre,_i)^2} \qquad (4.2)$$

$$x^2 = \frac{\sum_i^N (MRexp,_i - MRpre,_i)^2}{N-Z} \qquad (4.3)$$

$$RMSE = \left(\frac{1}{N}\sum_{i}^{N}(MRexp_i - MRpre_i)^2\right)^{1/2} \quad (4.4)$$

$$MAE = \frac{1}{N}\sum_{i}^{N}|MRpre_i - MRexp_i| \quad (4.5)$$

where N is number of observation, Z the number of model konstant, $MRexp_i$ the experimental moisture ratio, $MRpre_{,i}$ the predicted moisture ratio, $\overline{MRexp}$ the total mean of experimental moisture ratio, and i is the i^{th} data.

The image analysis was carried out using a special program written for this purpose by Sturm & Hofacker (2009). The sample was analyzed for L, a, b, and number of pixels. The change in sample size due to shrinkage (s) was calculated as the ratio of the number of pixels of the current surface area (A) to the number of pixels of the original surface area of the sample. The global color change or change in total color difference is calculated using Equation 4.6.

$$\mathrm{TCD} = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \quad (4.6)$$

where ΔL = change in lightness, Δa = change in redness and Δb = change in yellowness

4.2 Results and Discussion

4.2.1 Drying Kinetics

Figure 4.2, Figure 4.3, and Figure 4.4, depict the experimental and predicted grams of moisture content per gram of dry matter of the samples over time at different temperatures, dew point temperatures and air velocities, respectively. The figures show good agreement between the experimental and predicted values. The parameters of the drying kinetics of Midilli–Kucuk model are presented in Table 4.1. The R^2 value shows that the model explained more than 99% of the variation in change in drying kinetics.

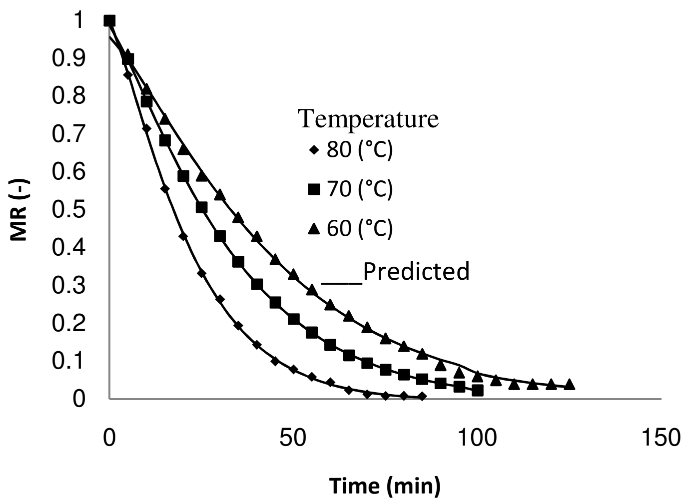


Figure 4.2: The experimental and predicted value of drying kinetics of potato slices at air temperature of 60 °C, 70 °C and 80 °C, velocity of 1 m/s and dew point temperature of 20 °C.

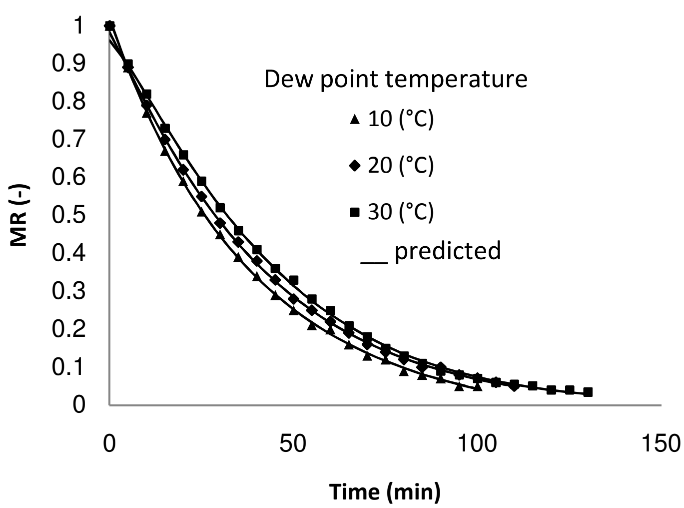


Figure 4.3: The experimental and predicted value of drying kinetics of potato slices at dew point temperature of 10 °C, 20 °C, 30 °C, temperature of 60 °C and velocity of 1.2 m/s.

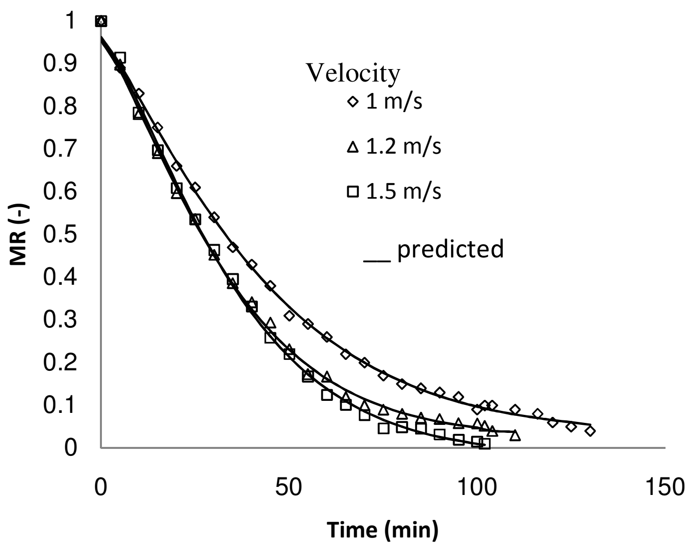


Figure 4.4: The experimental and predicted value of drying kinetics of potato slices at air velocity of 1 m/s, 1.2 m/s and 1.5 m/s, temperature of 70 °C and dew point temperature of 10 °C.

Considering heat and mass transfer is essential for drying. The driving force for heat transfer is a temperature gradient. The heat gain of potato slices from hot air is directly proportional to the temperature difference between the air and potato slices. The driving force for mass transfer (moisture removal) is vapor pressure difference between the air and the potato slices. The moisture removal from the potato slices is directly proportional to vapor pressure difference between the air and the potato slices. During drying, the temperature of the air is higher than the temperature of the sample. Due to this difference in temperatures, there is a transfer of heat from the air to the samples. The heat from the drying air is absorbed by the sample and provides latent heat to evaporate water from the surface of the sample.

As the temperature increased, the moisture removal also increased and resulted in the reduction of drying time since the temperature gradient between the air and the samples is higher for the sample dried at high air temperature as compared to low air temperature. McMinn. & Maere (1996); Krokida et al. (2003); Yadollahinia & Jahangiri, (2009) and Vega-Gálvez et al. (2012) reported similar results.

Even though, the effect of the change in air velocity has no strong influence as that of the change in temperature, the higher the air velocity of the air is, the faster the removal of moisture from the surface of the sample. This outcome is similar to the results obtained by other researchers (McMinn. & Maere, 1996;Krokida et al., 2003).

The change in dew point temperature has a limited effect on moisture removal as compared to the change in temperature and air velocity. Krokida et al. (2003) also found a limited effect of the relative humidity on the drying time for some vegetables such as potato, carrot, pepper, garlic, mushroom, onion, leek, pea, corn, celery, pumpkin, and tomato.

Table.4.1: Midilli–Kucuk coefficient, processing conditions and its statically analysis

T (°C)	DPT (°C)	V (m/s)	a	k	n	b	X^2	R^2	RMSE	MAE
80	20	1	1.00	0.021	1.23	-0.00004	$3x10^{-5}$	0.99912	0.00001	0.00421
70	20	1	0.99	0.014	1.20	-0.00003	$1x10^{-5}$	0.99980	0.00001	0.00210
60	20	1	0.96	0.009	1.23	0.00003	$15 x10^{-5}$	0.99858	0.00006	0.00801
60	10	1.2	1.02	0.027	0.99	-0.00027	$2x10^{-5}$	0.99928	0.00001	0.00489
60	20	1.2	0.98	0.018	1.08	-0.00005	$2x10^{-5}$	0.99920	0.00001	0.00380
60	30	1.2	0.96	0.010	1.20	0.0000	$6x10^{-5}$	0.99657	0.00003	0.00600
70	10	1	0.96	0.010	1.90	0.00019	$7x10^{-5}$	0.99613	0.00003	0.00878
70	10	1.2	0.95	0.010	1.28	0.00021	$10x10^{-5}$	0.99514	0.00004	0.01029
70	10	1.5	0.95	0.008	1.34	-0.00013	$10x10^{-5}$	0.99541	0.00004	0.01125

The drying rate is calculated from the experimental data as the slope of moisture ratio versus time (dMR/dt). The influence of air temperature, dew point temperature, and air velocity on the drying rate is shown in Figure 4.5, Figure 4.6, and Figure 4.7, respectively. At the beginning of the process, an increase in the drying rate was observed due to the evaporation of moisture increase from the sample as a result of heating. The maximum value of the drying rate was reached after a short period of time, and then followed by a falling rate in all drying conditions. No constant drying rate period was observed on the drying process graph, which is considered as a good agreement with the results of McMinn. & Maere (1996). From Figure 4.5., Figure 4.6, and Figure 4.7, it is noticed that the temperature effect on the drying rate is more pronounced than that obtained by the change in dew point temperature and air velocity. As expected, there is an acceleration of the drying rate due to the increase of the temperature from 60 °C to 80 °C. Since the temperature of the air increases, the temperature gradient between the samples and the air also increases. The result agrees with Chua et al. (2000) reports. The samples dried at an air velocity of 1.5 m/s had a higher drying rate as compared to samples dried at air velocities of 1 m/s and 1.2 m/s. This happened due to a high velocity, which is responsible for a high evaporation. Magee & Wilkinson (1992) reported a similar outcome. The limited effect of dew point temperature on drying rate was observed as compared to air temperature and velocity.

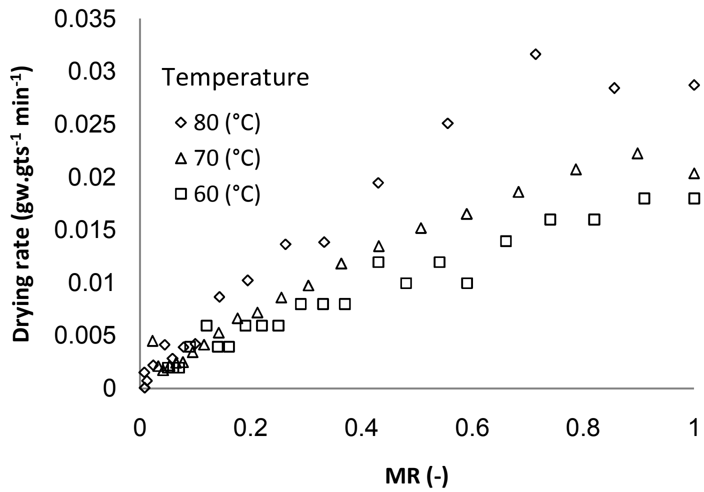


Figure 4.5: Drying rate of potato slices at air temperature of 60 °C, 70 °C and 80 °C, dew point temperature of 20 °C and velocity of 1 m/s.

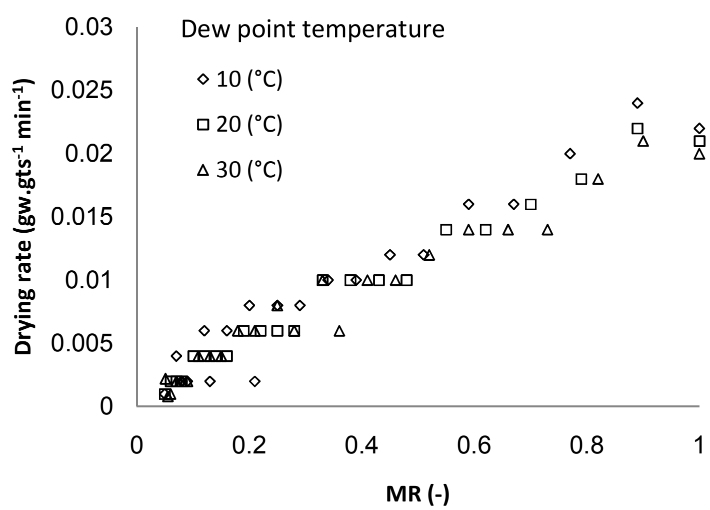


Figure 4.6: Drying rate of potato slices at dew point temperature of 10 °C, 20 °C and 30 °C, temperature of 60 °C and velocity of 1.2 m/s.

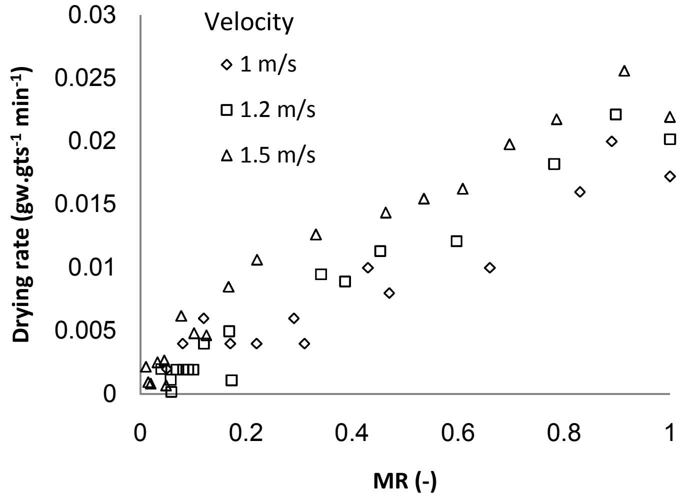


Figure 4.7: Drying rate of potato slices at air velocity of 1 m/s, 1.2 m/s and 1.5 m/s, temperature of 70 °C and dew point temperature of 10 °C.

4.2.2. Influence of Processing Condition on Kinetics of Shrinkage

Figure 4.8, Figure 4.9, and Figure 4.10 show the change in shrinkage versus the moisture ratio at different air temperatures, dew point temperatures, and air velocities. An increase in the shrinkage of the samples accompanied by a decrease in the moisture ratio was observed for all processing parameters under study conditions. As discussed in literature, when moisture is removed from potato slices, there is a pressure imbalance between the inside and outside of the potato slices. The pressure imbalance between inside and outside of the potato slices generates contracting stresses leading to shrinkage of the samples.

In the case of a sample's moisture ratio greater than or equal to 0.3, there was no significant difference on product shrinkage due to temperature variation. At the end of the drying process, as temperature decreased from 80 °C to 60 °C, the shrinkage of the product increased from 42% to 46%. At a higher air temperature, the moisture gradient within the potato slices was high and resulted in high internal stress and smaller degree of shrinkage was obtained (Khraisheh et al., 1997). Rahman. 2007 explained more about this phenomenon in his Article; at low temperature, the moisture gradient within the product is small, internal stresses are low, and hence the material shrinks down fully onto a solid core. At higher temperature, the surface moisture decreased very rapidly so that the surface became stiff which in turn limited any subsequent shrinkage. The experimental results for shrinkage showed good agreement with literature (Schiffmann, 2006; Yadollahinia & Jahangiri, 2009).

Similar trend was observed for variation in dew point temperature and air velocity as that of temperature change on product shrinkage. At the end of drying, the degree of increase in the shrinkage of dried slices was increased as the dew point temperature of the air increased. The influence of the change in air velocity also has a significant effect on the shrinkage of dried products. The highest value of shrinkage (52%) was obtained for the samples dried at a lower air velocity (1 m/s). This may be explained by the fact that the samples at higher dew point temperature or low air velocity take longer time to be dried. The prolonged drying time gives the chance for the samples to replace their solid content to the space released by the evaporated moisture content; as a result, higher shrinkage of the product is obtained**.** A high value of shrinkage was reported for the samples dried at low air velocity for potato slabs by Khraisheh et al., (1997) and for apple slices by Barbara Sturm et al., 2007.

The shrinkage of potato slices versus the dimensionless moisture content at studied temperatures, dew point temperatures, and air velocities is presented in Figure 4.8, Figure 4.9, and Figure 4.10. The graphs can be divided into two sections: section I for a moisture ratio greater than or equal 0.3 and section II for a moisture ratio less than 0.3. Linear regression analysis $A/A_o = b(MR) + a$ for $MR \geq 0.3$ and $MR < 0.3$ with Minitab 16 showed a linear relation between the shrinkage and the moisture ratio. The value of b (slopes) and a (the surface area ratio intercept) for $MR \geq 0.3$ and $MR < 0.3$ is presented in Table 4.2. The slope of the shrinkage at $MR < 0.3$ was greater than $MR \geq 0.3$. The linearity of the result agreed with literature(Yadollahinia & Jahangiri, 2009).

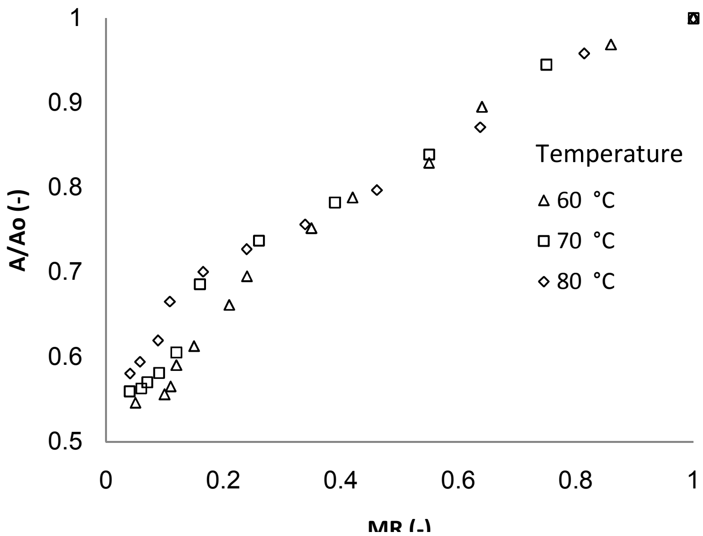


Figure 4.8: Shrinkage versus moisture ratio at air temperature of 60 °C, 70 °C and 80 °C, dew point temperature of 10 °C and velocity of 1.2 m/s.

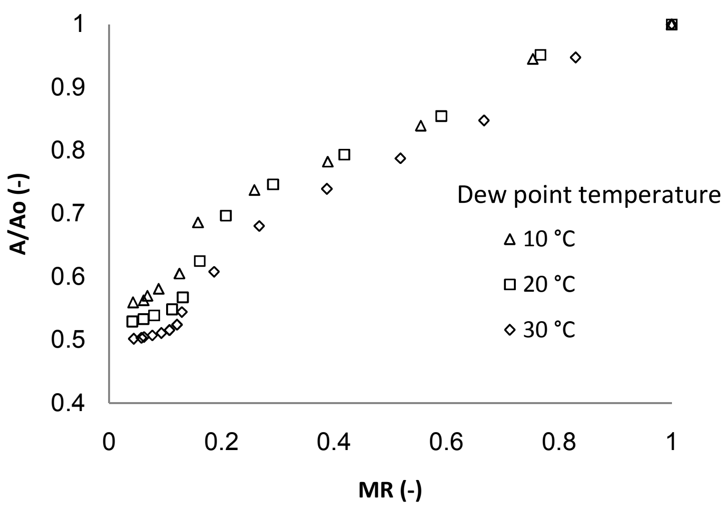


Figure 4.9: Shrinkage versus moisture ratio at dew point temperature of 10 °C, 20 °C and 30 °C, temperature of 80 °C and velocity of 1.2 m/s.

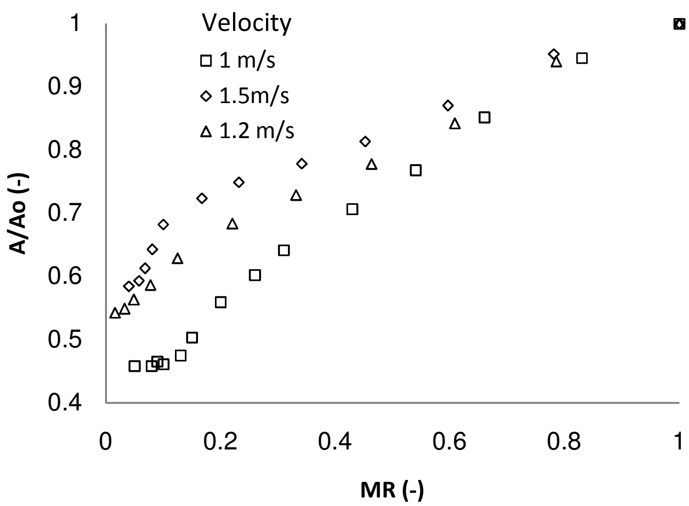


Figure 4.10: Shrinkage versus moisture ratio at air velocity of 1 m/s, 1.2 m/s and 1.5 m/s, temperature of 70 °C and dew point temperature of 10 °C.

Table 4.2: calculated value of slope and shrinkage intercept of A/A_o=b(MR) + a

T (°C)	DPT (°C)	V (m/s)	MR>=0.3			MR<0.3		
			A	B	R^2	a	b	R^2
60	10	1.2	0.6236	0.3907	0.981	0.4861	0.84	0.96
70	10	1.2	0.6429	0.3698	0.971	0.5119	0.9	0.949
80	10	1.2	0.6250	0.3869	0.988	0.5577	0.77	0.93
80	10	1.2	0.6423	0.3700	0.972	0.5108	0.97	0.95
80	20	1.2	0.6404	0.3734	0.98	0.4639	1	0.88
80	30	1.2	0.5621	0.4441	0.994	0.4552	0.71	0.85
70	10	1	0.6263	0.4016	0.943	0.4479	1.21	0.8
70	10	1.2	0.6109	0.3970	0.989	0	1	1
70	10	1.5	0.6340	0.3793	0.987	0.4973	1.08	0.95

Figure 4.11 to Figure 4.13 depict the kinetics of shrinkage of dried potato slices as a function of drying time for three levels of dew point temperatures, dry bulb temperatures, and velocities of the air, respectively. Even though shrinkage of the sample during the drying was seen, there was no difference in shrinkage due to the change in the dew point temperature in the range of 0 to 60 minutes of drying period. After a drying period of 60 minutes, the difference in shrinkage of the sample due to

change in the dew point temperature was observed. By drying potato slices at higher dew point temperatures, lower drying temperatures, and lower air velocities, a more uniform moisture distribution exists, inducing less internal stresses that allow the sample to continue to shrink until the last stages of drying.

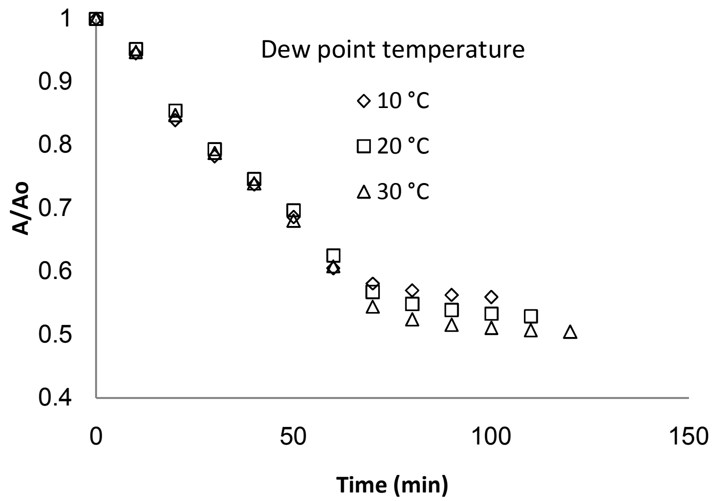


Figure 4.11: Shrinkage as a function of drying time at three levels of dew point temperatures, temperature of 80 °C and velocity of 1.2 m/s.

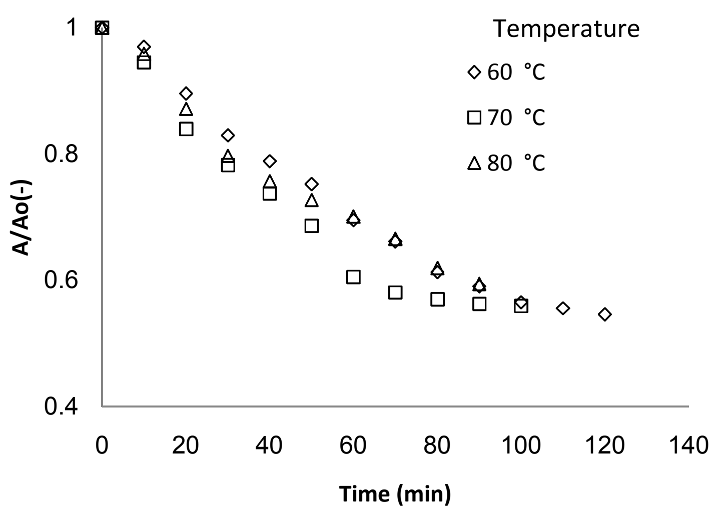


Figure 4.12: Shrinkage as a function of drying time at three levels of air temperatures (60 °C, 70 °C and 80 °C), dew point temperature of 10 °C and velocity of 1.2 m/s.

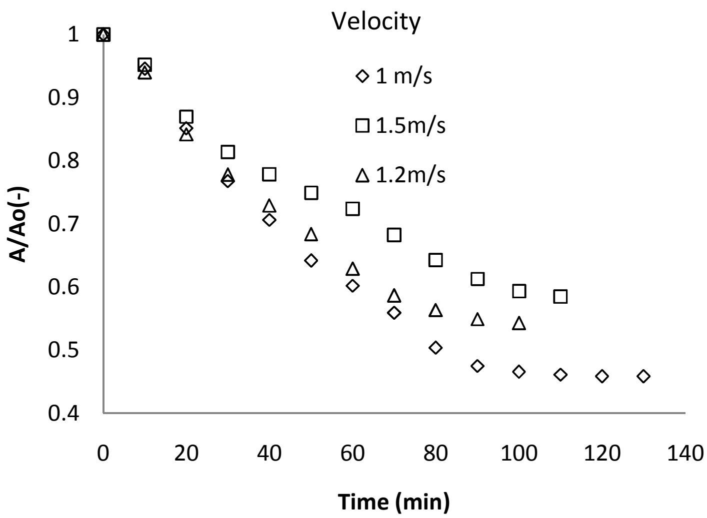


Figure 4.13: Shrinkage as a function of drying time at three levels of air velocity (1 m/s, 1.2 m/s and 1.5 m/s), temperature of 70 °C and dew point temperature of 10 °C.

Figures 4.14 - 4.16 show the experimental and predicted values of shrinkage as a function of drying time of drying potato slices for three levels of temperatures, dew point temperatures, and air velocities, respectively. As seen from the figures, good agreement in experimental and predicted values was observed. The second order polynomial regression equations describing the effect of temperature, dew point temperature, and air velocity as a function of drying time on shrinkage of potato slices are shown in Appendix Table 1. The R^2 value shows that regression model explains more than 99% of the variance in change in shrinkage. The linear regression term of shrinkage exhibited positive and the second order regression term negative effect on retention of the original size of dried potato slices for the samples dried at all temperatures, dew point temperatures, and air velocities.

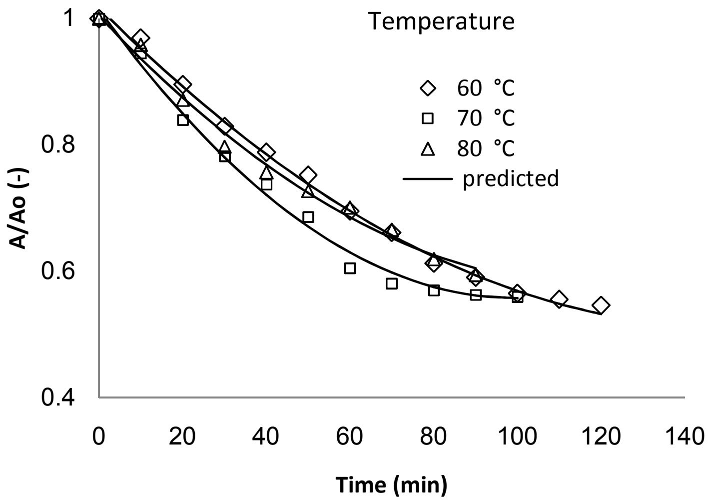


Figure 4.14: Experimental and predicted values of shrinkage of drying potato slices for three levels of temperature at 10 °C dew point temperature and 1.2 m/s air velocity.

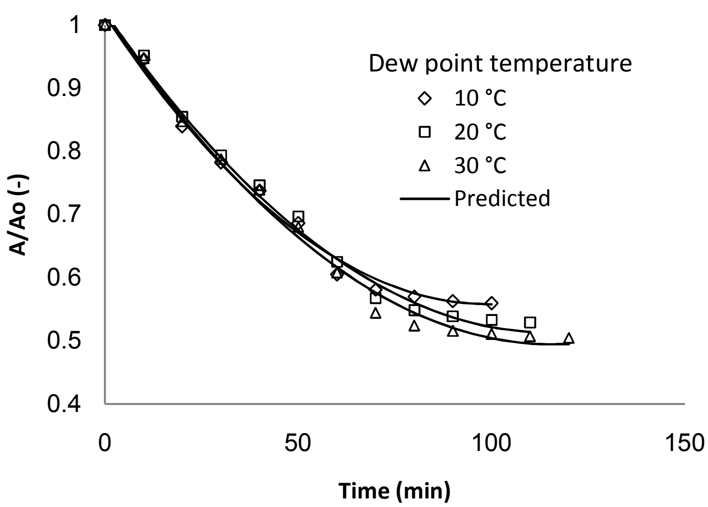


Figure 4.15: Experimental and predicted values of shrinkage of drying potato slices for three levels of dew point of temperature at 80 °C dry bulb temperature and 1.2 m/s air velocity.

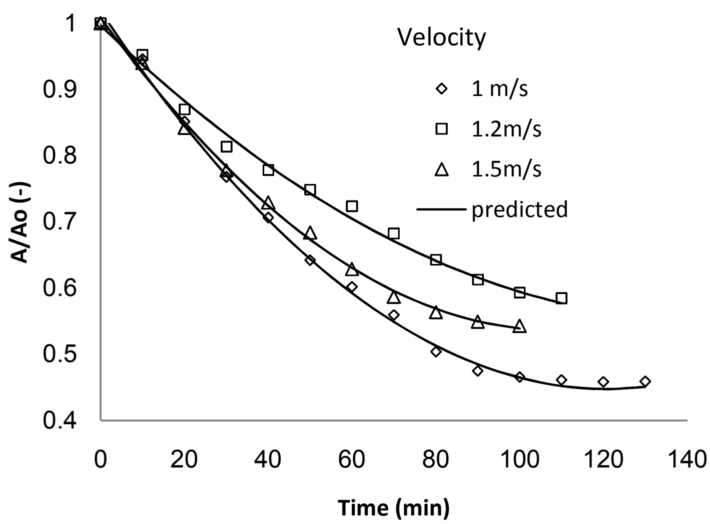


Figure 4.16: Experimental and predicted values of shrinkage of drying potato slices for three levels of air velocity at 70 °C dry bulb temperature and 10 °C dew point temperature.

4.2.3. Influence of Processing Condition on Kinetics of Total Color Difference

The dependency of total color difference on the moisture ratio of potato slices at different air temperatures is shown in Figure 4.17. The change in the total color difference increases with a decrease in moisture content of the samples. A considerable change in the total color difference was observed at the moisture ratio of less than 0.3. The change in total color difference (TCD) also increases with a decrease of the treatment temperature in a range of 60 °C to 80 °C. Similar to the result of Marcel et al. (2014) for pineapples, Sturm et al. (2012) for apples, and Akoy et al. 2008) for mangoes, applying high temperatures to the products resulted in a decrease in discoloration of potato slices. The plot between total color difference and moisture ratio at different air velocities is presented in Figure 4.18. The lowest value of total color change was obtained at air velocity of 1.5 m/s then 1.2 m/s and finally 1 m/s, keeping the dry bulb and wet bulb temperature of the air constant.

