University of Reading

Novel and Less Understood Methods of Food Dehydration: Understanding the Effects of Process Conditions and the Mechanisms of Water Loss

Thesis submitted for the degree of Doctor of Philosophy
Department of Food and Nutritional Sciences

By

Wan Mohd Fadli Wan Mokhtar

AUGUST 2019

DECLARATION

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

……

Wan Mohd Fadli Wan Mokhtar

ABSTRACT

Dehydration is one of the oldest food processing operations. It continues to be extensively employed today, and all indications point to its continued use in the foreseeable future. There are several dehydration techniques available for use in domestic and commercial practice. The main objective of this thesis is to focus on novel and less studied variants of two specific dehydrating methods: 1. Osmotic dehydration and 2. Frying. Osmotic dehydration is a natural process where water loss occurs by osmosis when food is brought into contact with a concentrated salt or sugar solution. Although this process consumes lower energy than other drying methods - which predominantly involve supplying the necessary latent heat for water evaporation from the food - a key problem is the high salt/sugar uptake which potentially poses health issues. In this thesis, a novel variant of osmotic dehydration called post-dipping dehydration – has been developed and studied. The technique involves dipping, say, potato slices, briefly in an osmotic solution, withdrawing it and allowing the water released to evaporate and/or drain under ambient conditions. The aim is to promote water loss just as in osmotic dehydration, but at the same time, minimize the uptake of the osmotic solute. The effects of osmotic medium concentration and dipping time on the water loss were initially investigated. Dipping potatoes in a higher concentration of osmotic solution was found to enhance post-dripping water loss, but the dipping time had no significant effect. Post dipping dehydration was also conducted as a multi-stage operation by repeatedly dipping potato slices in the osmotic solution followed by ambient exposure for a time period. The resulting water loss was comparable to osmotic dehydration but the uptake of the osmotic solute was significantly lower (less than 50%).

In the next part of the research, multi-stage dip dehydration was investigated as a pre-treatment prior to frying potato chips, in order to evaluate its effect on the product

quality. Multistage dip dehydration was found to decrease the frying time considerably which also resulted in about 17% lesser oil in the product. Colour measurements showed that the pre-treated samples were brighter and suffered lesser browning than blanched samples.

The final part of this thesis is dedicated to gaining insights into shallow frying of potato and chicken cubes – an extensively employed but less understood dehydration operation in relation to deep-fat frying. The experimental investigations involved determining transient temperature variations during the process, moisture loss, oil uptake and the development of product texture. A key outcome of this research was the observation that the significant amount of water released initially from the food tended to form an oil-in-water emulsion, which subsequently boiled off to result in a phase inversion (i.e. the formation of water-in-oil emulsion). The temperature clearly increased after the phase inversion when the crust and texture of the end-product were formed.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

First and foremost, thanks to God for giving me such a wonderful experience during completing my PhD in the University of Reading. I would like to acknowledge the Ministry of Education, Malaysia and Universiti Sultan Zainal Abidin for the financial support throughout my PhD study.

I would like to express my deepest appreciation to my academic supervisors, Prof. Keshavan Niranjan for their encouragement, guidance, and valuable advices throughout my study. Special thanks to Dr Sameer Khalil Ghawi for his time to help me in completing my experimental work.

I also would like to express my appreciation to all technical staffs in Food Bioscience (Harry Nursten) Building, my colleagues in Lab 3.39, Room 2.01 and others in University of Reading, thank you so much for your encouragement and continuous support you have given me during my study.

My special gratitude goes to my family, especially mum, dad, sisters, and brothers and in laws for supporting me spiritually during PhD studies. This work would not have been possible without their prayers.

Finally, will all my heart I would like to acknowledge my beloved wife, Fatimah Kari and my sons, Wan Muhammad Shafiy and Wan Ahmad Shakil Iman for your unbelievable support and sacrifice during our years here. I am truly thankful to have all of you in my life. Thank you for your understanding, always being by my side, providing me motivation and making me become a better person in general.

Wan Mohd Fadli Wan Mokhtar
(2 December 2019, 10.43pm)

CHAPTER 1

INTRODUCTION

1.1 Background

Most fresh foods including meat, poultry, fruits and vegetables contain high water content, which affects food stability due to adverse microbial action and undesirable biochemical transformations. Dehydration has been extensively employed to extend shelf life and keeping quality of products (Azoubel & Murr, 2004). In conventional drying, water is removed by simultaneous heat and mass transfer between air and the food material (Eroglu & Yildiz, 2010). However, this technique inevitably leads to undesirable changes in texture, sensory properties (including colour and visual appearance) and flavour and nutrient loss. All these effects arise as a result of the product being exposed to high temperatures over prolonged periods of times (Ochoa-Martinez, Ramaswamy, & Ayala-Aponte, 2007). Needless to say, air drying is also a highly energy intensive process.

Osmotic dehydration is a popular technique employed for extending the shelf life of products, especially fruits and vegetables, by enabling these materials to lose water without expending latent heat. It is a natural dewatering phenomenon resulting from the immersion of fresh fruits or vegetables in a concentrated solution of sugar or salt. The higher osmotic pressure in hypertonic solution creates a driving force for the diffusion of water through tissue cell into the solution (Chandra & Kumari 2015; Akbarian, Ghasemkhani, & Moayedi, 2014). At the same time, the solute also diffuses from the osmotic solution into the fruit tissue. Even though osmotic dehydration can be employed as the principal dehydration step, it is commonly used as a pre-processing step in the food

industry, prior to operations such as air drying, freezing or frying (Chavan & Amarowicz, 2012).

Osmotic dehydration has received considerable research attention as a food preserving operation, and it is generally recognised that this method has many drawbacks; the key problem is the diffusion of high levels of solute (salt or sugar) into the foods which also poses health issues. Moreover, the osmotic driving force also changes with the dilution of the osmotic solution caused by the leaching out of water and other components from tissue (Sun, 2014). Thus, there is an acute need to find ways of enabling the water from the tissue to diffuse into the osmotic solution, but at the same time, not allow high levels of the osmotic solute to diffuse into the fruit or vegetable.

This study aims to achieve this objective by employing a new variant of osmotic dehydration named here as post-dipping dehydration, which involves dipping the fruit or vegetable in an osmotic solution for a very short time so that it picks up a small quantity of the osmotic solution, which then generates adequate osmotic pressure for the water to leave the tissue over a period of time. A significant amount of water can be eliminated thus without expending any significant energy and this process does not expose the tissue to intense processing conditions, which also enables the natural attributes of the tissue to be retained.

Frying is also a well-established dehydration process, which lowers the moisture content of food in a relatively short time compared to conventional dehydration processes, by immersing the food in very hot oil generally around 200^{o}C (Gertz, 2014). The potential of the so-called deep fat frying, as a dehydration technique has been widely explored in earlier studies (Wu et al., 2012; Bravo et al., 2009; Pedreschi et al., 2005). Even though deep fat frying (immersion frying) is most commonly used due to its simplicity and very fast processing, it also results in high frying oil absorption into the

food, which has both economic and health implications. There are several methods used to reduce oil uptake during deep fat frying, and pre-treating vegetable tissues by osmotic dehydration is one reported method (Ren et al., 2018; Oladejo et al., 2017; Olayemi et al., 2017). In this thesis, post dipping dehydration has been explored as a pre-treatment step prior to frying potato chips and its effect has been studied on the oil uptake in the fried product.