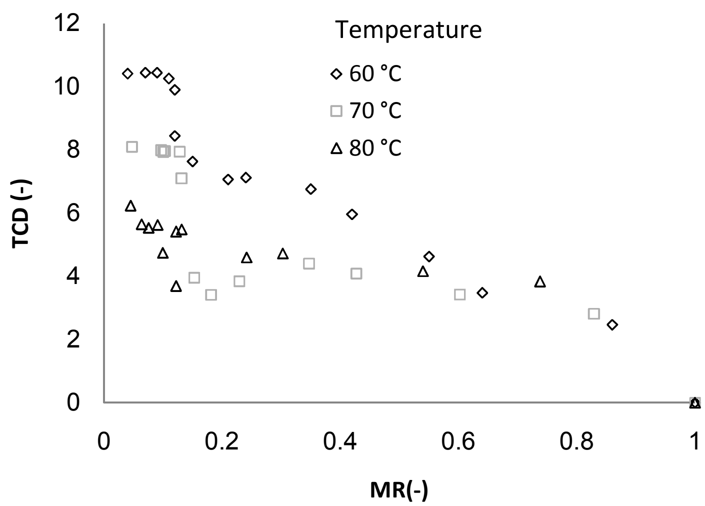


Figure 4.17: Dependency of total color difference at temperatures of 60 °C, 70 °C, and 80 °C, dew point temperature of 10 °C, and velocity of 1.2 m/s on moisture ratio.

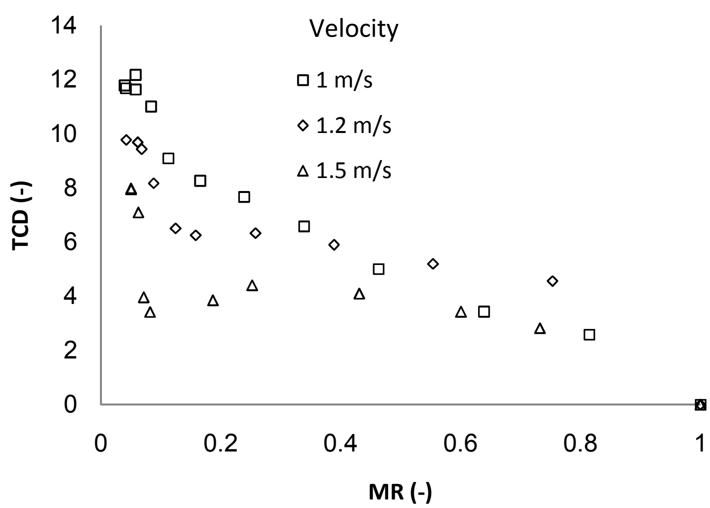


Figure 4.18: Dependency of total color difference at air velocity of 1 m/s, 1.2 m/s and 1.5 m/s, temperature of 60 °C, and dew point temperature of 30 °C on moisture ratio.

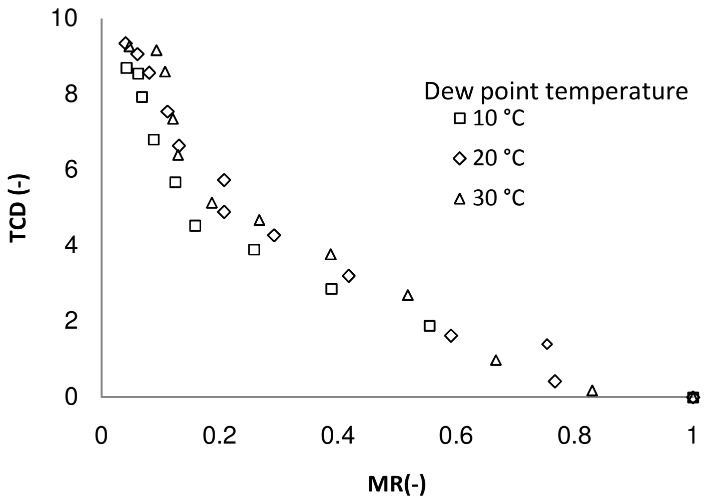


Figure 4.19: Dependency of total color difference at dew point temperatures of 10 °C, 20 °C, and 30 °C, temperature of 60 °C and velocity of 1.2 m/s on moisture ratio.

Figures 4.20 - 4.22 depict the dependency of total color difference on drying time of dried potato slices for three levels of air temperatures, dew point temperatures, and air velocities, respectively. A significant change in total color difference of dried potato slices was observed due to change in temperature and air velocity. Even though an increase in the change of total color difference of dried potato slices was observed as the drying time increased, there was no significant difference in change of total color difference of dried potato due to change in dew point temperature (Figure 4.21). As observed in Figure 4.20, there is clear four stage of total color change behavior for the samples dried at temperatures of 70 °C and 80 °C. At the first stage, as the drying time increases, there is a rapid increase in total color difference of the dried potato slices. At the second stage, as the drying time increases, there is small reduction in the value of change in total color difference of dried potato slices. At the third stage, as the drying time increases, there is a rapid increase in total color difference. At the last stage, as the drying time increases, there is a gradual increase in the total color difference of dried potato slices. The samples dried at a temperature of 60 °C, dew point temperature of 30 °C and air velocity of 1.5 m/s share the same behavior as that of the sample dried at temperatures of 70 °C and 80 °C. For the sample dried at a temperature of 60 °C, dew point temperatures of 10 °C, 20 °C, 30 °C, and air velocities of 1 m/s and 1.2 m/s , as the drying time increases, an increase of the change in total color difference throughout the process was observed.

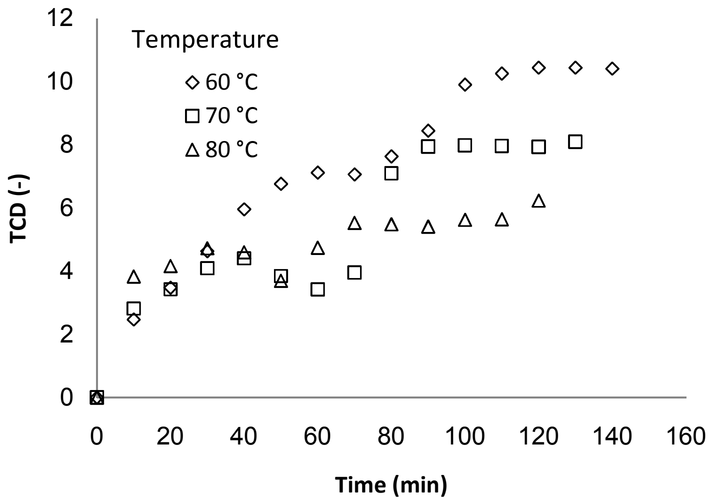


Figure 4.20: Total color difference as a function of drying time for three levels of air temperature (60 °C, 70 °C and 80 °C), dew point temperature of 10 °C and velocity of 1 m/s.

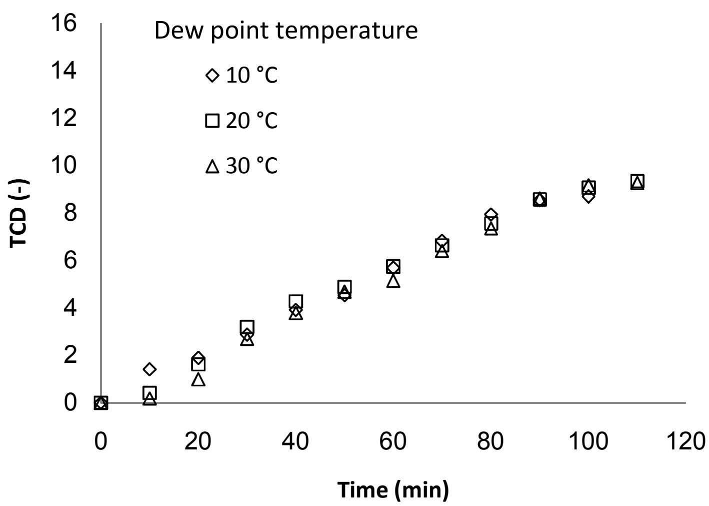


Figure 4.21: Total color difference as a function of drying time for three levels of dew point temperature (10 °C, 20 °C and 30 °C), temperature of 60 °C and velocity of 1.2 m/s.

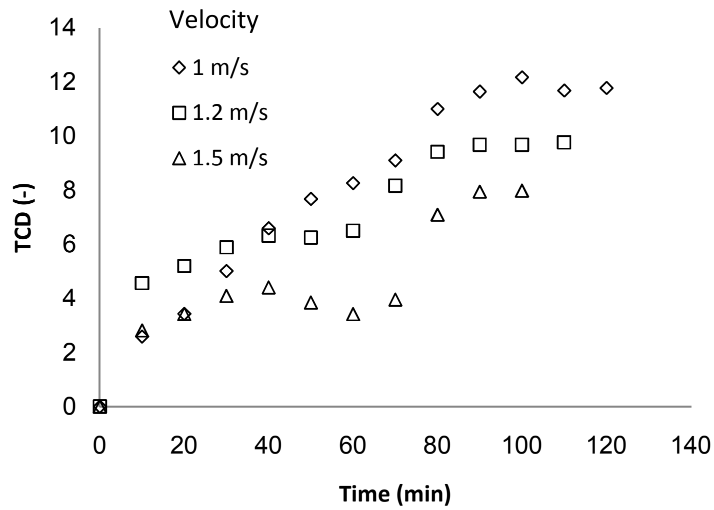


Figure 4.22: Total color difference as a function of drying time for three levels air velocity (1 m/s, 1.2 m/s and 1.5 m/s), temperature of 60 °C and dew point temperature of 30 °C.

Experimental and predicted value of total color difference as a function of drying time for three levels of temperature, dew point temperature, and air velocity are presented in Figure 4.23-4.25, respectively. Good agreements between experimental and predicted values were observed from the figures. Appendix Table 2 presents the equations for the total color difference as a function of drying time for the combination of dry bulb temperature, dew point temperature, and air velocity. As observed from the Appendix Table 2, the total color difference of the samples dried at a temperature of 70 °C and 80 °C with all combinations of dew point temperatures and air velocities is best fit to a fourth order polynomial regression equation. The value of total color difference of the samples dried at an air temperature of 60 °C, dew point temperature of 30 °C, and air velocity of 1.2 m/s and 1.5 m/s is also best fit to a fourth order polynomial regression equation. The total color difference value of samples dried at a temperature of 60 °C, air velocity of 1 m/s with all combinations of dew point temperatures is best fit to a second order polynomial regression equation. The R^2 value shows that the regression model explains in a range from 89% to 99% of the variance in change in total color difference. For those parameters that best fit to a fourth order regression equation, the linear and the third-order regression term of total color difference exhibited negative effect on color retention of the potato samples, and positive for the second, and the fourth order regression term.

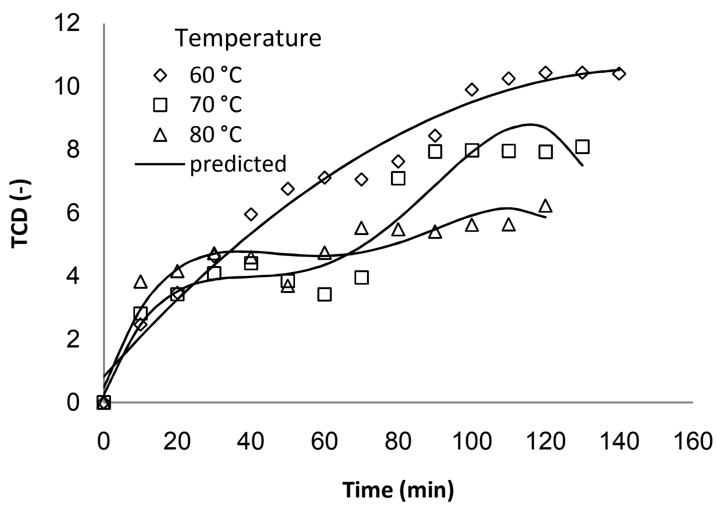


Figure 4.23: Experimental and predicted value of total color difference as a function of drying time for three levels of air temperature (60 °C, 70 °C and 80 °C), dew point temperature of 10 °C and velocity of 1.2 m/s.

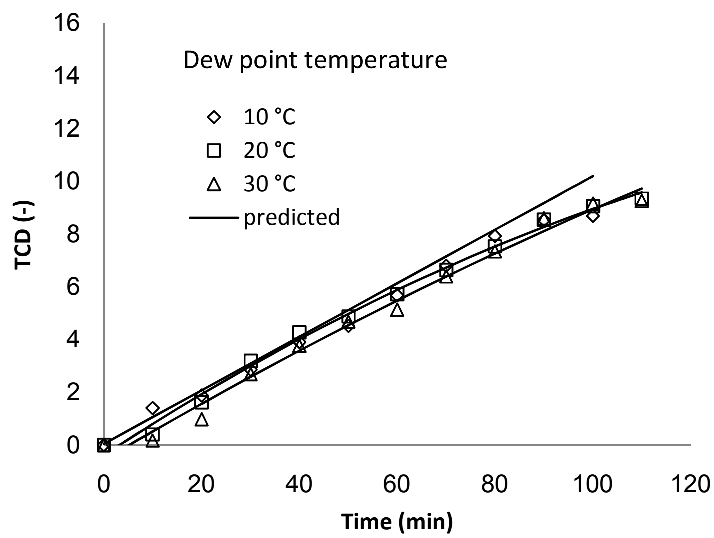


Figure 4.24: Experimental and predicted value of total color difference as a function of drying time for three levels of dew point temperature (10 °C, 20 °C and 30 °C), temperature of 60 °C and velocity of 1 m/s.

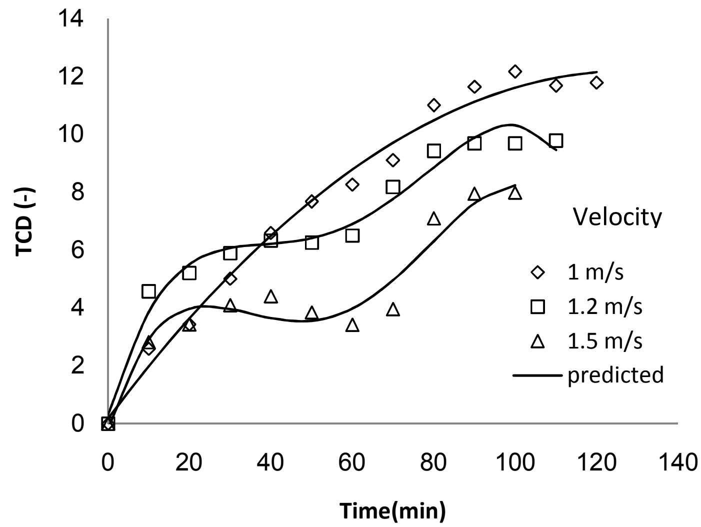


Figure 4.25: Experimental and predicted value of total color difference as a function of drying time for three levels of air velocity (1 m/s, 1.2 m/s and 1.5 m/s), temperature of 60 °C, and dew point temperature of 30 °C.

5 Process Optimization

As observed in a previous chapter, the drying processing conditions have influence on qualities of dried potato slices. Therefore, optimization of drying processing conditions is important for good retention of qualities of the dried potato slices. For food technologists, properties such as color, texture, and shape (shrinkage) are determinant factors for the quality of the dried product (Fernandez *et al.* 2005). For food nutritionist, nutrition is a determinant factor for the quality of the dried product. In this chapter, processing parameters were optimized for optical, physical, mechanical and nutritional properties of the dried potato slices. The drying time, at an optimum residual moisture content of the potato slices, obtained in chapter 4 taken as an input to end the drying process.

5.1 Process Optimization for Optical and Shape

Color (optical) and shape (physical) are two of the most important factors affecting people's choice of foods, and they are the basis for selection or rejection of the product. Optimizing the drying processing conditions for color and shrinkage of dried potato slices is very important to produce acceptable products. The objective of this section is to optimize processing parameters for optical and physical properties of dried potato slice.

5.1.1 Materials and Methods

The same potato variety, the method of sample preparation, and drying device similar to those mentioned in Section 4.2 were used here.

5.1.1.1 Determination of Color Changes and Shrinkage

Image analysis was carried out using a special program written for this purpose by Sturm & Hofacker (2009). The samples were analyzed for L, a, b and number of pixels. Percent of shrinkage (s) was calculated using Equation (5.1) as one minus the ratio of the current surface area (A) to the original surface area of the sample (A_o) multiplied by hundred. The global color change or change in total color difference was calculated using Equation (5.2).

$$S(\%) = (1 - \frac{A}{Ao}) \times 100 \quad (5.1)$$

$$\mathrm{TCD} = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \quad (5.2)$$

where: A= current surface area of the sample, A_o=the original surface area of the sample, ΔL = change in lightness, Δa = change in redness and Δb = change in yellowness

5.1.1.2 Experimental Design

The RSM was used to design the drying experiments. Three independent variables A_n (air temperature, °C), B (dew point temperature, °C) and C (air velocity, m/s) at three levels, for three dependent or response variables, were generated. The basic model used to describe the response variable (Y) involves the linear or main, interaction and curvature effects as shown in Equation (5.3).

$$Y = \beta_o + \beta_1 A + \beta_2 B + \beta_3 \mathrm{C} + \beta_4 AB + \beta_5 \mathrm{BC} + \beta_6 AC + \beta_7 A^2 + \beta_8 B^2 + \beta_9 C^2 \qquad (5.3)$$

where A, B, C are the coded values of the independent variables (air temperature, dew point temperature and air velocity); βo, β_1, β_2, β_3, β_4, β_5, β_6, β_7, β_8 and β_9 are the regression coefficients

5.1.1.3 Statistical Analysis

Optimization of drying process was performed using Design Expert software. It was performed using a multivariate response method called overall desirability index. The desirability index is a multi-criteria optimization approach used to show how desirable the various responses are. The desirability index ranges from zero (least desirable) to one (most desirable). The desired goal for each independent and dependent variables was chosen. All dependent variables, or responses (change in total color difference, drying time and shrinkage) were set minimum while the independent variables were kept within the range (as indicated in Table 5.2).

Table 5.1: independent variables used in optimization study

Variable (unit)	Symbol code	levels of Variable
Temperature (°C)	A	60 70 80
Dew point temperature (°C)	B	10 20 30
Air velocity (m/s)	C	1 1.25 1.5

Table 5.2: Desired goals for independent and dependent variables

Dependent and indipendent variables	Goal	Importance (1= least important,... 5= very important)
T (°C)	is in the range	3
DPT (°C)	is in the range	3
V (m/s)	is in the range	3
TCD (-)	Minimize	5
S (%)	Minimize	5
Time (min)	Minimize	5

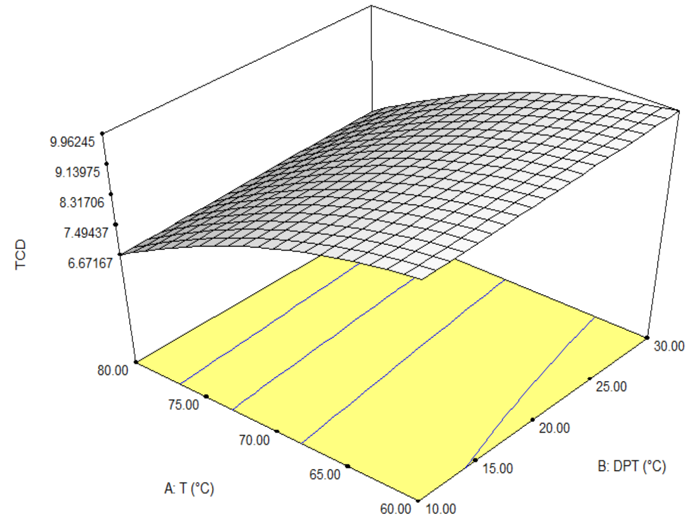
5.1.2 Results and Discussion

5.1.2.1 Effect of Drying Condition on Change in Total Color Difference

As observed in Appendix Table 3, the change in total color difference is significantly affected by air temperature (A), air velocity (C), interaction of temperature and air velocity, and the square of temperature at $P < 0.05$. Second order regression equation describing the effect of drying process variables on change in the total color difference of potato slices is given in Equation 5.2. The R^2 value shows that the regression model explains 94% of the variance in change in total color difference. Change in the total color difference of dried potato slices as influenced by drying conditions on response surface plots is depicted in Figure 5.1. As shown in Figure 5.1 and Appendix Table 3, the effect of an increase in both air temperature and velocity has a significantly positive effect on change in the total color difference of dried potato slices. This result agrees with the findings of Akoy et al. (2008) for mangoes, Sturm et al. (2012) for apples, and Marcel et al. (2014) for pineapples. Longer drying periods of time due to lower process temperature and air velocity may cause more discoloration than higher process temperature and air velocity for shorter drying periods of time (Khazaei et al. 2008).

$$TCD\ (-) = +8.82 - 1.50A + 0.15B - 0.76C - 0.50A^2 + 0.65AC \qquad (5.2)$$

where TCD = Total color difference, A =Air temperature, B = Dew point temperature and C = air velocity a)



b)

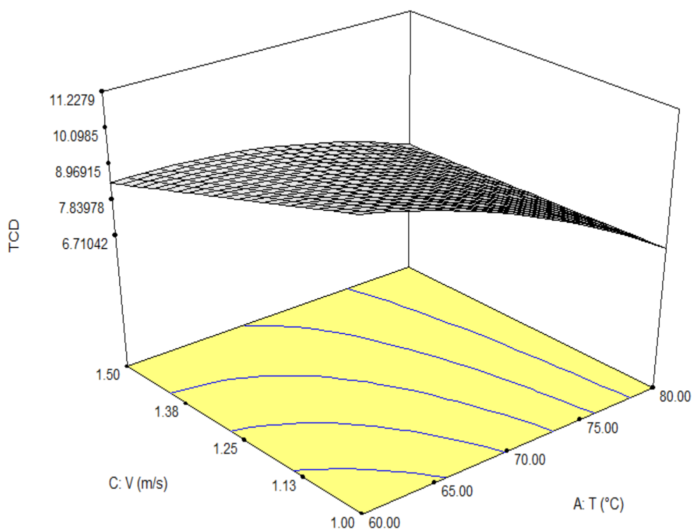


Figure 5.1: The effects of (a) temperature and dew point temperature at v=1.25 m/s and (b) temperature and air velocity at DPT=20 °C on response surface plots of change in the total color difference of potato slices.

5.1.2.2 Effect of Drying Condition on Shrinkage

The linear regression equation describing the effect of drying process variables on the percentage of area shrinkage of potato slices is given in equation 5.3. As indicated in Appendix Table 3, the R^2 value shows that the regression model explains 91% of the variance in percent of area shrinkage. The linear regression of both temperature and air velocity exhibited a positive effect on the percentage of area shrinkage. Lower shrinkage percentage leads to a positive impression by customers(Mayor & Sereno, 2004). Appendix Table 3 shows that area shrinkage is significantly affected by air temperature (A) and air velocity (C). The established result agrees with the findings of Sturm et al. (2012) for apples. Shrinkage of dried potato slices influenced by drying conditions on the response surface plots is depicted in Figure 5.2. As shown in Figure 5.2 and Appendix Table 1, percent of area shrinkage of dried potato slices was significantly decreased due to the effect of an increase in both air temperature and velocity.

$$S(\%) = +45.25 - 2.40A - 1.70C - 0.75AC \quad (5.3)$$

where S = shrinkage, A = air temperatureand C= air velocity

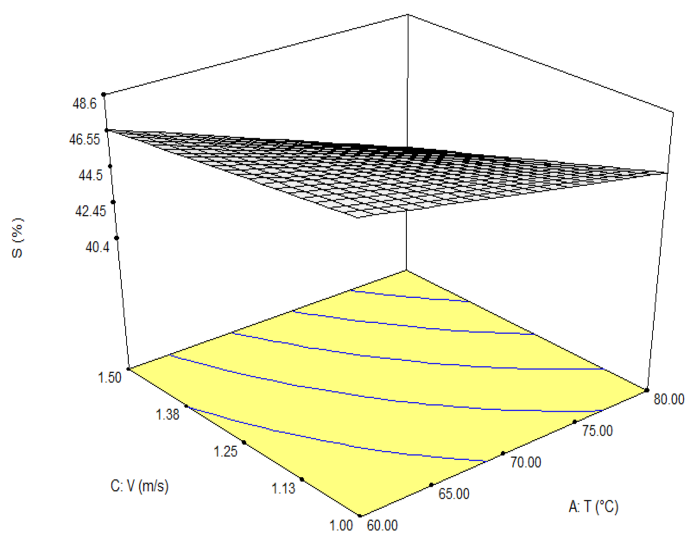


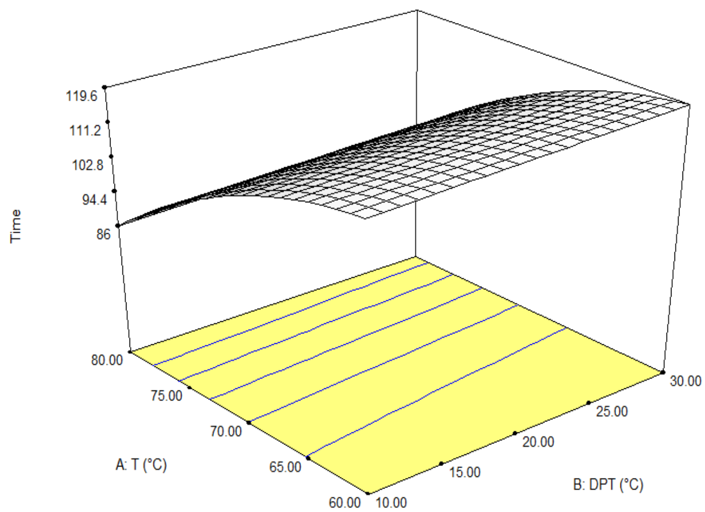
Figure 5.2: The effects of temperature and air velocity at DPT=20 °C on percent of surface area shrinkage of potato slices.

5.1.2.3 Drying Time

As observed in Appendix Table 1, the change in drying time is significantly affected by temperature and air velocity at $P < 0.05$. Hawlader et al. (1991) reported similar findings by showing the significant effect of drying air temperature and velocity on the drying period of time for tomatoes, and by Gupta et al. (2013) for cauliflowers. But drying time was not significantly affected by dew point temperature at $P > 0.05$. Figure 5.3 depicts the effect of drying process parameters on total drying time of potato slices. As shown in Figure 5.3, as temperature and air velocity increase, the total drying time of potato slices tends to decrease. Increasing the drying air temperature, Pardeshi et al. (2009), Hii et al. (2009), and Gupta et al. (2013) reported similar results for the reduced periods of drying time for green peas, cocoa, and cauliflower, respectively. The linear regression equation describing the effect of drying process variables on drying time of potato slices is given in Equation 5.4. Both air temperature and velocity exhibited a positive linear effect as shown in Equation 5.4.

$$\text{Time (min)} = +108.92 - 15.50\,A + 1.30\,B - 9.80\,C - 6.13A^2 + 6.35C^2 \qquad (5.4)$$

where: A= Temperature (°**C**), B= Dew point temperature (°**C)** and C= Air velocity (m/s)



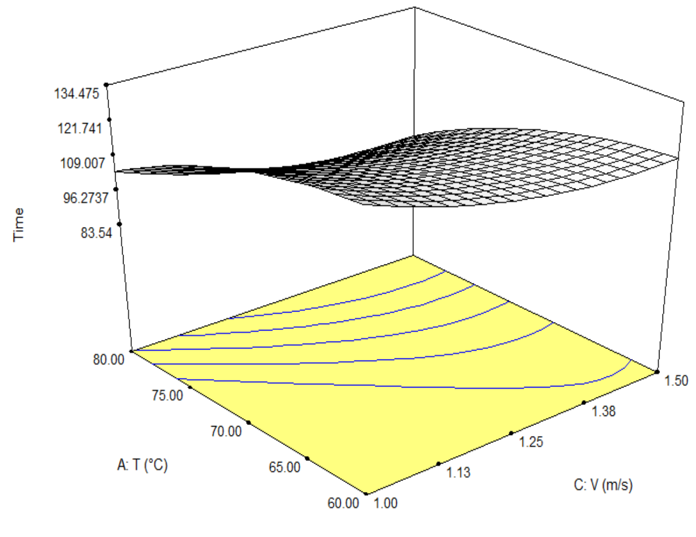


Figure 5.3: The effects of (a) temperature and dew point temperature at v=1.25 m/s and (b) temperature and air velocity at DPT=20 °C on response surface plots of drying time potato slices.

5.1.2.4 Optimization

The solutions for an optimum condition of drying of potato slices are presented in Table 5.3. Optimum conditions for hot air drying of potato slices were determined to obtain the criteria of minimum change in total color difference and shrinkage at a short period of drying time. To meet the requirements, the depending variables were weighed by their importance (1-5) as indicated in Table 5.2. Optimum percentage of area shrinkage, change in total color difference, and drying time were found to be 40.401%, 6.62, and 82.58 minutes, respectively, at a temperature of 80 °C, dew point temperature of 10 °C, and an air velocity of 1.5 m/s. The desirability of the results was 93.5%. The surface plot of the desirability for the optimum parameters is shown in Figure 5.4.

Table 5.3: solutions for optimum condition of drying of potato slices

Solution No	T (°C)	DPT (°C)	V (m/s)	S(%)	TCD (-)	Time (min)	Desirability
1	80.00	10.00	1.50	40.4014	6.56277	82.5847	0.942
2	80.00	10.10	1.50	40.4000	6.56365	82.5886	0.942
3	80.00	14.61	1.50	40.4000	6.6304	83.1737	0.935
4	80.00	16.21	1.50	40.4006	6.6543	83.3823	0.932
7(least solution)	78.23	10.00	1.50	40.9572	6.87377	87.2924	0.875

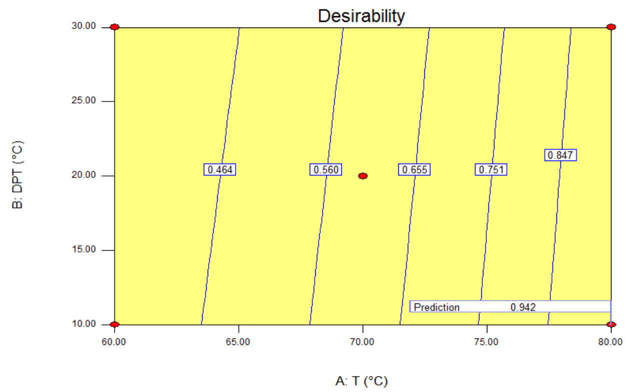


Figure 5.4: surface plot of the desirability index for the optimal drying condition at V= 1.5 m/s.

5.1.3. Conclusions

Drying the potato slices by using low temperature, high dew point temperature, and low air velocity leads to prolonged total period of drying. The prolonged total period of drying time resulted in high discoloration and shrinkage of potato slices. Optimum processing condition of drying was found to be at a temperature of 80 °C, dew point temperature of 10 °C, and an air velocity of 1.5 m/s for short periods of time, minimum percentage of shrinkage, and total color difference.

5.2 Process Optimization for Mechanical Properties

Texture is one of the important quality attributes used in the processing food industry to assess the product quality and acceptability. The objective of this section is optimization of processing conditions for the texture of dried potato slices.

5.2.1 Material and Methods

The same potato variety, the method of sample preparation, and drying device similar to those mentioned in Section 4.2 were used here.

The texture of the potato chips was evaluated by a compressive test using a texture analyzer(CT3-1500, USA). A sample was placed on the hollow planar base. The compressive force was then applied to the sample by a 3 mm cylindrical probe. The downward movement of the crosshead of the texture analyzer was adjusted at 2.00 mm/s until it cracked the sample. The cylindrical probe was returned back to its initial position at the same speed. Hardness, work, and deformation data were recorded during this test.