It may be noted that foods can be fried in different ways, other than deep fat frying, like shallow fat, pan or stir frying, which essentially vary in the amount of oil employed or consumed, the frying time and the equipment used. Shallow frying basically involves partial immersion of food in hot oil, thus, requiring relatively smaller quantities of oil. Although this method is used extensively in culinary practice, its scientific principles have not been systematically studied. Published studies are relatively few, which focus on the impact of shallow frying conditions on the quality of final products or the nutritional properties of oil (Raczyk et al., 2018; Kobyliński et al., 2016; Aniołowska, Zahran, & Kita, 2016; Grootveld, Rodado, & Silwood, 2014). Moreover, literature information on mass and heat transfer during shallow frying is very scarce, despite the fact that it is widely used in all cultures. The latter part of this thesis, therefore investigates the mechanism of mass and heat transfer occurring during shallow frying and sheds light on water loss and oil absorption mechanisms, product temperature profiles and texture development.

1.2 Objectives

As mentioned earlier, the general aim of the whole study is to investigate mechanisms of novel and less understood dehydration techniques: dip-dehydration and shallow frying. The specific objectives are:

- To establish the effect of the concentration of the osmotic dipping solution, and dipping times on subsequent water loss profiles, and understand the mechanism of water loss occurring in the post-dipping period.
- To investigate the possibility of using dip-dehydration as a multi stage process - where the food is repeatedly subjected to a series of dipping followed by ambient exposure steps – so that the cumulative moisture loss is comparable with that obtained by osmotic dehydration, but the osmotic solute uptake is significantly lower.
- To explore the potential advantage of multi stage dip dehydration as a pre-treatment step prior to deep fat frying, and compare the product quality with that obtained by using osmotic dehydration and hot water blanching as pre-treatments.
- To obtain insights into the dehydration behaviour, thermal profile, oil uptake and texture development during domestic shallow frying, with intermittent product turnover.

1.3 Structure of the Thesis

Chapter 2 reviews published literature on osmotic dehydration and frying. Chapter 3 describes a detailed experimental study on dip dehydration elucidating the effect of operating conditions on water loss and exploring the possibility of undertaking multi-stage dip dehydration. The potential of multi-stage dip dehydration as a pre-treatment stage prior to shallow frying potato chips is discussed in Chapter 4. Chapter 5 describes the dehydration behaviour, temperature profile and texture development occurring during the shallow frying of chicken and potato cubes; the effect of product turn-over during shallow frying is also investigated. Finally, Chapter 6 summaries all the findings of the research undertaken and makes recommendation for future work.

1.4 Publications

- Chapter 3 has already been published: "Wan Mokhtar, Ghawi, and Niranjan, (2019), Dehydration of potato slices following brief dipping in osmotic solutions: Effect of conditions and understanding the mechanism of water loss, *Drying Technology*, 37 (7), 885 – 895.
- Chapter 4 will shortly be submitted for publication: "Effect of dip dehydration as a pre-treatment to lower oil uptake in fried potato chips, *Journal of Food Science.*
- Chapter 5 has been forwarded for publication: "Shallow frying of potato and chicken cubes: Water loss, oil gain, temperature profiles and texture development, *Journal of Food Science".*

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Dehydration is one of the oldest technologies that is widely used in the food industry. It is a frequently used preservation method to produce dried food for extending shelf life. The important purpose of drying is to lower moisture content and reduce the water activity without introducing significant chemical changes, which also makes it difficult for microbial growth to occur. Generally in the traditional method, food samples are subjected to open air sun drying which is commonly used in the case of vegetables, grains, fruits and other agricultural products. However, there are problems in natural air drying such as the slow rate of drying and low product throughputs (Doymaz, 2004). Therefore, hot air drying is preferred as an alternative method to overcome the slowness of natural air drying. In hot air drying, fresh foods are contacted with air at high temperature in a chamber until the desired moisture content is attained. Since food is exposed to the hot air, its quality, in terms of texture, colour and sensory properties, can deteriorate. Hot air drying is also expensive due to high energy consumption (Ochoa-Martinez et al., 2007). To overcome this issue, many alternative methods are available and osmotic dehydration (OD) and frying techniques can be considered to be alternative dehydration processes.