5.2.1.1 Experimental Design

The RSM was used to design the drying experiments. Three independent variables A (air temperature, °C), *B* (dew point temperature, °C) and C (air velocity, m/s) at three levels, for three dependent, or response variables were generated. The basic model used to describe the response variable (*Y*) involves the linear or main, interaction and curvature effects as shown in Equation (5.3).

5.2.1.2 Statistical Analysis

Optimization of drying process was performed using Design Expert software. It was performed using a multivariate response method called overall desirability index. The desirability index is a multi-criteria optimization approach used to show how desirable the various responses are. The desirability index ranges from zero (least desirable) to one (most desirable). The desired goal for each independent and dependent variables was chosen. All dependent variables, or responses (work and deformation were set minimum, and hardness was set at maximum) while the independent variables were kept within the range (as indicated in Table 5.4).

Table 5.4: desired goals for independent and dependent variables

Dependent and indipendent variables	Goal	Importance 1=least important ... 5= very important)
T (°C)	is in the range	3
DPT (°C)	is in the range	3
V (m/s)	is in the range	3
Hardness (N)	Maximize	5
Deformation(mm)	Minimize	5
work (mJ)	Minimize	5

5.2.2 Results and Discussion

The typical force-distance curve of hot air dried potato slices obtained from the texture analysis tests is presented in Figure 5.5 the highest peak of the curve indicates the hardness of the chip. That is the point showing the maximum resistance (13.36 N) of the chip against the crushing jaw of the instrument. It represents the degree of hardness of the chip subjected to the test. It took place at a deformation of 0.62 mm.

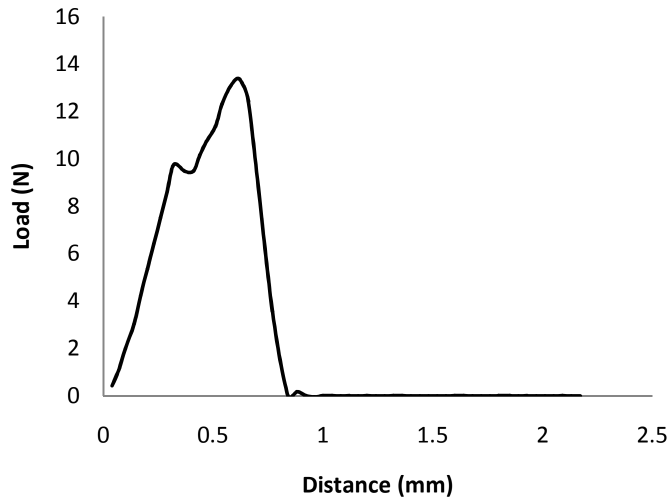


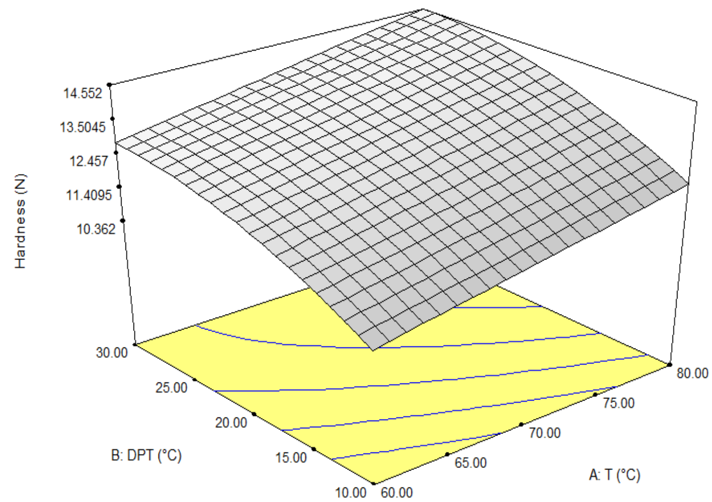
Figure 5.5: Force-deformation of hot air dried potato slices

The texture of the dried potato slices is reported in terms of hardness, work, and deformation. Hardness is defined from the sensory point of view as a maximum force required to compress a food between the molars. The mathematical definition of hardness is maximum load value of the compression cycle.

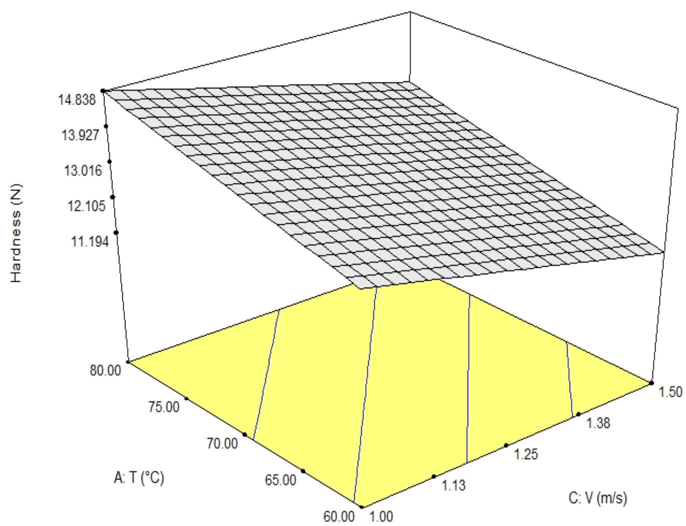
Figure 5.6 depicts the response surface plot of hardness as a function of dew point temperature and dry bulb temperature, and air velocity and dry bulb temperature, respectively. From the figures and Appendix Table 4, it is clearly seen that the amount of force required to fracture dried potato slices significantly increases with a decrease in air velocity, with a decrease of the square of dew point temperature, and with an increase in temperature and dew point temperature. Hardness best fit to the quadratic model is presented in Equation 5.6. In Appendix Table 4, the result of regression analysis and ANOVA are presented. The final predictive model for hardness is shown in the equation below:

$$Y=+13.02 + 0.87A + 1.23B - 0.95C - 0.56B^2 \quad (5.5)$$

where: A= Temperature (°**C**), B= Dew point temperature (°**C**)**,** C= Air velocity (m/s) and Y= Hardness (N)



a)



b)

Figure 5.6: The response surface plot of hardness as a function of a) dew point temperature and dry bulb temperature at V=1.25 m/s and b) air velocity and dry bulb temperature at DPT=20 °C.

Deformation at hardness is mathematically defined as distance value at the hardness point. Figure 5.7 shows the response surface plots of the deformation of potato slices as a function of air temperature and velocity. The potato slice dried at higher temperature and air velocity was fractured at lower distance as compared to the sample dried at lower air velocity and temperature (Figure 5.7). Dew point temperature has no significant effect on deformation of the potato slices. Deformation of the sample was influenced only by air temperature and velocity. A linear model is a best fit to predict deformation of dried potato slices. In Appendix Table 4, the result of regression analysis and ANOVA are presented. The final predictive model for deformation is shown in the equation below:

$$Y= 0.68 - 0.064A + 0.055C \quad (5.6)$$

where: A= Dry bulb temperature (°**C**), C= air velocity (m/s) and Y= Deformation (mm)

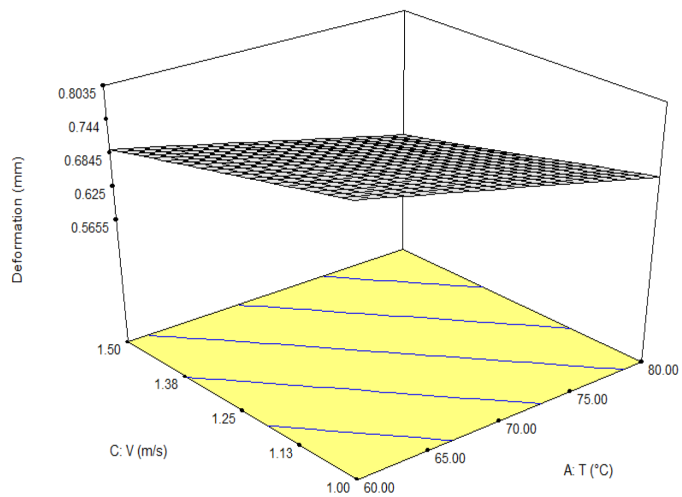


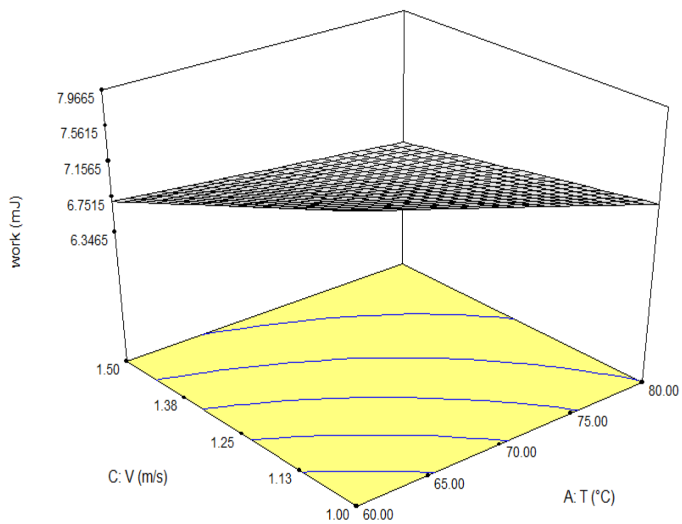
Figure 5.7: The response surface plots of the deformation of potato slices as a function of air temperature and velocity at DPT=20 °C

Hardness work done is defined from the sensory point of view as work necessary to overcome the internal strength of bonds within a food. Mathematical definition of hardness work done is the area under the load vs. distance curve from the cycle start to the target value (load or distance).

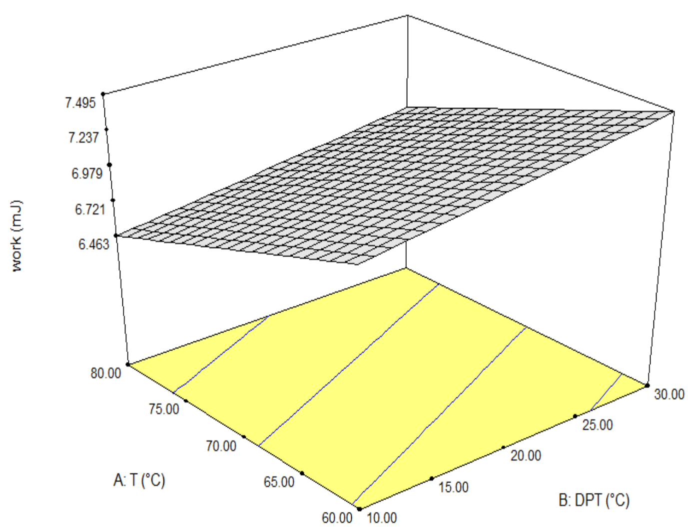
Figure 5.8 depicts the work as a function of air velocity and temperature, dew point temperature, and air velocity, respectively. From Figure 5.8, it is clearly observed that the energy required to overcome the internal strength of bonds within a dried potato slices increases as air temperature and velocity decrease. The temperature, the dew point temperature, the air velocity and the interaction of air velocity and temperature have significant effect on the work required to overcome the internal strength of bonds within a food (Appendix Table 4). A linear regression model best fits the work done on the potato samples. The final predictive model for work is described by the following equation:

$$Y=6.98 - 0.36A + 0.16 B - 0.45 C + 0.18AC \quad (5.7)$$

where: A= Temperature (°**C**), B= Dew point temperature (°**C**), C= Air velocity (m/s) and Y= work (mJ)



a)



b)

Figure 5.8: The response surface plots of the work required to fracture potato slices as a function of a) air temperature and velocity at DPT=20 °**C** and b) air temperature and dew point temperature at V=1.25 m/s.

5.2.1.3 Optimization

The solutions for an optimum condition drying for the mechanical property of potato slices are presented in Table 5.5. Optimum conditions for hot air drying of potato slices were determined to obtain the criteria of maximum hardness, and minimum deformation and work required to fracture the potato slices. To meet the requirements, the depending variables were weighed by their importance (1-5) as indicated in Table 5.4. Optimum force, deformation, and work required to fracture potato slices were found to be 12.6 N, 0.569 mm and 6.33 mJ, respectively, at a temperature of 79.37 °C, dew point temperature of 17.97 °C, and an air velocity of 1.5 m/s. The desirability of the results was 100%. The surface plot of the desirability for the optimum parameters is shown in Figure 5.9.

Table 5.5: solutions for optimum condition of mechanical property of drying of potato slices

Solutions Number	T (°C)	DPT (°C)	V (m/s)	Hardness (N)	Deformation (mm)	work (mJ)	Desirability
1	79.37	17.97	1.50	12.6031	0.5696	6.32604	1
2	79.72	19.43	1.49	12.8728	0.569575	6.3541	1
3	79.68	28.85	1.50	13.5594	0.568042	6.4947	1
4	79.61	29.96	1.50	13.5648	0.568085	6.51134	1
5	79.87	19.23	1.49	12.847	0.567889	6.34445	1
10	79.96	14.15	1.49	12.0617	0.568269	6.26741	1

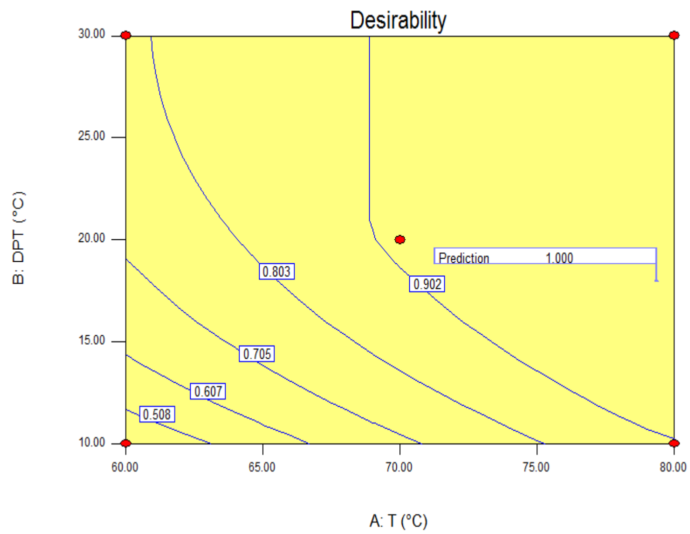


Figure 5.9: The surface plot of the desirability for the optimum parameters of mechanical properties of dried potato slices at V=1.5 m/s.

5.3 Process Optimization for Nutritional Property

Ascorbic acid can be considered as an indicator of the nutrient quality of food products due to its easily reactive nature. During the drying process, good retention of ascorbic acid is also an indicator of good retention of the other components. The objective of this section is optimizing the processing parameters for ascorbic acid.

5.3.1 Materials and Methods

The same potato variety, the method of sample preparation, and drying device similar to those mentioned in Section 4.2 were used here.

5.3.1.1 Ascorbic Acid Extraction and Determination

A certain amount of fresh, semi-dried and dried potatoes were prepared according to the European Standard EN 14130 (2003). Diluted meta-phosphoric acid was used to extract the fresh, semi-dried and dried samples. The suspension was then filtered. An appropriate amount of the filtrate was diluted with an L-Cysteine solution and adjusted to a pH value between 7.0 and 7.2. Subsequently, the solution was stirred and set to a pH value between 2.5 and 2.8. Prior to injection to the HPLC, the solution was diluted with ultrapure water. The true retention (TR) of the Vitamin C can be calculated using Equation 5.8:

$$\mathrm{TR} = \frac{\text{(Dried product weight)(conc.of Vitamin C in the dried product)}}{\text{(Fresh product weight)(conc.of Vitamin C in the fresh product)}} \quad (5.8)$$

5.3.1.2 Experimental Design

The response surface methodology (RSM) was used to design the experiments. Three independent variables: air temperature, dew point temperature and air velocity in m/s, for one dependent or response variable were generated. The basic model used to describe the response variable (*Y*) involves the linear or main, interaction and curvature effects as shown in Equation (5.3).

5.3.1.3 Statistical Analysis

Optimization of drying process was performed using the Minitab Software. The desirability index ranges from zero (least desirable) to one (most desirable). The desired goal for each dependent and the independent variable was chosen. The Vitamin C retention was set at the lower and upper target of 80% and 90%, respectively, while the independent variables were kept within the range (as indicated in Table 5.5).

Table 5.6: desired goals for independent and dependent variables

Dependent and indipendent variables	Goal	Importance 1= least important ... 5= very important
T (°C)	is in the range	3
DPT (°C)	is in the range	3
V (m/s)	is in the range	3
C/Co (-)	is in target	5

5.3.2 Results and Discussion

The contour plot of Vitamin C as a function of the drying temperature and the drying time is illustrated in Figure 5.10. As shown in Figure 5.10, the concentration of Vitamin C in a sample tends to decrease as both the drying time and temperature increase. For example, as the drying time increases from 60 minutes to 140 minutes for the sample dried at a temperature of 60 °C, the Vitamin C retention of the sample decreases from 96% to 88%. For the samples dried at a temperature of 80 °C, as the drying time increases from 60 minutes to 140 minutes, the Vitamin C retention of the samples decreases from the range of 80-88% to 56-64%. At higher temperatures and longer periods of drying processes, higher degradation of Vitamin C contents of the sample is observed. The final predictive model for ascorbic acid retention is presented in Equation 5.11. The linear model is a best fit to the Vitamin C retention of dried potato slices. The linear term of the drying temperature, the drying time, and the interaction of the drying temperature and time exhibited negative influence on the Vitamin C retention of the samples. Figure 5.10, Figure 5.11, Figure 5.12, and Appendix Table 4 show the significant influence of the drying temperature and drying time, and the limited effect of dew point temperature and air velocity on the Vitamin C retention of the sample. The results agree with the results of Santos & Silva (2008).

$$Y = 0.842 - 0.160A - 0.180B - 0.082\,AB \qquad (5.9)$$

where A=temperature (°C) and B= time (min) with R-Sq = 70.12% and $p<0.0001$

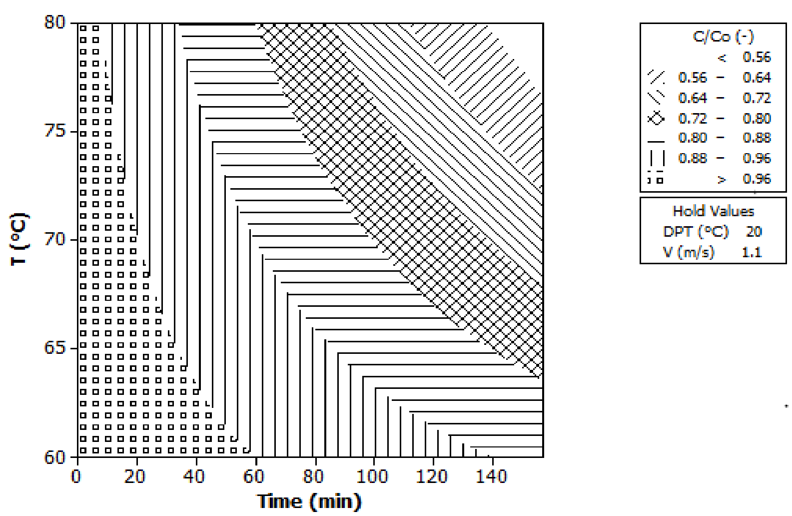


Figure 5.10: Contour plot of Vitamin C retention as a function of drying temperature and time

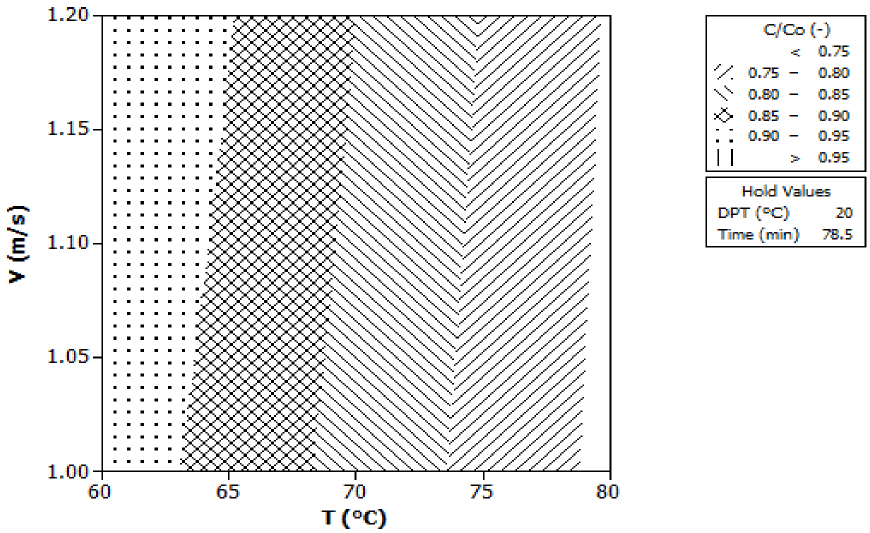


Figure 5.11: Contour plot of Vitamin C as a function of drying temperature and air velocity

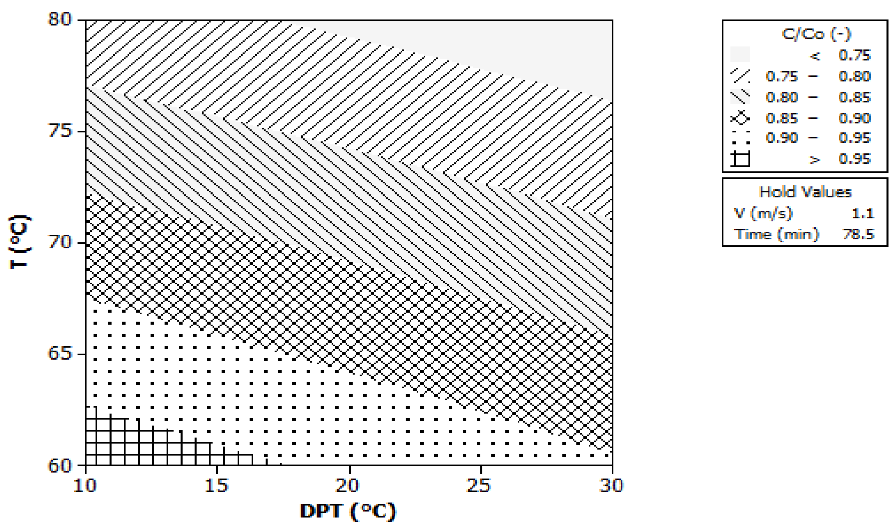


Figure 5.12: Contour plot of Vitamin C as a function of drying temperature and dew point temperature

5.3.2.1 Optimization

Optimum conditions for hot air drying of potato slices were determined to obtain the criteria of less ascorbic acid loss. To meet the requirements, variables were weighed by their importance (1-5) as indicated in Table 5.6. The optimum Vitamin C retention of the samples recorded 85% at the temperature of 68 °C, dew point temperature of 10°C, drying time of 116 minutes and an air velocity of 1.2 m/s. Figure 5.13 shows that the optimum processing condition for retention of Vitamin C. The value of Vitamin C retention obtained is not exactly coincident with the absolute minimum or maximum target values. It lies between the upper and lower target values. The desirability of the results is 0.95. Accordingly, the individual desirability for these functions is good.

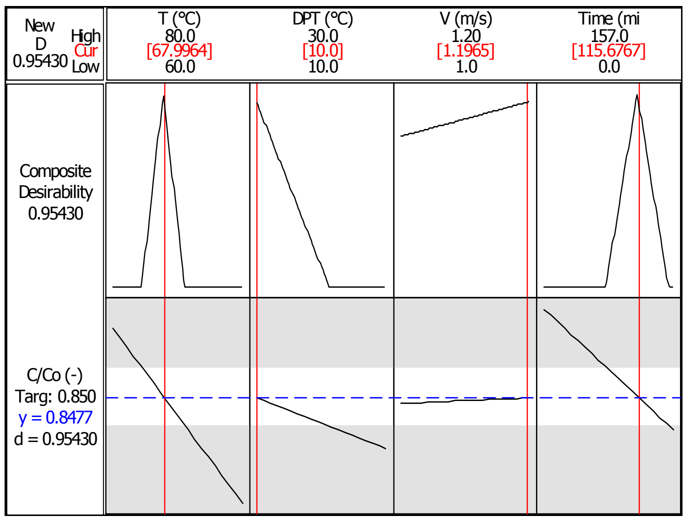


Figure 5.13: Optimization plot of vitamin C retention.

5.3.3 Conclusion

The influence of the temperature, the dew point temperature, and air velocity on Vitamin C and drying kinetics was examined. The drying temperature has a significant influence on the process of moisture removal from potato slices compared to the effect of the dew point temperature and the air velocity. The Vitamin C retention in potatoes significantly depends on the drying temperature, the drying time, and the interaction of both, the drying temperature and drying time. The optimum drying condition of dried potato slices with 85% of Vitamin C retention is obtained at a drying temperature of 68 °C, at a dew point temperature of 10 °C, drying period of 116 minutes, and an air velocity of 1.2 m/s.

6 A New Method Development and Determination for Glass Transition Temperature of Potato

In this chapter, a new method was developed for the determination of glass transition temperature of potato, to reduce the limitation of determination of glass transition temperature of real food. The glass transition temperature of potato was determined for applying the concept of glass transition temperature to the next chapter. The glass transition temperature (T_g) is defined as the temperature at which an amorphous system changes from the glassy to the rubbery state for a given heating rate. Its theory helps to understand textural properties of food systems and explain changes which occur during food processing and storage such as stickiness, caking, softening, and hardening. T_g is also used to fill the gap of water activity limitation when it comes to identifying the molecular mobility starting point of the food matrix. In drying of food products, glass transition temperature is one of the most important factors that has to be considered seriously. It can be taken as a reference parameter to characterize properties, quality, stability, and safety of food systems(Emy et al., 2012).

6.1 A New Method Development for Glass Transition Temperature of Potato

Liu et al. (2009) reported that measurement of T_g of starch and starch-based products by differential scanning calorimeter (DSC) is difficult because of the change of heat capacity or the signal on heat flow is usually weaker than that of conventional polymers. The author explains more by giving an example; the heat of fusion for polypropylene is about 80 kcal/g, whereas the measured energy for starch generalization is only about 0.95 cal/g. Furthermore, the multiple phase transitions that starch undergo during heating and the instability (such as evaporation) of water contained in starch make it more difficult to study the thermal behavior of starch materials using DSC. The instability of water contained in starch is also the reason why dynamic mechanical analysis is not suitable for studying the T_g of starch since the moisture evaporates during heating (Liu et al., 2009). The glass transition temperature of real food systems is difficult to measure due to their complexity and/or heterogeneity (Champion et al., 2000).The objective of this section is to develop a new method for the determination of glass transition temperature of potato. The experimental data can be also fit to the Gordon–Taylor model.

6.1.1 Materials and Methods

6.1.1.1 Preparation of Samples

Potato of Belena variety was purchased from a farmer (Lake Constance region, Germany) and it was stored at a temperature of 4°C. To start the experiment, good potatoes were selected, washed, and then sliced (Model Graff, Germany) into 3.5 mm thickness for glass transition temperature analysis.

6.1.1.2 Procedure to determine glass transition temperature by texture analyzer

Rahman (1995) defined glass transition as time-temperature dependent transition, which is characterized by a discontinuity or change in slope of mechanical and other properties of a material, when plotted as a function of temperature. The mass of the fresh samples as well as the mass of each sample were measured immediately during withdrawal of drying process. Out of twenty-eight potato slices, four slices were randomly selected and used for mechanical properties analysis of fresh samples. The remaining slices were randomly placed in a convective oven. Four slices were withdrawn from the oven at a regular time interval during drying process for the analysis. The samples were analyzed by compression test using a texture analyzer (CT3-1500, USA). The sample was placed on the hollow planar base. The force was then applied to the sample by a 3 mm cylindrical probe. The downward movement of the cross head of the texture analyzer was adjusted at 2 mm/s until it bent the sample, pre-test speed, and post test speed were the same as test speed of the probe (Moreno-Perez et al., 1996). Hardness and work data were recorded. The analysis was continued at least until one value higher than minimum in hardness and work value was observed. From the graph of hardness/ work versus moisture ratio of samples dried at constant temperature, the moisture ratio, at which minimum value of work and hardness were observed, was used as a transition point from glassy to rubbery state. Finally, the graph of the glass transition temperature versus the moisture ratio was plotted.

6.1.1.3 Data Analysis

The data were treated by the software Minitab 16. The glass transition temperature data was fit to Gordon–Taylor model (Gordon and Taylor, 1952):

$$T_g = \frac{(w_s T_{gs} + K w_w T_{gw})}{w_s + k w_w} \qquad (6.1)$$

The glass transition temperature of the water (T_{gw}) was taken at -135°C (Johary et al., 1987). T_g and T_{gs} are glass transition temperature of the binary mixture and the dry matter (solids), respectively. Weight fraction of dry matter (solids) and water are indicated by W_s and W_w, respectively. The parameter k is a constant of the model.

6.2 Results and Discussion

As mentioned in the literature, DSC is not suitable for determination of T_g of real food. T_g is defined as the temperature at which an amorphous system changes from the glassy (hard) to the rubbery state (soft). When the sample becomes soft, it is clear that the force and the energy (work) required for bending the sample becomes smaller.

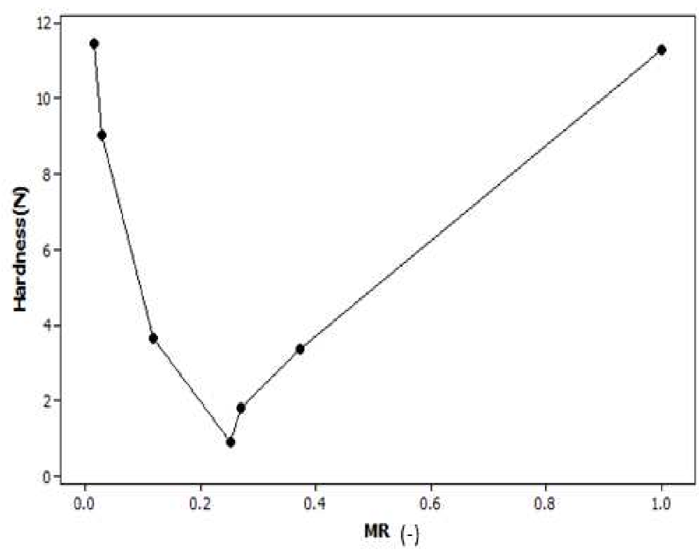


Figure 6.1: Hardness versus moisture ratio of samples dried at temperature 70 °C.

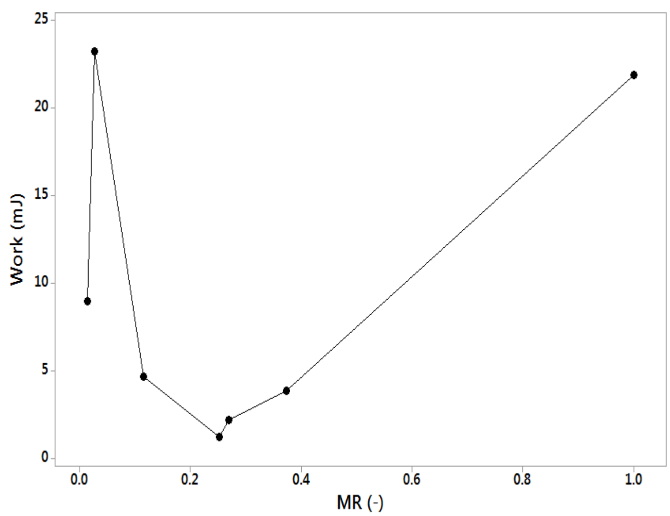


Figure 6.2: Work versus moisture ratio of samples dried at temperature of 70 °C.