2.2 Osmotic Dehydration

Osmotic dehydration involves immersion of food samples in hypertonic solution, either sugar or salt solutions, in order to reduce the initial moisture content of material. It is a natural phenomenon of dewatering and impregnation soaking process (Raoult-Wack, 1994). It involves simultaneous counter-current mass transfer between solution inside tissue sample and a concentrated solution outside. First, due to driving force from higher osmotic pressure of the hypertonic solution, water flows out from the food tissue into the osmotic solution. Simultaneously, the diffusion of water is accompanied by the solute infusion from the osmotic solution into the food tissue. In addition, some natural materials present in the food, such as sugar, vitamins, organic acids and minerals, can also leach out into the osmotic solution since the membrane of the food sample is not perfectly selective. Generally, the amounts of natural material lost from the food (other than water) are quantitatively negligible compared the water lost or the solute gained (Akbarian et al., 2014).

Due to the difference between the chemical potentials of water in the food tissue and the external solution, and the difference between the chemical potentials of the solute present in the external solution and the food tissue, simultaneous mass transfer of water and solute occur with the water leaving the food tissue while external solute entering the food . After some time, the driving forces for mass transfer decrease, until eventually, the system achieves a dynamic equilibrium. Generally, this technique is considered to be a natural process which can operate under ambient conditions, where heat damage to colour, flavour and texture can be minimized (Torreggiani, 1993). Since there is no phase change involved in this process, it is recognised as being an energy efficient method for partial dehydration. In addition, a great reduction in the cost of transport, packing and

storing also can be achieved due to lower moisture content of the product (Chwastek, 2014).

Although it is a mature area of research, osmotic dehydration is still receiving attention from active researchers from around the world. Numerous research papers have already been published regarding the positive effect of osmotic dehydration in removing the water content of various fresh fruits and vegetables (Soquetta et al., 2018; Yuan et al., 2018). Besides, this technique has also been used in dewatering fish and meat products (Filipovic et al., 2017; Maciel, Manoel and Pena, 2016; Agustinelli et al., 2014; Medina-vivanco, Sobral and Hubinger, 2002). Table 2.1 summarises the maximum water loss that can be achieved under different process conditions.

Osmotic dehydration also has a positive effect on the retention of volatile compound in foods as reviewed by (Paula, Barbosa and Junior, 2016). According to Almeida et al. (2015), Giovanelli et al. (2012), Devic et al. (2010b) and Rizzolo et al. (2007), the extent of retention of bioactive compound in foods depends on the osmotic conditions such as concentration, temperature, osmotic agent used and immersion time. For example, a recent study by Rahman et al., (2018) found that higher concentration of sucrose resulted in higher myristicin content, while longer immersion time decreased the antioxidant properties and free radical scavenging activity of nutmeg pericarp.

It may be noted that the amount of water removal through OD is not sufficient to result in shelf stable products. Therefore, osmo-dehydrated products are subjected to further dehydration by employing freezing, drying or conventional hot air drying. In some cases, frying of osmo-dehydrated products can yield shelf stable products. Figure 2.1 illustrates the application of osmotic dehydration in fruit and vegetable processing (Yadav and Singh 2014; Torreggiani, 1993). After going through osmotic dehydration, the treated products are drained for a short time to recover occluded osmotic medium.

The drained solution (also called as syrup) is generally recovered by concentration and reused.