The graph of hardness and work versus moisture ratio of hot air dried potato slices at a temperature of 70 °C are presented in Figures 6.1 and 6.2, respectively. Up to a moisture ratio 0.25, as moisture ratio of the samples decreases, a decrease in hardness (the resistance of the samples for bending) and the work required to overcome the internal strength, were observed. At a moisture ratio of 0.25, the samples attained the minimum hardness value (soft) and work. A temperature of 70 °C was taken as glass transition temperature at a moisture ratio of 0.25 for the samples dried at a temperature of 70 °C. In a similar manner, the glass transition point for other temperatures was determined. Concerning mechanical properties of potatoes, the trends of the result agree with the report of Moyano et al. (2007). Along with other researchers, Moyano reported that during thermal processing, the raw potato tissue becomes progressively softer and then it turns harder. According to Mali et.al. (2005), the glass transition temperature T_g of yam starch films were analyzed through a thermomechanical analysis (TMA); the T_g was analyzed only as a function of glycerol and starch content. Samples of 20–40 mg and 2–3 mm in diameter were placed in open aluminum pans. A penetration standard probe of quartz was used and the applied force was 980 mN (10 g). Samples were heated from -80 to 90 °C within a heating rate of 10 °C/min. The temperature of glass transition was determined by the change in the slope of the obtained TMA curves (dimension change versus temperature). Both, the method described in this paper and in Mali et.al. (2005) use mechanical property change as indicator of glass transition temperature. The method described in this paper uses the texture analyzer to determine the glass transition temperature (T_g). It is a new idea to use texture analyzer for determination of T_g of the sample. In most researches, the extracted starch from the samples was used to determine the glass transition temperature of the samples which are usually composed of many compounds. In this method, the sample itself (not extracted starch) was used to determine the Tg of the sample. A completely new method of sample preparation and procedure was applied.

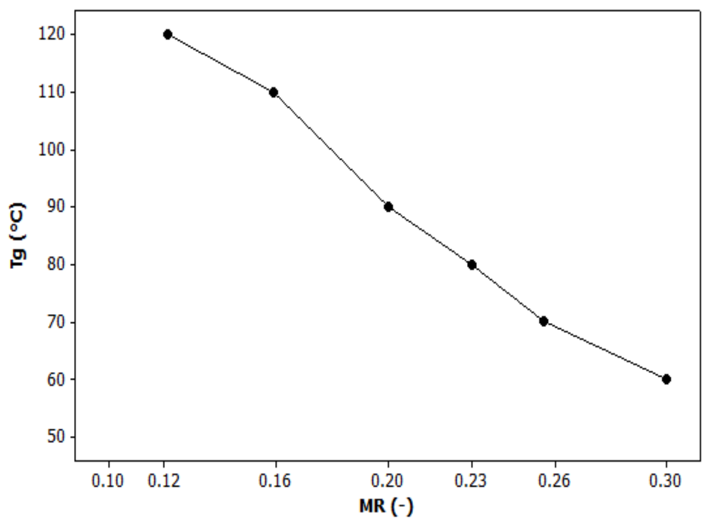


Figure 6.3: Glass transition temperature versus moisture ratio of potatoes.

Figure 6.3 shows a glass to rubber transition diagram of potato where the line represents the glass temperature at different moisture ratios. The glass transition point is the transition temperature at given moisture ratio where a transition from a glassy stable (solid state) to a rubbery (soft) state can begin to take place. For each moisture ratio, there was a unique glass transition temperature. For example, the glass transition point of potato slice at MR of 0.26 was 70°C (Figure 6.3). This means the molecular mobility of the matrix for the samples dried at a temperature of 70 °C starts at MR of 0.26. However, the optimum residual moisture content of the samples at its table a_w (a_w= 0.2) for the sample dried at 70 °C is 0.036 as discussed under chapter 3. As reported by Mcminn & Magee (2002), products having a_w = 0.2 are most stable with respect to lipid oxidation, non-enzymatic browning, enzyme activity, and of course, the various microbial parameters. Glass transition temperatures as a function of moisture ratio stands as an implication for keeping the process in a glass state, and for producing better quality of dried products. It is recommended to process in a glassy state by adjusting the temperature. Rahman, (2012) reported the stability of food at a glassy state since below the glass transition temperature, compounds involved in the deterioration reactions take time to diffuse over molecular distances and approach each other to react.

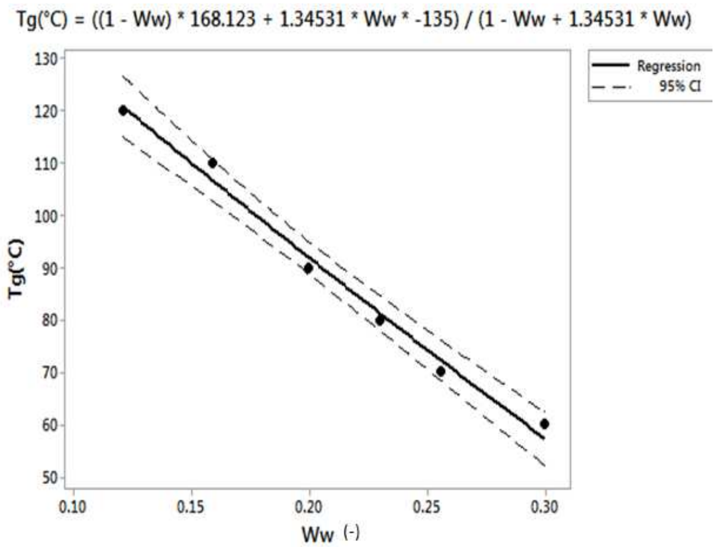


Figure 6.4: Comparison between experimental and predicted values of the glass transition temperature versus W_W (MR) using Gordon Taylor equation.

Compression between experimented and predicted values of the glass transition temperature is presented in Figure 6.4. All the experimented values lie between the dotted lines. This implies that the experimental data satisfactorily fit to the Gordon-Taylor model at the confidence interval of 95%. The line represents the transition of the sample's state from glassy to rubbery. The region below and above the line represents the glassy and rubbery state, respectively. Drying the sample within the glass state may give better quality and shelf stability. Roos (1992) reported T_g as indicator of the molecular mobility starting point of the solid matrix. The increase in temperature of a product above its T_g increases molecular mobility, and also affects diffusion of the matrix and results in an increase in rates of deterioration: enzymatic reaction, non enzymatic browning, and oxidation (Roos, 1992).

6.3. Conclusions

A new developed glass transition temperature method is simple and easy for sample preparation as well as for the analysis. It is possible to use the same sample thickness for the drying process as well as the process of glass transition temperature determination. For drying samples, either a drier or an oven can be used. A disadvantage of this method is that it has to be known, whether the sample is starch or a starch based material. The method might work for starchy fruits, roots, and tubers.

7 Application of the Concept of Glass Transition Temperature

The glass transition temperature graph of potato obtained in the previous chapter was used as an input for this chapter. The concept of glass transition temperature was applied to reduce quality deterioration of dried potato slices. Although one of the main objectives of drying is to maintain the quality of the dried product to meet consumers' interest**,** there is a deterioration of quality of the dried product due to processing conditions. Many of the quality changes took place due to chemical and biochemical reactions. As reported by Tsotsas and Mujumdar (2011), the rates of both reactions depend strongly on the processing parameters. Karmas et al. (1992) studied the effect of glass transition on rates of non-enzymatic browning in food systems and reported the presence of very slow browning below glass transition temperature.

Rahman (2012) also reports the stability of food products in the glassy state. At this state, compounds involved in the deterioration reactions take time to diffuse over molecular distances and approach each other to react. Although glass transition temperature of food products has been pointed out to be responsible for the deterioration mechanisms during processing, as well as an indicator of food stability, the quantifiable expressions between quality parameters and glass transition have not been yet found(Ratti, 2001). Therefore, the objective of this section is to minimize quality degradation of the dried products of the sample by stepping down temperature profiles before the sample develops a moisture content at which its corresponding glass transition temperature takes place.

7.1 Materials and Methods

The same potato variety, the method of sample preparation, and drying device similar to those mentioned in Section 4.2 were used here. Samples were dried until they reached an equilibrium moisture content of approximately 0.042 and 0.037 for drying at temperatures of 80 °C and 70 °C, respectively. At the end of the drying experiments, samples were put into an electric oven for 48 hours at a constant temperature of 70 °C for the dry matter's determination.

Moisture ratio (MR) is termed as

$$MR = \frac{M_{t} - M_{e}}{M_{o} - M_{e}} \quad \textbf{(7.1)}$$

where M_t, M_o and M_e are the instantaneous, initial, and the end moisture content in (g_w/g ts), respectively.

The values of M_e are relatively small when compared with the values of M_t and M_o for long periods of drying time. Therefore, Equation 7.1 can be simplified to: MR= M_t/Mo.

7.1.1 Determination of Color Changes and Shrinkage

Image analysis was carried out using a special program written for samples' color and shrinkage determination by (Sturm & Hofacker, 2009). The sample was analyzed for L, a, b and number of pixels. The change in total color difference was calculated using Equation (7.2). Change in a sample size due to shrinkage (s) was calculated using Equation (7.3) as a ratio of the current surface area (A) to the original surface area of a sample (A_o).

$$\text{TCD} = \sqrt{(\text{L} - \text{Lo})^2 + (\text{a} - \text{a}_0)^2 + (\text{b} - \text{bo})^2} \quad (7.2)$$

where a_o, b_o and L_o represent the initial values for the redness, yellowness and lightness of the samples, respectively; and a, b and L represent the instantaneous individual readings of the mentioned parameters.

$$S = \frac{A}{A_o} \quad (7.3)$$

7.1.2 Experimental Design and Statistical Analysis

The experiment was carried out using five selected temperature profiles (Table 6.1) for the through-flow drying arrangement. Models for quality parameters: total color change, change in lightness, change in redness, change in yellowness and change in shrinkage as a function of drying time were developed using the basic third order polynomial equation (Equation 7.4).

$$Y = ß_o + ß_1 x + ß_2 x^2 + ß_3 x^3 + \varepsilon \quad (7.4)$$

where ε stands for the random fluctuation (error). In this case, the response variable Y is predicted from predictor (or explanatory) variables X, X^2 and X^3 and b_0, b_1, b_2 and b_3 are the regression coefficients.

7.1.3 Temperature Profiles Selection

The temperatures profiles shown in Table 7.1 were selected based on the effect of glass transition temperature on the drying behavior of the potato slices. The graph of glass transition temperature and changing points of temperature profiles are depicted in Figure 7.1. The difference between air temperature and glass transition temperature (T-T_g) values of selected profiles at moisture ratio (MR) less than or equal to 0.28 are presented in Table 7.2. In the rubbery state, the value of T-T_g of temperature profile II is negative whereas the other temperature value has a positive value of T-T_g. In glass state, the T-T_g values of the temperature profiles I, II and III are less than or equal to 0. The T-T_g values of temperature profiles IV and V are -40 and -30, respectively.

Table 7.1: drying temperature profiles at dew point temperature of 10 °C and air velocity of 1 m/s

Profiles	Drying conditions
I	At a constant air temperature of 120 °C
II	Stepping the air temperature down (at moisture ratio of 0.28) from an initial value of 120 °C to a final drying temperature of 70 °C
III	Stepping the air temperature down (at moisture ratio of 0.28) from an initial value of 120 °C to a final drying temperature of 80 °C
IV	Stepping the air temperature down (at moisture ratio of 0.16) from an initial value of 120 °C to a final drying temperature of 70 °C
V	Stepping the air temperature down (at moisture ratio of 0.16) from an initial value of 120 °C to a final drying temperature of 80 °C

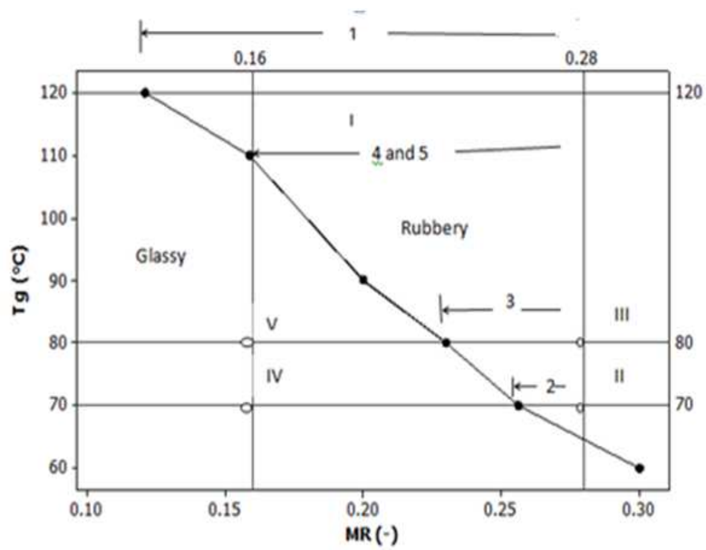


Figure 7.1: Glass transition temperature and changing point of temperature profiles

Table 7.2. T-Tg of selected profiles at MR ≤ 0.28

Profiles	(T-Tg) in °C in the rubbery state	(T-Tg) in °C in the glass state
Profile I	≤46	≤0
Profile II	≤-4	≤0
Profile III	≤6	≤0
Profile IV	≤46	≤-40
Profile V	≤46	≤-30

where T is air temperature and T_g is glass transition temperature.

7.2 Results and Discussion

7.2.1 Product Surface Temperature and Air Temperature

Figure 7.2 depicts product and air temperature as a function of the drying time for temperature profiles I, II, III, IV and V. For the constant temperature profile I, as the drying time increases, the increment in product temperature was observed. Gradually, the product's temperature approached the air temperature. As the heat gain of the samples from the hot air increased, the product surface temperature also increased until a temperature of the samples reached equilibrium with the drying temperature(Leeratanarak et al., 2006). An increase in heat gain of the samples led to an increase in warming of the product. Until the change in temperature is allowed to the samples, the pattern of product surface temperature becomes similar for all temperatures profiles. After the change in temperatures allowed to the samples for all time varying temperature profiles takes place, the reduction in value of product temperatures was observed. The reduction in surface temperature value of the samples is due to heat loss from the sample. A subsequent increase in product temperature with time was also observed.

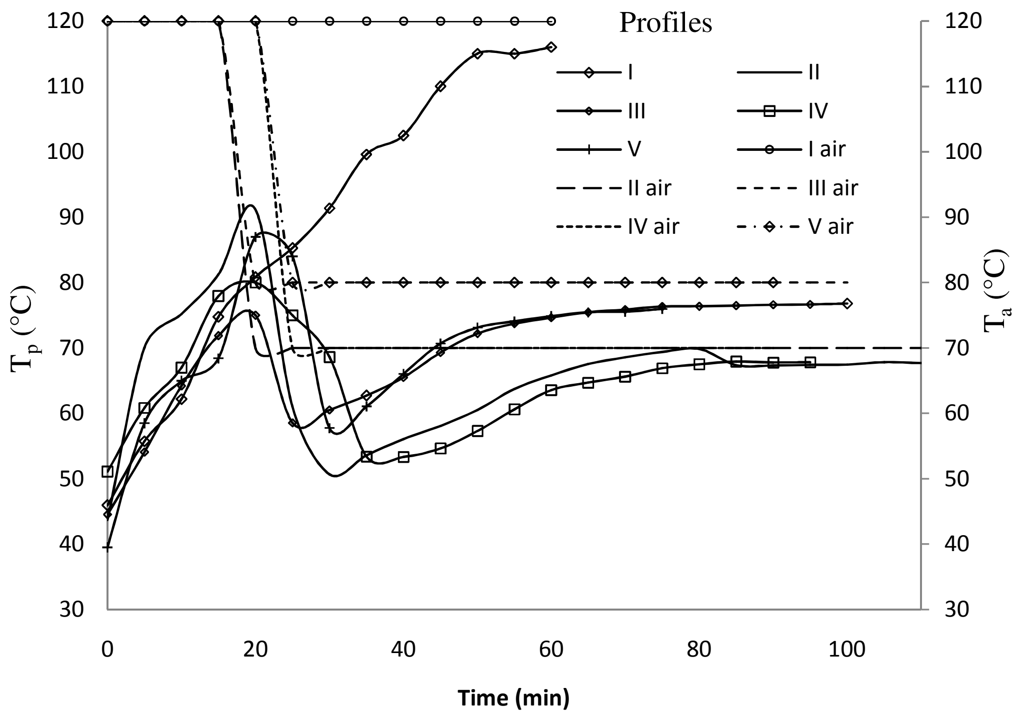


Figure 7.2: Product and air temperature as a function of time for profiles I, II, III, IV and V.

7.2.2 Moisture Ratio

Potato slices with initial moisture contents in the range of 79.41- 83.07(w.b) were dried until reaching their equilibrium moisture contents. The sample moisture content was expressed as dimensionless moisture ratio in order to avoid ambiguity results due to differences in samples initial moisture content. Figure 7.3 depicts the moisture ratio as a function of drying time for different profiles. The samples dried by exposing at a temperature profile I resulted in a faster reduction in moisture content as compared to the samples dried by exposing to other temperature profiles. Moisture diffusivity of the samples is higher when processed at higher drying temperatures(Leeratanarak et al., 2006). For the remaining profiles, faster reduction in moisture content was initially observed. Then the increments in moisture content of the samples were observed at the time temperature changes of air were allowed to the samples. These results are due to change in temperature gradient direction as observed in Figure 7.2. Then the reduction in moisture content of the samples with an increase in drying time was proceeding for all time varying temperature profiles. Finally, almost no changes in the reduction of the moisture content of the samples were observed for all temperature profiles.

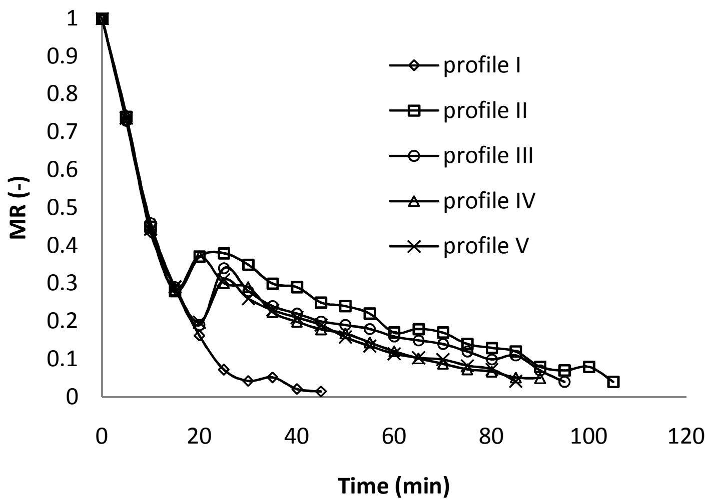


Figure 7.3: Moisture ratio as a function of drying time for different temperature profiles I, II, III, IV and V.

7.2.3 Total Color Difference

The third order polynomial regression equations describing the effect of temperature profiles on a change in the total color difference of potato slices are shown in Appendix Table. 6. The R^2 value shows that regression model explains in a range from 93% to 99 % of the variance in change in total color difference. The linear and the third-order regression term of total color difference exhibited positive and the second order regression term negative effect on color retention of the potato samples for all temperature profiles, except for temperature profile II. Figure 7.4 depicts changes in total color difference versus time for temperature profiles I, II, III, IV and V. The change in total color difference increases with time. At the end of drying stage, the highest value of the total color difference (TCD= 7.9) was observed for temperature profile I as compared to all other temperature profiles. The lowest value of the total color difference (4.7) was obtained for the temperature profile II, since at lower moisture ratio < 0.28, the samples were dried at a temperature of less than or equal to glass transition temperature. All time-varying temperature profiles resulted in better color retention as compared to temperature profile I. The increase in temperature of a product above its T_g increases molecular mobility, and also affects diffusion of the matrix and results in an increase in rates of deteriorative changes: enzymatic reaction, non-enzymatic browning, and oxidation(Roos, 1992).

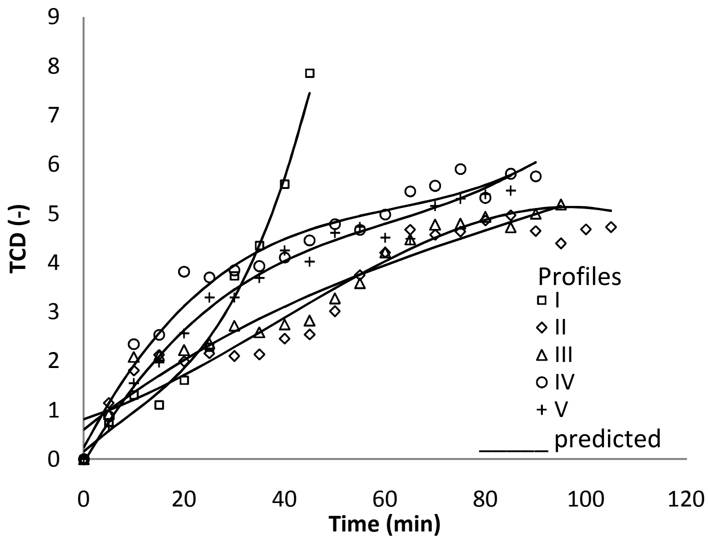


Figure 7.4: Changes in total color difference versus time for temperature profiles I, II, III, IV and V.

7.2.4 Change in Redness (Δa)

As shown in Figure 7.5, all temperature profiles resulted in redness above the original level. This means that the redness values of all dried potato chips were greater than the redness values of fresh potato. Leeratanarak et al. (2006) also reported that the hot air dried potato chips show higher redness values when compared to the fresh potato chips. Krokida et al., 1998 studied the kinetics on color changes during drying of apples, bananas, carrots and potatoes. Krokida's study concluded that the redness values increase during drying for apples, bananas, and potatoes. The highest redness level increment (Δa=4.1) was observed at constant temperature profile I. The lowest change in redness (Δa=1) was obtained for the sample dried at a temperature profile II. This means profile II was the best option for maintaining the redness of the original samples. This indicates that potato slices, at lower moisture ratio < 0.28, dried at a temperature less than or equal to glass transition temperature resulted in good retention in redness of the samples.

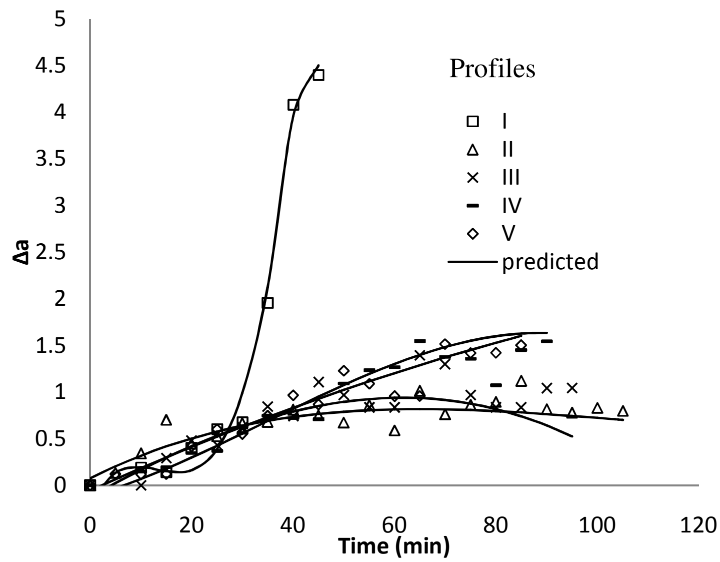


Figure 7.5: Changes in redness versus time for temperature profiles I, II, III, IV and V.

7.2.5 Change in Lightness (ΔL)

Changes in lightness versus time for temperature profiles I, II, III, IV and V are shown in Figure 7.6. The samples dried at temperature profiles II, III and IV resulted in lightness above the original level. For the samples dried at temperature profile I, the increase in lightness was observed for the first 10 minutes of drying and at drying time interval of 15-30 minutes. However, at drying time interval of 10-15 minutes and from 30 minutes until the end of drying process, a decrease in ΔL value was observed. Profile V almost maintained the original lightness of the fresh product. Profile II would appear to be a better option with an increase in lightness. The trend of the result for the constant temperature profile I agrees with the findings of Pedreschi et al. (2007), and Amjad et al. (2015). The trend of the result of ΔL for all temperature profiles, except for temperature profile I, agrees with the trend result of Chua et al. (2000). At the end of the drying process, change in lightness values recorded -4, 4.1, 3.6, 3.3 and 0.24 for potato slices dried at temperature profiles I, II, III, IV and V, respectively.

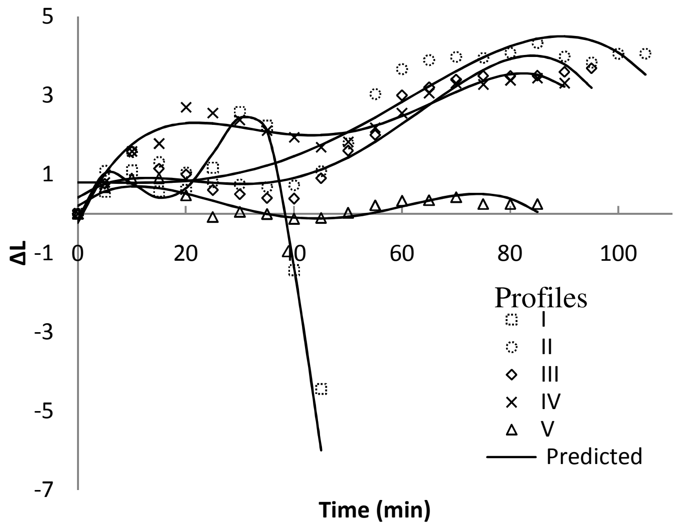


Figure 7.6: Changes in lightness versus time for temperature profiles I, II, III, IV and V.

7.2.6 Change in Yellowness (∆b)

Figure 7.7 depicts changes in yellowness versus time for temperature profiles I, II, III, IV and V. Change in yellowness decreases with time of drying cubically for all temperature profiles (Table 7.2.). All temperature profiles resulted in a reduction of the yellowness of the samples as compared to the original product. However, temperature profile II resulted in good retention in yellowness as compared to the remaining temperature profiles. The trend of the results agrees with the results of Amjad et al. (2015). At the end of the drying process, the change in yellowness values were -4.42, -2.27, -3.49, -4.46, and -5.25 for temperature profiles I, II, III, IV and V, respectively.

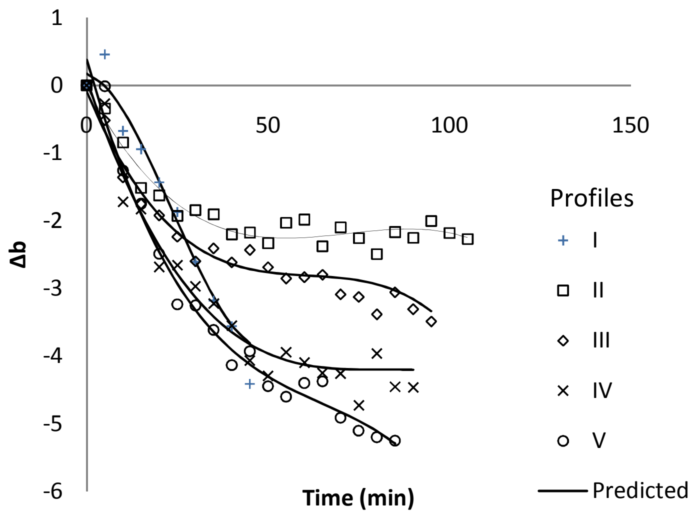


Figure 7.7: Changes in yellowness versus time for temperature profiles I, II, III, IV and V.

7.2.7 Shrinkage

Figure 7.8 depicts the change in normalized shrinkage versus time for potato slices dried at temperature profiles I, II, III, IV and V. The slope of the diagram is reduced by increasing the drying time for temperature profiles II, III, IV, and V. At the end of the drying stage, samples dried at all time varying temperatures resulted in significantly less shrinkage as compared to constant temperature profile I. The constant temperature profile keeps 58% of its original surface area. This means that there is 42% of shrinkage in surface area. Profile II keeps about 67% of its original surface area. The remaining 33% of its surface area was shrinking. This means that the samples dried at temperature profile II resulted in 27% less shrinkage of dried potato slices as compared to temperature profile I. As Bonazzi and Dumoulin (2011) discuss in their book the results of Willis et al, (1999). During drying of pasta, Willis et al. (1999) observed a higher shrinkage when samples were dehydrated at 100 °C and 50% relative humidity than in samples dehydrated at 40 °C at the same air relative humidity. In the first case, the temperature of the pasta was higher than the glass transition temperature, and the product remained in the rubbery state and shrank uniformly during the whole drying process. In the second case, the surface of the material became glassy, decreasing shrinkage and increasing residual stresses in the dried material. Leeratanarak et al. (2006) reported 48% and 50% of surface shrinkage of potato slices dried at constant temperatures of 80 °C and 60 °C, respectively.

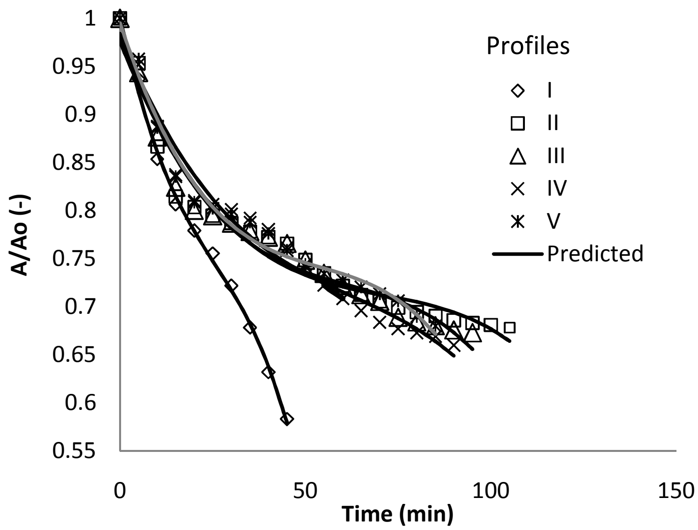


Figure 7.8: Change normalized shrinkage versus time of potato slices dried at temperature profiles I, II, III, IV and V.

7.2.8 Drying Time

Figure 7.9 shows the influence of temperature profiles on drying time of dried potato slices. The lowest drying time was 45 minutes for the samples dried at temperature profile I. The highest drying time was 105 minutes corresponding to temperature profile II. Even though the drying time for the samples dried at a temperature of profile II was relatively high as compared to temperature profile I, the best quality in optical and shape was observed for the samples dried at a temperature of profile I. The drying time of 105 minutes is also not long time to dry the samples under the normal condition.

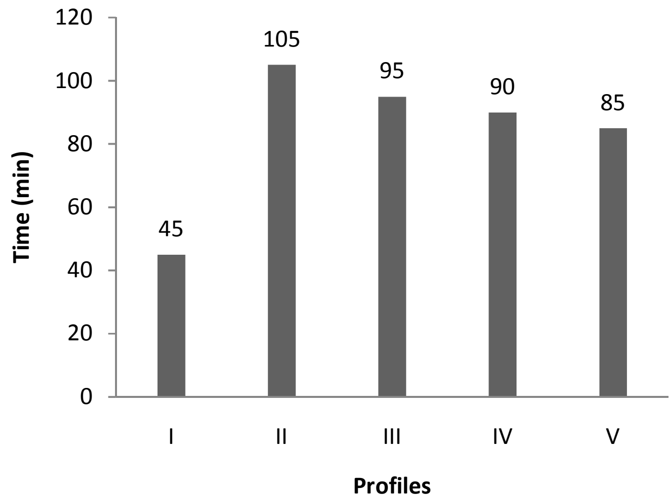


Figure 7.9: Drying time of dried potato slice for temperature profiles I -V.

7.2.9 Mechanical Property

Resilience is the ability of a substance or object to spring back into shape. Figure 7.10 depicts the influence of temperature profiles I-V on the resilience of dried potato slices. As shown in Figure 7.10, it can be clearly seen that the resilience of the samples dried at all temperature profiles is almost zero. This implies that the samples dried at all temperature profiles were brittle.

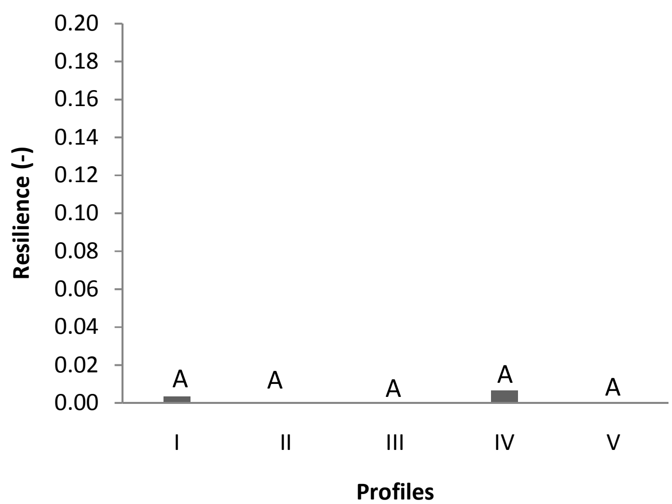


Figure 7.10: The influence of temperature profiles on resilience of the samples.

Figure 7.11 - 7.13 show the influence of temperature profiles on hardness, work, and deformation, respectively. The mean of the evaluated results that do not share a letter are significantly different. It is to be noted that the highest force was required to fracture the samples dried at temperature profile II. As observed in Table 6.2, the samples dried at temperature profile II passed most of the process in glass state. Therefore, the surface of the material became glassy and residual stresses in the dried material increased. This explains why the highest force was required to fracture the dried samples. Temperature profiles do not have a significant influence on the deformation of the samples, and on the work required to fracture the dried samples.

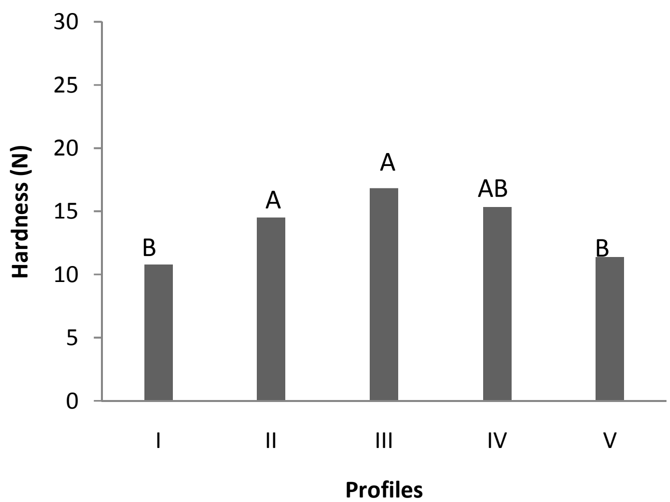


Figure 7.11: The influence of temperature profiles on hardness of the dried samples.

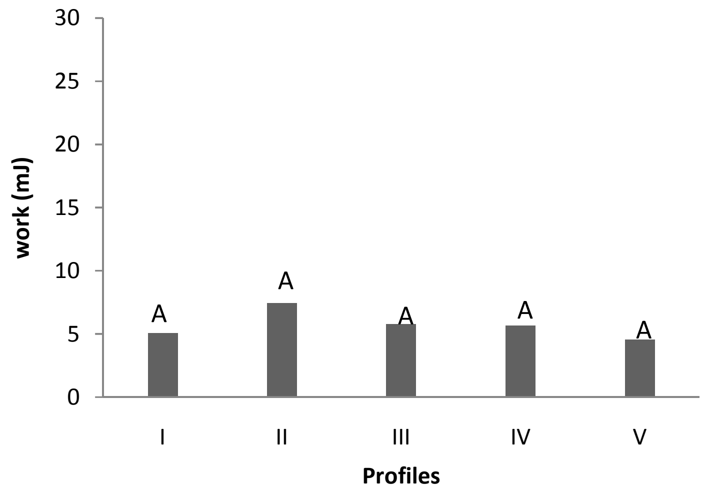


Figure 7.12: The influence of temperature profiles on work required to fracture the dried samples.

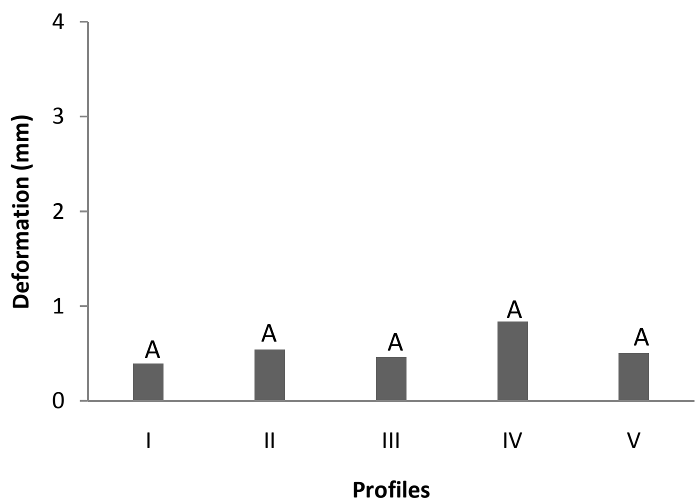


Figure 7.13: The influence of temperature profiles on deformation of dried potato slices.

7.3. Comparison

In Chapter 5, the optimum percent of shrinkage, change in total color difference, and time were found to be 40.4%, 6.62, and 82.58 minutes, respectively, at a temperature of 80 ℃, a dew point temperature of 10 ℃ and an air velocity of 1.5 m/s. For the sample dried at the temperature profile II, percent of shrinkage, change in total color difference, and time were found to be 33%, 4.7, and 105 minutes, respectively. This implies that the sample dried at temperature profile II (applying the concept of glass transition temperature) resulted in 18% less change in shrinkage, 29% less in discoloration, and 21% longer time than the sample dried at the optimum processing conditions mentioned above (at a temperature of 80℃ , dew point temperature of 10 ℃ and air velocity of 1.5 m/s). The sample dried at a temperature profile V(applying the concept of glass transition temperature) resulted in 21% less in shrinkage, 17% less in discoloration, and 9% longer time than the sample dried at optimum processing conditions (at a temperature of 80℃ , dew point temperature of 10 ℃ and air velocity of 1.5 m/s).

7.4. Conclusions

The sample dried at constant temperature resulted in a reduction in quality of color, high shrinkage, and low value of hardness of the samples. The samples were dried at a high temperature initially and proceeded at temperatures less than or equal to glass temperature within a moisture ratio less than 0.28. This resulted in better color retention, less shrinkage and crispy products. In general, drying the samples by initially applying a high air temperature and then reducing the drying temperature below the glass transition temperature of the sample has a positive effect on the quality attributes of the drying products. Further research would be needed to apply the concept of glass transition temperature on other drying food products.

8 Solar Tunnel Drying

The previous chapters focus on the optimization of drying condition on retention of the quality of hot air dried potato slices. For commercial countries, and the industries in the developing countries, this finding used as an input for drying good quality of dried potato slice. In one hand, hot air drying is unaffordable for medium and small-scale industry in developing country. On another hand, there is an abundant source of solar energy in tropical regions. Therefore, in tropical regions, solar tunnel dryer may become a more convenient alternative for rural sector and small-scale industry, and other areas in which electricity is scarce. Solar drying preserves crops, significantly reduces the quality deterioration of dried product, and is economically beneficial compared to the sun drying method (Sacilik, 2007). Although there are some food processing Industries in Ethiopia, there is no industry involved in the drying of food. To provide information for small and medium scale industries, investigation of processing parameters on the quality of solar tunnel drying is important.

The objective of this chapter is to investigate the effect of variety, slice thickness of the samples, and the position of the tray on the quality characteristics of dried potato slices, and the drying time for processing with solar tunnel dryer. The considered quality parameters were the total color difference, shrinkage, hardness, deformation, Vitamin C content, and the total phenolic content. The drying kinetics and time were also considered.

8.1 Materials and Methods

Three potato varieties of Gutteme, Gudene, and Alchole were purchased from a farmer in Dedo District, Jimma, Ethiopia. The potato varieties were sorted out, and washed from dust and dried at room temperature and then stored in a cooler (MC785-DE, Holand) at 4°C until the experiment took place. Peeling was done manually using a knife. The peeled potato from one variety at a time was sliced by food processor slicer (FP 700, China) to a thickness of 2 mm, 4 mm, and 6 mm. Then the sliced potatoes were placed in the labeled trays for drying.

8.1.1 Drying Device

The schematic diagram of a standard solar tunnel dryer (taken from Innotech) is presented in Figure 8.1. The standard solar tunnel dryer was modified and used for this study. The dimension and the content of the modified solar tunnel dryer are written below.

A solar tunnel dryer (Hohenheim) with the dimensions of 2 x 24 m was used for conducting the experiment. The 2 x 8 m portion of the dryer is a solar collector. The remaining part of the dryer is a drying tunnel. The surface of the collector is painted black to absorb solar radiation. In the dryer, the trays were arranged in series by two layers (upper and lower). The whole part of solar tunnel dryers was covered with a polyethylene plastic sheet. On one side of the solar tunnel dryer, a solar panel was fixed to absorb the sun's rays as a source of energy for generation energy, which is used as a supply for driving a fan. The air is drawn through the dryer by a fan. It is heated as it passes through the collector. The trays were labeled for each treatment. For this experiment, 12 trays were used. These trays were arranged as follows: three in the left upper part, three in the right upper part, three in the left lower part, and three in the right lower part of the dryer. All the trays were arranged at the air exit (at the back) of the dryer. Approximately, only the last two meters of the dryer was used for conducting the experiment. The preliminary test results show that the air temperature at the exit of the dryer was higher compared to the temperature at the front and in the middle part of the dryer. That is why the exit part of the dryer was selected for conducting the experiment. All the treatments were conducted in one run to avoid variation in external influencing factors such as temperature, relative humidity, solar radiation, and so on. The ambient temperature was recorded using a thermometer. The temperatures of air inside the solar tunnel dryer were recorded by using thermocouples with k-type sensors. The sensor inside the dryer is fixed in between the middle and the back portion of the dryer.

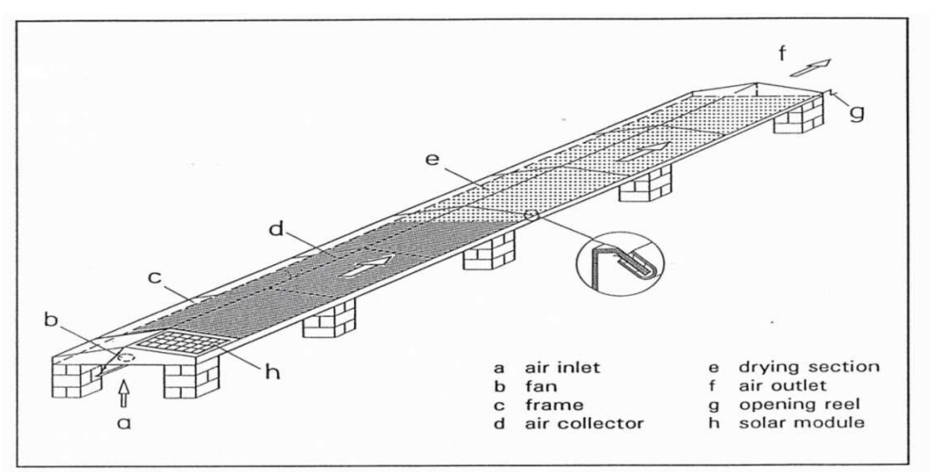


Figure 8.1: Diagram of Solar tunnel dryer.

8.1.2 Total Color Difference and Shrinkage Determination

A box with the dimensions of 40 x 40 x 40 cm was used to prevent the entrance of light to the sample during taking an image of the sample. On the top side of the box, a hole with a diameter of 5 cm was drilled to insert the camera. The box was placed on the top of an 80 x 80 cm size black painted wood plate. As the sample was placed in the box, an image of the sample was taken by the camera for analysis. 60 w an electric bulb was used for illumination in the box. Image analysis was carried out using a special program written for this purpose (color and shrinkage determination) by Sturm and Hofacker (2009). The sample was analyzed for L, a, b, and number of pixels. Percent of shrinkage (s) was calculated using Equation 8.1, as one minus the ratio of the current surface area (A) to the original surface area of the sample (A_o) multiplied by one hundred. The global color change or change in total color difference is calculated using Equation 8.2. The image analysis of the sample was recorded at the beginning (before placing into the dryer) and at the end of drying (after taken out from the dryer) out of the dryer. Drying kinetics, hardness, and deformation of the samples were determined as the same as written under chapter 4.

$$S\ (\%) = \left(1 - \frac{A}{A_o}\right) \times 100 \qquad (8.1)$$

$$TCD\ (-) = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \qquad (8.2)$$

8.1.3 Vitamin C Determination

Vitamin C content in the potato sample was determined using a titration method with 2, 6-dichloro-indophenol reagents (AOAC, 1990). Two grams of the dried sample or 8 grams of the fresh sample were mixed with 100 ml of 0.1 N meta-phosphoric acid. 10 ml solution was titrated with 2, 6-dichloro-indophenol. Three replicates were then performed for each analysis.

8.1.4 Determination of Total Phenolic Content

10 grams of potato flour was mixed with 80 ml methanol and kept overnight. The suspension of the samples was filtered through filter paper, and the filtrate was diluted to 100 ml with methanol. Sample solutions were stored at 4 °C in amber bottles and served as the stock solution (100 mg/ml) for analyses. A modified method by Slinkard and Singletion (1997) was used to determine the total phenolic content of the potato samples.

Shortly, 200 micro liters of the sample was mixed with 1.4 ml of distilled water and 100 ml of Folin-Ciocalteu reagent. At least after 30 seconds and at most before 8 minutes, 300 ml of 20% Na_2CO_3 solution was added, and the mixture was allowed to stand for 2 hours. The absorbance was read at 765 nm using UV-Visible spectrophotometer (T80 China). Gallic acid solutions (10–100 ppm) were prepared similarly to the construction of the calibration curve. The results were expressed as mg Gallic Acid/100 g dry sample of potato. The test and analysis of the samples were run in triplicate.

8.1.5 Texture Determination

The texture of the potato chips was evaluated by a compressive test using a texture analyzer (TA.XT plus, England). The method used in this chapter for the determination of the texture of the potato slice is the same as the method described in Chapter 5.

8.1.6 Experimental Design

The variables considered in the experiment were the three potato varieties, the three slice thicknesses, and the two tray positions. Accordingly, the experiment had a $3 \times 3 \times 2$ factorial design, with three replications.

8.1.7 Statistical Analysis

All data were analyzed using three factors analysis of variance (ANOVA). Tukey's test was used to establish the multiple comparisons of mean values. Mean values were considered at a 5% significance level ($p<0.05$). The statistical analyses of the data were conducted using Minitab 16 statistical software package. Statistical significance was expressed at the $p<0.05$ level.

8.2 Results and Discussion

8.2.1 Physical Property and Composition of Potato Varieties

The physical properties and composition of the three potato varieties used in the study, namely Gudene, Geteme, and Alchole are presented in Table 8.1. Varieties Gudene, Geteme, and Alchole resulted in to have a specific gravity of 1.056, 1.090 and 1.083, and a moisture content of 84, 81 and 82% (wb), respectively.

Table 8.1: Physical properties and composition of raw potato

Variety	Specific gravity	Moisture content of slices (%wb)
V_1=Gudene	1.056	84
V_2= Guteme	1.090	81
V_3=Alchole	1.083	82

8.2.2 Drying Kinetics

Figure 8.2 shows the normalized moisture content as a function of the drying time for three levels of thickness of the samples. The moisture content of the sample decreased faster as the thickness of the sample decreased. Thinly sliced samples were dried faster due to the reduced distance the water has to travel in order to be extracted. As a result, the drying time decreases with a decrease in the slice thickness of potato. Figure 8.3 and Figure 8.5 depict the normalized moisture content as a function of the drying time for two levels of the position of the tray and the three varieties, respectively. As observed from the figures, the positions of the trays and varieties have limited effect on moisture content removal as compared to the effect of slice thickness.

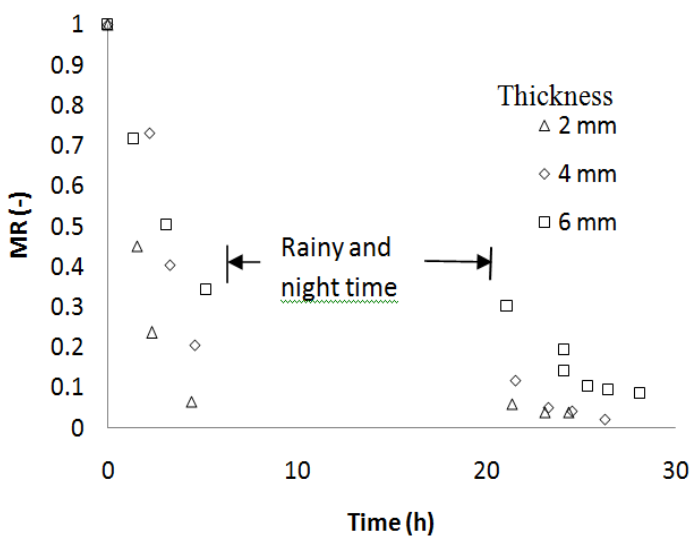


Figure 8.2: Normalized moisture content as a function of drying time for three level thickness of solar tunnel dried potato slice of Gudene placed at upper position of the trays

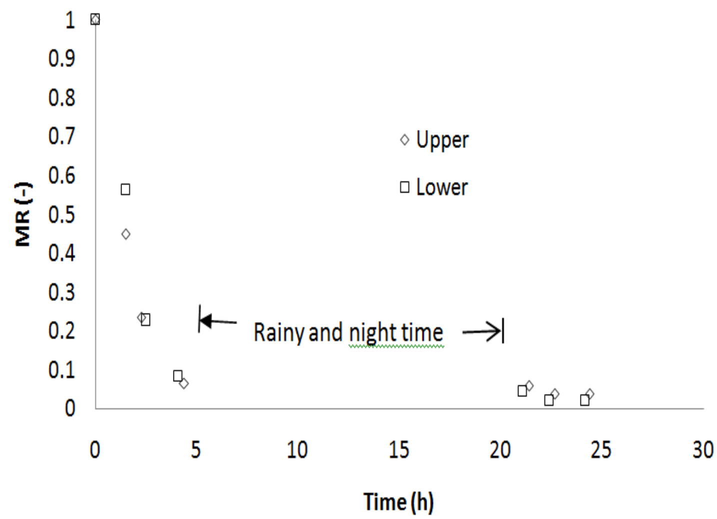


Figure 8.3: Influence of position of tray on normalized moisture content as a function of drying time for variety 1 of 2 mm thickness.

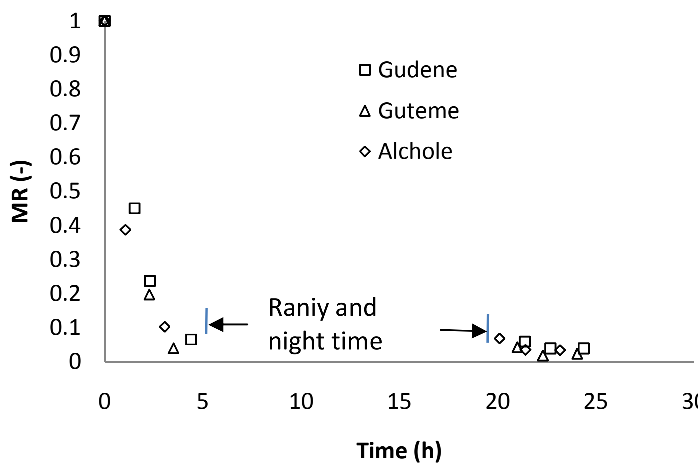


Figure 8.4: Influence of variety on normalized moisture content of potato slices of thickness of 2 mm placed at upper trays.

8.2.3 Total Color Difference

The influence of the thickness of the potato slices on the overall color change is presented in Figure 8.5. The result of total color difference (between the fresh and dried sample) showed a direct relationship between the effects of slice thickness and discoloration of the samples. As the thickness of the sample increases from 2 mm to 6 mm, the total color difference of the sample increases from 36.9 to 53.2. The samples dried at a thickness of 2 mm resulted in 44% more retention in color change than the samples dried at a thickness of 6 mm. Analysis of variance showed that the global color of potato slices was significantly affected (at P<0.001) by the thickness. The influences of the position of the trays and the variety have limited effect on the total color difference of dried potato slices. The limited effect of potato variety on total color difference may be due to the fact that all the three potato varieties pass through the same agronomic and storage condition. In general, high discoloration of the dried potato slices was observed due to the semi ran weather condition.

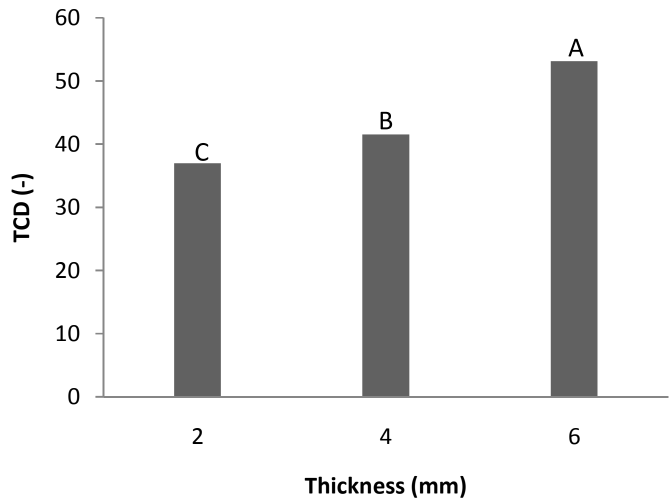


Figure 8.5: Influence of slice thickness on total color difference (Means with the different letter are significantly different).

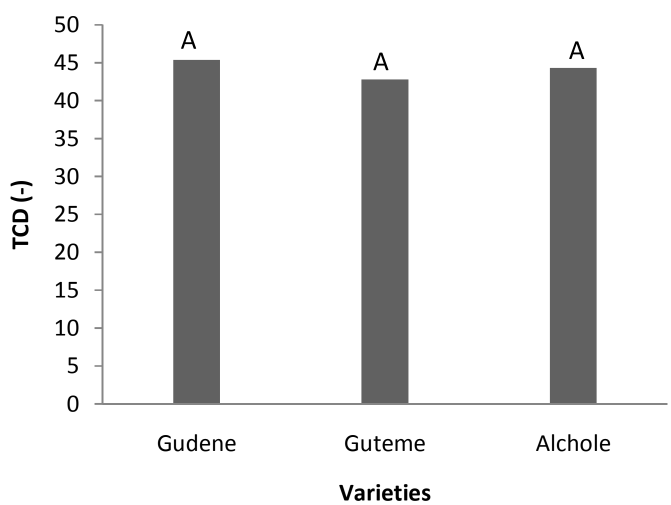


Figure 8.6: Total color difference of dried potato slices for three varieties (Means with the same letter are not significantly different).

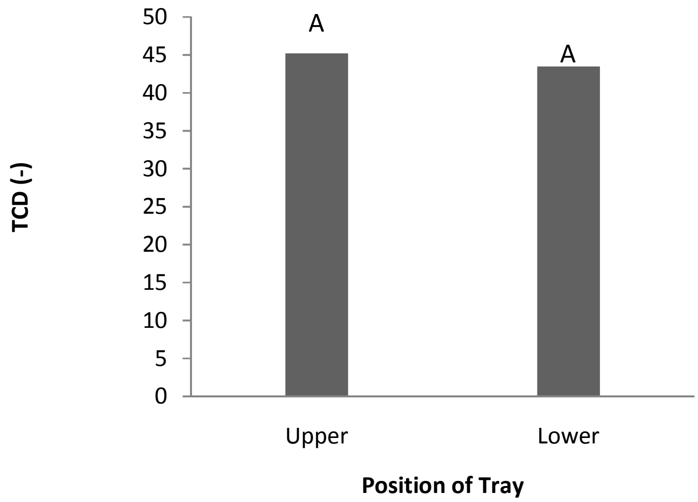


Figure 8.7: Total color difference of dried potato slice at two positions of the trays (Means with the same letter are not significantly different).

8.2.4 Drying Time

The influence of slice thickness and variety on total drying time of potato slices is presented in Figure 8.8 and Figure 8.9. The thinner the potato slice, the faster it dried, and thus, resulted in shorter drying time. As the thickness of the slice increased from 2 mm to 6 mm, the drying time of the samples increased from 25 hours to 29 hours. Due to high moisture content of Gudene, an additional hour was required to dry the sample compared to the drying time of Guteme. Analysis of variance showed that the drying time of potato slices was significantly affected (at $P<0.05$) by the thickness and variety. However, the drying time of potato slices was not significantly affected by the position of the trays.

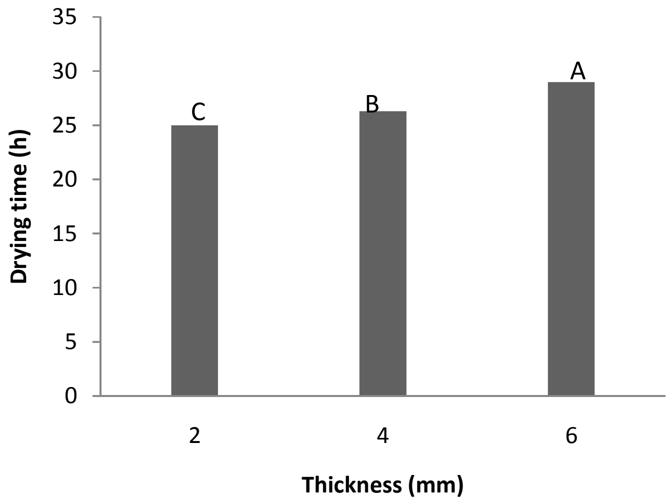


Figure 8.8: Drying time as a function of slice thickness of dried potato slices (Means with the different letter are significantly different).

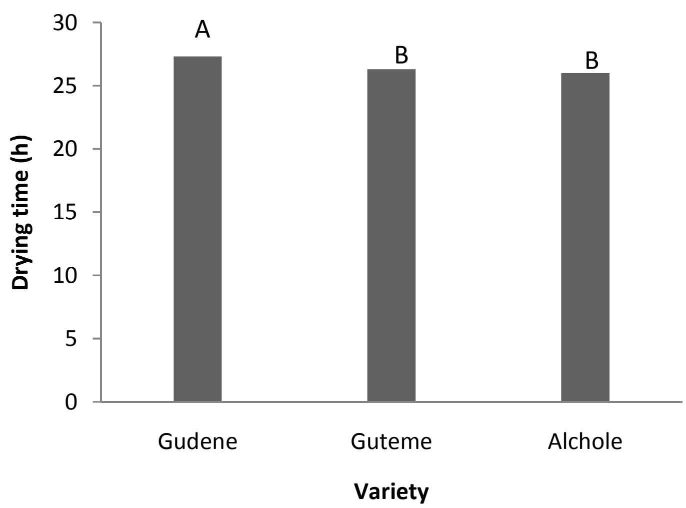


Figure 8.9: Drying time for drying three varieties of potato slices (Means with the different letter are significantly different).

8.2.5 Shrinkage

As shown in Figure 8.10, drying shrinkage is slightly higher in the slices of the Gedene variety than in those of the Geteme and Alchole potato varieties. The slightly highest resistance to shrinkage was observed in the Geteme and Alchole potato varieties. The slightly higher shrinkage observed on the variety of Gedene may be due to its high, initial moisture content of the sample. Figure 8.12 shows the maximum shrinkage percentage and the minimum shrinkage percentage of the dried potato slices for the slice thickness of 2 mm and 6 mm. A shrinkage percentage of 60% and 57% was computed at the thickness of 2 mm and 6 mm, respectively. Analysis of variance showed that shrinkage was not significantly affected by the position of the tray, variety and thickness of the slices.

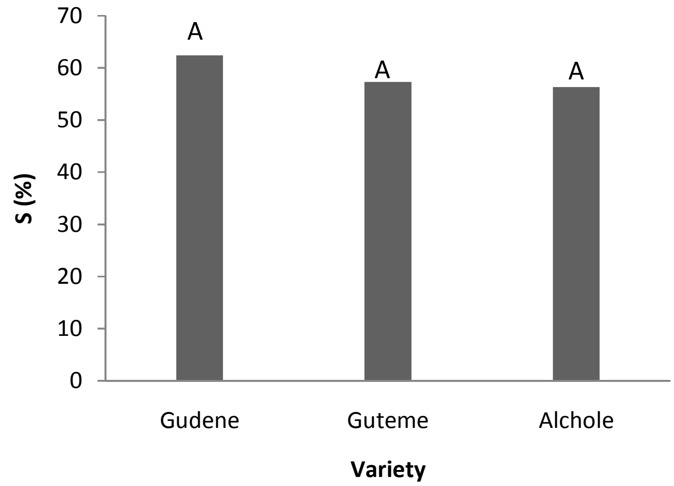


Figure 8.10: Percentage of shrinkage for three varieties of dried potato slices (Means with the same letter are not significantly different).

Figure 8.11: Percentage of shrinkage for dried potato slices at two positions of the trays (Means with the same letter are not significantly different).

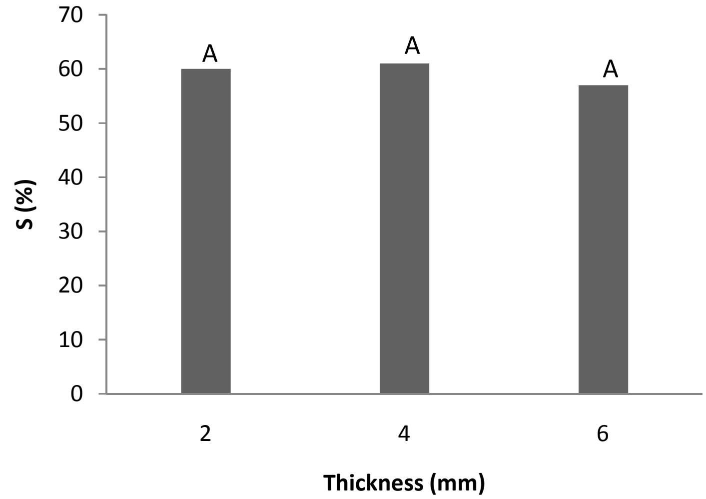


Figure 8.12: Shrinkage of dried potato slices as a function of slice thickness (Means with the same letter are not significantly different).

8.2.6 Texture

The effect of thickness on the hardness of the dried potato slices is presented in Figure 8.14. The thicker the slice of the potato, the higher the resistance force against the probe. The samples dried at a thickness of 6 mm had double resistance against the probe as compared to the samples dried at a thickness of 2 mm. As a result, as the thickness of the sample increases from 2 mm to 6 mm the force required to fracture the dried potato slices increases from 13.87 N to 28.95 N. Analysis of variance showed that thickness has a significant effect (at $P<0.001$) on the hardness of dried potato slices. As can be seen from Figure 8.13, the resistance force against the force required to fracture the sample is significantly higher in the slices of the Gudene variety than in those of the Guteme and Alchole. The lowest resistance force against the force required to fracture the dried samples was observed in the Guteme and Alchole varieties of potato. Analysis of Variance showed that the position of the tray has no significant effect on the hardness of dried potato slices.