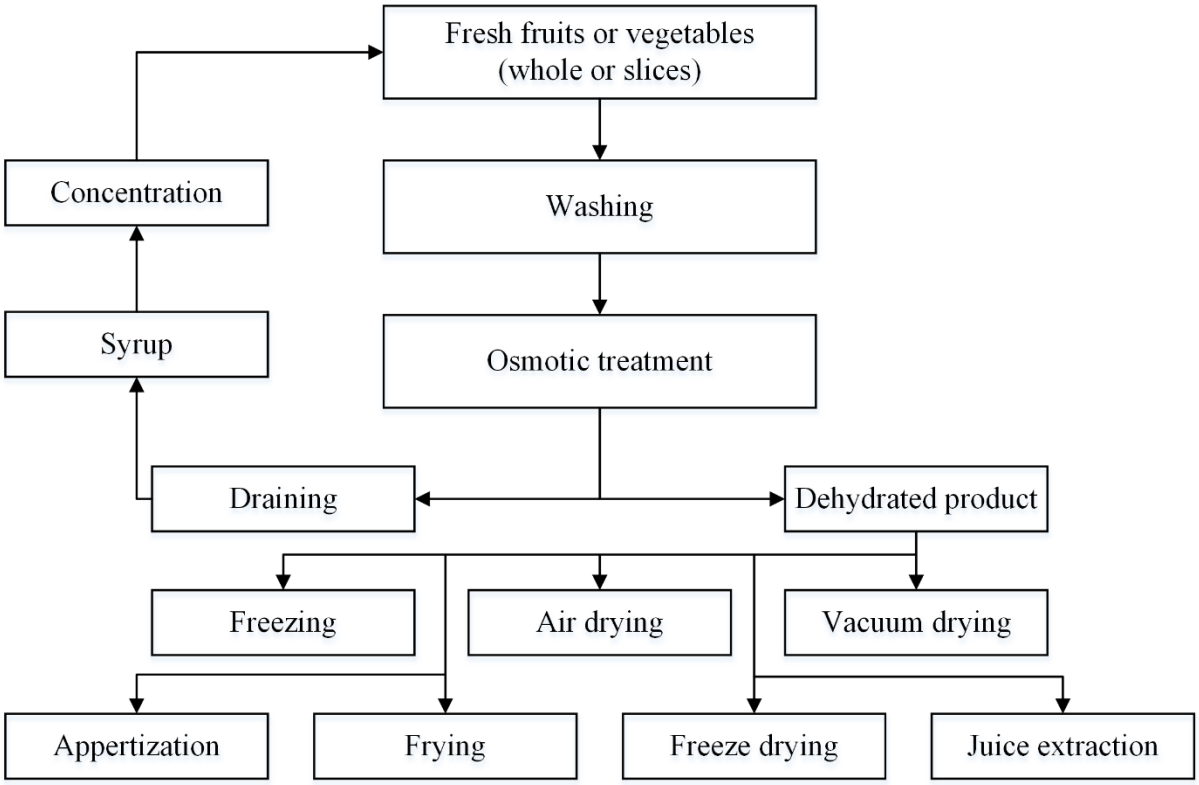

Figure 2.1 Application of osmotic dehydration as pre-treatment prior to further processing in the case of fruit and vegetable products.

Table 2.1 Selected publications on osmotic dehydration conditions to remove at maximum water loss for various fruits and vegetables.

Product	Conditions	Maximum water loss	References
Broccoli stalk	T = 42 °C, O.A = sucrose 56% w/v, I.T. = 4 hr	62%	(Md Salim et al., 2016)
Litchi	T = 50 °C, O.A = sucrose 50 °Brix, I.T. = 3 hr	53%	(Lakshmishri Roy, 2015)
Pineapple	T = 50 °C, O.A = sucrose 60% w/w, I.T. = 4 hr	36%	(Filho et al., 2015)
	T = 27 °C, O.A = sucrose 50%/calcium lactate 4%, I.T. = 6 hr	40%	(Silva, Fernandes and Mauro, 2014)
Oyster mushroom	T = 45 °C, O.A = NaCl 15% w/v/sucrose 55 °Brix, I.T. = 1 hr	41%	(Ramya and Kumar, 2015)
Yacon	T = 30 °C, O.A = sorbitol 70% w/v /calcium lactate 20% w/v, I.T. = 6 hr	70%	(Brochier, Marczak and Noreña, 2015)
Cantaloupe	T = 30 °C, O.A = sorbitol 50 °Brix, I.T. = 18 hr	45%	(Naknean, Maneyam and Kam-Onsri, 2013)
Banana	T = 48.92 °C, O.A = sucrose 53.92 % w/w/NaCl 7.97% w/w. I.T. = 10 hr	70%	(Mercali et al., 2012)
Green bean	T = 50 °C, O.A = NaCl 26.5% w/w, I.T. = 6 hr	40%	(Abbasi Souraki, Ghaffari and Bayat, 2012)
Sweet potato	T = 25 °C, O.A = maltodextrin 80% w/w, I.T. = 8 hr	34%	(Wang, Yu and Song, 2011)
Carambola	T = 60 °C, O.A = sucrose 50% w/w, I.T. = 8 hr	70%	(Ruiz-López et al., 2011)
Pomegranate	T = 45 °C, O.A = sucrose 60 °Brix, I.T. = 4 hr	68%	(Mundada, Hathan and Maske, 2011)
Apple	T = 65 °C, O.A = sugar beet molasses 80% w/w, I.T. = 5 hr	84%	(Mišljenović et al., 2011)
Carrot	T = 54.8 °C, O.A = sucrose 50 °Brix/ NaCl 15% w/v, I.T. = 2 hr	43%	(Singh et al., 2010)

*T= temperature of osmotic solution; O.A.= osmotic agent; I.T.= immersion time

2.2.1 Mechanism of Osmotic Dehydration

Figure 2.2 shows the mass transfer mechanism and the state of cellular material tissue during osmotic dehydration. When a food sample is immersed into a concentrated solution, the high differences in the amount of water and solute between the cells and the osmotic solution, yields chemical potential for natural mass transfer to occur. The water outflow from the tissue begins at a first layer of material that is in contact with osmotic solution, and tissue structure at this point begins to shrink due to water loss. Then, a similar chemical potential difference is generated between successive layers of cells, and water leaves the tissue as it shrinks. The mass transfer and tissue shrinkage occur simultaneously which continues until the innermost layers of the sample are reached. At the same time, due to the solute concentration gradient between the osmotic solution and the tissue, the osmotic solute diffuses into it (Falade and Igbeka 2017).

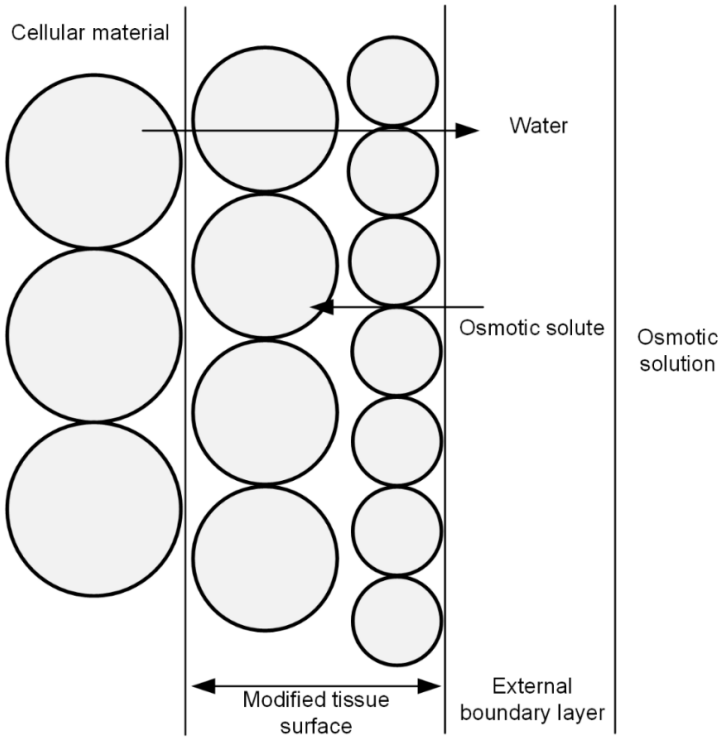

Figure 2.2 Schematic cellular material tissue representation and mass transfer pattern.

2.2.2 Effect of Process Conditions on the Osmotic Dehydration

The effectiveness of osmotic dehydration is influenced by a number of factors such as concentration and temperature of the osmotic agent, material size, contact time, mass ratio of solution to material and level of agitation of the solution (Brochier et al. 2015). Besides, the properties of the osmotic agent used also influences dehydration (Silva et al., 2014).