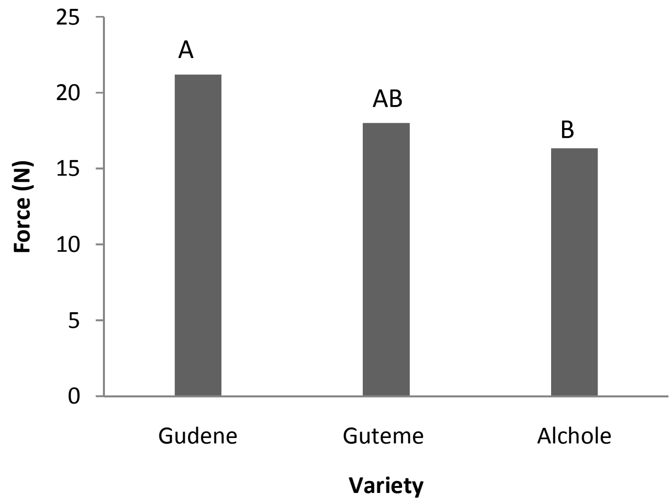


Figure 8.13: Hardness of three varieties of dried potato slices (Means with the different letter are significantly different).

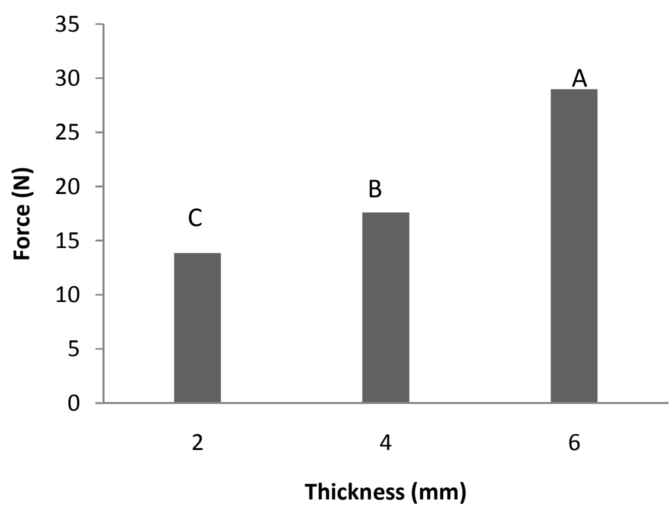


Figure 8.14: Hardness of the dried potato slices as a function of slice thickness of slices (Means with the different letter are significantly different).

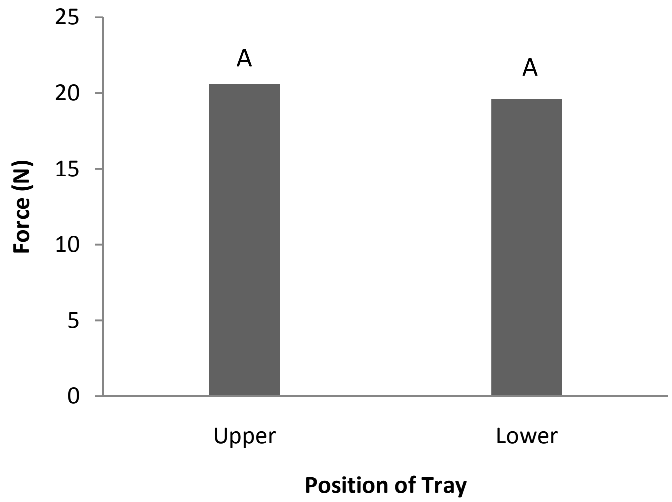


Figure 8.15: Hardness of the dried potato slices as a function of position of the trays (Means with the same letter are not significantly different).

The results of the instrumental analysis of the deformation of the dried potato slices for the two levels of tray position and the three levels of variety and thickness of the slices are shown in Figures 8.16- 8.18, respectively. Deformation at fracture varied significantly among the potato chip variety. However, deformation at fracture was not significantly different due to the influence of slice thickness and position of the tray.

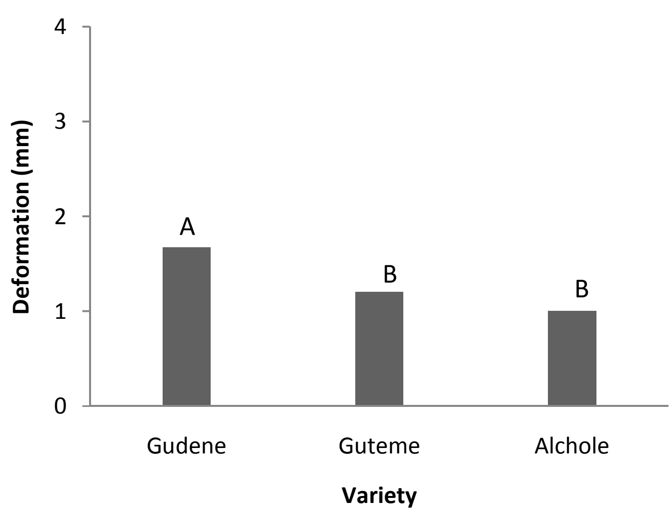


Figure 8.16: Deformation at fracture for three levels of potato varieties (Means with the different letter are significantly different).

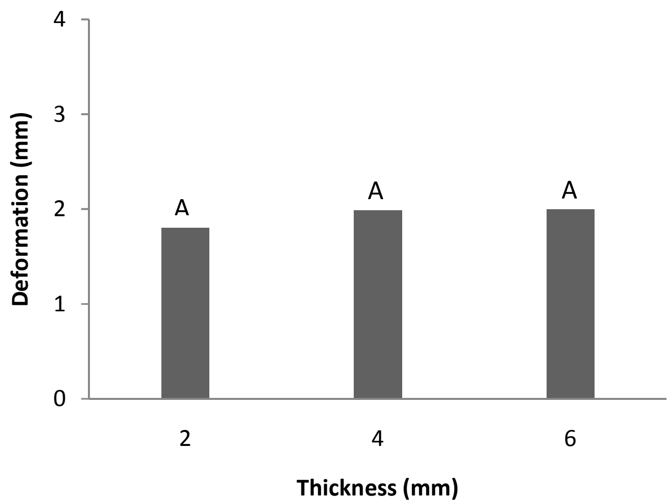


Figure 8.17: Deformation at fracture for three levels of slice thickness (Means with the same letter are not significantly different).

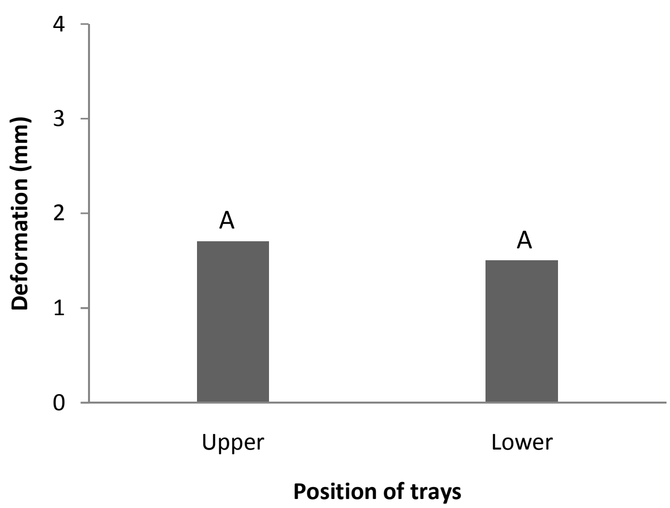


Figure 8.18: Deformation at fracture for two levels of position of trays (Means with the same letter are not significantly different).

8.2.7 Total Phenolic Content

The contour plot of total phenolic content of dried potato slices are presented in Figure 8:19 and 8:20. The results in Appendix Table.16 revealed that the interaction effect of the thickness of the slices, the position of the tray, and the potato variety were significant ($P<0.05$) in the total phenolic contents. As observed in Figure 8:19 and 8:20, the highest value ((30- 40) mg GAE/100 g dw) was recorded for thinner slices of Guteme dried at lower trays. The lowest value (<10 mg GAE/100 g dw) was recorded for the thicker slices of Alchole dried at upper trays. The decrease in the slice thickness of potato slices from 6 mm to 2 mm dried at lower trays resulted in an increase in the retention of total phenolic content from the range of (30-40 GAE g/100 g dw) to less than 10 GAE g/100 g dw). This could be caused by longer total drying time required by the thicker slices to reach equilibrium moisture content, which in turn intensifies the thermal degradation and oxidation of total phenolic content in the potato slices(Chin et al., 2015)

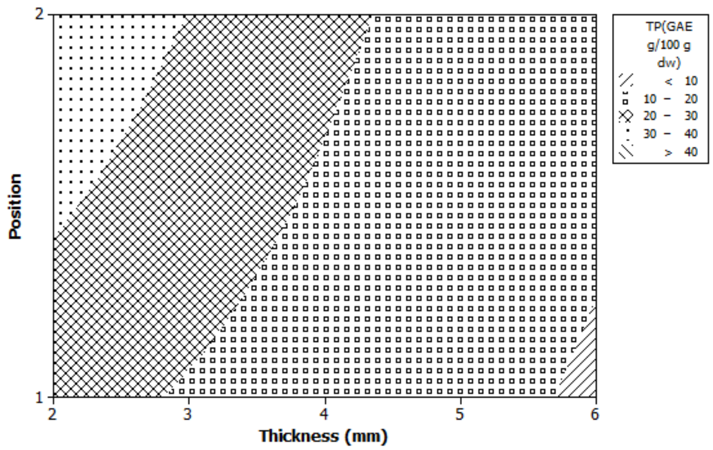


Figure 8.19: Contour plot of total phenolic content as a function of slice thickness and position of trays. Where position 1= upper trays and position 2= lower trays.

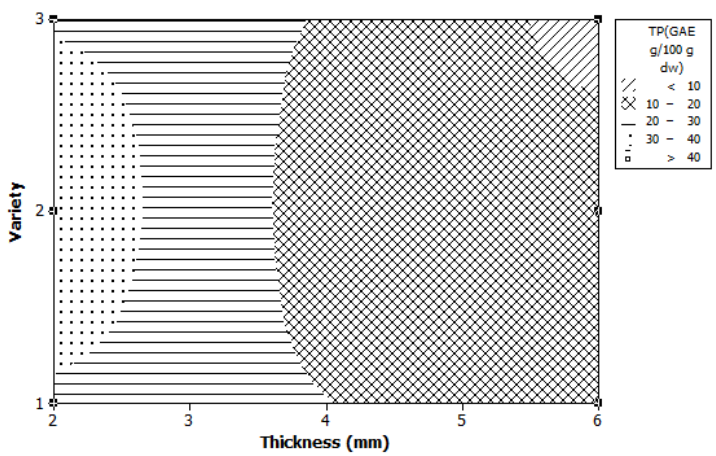


Figure 8.20: Contour plot of total phenolic content as a function of slice thickness and variety. Where variety 1= Gudene, Variety 2= Guteme and variety 3= Alchole .

8.2.8 Ascorbic Acid

Figure 8.21 and Figure 8.22 shows the retention of Vitamin C content of the three potato varieties dried at different slice thicknesses and position of the trays. The results in Appendix Table. 17 revealed that the interaction effect of the thickness of the slices, the position of the tray, and the potato variety were significant ($p< 0.05$) in Vitamin retention content. As shown in Figure 8.22 the obtained retention value of Vitamin C content of potato slices for Guteme dried at the highest slice thickness was low (less than 0.55). The highest value of Vitamin C retention was obtained for the variety Gudene and Alchole dried at a thickness of 2 mm. When the slice thickness of Alchole increased from 2 mm to 6 mm, the obtained retention value of Vitamin C content was 0.75-0.8 and 0.60 -0.65, respectively. When the slice thickness of Gudene increased from 2 mm to 6 mm, the obtained retention value of Vitamin C content was 0.75-0.8 and 0.55 -0.60, respectively. This is due to the fact that a longer drying period is needed for the thicker slices to achieve equilibrium moisture content which in turn causes higher Vitamin C degradation due to thermal damage and irreversible oxidation reactions (Ekow *et al.*, 2014).

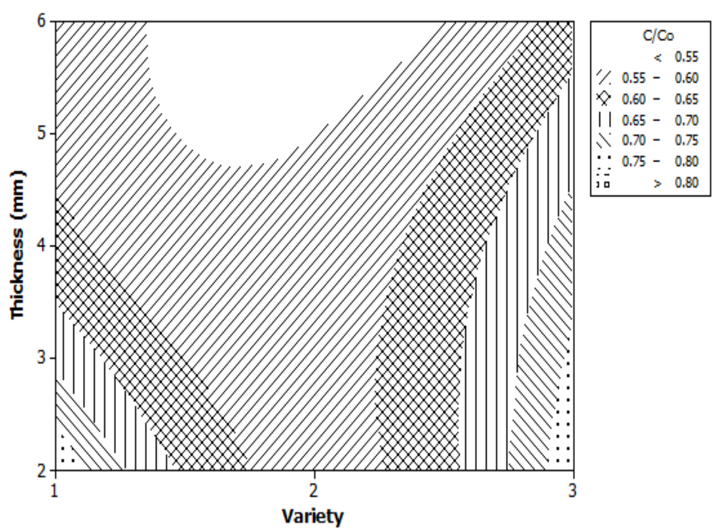


Figure 8.21: Contour plot of Vitamin C as a function of slice thickness and variety. Where variety 1= Gudene, Variety 2= Guteme and variety 3= Alchole .

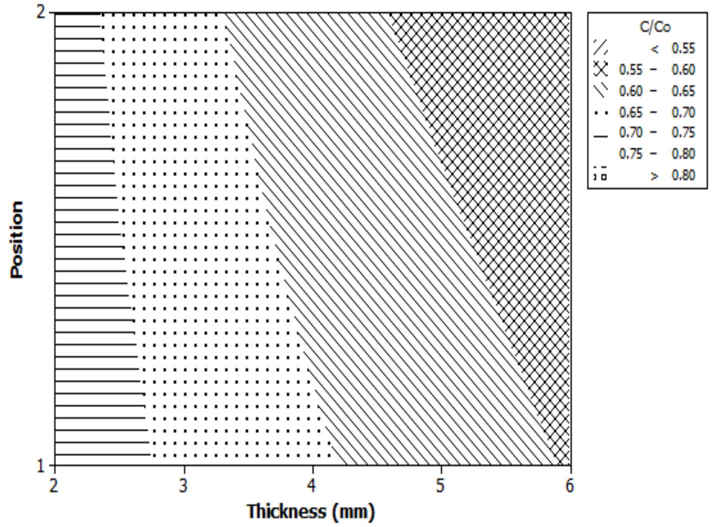


Figure 8.22: Contour plot of Vitamin C as a function of slice thickness and position of trays. Where position 1= upper trays and position 2= lower trays.

8.3. Conclusion

The interaction effect of variety, slice thickness, and position of trays has a significant effect on retention of Vitamin C and total phenolic content of the dried potato slices. The thinner slice of Guteme and of Alchole varieties dried at the lower positions of tray have a positive influence on most of the quality attributes of dried potato slices. The quality of the dried product depended directly on the weather condition. In general, high discoloration of dried potato slices, high shrinkage, and longer drying time were recorded due to semi rainy weather. Drying the sample in sunny weather at a thickness of 2 mm was recommended to get better quality for the dried potato slices.

9 Proof of Utilization

In the previous chapter, the perishable root and tubers changed to the stable form. The final target of every processed food product is to change into consumable form. Then the product needs to be checked for being acceptability by the consumer. If it is not checked, it may result in unaccepted the product in the utilization. The objective of this chapter is to change the stable root and tuber into utilized form. Bread is one of the most important sources of energy in our diet. In the UK, bread is one of the products developed by taking the dried potato flour as an ingredient. In this chapter, potato flour and Anchote flour will be used as partial replacement of wheat flour for making bread. The sensory acceptability of the bread will then be evaluated.

9.1 Materials and Methods

Sample Preparation

Potato variety of Gudene was purchased from a farmer in Dedo District, Jimma, Ethiopia. Anchote (*Coccinia Abyssinica)* was taken from Jimma Unversity farm. Potato and Anchote were sorted, and washed from dirt and dried at room temperature and then stored in a cooler (MC785-DE, Holand) at 4 °C until the experiment took place. Prior to drying, both Anchote and Potato were sliced into a thickness of 2 mm. The slices of the sample were dried in the solar tunnel dryer on a sunny day.

The dried potato and Anchote slices were stored in heat-sealed polyethylene bags at room temperature (25 ± 2°C) and transported to the laboratory of the post harvest management at Jimma University College of Agriculture and Veterinary Medicine, Ethiopia. The chips were milled into the flour using a laboratory mill (Karl Kolb D-6072 Germany) followed by sieving (0.5mm) to produce fine flour. The flour samples were then packed in polyethylene bags.

9.1.1 Baking Test

Bread was prepared in the laboratory from a combination of wheat, Anchote, and potato flour. The levels of substitutions of wheat flour by Anchote and potato flour were 5-10% and 5-20%, respectively. Bread was baked using a straight-dough method as described in the AACC (2000). Wheat, Anchote and potato flour of 250 g, 18 g sucrose, 4.5 g Sodium Chloride ($NaCl$), 4 grams of instant yeast and 170 ml distilled water were used. The temperature of water to be added was controlled at 30 ± 1 °C. The dough was made manually and then fermented at 30°C for 60 minutes. The fermented dough was punched, sheeted, and rolled, and then placed into a lightly oiled bread pan. The loaves were proofed for 60 minutes followed by baking at 182 °C for 32 minutes in a preheated baking oven.

9.1.2 Experimental Design

Parameters for D-optimal mixture design in blending flour for making bread were prepared using Design-Expert Version 6.2 software as shown in Table 9.1. Three independent factors were studied: the amount of Anchote flour, potato flour, and wheat flour. Moreover, five responses were examined: specific volume, appearance, texture, flavor, and overall acceptability of the bread product. These three variables generated 14 formulations of blend of flours with different composition of each ingredient as shown in Table 9.1.

9.1.3 Statistical Analysis

D-optimal mixture design was used to determine the optimum amount of ingredients used in bread making formulation toward the response. The desired goal for each independent and dependent variable was chosen. All dependent variables or responses (specific volume, appearance, texture, flavor and overall acceptability of bread) were set maximum while the independent variables were kept within the range.

9.1.4 Sensory Evaluation

Thirty panelists (men and women) were selected from graduate students and staff of Food Science and Post Harvest Technology Department at the Jimma University to assess the sensory quality of the bread product. The evaluation included sensory attributes such as appearance, texture, flavor and overall acceptability of the product. For all acceptability of the product, 5-point hedonic scale rating from 1(very much disliked), 2 (disliked), 3(neither liked nor disliked), 4 (liked) and 5 (very much liked) were used. Conversation or any other form of exchange of ideas was not allowed between panelists during testing. Before each test, orientation was given to the panel members on the procedure of sensory evaluation. The panelists were requested to rinse their mouth with water in between different tests. Samples were coded with randomly selected 3-digit numbers labeled on the plates.

Table 9.1: D-Optimal mixture design of flour blend for bread making

Std	Run	Anchote (%)	Potato (%)	Wheat (%)
5	1	5.00	20.00	75.00
11	2	5.00	20.00	75.00
4	3	7.50	20.00	72.50
13	4	5.00	5.00	90.00
7	5	6.25	8.75	85.00
14	6	10.00	20.00	70.00
12	7	10.00	5.00	85.00
9	8	10.00	12.00	77.50
2	9	10.00	5.00	85.00
3	10	7.50	12.00	80.00
6	11	5 .00	5.00	90.00
10	12	8.75	8.75	82.50
1	13	10.00	20.00	70.00
8	14	8.75	18.25	75.00

Where : Std is standard order of the treatment, Run is the order of the run of the experiment

9.2 Results and Discussion

9.2.1 Specific Volume

The specific volume of the bread is presented in Figure 9.1. The specific volume of bread, prepared from the composite whole flour blends, varied between 1.6 and 2.4 within the combination of variables studied. From Figure 9.1, an increase in the specific volume of bread was observed with an increase in the proportion of wheat and a decrease in the proportion of Anchote and potato flour in the blend. The maximum specific volume was recorded for bread prepared from high proportion of wheat, low proportion of Anchote and potato flour in the blends. Adding Anchote and potato flour in wheat flour for baking bread resulted in a decrease in the loaf volume. This inferior baking quality is principally attributed to lack of gluten proteins.

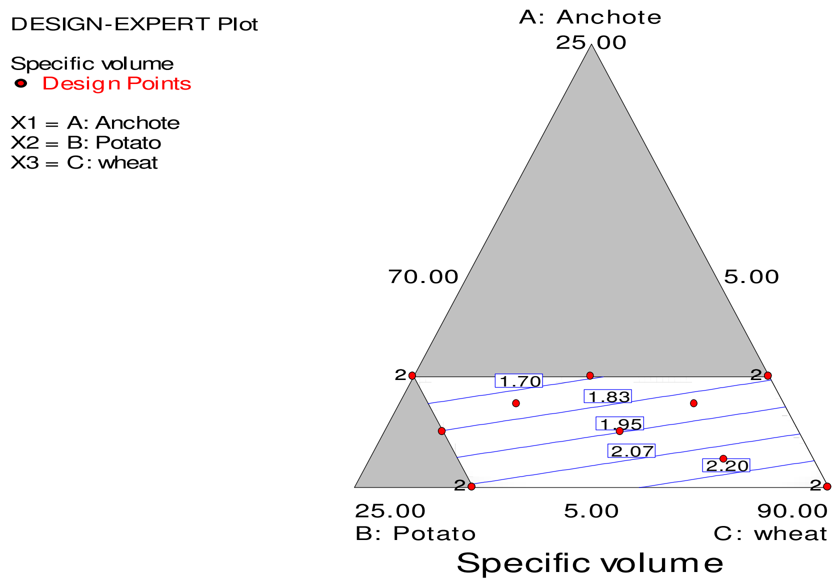


Figure 9.1: Counter plots showing the effect of wheat flour, Anchote flour and potato flour on specific volume of bread.

9.2.2 Sensory Evaluation

Figure 9.2 - Figure 9.5 depict the counter plots showing the effect of wheat flour, Anchote flour, and potato flour on the appearance, texture, flavor and overall acceptability of bread. As observed from the figures, the increase in the proportion of the wheat flour and the decrease in the proportion of Anchote and potato flour resulted in an increase in the sensory quality of appearance, flavor, texture, and overall acceptability of the bread. The maximum score for appearance (4.8), flavor (4.7), texture (4.6) and overall acceptability (4.6) were recorded for bread prepared from the highest proportion of wheat, and the lowest proportion of Anchote and potato flour. The minimum scores for appearance, flavor, texture and overall acceptability were recorded for the bread prepared from highest proportion for Anchote, and potato flour, and the lowest proportion of wheat flour.

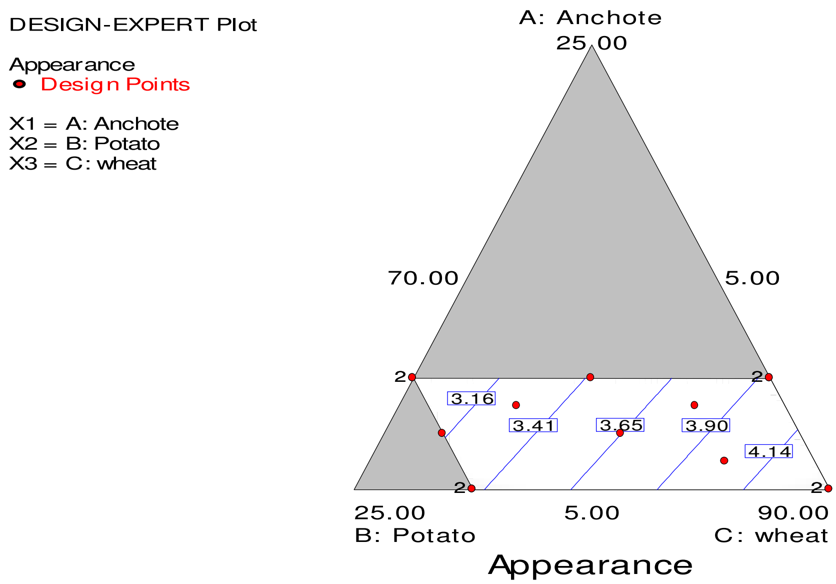


Figure 9.2: Counter plots showing the effect of wheat flour, Anchote flour and potato flour on color of bread.

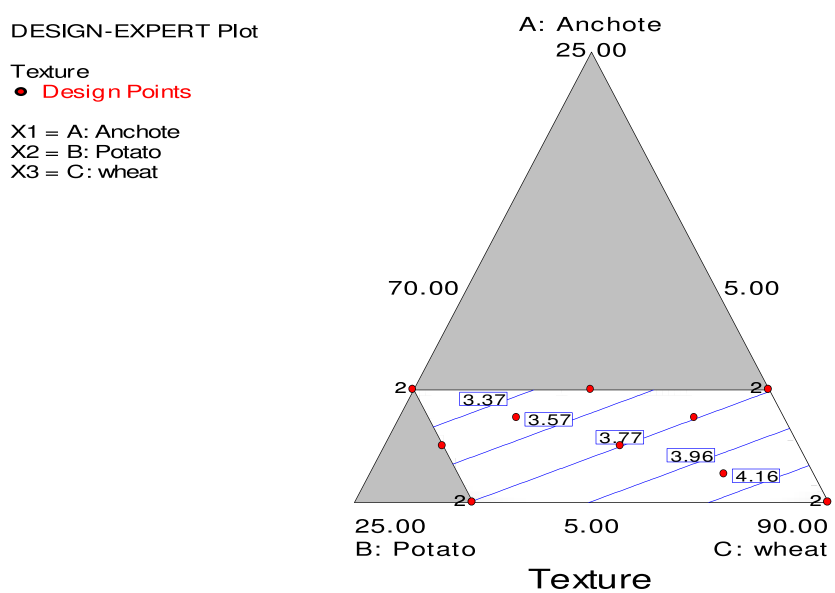


Figure 9.3: Counter plots showing the effect of wheat flour, Anchote flour and potato flour on texture of bread.

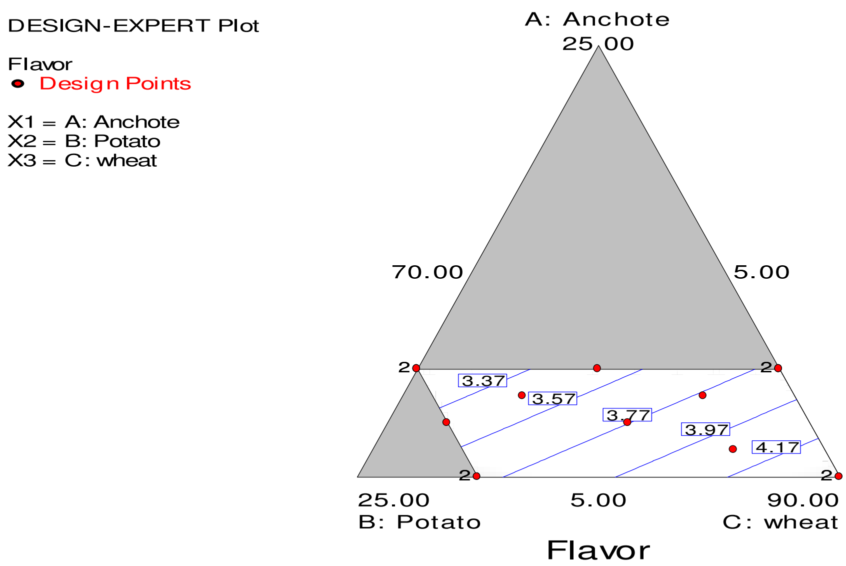


Figure 9.4: Counter plots showing the effect of wheat flour, Anchote flour and potato flour on flavor of bread.

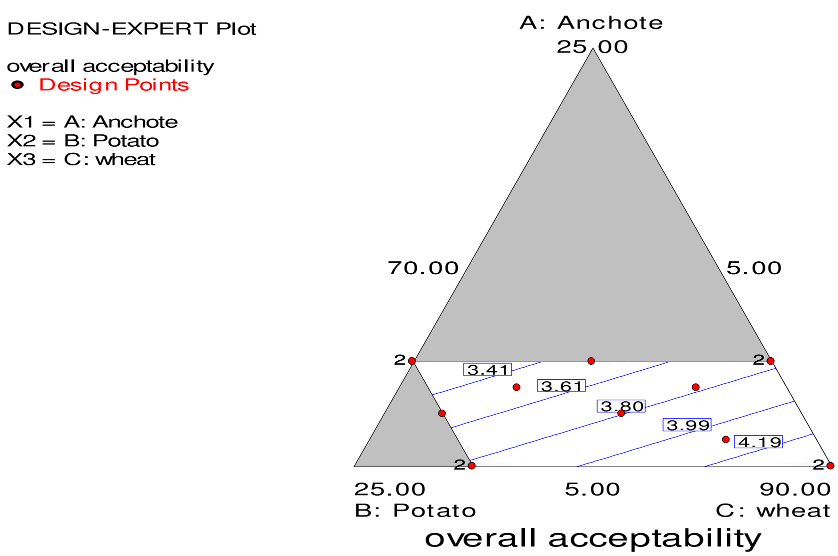


Figure 9.5: Counter plots showing the effect of wheat flour, Anchote flour and potato flour on overall acceptability of bread.

9.2.3 Optimization of the Level of Independent Variables

All five responses: specific volume, appearance, flavor, texture and overall acceptability of the bread were taken into consideration for optimization of level of variables. Numerical optimization was carried out for the level of variables to obtain the best product. The desired goals for each factor and response were chosen, and weights were assigned to each goal. Among the solutions obtained, the solution with maximum desirability was selected as optimum ingredients composition. Numerical optimization was done and optimized values were 5.00 grams of Anchote flour, 5.00 grams of potato flour, and 90.0 grams of wheat flour with 86% desirability. These were blends with whole wheat, Anchote, and potato flour to make up the total blend to 100 g.

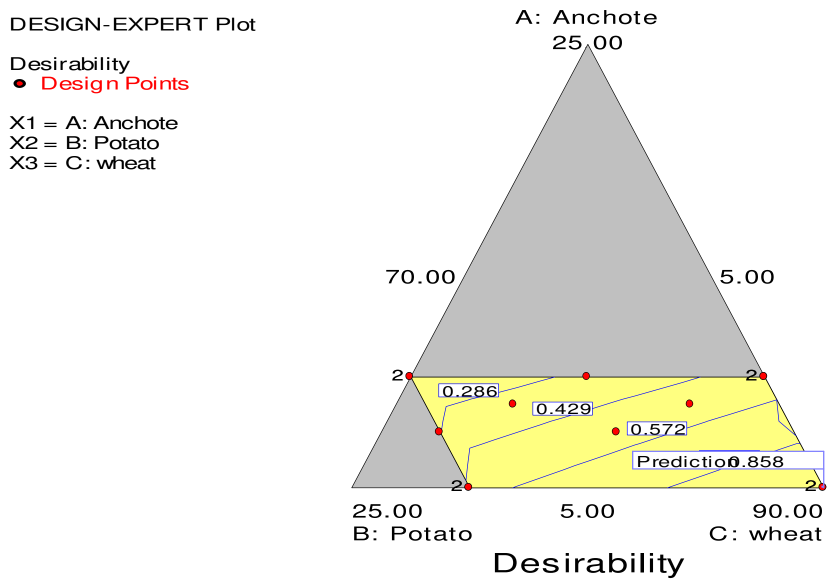


Figure 9.6. Contour plot of the desirability index for the optimal blend of baking bread.

9.3 Conclusion

Potato slices (variety of Gudene) and Anchote (*Coccinia Abyssinica*) were dried in the solar tunnel dryer during a sunny day. The dried potato and Anchote chips were milled into the flour. The milled flour of potato and Anchote were used as a partial replacement of wheat flour for baking bread. D-optimal mixture design was used for blending flour for making bread. Five quality parameters of bread (specific volume, appearance, texture, flavor, and overall acceptability) were examined. The numerical optimization process was subsequently achieved. The numerical optimization result shows that 5% of Anchote flour and 5% of potato flour were required for an optimal partial replacement of wheat flour for baking bread.

10 Overall Discussions and Outlook

The following chapter summarizes the findings and concludes the results of the research study, which was proposed to solve the problems that could show up during the drying process of the potato slices**.**

10.1 Optimum Residual Moisture Content

The value of optimum water activity for potato was taken from literature. The desorption curves of potato were determined at three different temperatures (60°C, 70°C, and 80°C). The experimental data of desorption isotherms were fit to four different mathematical models. At considered conditions, the best fitting was obtained for the model of GAB that represent the behavior of desorption data. Wang & Brennan (1991), McLaughlin & Magee (1998), McMinn & Magee (2003), Chemkhi & Zagrouba (2011) also reported the suitability of GAB model to represent the behavior of desorption of potato. As observed from Figure 2.1 (Chapter 2), the sample with water activity of 0.2 minimum lipid oxidation is expected, there is no non-enzymatic browning, enzymatic reaction, and spoilage by mold fungi, yeasts and bacteria. Therefore, drying the sample up to the moisture content equivalent to water activity of 0.2 is reported to be safe. By substituting optimal water activity (a_w=0.2) with the GAB model, the optimal moisture content could be obtained. The optimal moisture ratios for the examined potato slices were 0.042, 0.036, and 0.033 in the dry base for drying the sample at the temperatures of 60 °C, 70 °C, and 80 °C, respectively.

10.2 Processing Parameters

The optimum residual moisture content was taken into consideration to stop the drying process. Drying kinetics of dried potato slices fit to Midilli–Kucuk model at $R^{2\,>}$ 0.99. Since Naderinezhad et al. 2016 investigated mathematical modeling of drying of potato slices in a forced convective dryer. Then the drying data were fit to eight different empirical models. Among the models, Midilli–Kucuk was the best to explain the single layer drying of potato slices. From the literature, it is known that the drying conditions have a significant influence on the quality of dried products (Kawongolo, 2013). Fast drying rate, low change in total color difference, and shrinkage of dried potato slices were observed at moisture ratio greater than 0.3. At moisture ratio less than or equal to 0.3, slow drying rate, high discoloration, and high shrinkage were observed. The drastic deterioration of the quality of the dried potato slices can be explained by referring to the temperatures. At low moisture ratio, drying the potato slices at temperatures higher than the glass transition temperature of the sample could have lead to a more noticeable deterioration rate.

Regarding the influence of processing condition on most of the quality parameters, changes in temperature and air velocity have dominant effect when compared to the effect of the dew point temperature. Although the change in dew point temperature has a limited effect on the quality parameters of dried potato slices, drying the potato slices at low dew point temperature can slightly influence the quality of the dried potato slices. Drying the samples at a lower dew point temperature, a higher air temperature, and a higher air velocity led to a rapid decrease of the surface moisture ratio of the samples. The sample's surface became stiff which in turn limited any subsequent shrinkage. Bonazzi and Dumoulin, (2011) reported that at higher air temperatures, case hardening of the surface may take place. This means that the volume of the sample becomes fixed at an early stage, inducing less shrinkage and a more intensive pore formation. On the contrary, at lower drying temperatures, a more uniform moisture distribution exists, inducing less internal stresses that allow the sample to continue to shrink until the last stages of drying. Drying potato slices at lower dew point temperature, higher temperature, and higher air velocity has a positive influence on most of the quality parameters of the dried potato slices.

10.3 Optimization

Processing conditions (temperature, dew point temperature, and air velocity) were optimized for better mechanical, optical, nutritional, and physical properties of the dried potato slices. Response surface methodology with the concept of desirability was used for optimization of the processing conditions. The basic second order regression model was used to predict the influence of processing condition on quality parameters. According to the statistical significance of processing condition on the quality parameters of the dried potato slices, appropriate quality predicting models were proposed.

The optimal combination of processing conditions applied to minimize the total color change, shrinkage, and drying time of dried potato slices was recorded as follows: a drying temperature of 80 °C, a dew point temperature of 10 °C, and an air velocity of 1.5 m/s. The recorded minimal total color change, shrinkage, and drying time for this combination were 6.62, 40.401% and 82.58 minutes, respectively. For this optimal combination, the desirability of the results was 0.94.

Sturm *et al*, (2012) studied the influence of the drying parameters of air temperatures (35–85 °C), dew point temperatures (5–30 °C), and air velocities (2.0–4.8 m/s) on drying time, color changes, and shrinkage of apples. For all quality parameters, the higher temperature level (75 °C) proved to be preferable to the lower one and the maximum allowed air velocity (4.8 m/s) was required. According to Sturm *et al*, (2012) justification to minimize color changes, high temperature, air velocities and low dew point temperatures is required. The minimizing of the duration of the process due to high temperature, air velocities, and low dew point temperatures leads to a reduction of the thermal damage. Moreover, potentially polyphenol oxidases are rapidly inactivated, which limits enzymatic oxidation.

The optimization processes of the following mechanical properties of hardness (the resistance of dried potato slice against the applied force by the probe), work (work necessary to overcome the internal strength of bonds within the dried potato slices), and deformation (distance value at the hardness point) were considered. The goal was set to maximize hardness, and to minimize both work and deformation of the dried potato slices. According to Miranda et al. (2006), a crispy product will exhibit a large hardness, low work to fracture and a sudden drop in force as the crack propagates rapidly. The optimal combination of processing conditions applied to maximize hardness and to minimize work and deformation during the drying process of the potato slices was recorded at a drying temperature of 79.37 °C, a dew point temperature of 17.97 °C, and an air velocity of 1.5 m/s. The recorded optimal values for the force, deformation, and work required to fracture the potato slices for this combination were 12.6 N, 0.569 mm, and 6.33 mJ, respectively. For this optimal combination, the attained desirability of the results was a 1.

The retention of Vitamin C is used as a good indicator for the retention of other nutrients (Lee & Kader, 2000). During the drying process, the ascorbic acid degradation was found to be more dependent on the drying condition (especially temperature, moisture and time) (Santos and Silva 2008). A large number of relevant works have been carried out to demonstrate the effect of drying temperature on Vitamin C retention: Mclaughlin and Magee (1998) on potatoes: Ramallo and Mascheroni (2012) on pineapple: Santos and Silva 2008; Hanif et al. (2015) on persimmons. They concluded that the Vitamin C content tends to decrease with increasing temperatures. The result of this thesis agrees with their conclusions. Therefore, optimization of drying condition is necessary for dry potatoes to reduce ascorbic acid loss. The goal of the Vitamin C retention was set at the lower and upper target of 80% and 90%, respectively. The optimum Vitamin C retention of the samples recorded 85% at a temperature of 68 °C, dew point temperature of 10°C, drying time of 116 minutes, and an air velocity of 1.2 m/s. For this optimal condition, the desirability of the results was 0.95.

10.4 A New Method Development and Determination of Glass Transition Temperature

Liu et al. (2009) reported that measurement of Tg of starch and starch-based products by differential scanning calorimeter (DSC) are difficult because of the change of the heat capacity. Similarly, the signal on heat flow is usually weaker than that of conventional polymer. The author explains his findings by giving more examples: the heat of fusion for polypropylene is about 80 kcal/g, whereas the measured energy for starch generalization is only about 0.95 cal/g. Furthermore, the multiple phase transitions that starch undergo during heating and the instability (such as evaporation) of water contained in starch makes it more difficult to study the thermal behavior of starch materials using DSC. The instability of water contained in starch is also the reason why dynamic mechanical analysis is not suitable for studying the Tg of starch since the moisture evaporates during heating (Liu et al., 2009).

However, other significant results were also found. For instance, Lourdin et al. (1997) reported a Tg at about 90°C –100 °C with 13% –15% moisture content for potato starch. Rindlava et al. (1997) reported a Tg of 75°C–95 °C with 13%–15% moisture content for potato starch. The Tg decreased; however, linearly as the moisture content increased. Farahnaky et al. (2009) result shows glass transition temperature range of 62-175 °C with 7.8-18% moisture content for potato starch.

In order to reduce the existing limitation of determining the glass transition temperature of food products, a new method was developed for the determination of the glass transition temperature of potato. This new method involves the sudden drop in the mechanical properties of the drying potato slices which in turn indicates the transition point from the rubbery state to the glassy state. The mechanical properties (hardness and work) of the sample were analyzed by compression test using a texture analyzer. From the graph of hardness/ work versus moisture ratio of the samples dried at a constant temperature, the moisture ratio, at which a minimum value of work and hardness were observed, was used as the transition point from the rubbery to the glassy state. The constant temperature was used as the glass transition temperature at moisture ratio of transition point. The recorded value of glass transition temperature data of potato is best fit to Gordon–Taylor model (Gordon and Taylor, 1952). This method is reported to be simple and easy.

10.5 Applying the Concept of Glass Transition *Temperature*

The influence of the temperature with five temperature profile levels on color change, texture, and shrinkage was determined. One level of the temperature profiles was kept constant. The other remaining four levels of the temperature profile were stepped down from high temperature to low temperatures before the samples attained the moisture content at which glass transition temperature is reached. The response variables of color changes and shrinkage were measured. The basic third order polynomial equation was used to fit the quality parameters (color and shrinkage). Change in lightness as a function of time was best fit to the fourth order polynomial function. Shrinkage and change in redness and yellowness versus time were best fit to a third order polynomial function. The models were significant for all parameters described ($P < 0.001$). Moreover, the coefficient of determination R^2 for most models was greater than or equal to 0.9. Hence, the obtained models for the responses were adequate. Drying the samples for short time by applying high temperature in the rubbery state and proceeding the process at a temperature less than or equal to the glass transition temperature in the glassy state resulted in less change in redness, yellowness, and shrinkage, and improved the rate of change in lightness of potato slices. Good qualities of dried potato slices were obtained for the samples dried at the temperature profile II since the samples dried at this temperature profile were dried mostly at a temperature less than the glass transition temperature (a negative value of $T\text{-}T_g$). Rahman, (2012) reports the stability of foods in the glassy state. He explains that during this state, compounds involved in the deterioration reactions take time to diffuse over molecular distances and approach each other to react. The worst quality of the dried product was recorded for the samples dried at the temperature profile I since the samples dried at this temperature profile were dried mostly at a temperature greater than the glass transition temperature (a positive value of $T\text{-}T_g$). Drying the potato slices at a temperature greater than glass transition temperature resulted in high quality deterioration. This is due to the fact that an increase in the temperature of a product above glass transition temperature increases the molecular mobility and affects the diffusion of the matrix which leads to an increase in the rate of deterioration: enzymatic reaction, non-enzymatic browning and oxidation (Roos, 1992).

Another investigated mechanical property is shrinkage. It is shown that samples dried at the temperature profile II resulted in 27% less shrinkage of the dried potato slices compared to temperature profile I (constant temperature of 120 °C). As Bonazzi and Dumounlin, (2011) discuss in their book the results of Willis et al.(1999). During drying of pasta, Willis et al. (1999) observed a higher shrinkage when the samples were dehydrated at a temperature higher than glass transition temperature and a lower shrinkage when the sample rehydrated at a temperature less than its glass transition temperature.
Change in total color difference recorded for temperature profiles I and II were 7.9 and 4.7, respectively. Considering the drying period, the drying process of the samples at the temperature profile II took a longer time compared to the samples dried at the temperature profile I. Another important quality parameter of the dried potato slices considered in this part was the potato's crispiness. The sample dried at the temperature profile II was crispier than the samples dried at temperature profile I.

To sum up, good color retention, less shrinkage, and crispy dried potato slices were attained for the samples dried at high temperatures (120 °C) in a rubbery state at high moisture content, and to proceed the process at a temperature less than or equal to the glass transition temperature in the glassy state at low moisture content. Under these conditions, the quality of the dried potato slices was also better than the samples dried at optimal processing conditions for constant temperature obtained in chapter 5.

10.6 Solar tunnel drying

The influence of variety, slice thickness, and position of the tray on quality parameters of solar tunnel dried potato slices was studied. The considered quality parameters were total color difference, shrinkage, hardness, deformation, Vitamin C, and total phenolic content. Drying kinetics and drying time were also determined. The result shows that total phenolic content and the content Vitamin C were significantly influenced by the interaction effect of variety, slice thickness, and position of the trays. As the thickness of the slice increases, the Vitamin C and total phenolic content of slices decrease. This is due to the fact that a longer drying period is needed for the thicker slices to achieve equilibrium moisture content which in turn causes higher total phenolic content and Vitamin C degradation due to thermal damage and irreversible oxidation (Ekow et al., 2014; Chin et al., 2015). The most significant factor affecting the total color difference was the slice thickness. As expected the thicker the sample, the longer the drying process was. The drying of samples of a thickness of 2 mm resulted in 44% more retention in color change than the samples of a thickness of 6 mm. Since the minimum the duration of the processing due to lower thickness leads to reduction of thermal damage and potentially polyphenol oxidases are rapidly inactivated, which limits enzymatic oxidation. The most influencing factors on the drying periods and hardness of the samples were variety and slice thickness. The influence of all the three factors (variety, slice thickness, and position of trays) on shrinkage was negligible.

10.7 Proof of Utilization

Proofing the utilization of the dried product encourages the producer to start the production of the dried product at a small, middle, or industrial level. Solar tunnel dried potato and Anchote flour were used as a partial replacement of wheat flour for baking bread. The specific volume of the bread, and appearance, flavor, texture, and overall acceptability of the bread from the sensory evaluation were used as quality evaluating criteria. High scores for the appearance, flavor, texture, specific volume and overall acceptability of the bread were set as a goal. Among the solutions obtained, the solution with the maximum desirability was selected as the optimum composition of ingredients. Numerical optimization was performed and optimized values were recorded as 5% Anchote flour, 5% potato flour, and 90% wheat flour with a desirability value of 0.86. Trejo, et al (1981) studied the partial replacement of wheat flour with potato flour in bread baking as well as the nutritional values of bread containing graded levels of potato flour. Moreover, Trejo, et al (1981) reports the feasibility of the incorporation of potato flour in bread baking. Based on sensory properties, wheat flour replacement with 10% sweet potato flour yielded a bread product of a good quality (Yanez et al., 2014)

10.8 Overall experimental approaches

The hot air drying of the potato slices, determination of quality parameters (optical, physical, and mechanical properties) of hot air dried potato slices, and the above-mentioned thermo physical parameters were conducted in the laboratory of the Institute of Applied Thermo-and Fluid dynamics, University of Applied Sciences Konstanz in Konstanz, Germany. Solar tunnel drying was conducted in Jimma University College of

Agriculture and Veterinary Medicine, Ethiopia. Product development and determination of quality parameters of solar tunnel dried product were investigated in the laboratory of the post harvest management at Jimma University College of Agriculture and Veterinary Medicine, Ethiopia. The overall methodologies of each quality parameters were discussed in Chapter 2.

About sample arrangement in hot air drying, seven slices from the same tuber were taken for each experimental run to minimize the error caused by heterogeneity in the raw material. Initial weight, diameter, and thickness of the samples were measured. Then seven slices were placed on the drier mesh with a white standard reference. The weight of each sample was also measured at the end of the drying process. The first and the second samples were used to determine the product's surface temperature of the sample and develop image analysis during online measurement respectively, and they used again for determination of mechanical property after taking out them from the drier at the end of the drying process. The third, fourth, and fifth samples were used for dry matter determination. The remaining two samples with the first and second samples were used to determine the mechanical properties of the dried samples.

Randomization and replication were taken into consideration to all experiments allowing the greatest reliability and validity of statistical estimates of treatment effects. Blocking was also taken into consideration when required. The drying experiment was conducted using three independent factors; namely, air temperature (60 °C to 120 °C), dew point temperature (10°C, 20°C and 30 °C), and air velocity (1 m/s, 1.2 m/s and 1.5 m/s). The influence and optimization of the stated independent factors on optical, physical, mechanical, and nutritional property were determined.

For solar tunnel drying, the three varieties of potato were purchased from one farmer. Then the potatoes were transported from the farmer's house to the University (where the experiment was conducted) by car. They were washed, sorted free from mechanical damage and then stored in a cooler at 4 °C. The potato tubers were taken randomly one variety at a time. They were sliced by a food processor (FP 700, China) into three different thicknesses (2 mm, 4 mm, and 6 mm). The slices were thenput on labeled place on the dryer discussed in Chapter 8. The same procedure was applied for the other varieties. The solar tunnel drying experiment was conducted using three independent factors; namely, the variety of the potato, the thickness of the samples, and the position of the trays. The influence of the mentioned three factors on optical, physical, mechanical, Vitamin C, and total phenolic content were investigated. To avoid the result variation caused by weather condition, all treatments of drying were conducted in one run.

Image analysis was carried out using special program written for this purpose by Sturm and Hofacker (2009). A specific RGB value was determined for the white and the black background reference. The region of the sample that should be analyzed was specified by mouse operation. All pixels in the analysis region were evaluated: if the pixels were part of the product surface, the program recorded the RGB-values; if they were of the background color, they were discarded. The texture of the potato chips was evaluated by a compressive test using a texture analyzer. The texture analyzer was calibrated according to manual of BROOKFIELD TEXTURE PRO CT (http://www.brookfieldengineering.com).
To sum up, in this work: The drying kinetics data were fit to the existing model (Midilli-Kucuk). Since the best fitness of this model for explanation of the behavior of drying potato slices were reported by many studies. Simulation is another possible way to express the behavior of drying kinetics of drying products. However, most simulation has assumption like ignoring the shrinkage of the sample during drying. That is why most models easy to solve but not valid for all substances in all moisture ranges. To simulate the quality parameters of the dried potato slices such as optical, mechanical and nutritional properties were not common neither in the literature nor simulation systems due to the complex reaction (nature) of drying products. Analytical solution of the quality parameters of the dried potato slice is presented in this research work. In particular, up to researcher knowledge, there is no analytical solution for glass transition temperature determination of real starch food and this newly developed method can help more.

10.9 Outlook

Knowing, the optimum residual moisture content of potato slice reduces the quality deterioration due to over or under drying of the product. The new method developed for the determination of glass transition temperature of potato is best fit to Gordon-Taylor model. The method is shown to be simple and easy. The same sample thickness could be used for drying and determination of glass transition temperature of potato. The development of this method may become an input for the researcher for further research on applying the concept of glass transition temperature on drying potato slices. Furthermore, a new method developed for the determination of glass transition temperature of potato could be used for starchy fruit and vegetables. Further study is required to proof the suitability of the new method for determination of glass transition temperature of fruit and vegetable.

The sample dried at temperature Profile II (applying the concept of glass transition temperature) resulted in 18% less change in shrinkage and 29% less change in discoloration than the sample dried at the optimum processing conditions mentioned in Chapter 5 (at a temperature of 80 °C , dew point temperature of 10 °C and air velocity of 1.5 m/s). The color and the shape of the dried product are the bases for the selection or the rejection of the product by consumers. Therefore, this finding could be used as an input for a better quality of industrial mass production of dried potato slices.

Regarding solar tunnel drying, the possibility of drying produce in semi rainy weather was also observed. The dried potato slices and Anchote slices were processed into flour. 5 % Anchote flour and 5 % potato flour should be used as a partial replacement of wheat flour for bread making. On one hand, using 10% tubers flour as a partial replacement of wheat flour for bread baking reduce currency expend to import wheat by Ethiopia.

11 Summary

According to the World Food Organization, nearly half of all root and tuber crops worldwide are not consumed, but are lost due to inappropriate storage and post-harvest losses. In developing countries such as Ethiopia, potatoes have not been dried, but are traditionally stored in potato clamps. So far, dried potatoes have not been converted into usable foods.

The aim of the present work is to convert potatoes - perishable rootlets and tubers - into stable products by hot air drying. Hot air dryers are economical to operate in industrialized countries. In Africa, this is reserved for larger industrial companies only. In regions with a tropical climate, however, the use of solar tunnel dryers is worthwhile. These are a good choice for farming and small industries and wherever electrical energy is difficult or impossible to obtain.

In a first part of the work, the drying process of potatoes was investigated, in particular with regard to the change of thermal, mechanical and chemical quality parameters. In an evaluation of the literature it was found that potatoes are not subject to quality changes if the water activityis below a value of 0.2. In order to determine the water content associated with this value at storage temperature, the known equations for the sorption equilibrium were evaluated and verified with own experimental investigations. This determined the end point of the drying process.

The following experimental investigations showed a process-dependent change of the quality criteria such as color, shrinkage, and mechanical properties as well as the content of value-determining substances such as vitamin C and starch. The differences in the course and magnitude of the quality changes were attributed to the glass transition that takes place during the drying process. For the determination of the glass transition temperature a new, simple method based on the measurement of mechanical properties could be developed. The knowledge of the glass transition temperature allowed optimizing the drying process. The drying process could be carried out in the rubbery or glassy region, depending on the expected quality changes. Thus, all information was available to produce high quality dried potatoes in an industrial process.

Since the production of potato products in less industrialized regions without sufficient supply of electrical energy should be included, potatoes were dried with a solar tunnel dryer. Examination of the quality properties mentioned above confirmed the process-dependent quality changes.

Finally, the dried product was ground and with the flour thus produced, wheat flour was replaced for baking bread. An evaluation of the finished bread by a panel showed that the acceptance of the bread according to the new recipe was high, also with regard to baking volume, taste, texture and color.

This work shows that by drying potatoes can be transformed a well accepted, storable and easily transportable product. The risk of losses or degradation is minimized. It can be produced on an industrial as well as on farm level. If the influence of the glass transition is taken into account, it is possible to optimize the quality of the product.

Zussamenfasung

Nach Angaben der Welternährungsorganisation werden weltweit fast die Hälfte aller Wurzel- und Knollenfrüchte nicht konsumiert, sondern gehen wegen ungeeigneter Lagerung und aufgrund von Nachernteverlusten verloren. In Entwicklungsländern wie Äthiopien wurden Kartoffeln bislang nicht getrocknet, sondern traditionell in Mieten oder ähnlichem gelagert. Die Trocknung wurde daher bislang auch nicht zur Haltbarmachung von Kartoffeln eingesetzt.

Das Ziel der vorliegenden Arbeit ist es, Kartoffeln, -gehördend zur Gruppe derverderblichen Wurzel- und Knollenfrüchte- durch Warmlufttrocknung in stabile Produkte zu überführen. Warmlufttrockner sind in Industrieländern wirtschaftlich zu betreiben. In Afrika ist dies nur größeren Industriebetrieben vorbehalten. In Regionen mit tropischem Klima lohnt sich aber der Einsatz von solaren Tunneltrocknern. Diese sind eine gute Wahl für den Betrieb in der Landwirtschaft und in kleinen Industriebetrieben sowie überall dort, wo elektrische Energie nicht oder nur schwer verfügbar ist.

Zu Beginn der Arbeit wurde der Trocknungsprozess untersucht, insbesondere hinsichtlich der ablaufenden thermischen, mechanischen und chemischen Vorgänge. Es zeigte sich in einer Auswertung der Literatur, dass Kartoffeln dann keinen Qualitätsveränderungen unterliegen, wenn die Wasseraktivität unter einen Wert von 0,2 abgesunken ist. Um den zu diesem Wert bei Lagertemperatur gehörenden Wassergehalt zu ermitteln, wurden die bekannten Gleichungen für das Sorptionsgleichgewicht ausgewertet und mit eigenen experimentellen Untersuchungen verifiziert. Damit war der Endpunkt des Trocknungsprozesses bestimmt.

Die folgenden experimentellen Untersuchungen zeigten eine prozessabhängige Veränderung der Qualitätskriterien wie Farbe, Schrumpfung, und mechanische Eigenschaften sowie der Gehalt an wertbestimmenden Substanzen wie Vitamin C. Die Unterschiede in Verlauf und Größe der Qualitätsveränderungen wurden auf den Glasübergang zurückgeführt, der während des Trocknungsprozesses erfolgt. Für die Bestimmung der Glasübergangstemperatur konnte eine neue, einfache, auf der Messung mechanischer Eigenschaften beruhende Methode entwickelt werden. Die Kenntnis der Glasübergangstemperatur erlaubte es, den Trocknungsprozess zu optimieren. Der Trocknungsprozess konnte Im gummiartigen oder im glasartigen Bereich festgelegt werden, je nach den erwarteten Qualitätsveränderungen. Somit lagen alle Informationen vor, um in einem industriellen Prozess getrocknete Kartoffeln von hoher Qualität zu erzeugen.

Da auch die Produktion von Kartoffelerzeugnissen in weniger industrialisierten Regionen ohne ausreichende Versorgung mit elektrischer Energie einbezogen werden sollte, wurden Kartoffeln mit einem solaren Tunneltrockner getrocknet. Die Untersuchung der oben angeführten Qualitätseigenschaften bestätigten die prozessabhängigen Qualitätsveränderungen.

Abschließend wurde das Trockenprodukt gemahlen und mit dem so erzeugten Mehl Weizenmehl beim Backen von Brot ersetzt. Eine Untersuchung des fertigen Brotes durch ein Panel zeigte, dass die Akzeptanz des Brotes nach der neuen Rezeptur hoch war, auch hinsichtlich Backvolumen, Geschmack, Textur und Farbe.

Die Arbeit zeigt, dass durch Trocknung aus Kartoffeln sowohl auf industriellem Niveau wie auch auflandwirtschaftlicher Ebene ein akzeptiertes Produkt erzeugt werden kann. Wenn der Einfluss des Glasüberganges berücksichtigt wird, ist es möglich, die Qualität des Produktes zu optimieren.

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13 APPENDICES

Appendix Table 1: equations for the shrinkage as a function of drying time

T (°C)	DPT (°C)	V (m/s)	Equation	R^2	S	P
60	10	1.2	$A/A_o(-) = 1.017 - 0.006682t + 0.000022t^2$	99.6%	0.0108074	<0.0001
70	10	1.2	$A/A_o(-)=1.014 - 0.009166t + 0.000046t^2$	99.2%	0.0158476	<0.0001
80	10	1.2	$A/A_o(-)=1.004 - 0.007050t + 0.000029t^2$	99.0%	0.0153677	<0.0001
70	10	1	$A/A_o(-)=1.018 - 0.009435t+ 0.000039t^2$	99.7%	0.0104938	<0.0001
70	10	1.2	$A/A_o(-)=0.9966 - 0.006124t+ 0.000021t^2$	99.4%	0.0118086	<0.0001
70	10	1.5	$A/A_o(-)=1.008 - 0.008692t + 0.000040t^2$	99.8%	0.00893048	<0.0001
80	10	1.2	$A/A_o(-)=1.014 - 0.009166t + 0.000046t^2$	99.2%	0.0158476	<0.0001
80	20	1.2	$A/A_o(-)=1.019 - 0.008776t + 0.000038t^2$	99.2%	0.0165472	<0.0001
80	30	1.2	$A/A_o(-)=1.018 - 0.009041t + 0.000039t^2$	99.2%	0.0166687	<0.0001

where t = time in minutes

Appendix Table 2: equations for the total color difference as a function of drying time

T(°C)	DPT(°C)	V(m/s)	Equation	R^2	S	P
60	30	1	TCD (-) = 0.1867 + 0.1869t- 0.000727t^2	98.9%	0.466604	<0.0001
60	30	1.2	TCD (-) = 0.306325 + 0.482956t- 0.0146342t^2 + 0.000188618t^3 - 8.0565e-007t^4	97.83%	0.526935	<0.0001
60	30	1.5	TCD (-) = -0.161868 + 0.44926t - 0.01622t^2 + 0.000223223t^3 - 9.75421e-007t^4	94.55%	0.719954	<0.0001
60	10	1.2	TCD (-)=0.8256 + 0.1306t - 0.000438t^2	97.6%	0.545026	<0.0001
70	10	1.2	TCD (-) = 0.249586 + 0.299215t- 0.00874045t^2 + 0.000106247t^3 -4.10854e-007t^4	92.50%	0.850246	<0.0001
80	10	1.2	TCD (-)=0.475511 + 0.325777t - 0.00864526t^2 + 9.32099e-005t^3- 3.38912e-007t^4	89.03%	0.640533	<0.0001
60	10	1	TCD (-) = 0.0482 + 0.1016t - 0.000109t^2	99.2%	0.306782	<0.0001
60	20	1	TCD (-) = - 0.3732 + 0.1208t - 0.000275t^2	99.4%	0.276561	<0.0001
60	30	1	TCD (-) = - 0.5567 + 0.1091t - 0.000141t^2	98.8%	0.404293	<0.0001

where: TCD= Total color difference, t=time [min]

Appendix Table. 3. ANOVA for total color difference, shrinkage and drying time by response surface linear and quadratic models

	TCD			S			Time		
Source	DF	Sum of Squares	Prob > F	DF	Sum of Squares	Prob > F	DF	Sum of Squares	Prob > F
Model	5	33.10	< 0.0001	3	91.00	< 0.0001	5	3536.30	< 0.0001
A	1	*22.41*	< 0.0001	*1*	*57.60*	*<0.0001*	1	2402.50	< 0.0001
B	1	*0.22*	0.2600	-			1	16.90	*0.3072*
C	1	*5.80*	< 0.0001	*1*	*28.90*	*<0.0001*	1	960.40	< 0.0001
A^2	1	*1.26*	*0.0138*		-	-	1	120.05	0.0135
C^2	-	-	-	-	-	-	*1*	130.05	*0.0108*
AC	1	*3.40*	*0.0004*	1	*4.50*	*0.0111*	-	-	-
Residual	14	2.24		16	7.25		14	210.65	0.1673
Lack of Fit	9	1.97	0.0682	*11*	*0.66*	*0.1986*	9	171.82	
Pure Error	5	0.27		*5*	*1.50*		5	38.83	
Cor Total	19	35.34		19	99.75		19	3746.95	
R^2	0.9367			0.9123			0.9438		
Std dev	0.40			0.74			3.88		
mean	8.57			45.25			109.05		
CV	4.66			1.63			3.56		

Significant at $p< 0.05$, Where: TCD = total color difference, S= shrinkage A= air temperature, B=dew point temperature and C= air velocity

Appendix Table. 4. ANOVA for hardness, work and deformation by response surface linear and quadratic models

	Hardness				Work			Deformation	
Source	DF	Sum of Squares	Prob > F	DF	Sum of Squares	Prob > F	DF	Sum of Squares	Prob> F
Model	4	33.25	< 0.0001	4	3.83	< 0.0001	2	0.071	< 0.0001
A	1	*7.53*	0.0002	1	*1.28*	< 0.0001	1	*0.041*	*< 0.0001*
B	1	*15.06*	< 0.0001	1	*0.25*	*0.0310*	-	-	-
C	1	*9.10*	< 0.0001	1	*2.04*	*< 0.0001*	-	*0.030*	*< 0.0001*
B^2	1	*1.56*	*0.0434*	-	-	-		-	-
AC	-	-	-	1	*0.25*	*0.0303*		-	-
BC	-	-	-		-	-		-	-
Residual	15	4.82	-	15	0.66	-	17	0.011	-
Lack of Fit	10	*3.48*	*0.4084*	10	*0.55*	*0.1564*	*12*	*9.202E-003*	*0.4280*
Pure Error	5	*1.34*	-	5	*0.11*	-	*5*	*1.883E-003*	
Cor Total	19	38.07	-	19	4.49	-	19	0.082	
R^2	0.8735			0.8527			0.8653		
Adj R^2	0.8398			0.8134			0.8495		
Pred R-Squared	0.7262			0.6644			0.7983		
Adeq Precision	21.774			18.442			24.065		
Mean	12.74			6.98			0.69		
CV	4.45			3.01			3.03		

Appendix Table. 5. ANOVA for Vitamin C retention by response surface linear and quadratic models