According to Tortoe (2010), the temperature of osmotic solution is the most important factor influencing the kinetics of dehydration. This was also confirmed by earlier studies conducted on several fruits and vegetables e.g. apple (Li and Ramaswamy 2006; Salvatori et al. 1999), guava (Panades et al., 2008), potato (Karizaki et al., 2013) and carrot (Singh et al. 2010; Uddin et al. 2004). This is because the higher temperature 1) reduces the viscosity of the osmotic solution; 2) causes swelling and plasticising of the cell membrane; and 3) increases the rate of diffusion (Ciurzyńska et al. 2016; Phisut 2012).

Kaymak-Ertekin and Sultanoglu (2000), while conducting experiments with apple between 20 to 50 °C, reported that temperature increase resulted in increased water loss, but did not result in a proportionately high sugar gain. A similar finding was also reported by Uddin et al. (2004) where temperature contributed less to the rates of solid gain than water loss, although solid gain increases rapidly with increasing concentration of the osmotic solution. However, at temperatures above 45 or 50 °C, the solute gain increases dramatically. Devic et al. (2010) found that sugar gain increased by up to 50% at 60 °C compared to 45 °C. Ruiz-López et al. (2011) also reported a similar result when experiments were conducted with carambola slices using sucrose solution.

Although the use of higher temperatures contributes significantly to mass transfer rates, some previous studies have highlighted the negative effects of temperature

increases on the final product properties such as the structural changes, colour, loss of nutrients and deformation of materials (Segui et al. 2010; Barat et al. 2001). Based on literature reports, it appears that the solution temperature must not greater than 50 °C for both vegetable and fruit tissues in order to prevent enzymatic browning, flavour deterioration and loss of thermos-sensitive compounds (Akbarian et al., 2014).

Another interesting variable which impacts significantly on the process is the concentration of the osmotic solution. The mass mobility generally increased at higher solute concentration. According to Azoubel and Murr (2004), an increases in the solution concentration caused enhanced water loss and solid gain. Besides, greater swelling of the tissues may increase cell membrane permeability (Phisut, 2012). Giraldo et al. (2003) studied the effect of increasing sucrose concentration between 35^{o}Brix and 65^{o}Brix to conclude that the water transfer rate increased up to 55^{o}Brix, beyond which it did not change, possibly because of case hardening effects. Wang, Zhang and Mujumdar (2010) also reported similar observations while studying the osmotic dehydration of potato in sucrose solutions. This may be due to the high uptake of sugar at higher concentration and the possible development of peripheral layer of sugar, which lowers water loss. Manafi *et al.* (2010) also reported the same outcome in the case of apricot dehydration in salt solutions. Some authors suggest that osmotic dehydration employing low concentration solution lowers the process efficiency (i.e. lowers the ratio of water loss to solid gain) (Tortoe, 2010). According to Antonio et al. (2008), the suitable range of sugar concentration is 40 to 70%, while in the case of salt concentration, the range is 5 to 20%.

Literature reports suggest that sucrose or glucose and sodium chloride are the most common osmotic agents used for fruits and vegetables, respectively, but other osmotic agents such as calcium chloride, glucose, fructose, lactose, dextrose, maltose, maltodextrin and corn syrup have also used in previous works (Chandra and Kumari,

2015; Chavan and Amarowicz, 2012). The selection of an osmotic agent must consider the following three main factors: the impact of solute in term of sensory characteristics of the product, the relative cost of solute in relation to the final value of the product, and the stability of final product.