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	13	0.469876	0.469876	0.036144	9.01	0.000
Linear	4	0.392334	0.172464	0.043116	10.75	0.000
T (°C)	1	0.068168	0.097816	0.097816	24.39	0.000
DPT (°C)	1	0.006249	0.011492	0.011492	2.87	0.097
V (m/s)	1	0.000468	0.000799	0.000799	0.20	0.657
Time (min)	1	0.317449	0.090107	0.090107	22.47	0.000
Square	3	0.004078	0.002608	0.000869	0.22	0.884
T (°C)*T (°C)	1	0.000308	0.000492	0.000492	0.12	0.728
DPT(°C)*DPT(°C)	1	0.000000	0.000799	0.000799	0.20	0.657
Time (min)*Time (min)	1	0.003770	0.001265	0.001265	0.32	0.577
Interaction	6	0.073464	0.073464	0.012244	3.05	0.013
T (°C)*DPT (°C)	1	0.000791	0.000350	0.000350	0.09	0.769
T (°C)*V (m/s)	1	0.002475	0.000442	0.000442	0.11	0.741
T (°C)*Time (min)	1	0.057067	0.049505	0.049505	12.34	0.001
DPT (°C)*V (m/s)	1	0.001896	0.002064	0.002064	0.51	0.477
DPT (°C)*Time (min)	1	0.010957	0.009738	0.009738	2.43	0.126
V (m/s)*Time (min)	1	0.000278	0.000278	0.000278	0.07	0.793
Residual Error	49	0.196536	0.196536	0.004011		
Pure Error	16	0.000000	0.000000	0.000000		
Total	62	0.666412				
R^2	70.51%					
S	0.0633320					

Appendix Table. 6: Equations for the responses investigated and their statistics at P < 0.005

Profiles	Response	Model	R^2
I	TCD(-)	$TCD=0.1625+0.9051t-0.001786t^2+0.000075t^3$	0.98
	ΔL	$\Delta L=-0.145734+0.497873t-0.067202t^2+0.00307964t^3 - 4.32446e^{-005}t^4$	0.95
	Δa	$\Delta a =-0.1902+0.1021t-0.008482t^2+0.000213t^3$	0.97
	Δb	$\Delta b =0.1718-0.01639t-0.004394t^2+0.000062t^3$	0.98
	A/A_o	$A/Ao=1.006-0.01958t+0.000571t^2-0.000008t^3$	0.99
II	TCD(-)	$TCD=0.8183+0.03335t+0.000697t^2-0.000006t^3$	0.93
	ΔL	$\Delta L=0.793497+0.00154225t+0.000508766t^2-3.1398e^{-005}$ t3-$2.31726e^{-007}t^4$	0.93
	Δa	$\Delta a=0.07533+0.02708t-0.000309t^2+0.00001t^3$	0.80
	Δb	$\Delta b=-0.0266-0.1023t+0.001508t^2-0.000007t^3$	0.94
	A/A_o	$A/Ao=0.9754-0.009634t+0.000125t^2-0.000001t^3$	0.96
III	TCD(-)	$TCD(-)=0.6070+0.08073t-000536t^2+0.000002t^3$	0.95
	ΔL	$\Delta L=0.415376+0.0929784t-0.00568084t^2+0.000119864t^3-7.06586e^{-007}t^4$	0.92
	Δa	$\Delta a=-0.1251+0.03076t-0.000157t^2-0.000001t^3$	0.86
	Δb	$\Delta b=-0.0957-0.1269t+0.002022t^2+0.00011t^3$	0.97
	A/A_o	$A/Ao =0.9799-0.01042t+0.000152t^2-0.0001t^3$	0.97
IV	TCD(-)	$TCD(-)=0.2439+0.1933t-0.002782t^2+0.000015t^3$	0.96
	ΔL	$\Delta L=-0.225561+0.302375t-0.0122382t^2+0.0009t^3-9.69807e^{-006}t^4$	0.94
	Δa	$\Delta a=-0.1185+0.01588t+0.000310t^2-0.000003t^3$	0.94
	Δb	$\Delta b=0.0731-0.1582t+0.0019t^2-0.000008t^3$	0.97
	A/A_o	$A/Ao=0.9841-0.009595t+0.000125t^2-0.000001t^3$	0.98
V	TCD(-)	$TCD(-)=-0.0617+0.1767t-0.0023276t^2+0.000013t^3$	0.99
	ΔL	$\Delta L=0.612674+0.325413t-0.0152951t^2+0.000252046t^3-1.3214e^{-006}t^4$	0.82
	Δa	$\Delta a=-0.0553+0.02451t+0.000059t^2-0.00003t^3$	0.93
	Δb	$\Delta b=0.3774-0.1873t+0.002524t^2-0.000013t^3$	0.98
	A/A_o	$A/Ao=0.9950-0.01182t+0.000197t^2+0.000001t^3$	0.98

Appendix Table. 7 ANOVA of resilience versus temperature profiles

Source	DF	SS	MS	F	P
Profiles	4	0.0000500	0.0000125	0.75	0.588
Error	7	0.0001167	0.0000167		
Total	11	0.0001667			
Mean	0.001667				
CV	0.004082				

Appendix Table. 8 ANOVA of hardness versus temperature profiles

Source	DF	SS	MS	F	P
Profiles	4	82.17	20.54	11.41	0.003
Error	7	12.60	1.80		
Total	11	94.77			
Mean	14.05				
CV	1.342				

Appendix Table. 9 ANOVA of deformation versus temperature profiles

Source	DF	SS	MS	F	P
Profiles	4	0.3079	0.0770	1.24	0.377
Error	7	0.4351	0.0622		
Total	11	0.7431			
Mean	0.55				
CV	0.2493				

Appendix Table. 10 ANOVA work versus temperature profiles

Source	DF	SS	MS	F	P
Profiles	4	58.7	14.7	1.47	0.309
Error	7	70.1	10.0		
Total	11	128.8			
Mean	6.75				
CV	3.164				

Appendix Table. 11 ANOVA of total color difference for solar dried potato slices

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	82.46	55.75	27.88	0.73	0.495
B	2	2062.94	1863.08	931.54	24.43	0.000
C	1	29.65	25.36	25.36	0.67	0.425
A*B	4	103.54	106.50	26.63	0.70	0.603
A*C	2	176.20	165.21	82.61	2.17	0.144
B*C	2	7.00	2.77	1.39	0.04	0.964
A*B*C	4	32.68	32.68	8.17	0.21	0.927
Error	18	686.39	686.39	38.13		
Total	35	3180.86				

Where A=variety, B= thickness and C= position

Appendix Table.12 Analysis of Variance for A/A0(-), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	0.025631	0.028605	0.014302	2.29	0.130
B	2	0.026763	0.021578	0.010789	1.73	0.206
C	1	0.007177	0.003370	0.003370	0.54	0.472
A*B	4	0.026690	0.031347	0.007837	1.26	0.323
A*C	2	0.014116	0.016189	0.008094	1.30	0.298
B*C	2	0.004154	0.006189	0.003095	0.50	0.617
A*B*C	4	0.042611	0.042611	0.010653	1.71	0.192
Error	18	0.112314	0.112314	0.006240		
Total	35	0.259456				

Where A=variety, B= thickness and C= position

Appendix Table. 13 Analysis of Variance for Total time (h) of solar dried potato slices

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	7.1403	4.2547	2.1273	11.48	0.001
B	2	109.0373	100.2992	50.1496	270.60	0.000
C	1	0.1162	0.0838	0.0838	0.45	0.510
A*B	4	2.7045	2.8120	0.7030	3.79	0.021
A*C	2	0.2609	0.3263	0.1631	0.88	0.432
B*C	2	0.0452	0.0468	0.0234	0.13	0.882
A*B*C	4	0.7323	0.7323	0.1831	0.99	0.439
Error	18	3.3358	3.3358	0.1853		
Total	35	123.3725				

Where A=variety, B= thickness and C= position

Appendix Table. 14 ANOVA of hardness for solar dried potato slices

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	1248.07	845.90	422.95	4.91	0.011
B	2	2381.35	2806.41	1403.20	16.27	0.000
C	1	50.80	14.95	14.95	0.17	0.679
A*B	4	243.89	375.47	93.87	1.09	0.371
A*C	2	766.33	604.41	302.20	3.50	0.037
B*C	2	366.04	236.15	118.07	1.37	0.263
A*B*C	4	1153.46	1153.46	288.36	3.34	0.116
Error	54	4656.17	4656.17	86.23		
Total	71	10866.11				

Where A=variety, B= thickness and C= position

Appendix Table. 15 ANOVA of deformation for solar dried potato slices

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	6.3261	4.6886	2.3443	4.01	0.024
B	2	3.6014	3.0338	1.5169	2.60	0.084
C	1	0.0480	0.0781	0.0781	0.13	0.716
A*B	4	0.8698	0.4650	0.1162	0.20	0.938
A*C	2	0.5482	0.6867	0.3433	0.59	0.559
B*C	2	0.2215	0.2866	0.1433	0.25	0.783
A*B*C	4	1.9252	1.9252	0.4813	0.82	0.516
Error	54	31.5555	31.5555	0.5844		
Total	71	45.0958				

Where A=variety, B= thickness and C= position

Appendix Table. 16 Analysis of Variance for TP(GAE g/100 g dw), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	187.87	187.87	93.94	6.88	0.006
B	2	2556.32	2556.32	1278.16	93.67	0.000
C	1	666.58	666.58	666.58	48.85	0.000
A*B	4	355.98	355.98	88.99	6.52	0.002
A*C	2	250.26	250.26	125.13	9.17	0.002
B*C	2	240.68	240.68	120.34	8.82	0.002
A*B*C	4	432.43	432.43	108.11	7.92	0.001
Error	18	245.63	245.63	13.65		
Total	35	4935.75				

Where A=variety, B= thickness and C= position

Appendix Table. 17 Analysis of Vitamin C, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS_1	Adj_1 MS	F	P
Variety	2	0.153643	0.153643	0.076822	6913.94	<0.001
Thickness mm	2	0.125596	0.125596	0.062798	5651.8	<0.001
Position	1	0.005782	0.005782	0.005782	520.35	<0.001
Variety*Thickness mm	4	0.035938	0.035938	0.008985	808.61	<0.001
Variety*Position	2	0.009729	0.009729	0.004864	437.79	<0.001
Thickness mm*Position	2	0.001264	0.001264	0.000632	56.89	<0.001
Variety*Thickness mm*Position	4	0.002907	0.002907	0.000727	65.41	<0.001
Error	18	0.0002	0.0002	0.000011		
Total	35	0.335059				

Appendix Table. 18 ANOVA of specific volume

Source	DF	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	2	0.76	2	0.38	11.48	0.0020
Linear Mixtur	2	0.76	2	0.38	11.48	0.0020
Residual	11	0.37	11	0.033		
Lack of Fit	7	0.31	7	0.044	3.27	0.1345
Pure Error	4	0.054	4	0.014		
Cor Total	13	1.13	13			

Appendix Table. 19 ANOVA of appearance of the bread

Source	DF	Sum of Squares	Mean Square	F Value	Prob > F
Model	2	3.04	1.52	4.80	0.0318
Linear Mixture	2	3.04	1.52	4.80	0.0318
Residual	11	3.48	0.32		
Lack of Fit	7	2.75	0.39	2.14	0.2404
Pure Error	4	0.73	0.18		
Cor Total	13	6.52			

Appendix Table. 20 ANOVA of Texture of the bread

Source	DF	Sum of Squares	Mean Square	F Value	Prob > F
Model	2	1.73	0.87	4.15	0.0453
Linear Mixture	2	1.73	0.87	4.15	0.0453
Residual	11	2.29	0.21		
Lack of Fit	7	1.39	0.20	0.88	0.5854
Pure Error	4	0.90	0.23		
Cor Total	13	4.02			

Appendix Table. 21 ANOVA of Flavor of the bread

Source	DF	Sum of Squares	Mean Square	F Value	Prob > F
Model	2	1.77	0.88	5.23	0.0253
Linear Mixture	2	1.77	0.88	5.23	0.0253
Residual	11	1.86	0.17		
Lack of Fit	7	1.14	0.16	0.90	0.5782
Pure Error	4	0.72	0.18		
Cor Total	13	3.62			

Appendix Table 22 ANOVA of Overall acceptability of the bread

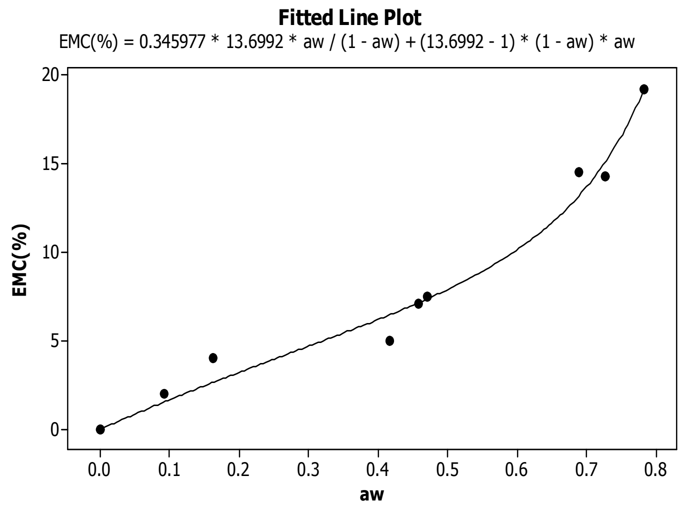
Source	DF	Sum of Squares	Mean Square	F Value	Prob > F
Model	2	1.66	0.83	6.75	0.0122
Linear Mixture	2	1.66	0.83	6.75	0.0122
Residual	11	1.36	0.12		
Lack of Fit	7	1.03	0.15	1.81	0.2948
Pure Error	4	0.32	0.081		
Cor Total	13	3.02			

Appendix Table 23 Sensory evaluation sheet

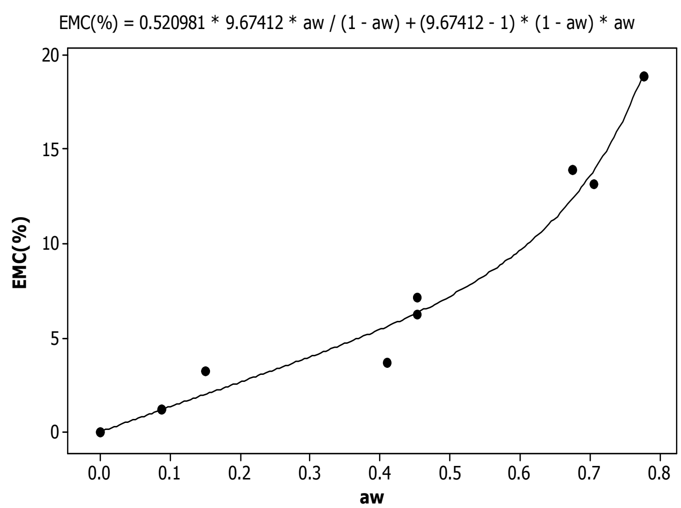
You are given servings of bread to taste and express your degree of liking of each sensory attributes provided. Taste each sample and indicate your response by marking (x) in the corresponding acceptances. Please rinse your mouth between tastes to remove after tastes. Thank you for your participation.

Acceptance with scale		Sensory Attribute			
		Color	Texture	Flavor	Over all acceptability
Extremely Like	5				
Like Moderately	4				
Neither like nor dislike	3				
Dislike moderately	2				
Dislike Extremely	1				

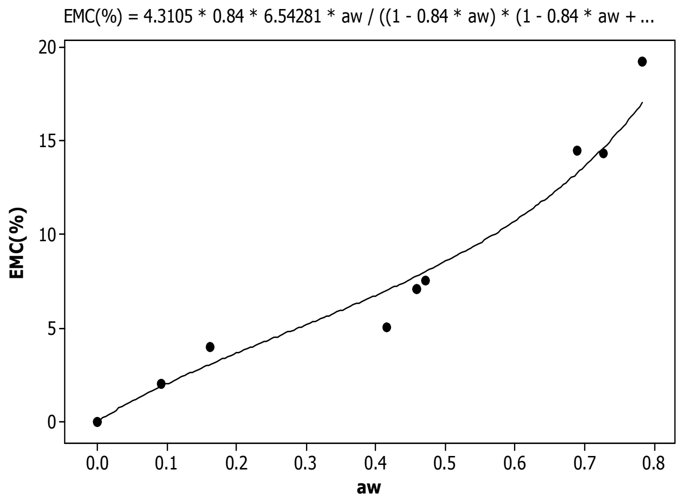
Comments



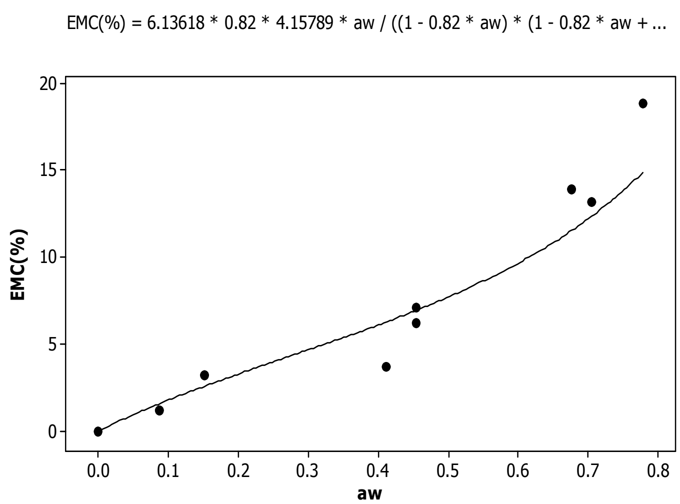
Appendix Figure 1: comparison between experimental and predicted values of the desorption isotherm using the BET equation at a temperature of 70°C.



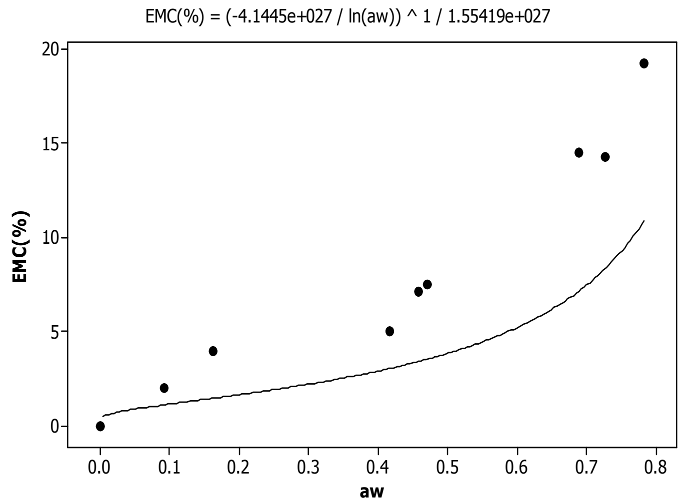
Appendix Figure 2: comparison between experimental and predicted values of the desorption isotherm using the BET equation at a temperature of 80 °C.



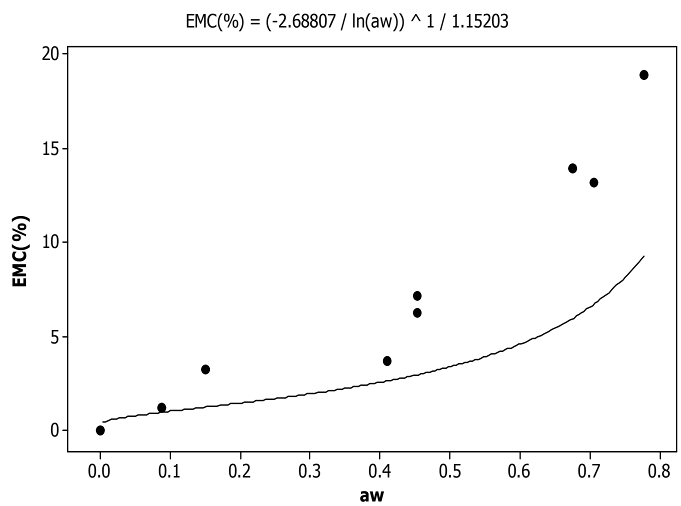
Appendix Figure 3: comparison between experimental and predicted values of the desorption isotherm using the GAB equation at a temperature of 70 °C.



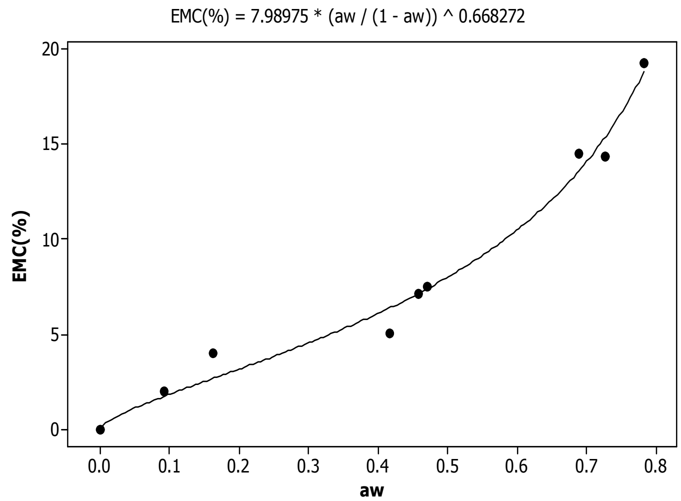
Appendix Figure 4: comparison between experimental and predicted values of the desorption isotherm using the GAB equation at a temperature of 80 °C.



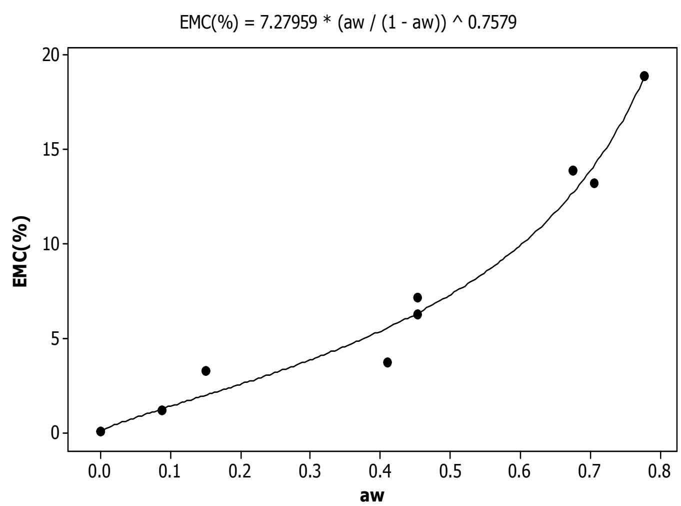
Appendix Figure 5: Comparison between experimental and predicted values of the desorption isotherm using the Halsey equation at a temperature of 70 °C.



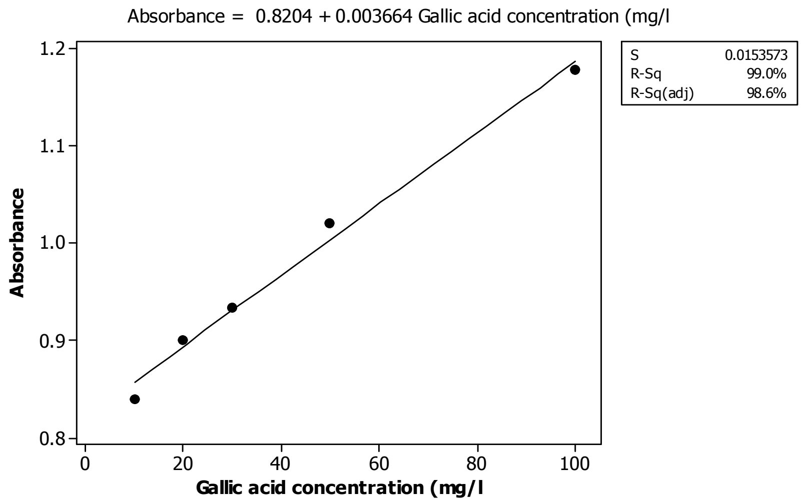
Appendix Figure 6: Comparison between experimental and predicted values of the desorption isotherm using the Halsey equation at a temperature of 80 °C.



Appendix Figure 7: Comparison between experimental and predicted values of the desorption isotherm using the Oswin equation at a temperature of 70 °C.



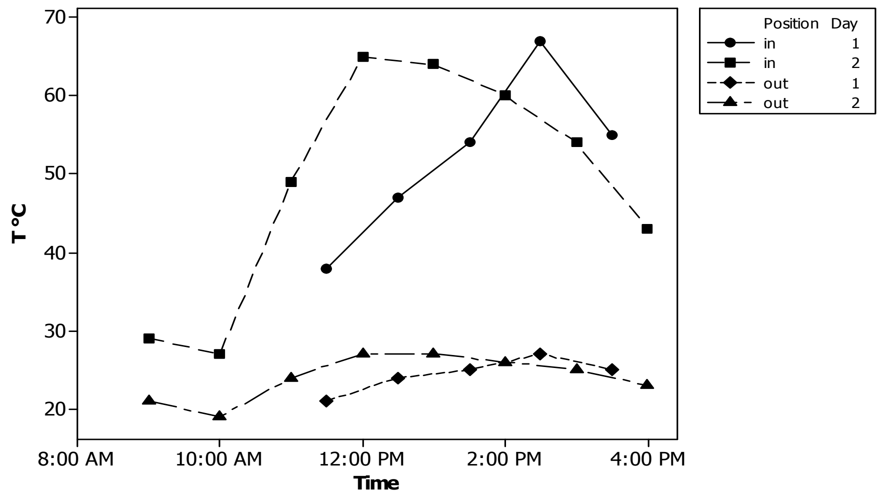
Appendix Figure 8: Comparison between experimental and predicted values of the desorption isotherm using the Oswin equation at a temperature of 80 °C.



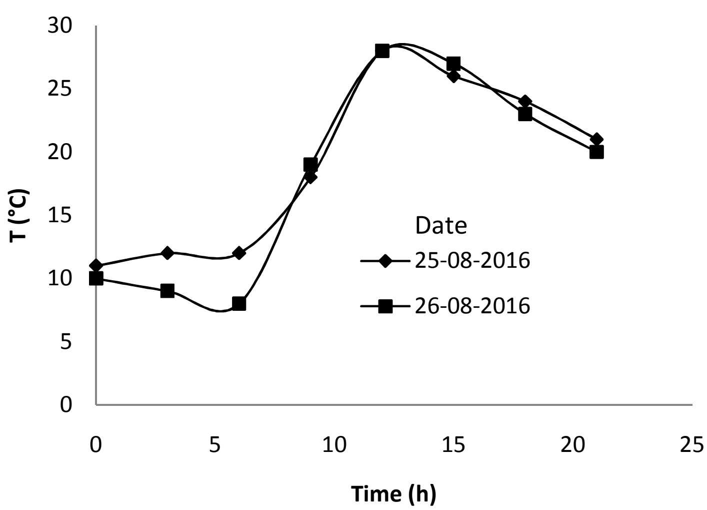
Appendix Figure 9: Standard curve of Gallic Acid

Temperature for solar tunnel drying

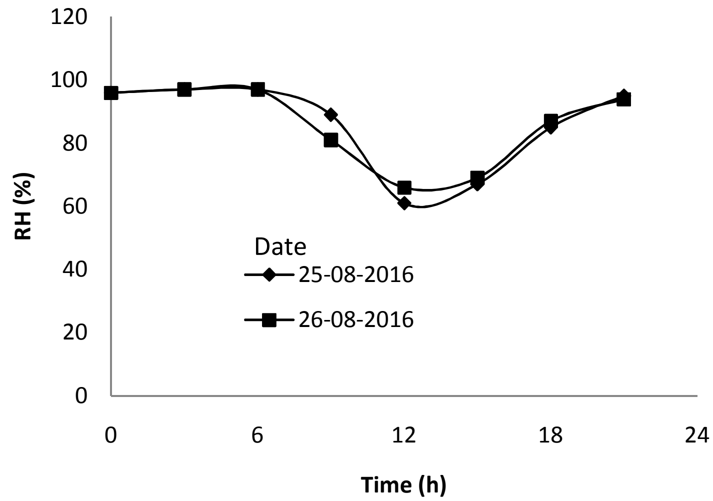
The temperature of the air inside and outside the dryer was recorded only during the time interval between 9:00 am to 4:00 pm. The temperature of air during the night and rainy time was not recorded. The days in which the experiment was conducted were semi rainy. The graph of the drying temperature is presented in Figure 8.2. The maximum temperatures of the air inside the dryer were 67 °C and 65 °C for day 1 and day 2, respectively. The remaining data for weather conditions of the two days was collected from Jimma-National Meteorology Agency. The weather conditions of the two days of drying of the samples are presented in Appendix Figure 11-14.



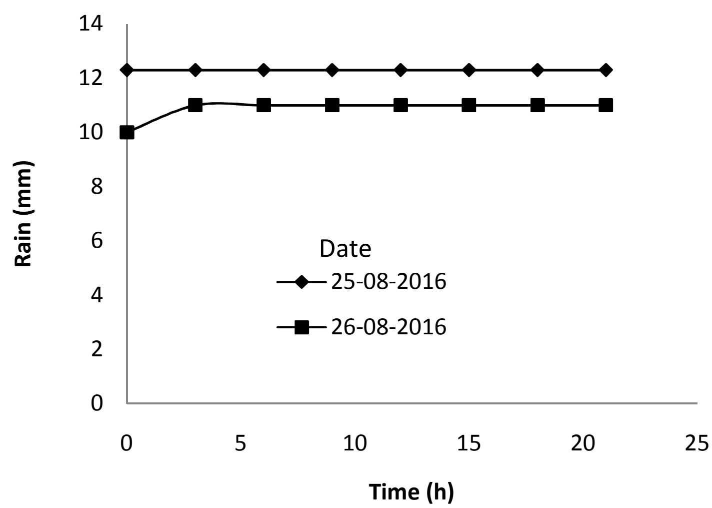
Appendix Figure 10: Temperature inside and outside the drier



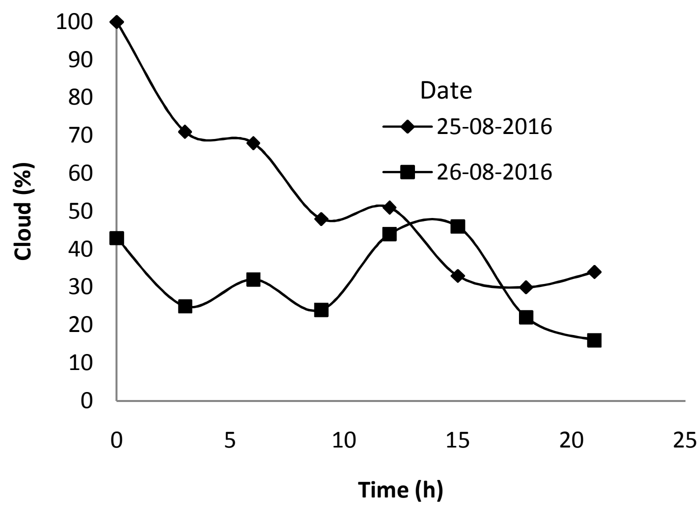
Appendix Figure 11: the temperature of the weather during drying the potato samples



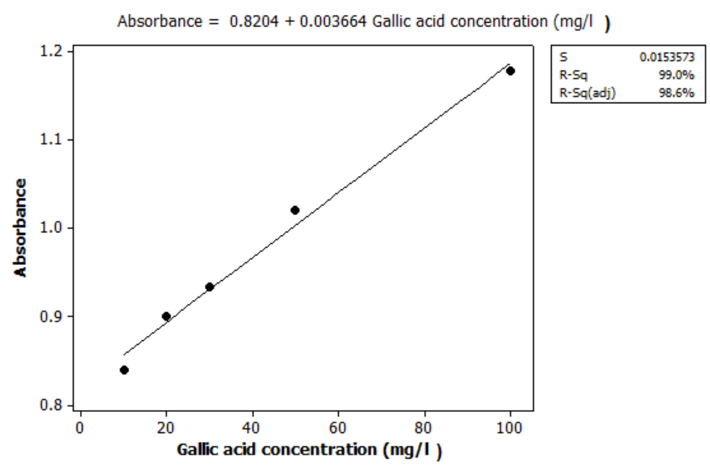
Appendix Figure 12: the relative humidity of the weather during drying the potato samples



Appendix Figure 13: the rain of the weather during drying the potato samples



Appendix Figure 14: the cloud of the weather during drying the potato samples



Appendix Figure.15. Standard curve of Gallic Acid