Most studies report sucrose and salt solution to be reliable osmotic agents on various type of fruits and vegetables. Khin, Zhou and Perera (2007) studied the effect of osmotic agents on mass transfer during osmotic dehydration of apple and found that sucrose yielded higher dehydration efficiency (ratio of the water diffusivity to the solute diffusivity in the food) compared to dextrose. Also Ispir and Toğrul (2009) and Saputra (2008) identified sucrose as the best osmotic agent for apricot and pineapple due to high water loss and low sugar gain. Owing to high molecular weight, sucrose only accumulated in the thin sub-surface layer and did not penetrate through the cell tissue, which reduces the solid gain. Furthermore, this thin layer of sucrose can potentially prevent colour loss by limiting the enzymatic browning (Cortellino, Pani and Torreggiani, 2011). On the other hand, lower molecular mass osmotic solutes, such as salt can easily diffuse into the cell (Silva et al., 2014).

It may be noted that sucrose gave poor mass transport performance than other solutes. A comparison between sucrose and maltose for the dehydration of melon cubes was reported by Ferrari and Hubinger (2008), who observed that maltose promoted greater water loss but lower solute gain. A similar effect was also noted during osmotic dehydration of tropical fruits like guava and papaya (Pereira et al., 2006). These authors noted that maltose, due to its relatively high molecular weight, showed lower rates of sugar diffusion into cell. Matusek, Czukor and Merész (2008) also made similar observations when comparing sucrose with fructo-oligosaccharide which has higher molecular weight than sucrose, while dehydrating apple cubes. However, Ispir and

Toğrul (2009) reported greater maltodextrin gain than sugar with lower molecular weight in the case of apricot. Although maltodextrin has higher molecular weight than others, but it revealed the highest sugar gain due to high absorption characteristics.

Meanwhile, several studies have investigated the efficiency of combinations of sugar and salt solutions, and the results show that such combinations can result in maximum water loss. For example, Rodrigues and Fernandes (2007) found that adding 5 % w/w of salt into 70 % w/w sucrose increased the water loss by 24 % (after 3 hrs of osmotic dehydration) when compared with just 70 % w/w sucrose. Salt addition also seemed to work in the case of lower concentration sucrose solutions, and its influence seemed to be more significant than temperature or just the concentration of sucrose. Others researchers also reported the benefit of ternary system (water/sugar/salt) especially in water loss materials such as for acerolas, (Alves et al., 2005), onions and tomatoes (Tsamo et al., 2005; Telis, Murari and Yamashita, 2004), tilapia fillets (Medina-vivanco et al. 2002) and guavas (Pereira et al. 2006). Apart from improved mass transfer, the addition of calcium salts to osmotic dehydration also reduced the damages of cell wall structure during dehydration (Silva, Fernandes and Mauro, 2014; Ferrari et al., 2010; Heredia, Barrera and Andrés, 2007).

Other factors that favour mass transfer are ratio of the masses of the materials to be dried and osmotic solution, extent of agitation, and sample size and geometry. During osmotic dehydration, the water loss is higher when the osmotic medium is circulated or agitated, when compared with static condition. Agitation lowers the mass transfer resistance offered by the osmotic medium, especially when the viscosity of the osmotic medium is high (Amami et al., 2014; Tonon, Baroni and Hubinger, 2007). Chandra and Kumari (2015) reported no significant increase in solid gain due to increased agitation, whereas Amami et al. (2014) reported that agitation at high speed promoted high levels of sugar

incorporation. Meanwhile, Yadav and Singh (2014) stated that osmotic dehydration without agitation may be better in some cases because breakage of fruit or vegetable pieces can be minimised.

Process duration is another factor that influences mass transfer during osmotic dehydration. Generally, as the time is increases, the water loss is greater but the rate of water loss decreases until equilibrium is achieved. Many studies showed that significant moisture loss takes place within the first two hours of the process following which the rate slows down (Li and Ramaswamy, 2006; Behsnilian and Spiess, 2006). The rapid initial rate of water loss is due to the high osmotic driving force between the dilute sap of the fresh fruit and the surrounding hypertonic solution. According to Brochier, Marczak and Noreña (2015), osmotic dehydration is not recommended to proceed for more than 4 hrs, since no significant change occurs in moisture loss thereafter. In contrast, the solid gain increases steadily.

Mass ratio of the sample to be dehydrated and the osmotic solution is also an important factor to consider. Generally, when the ratio increases, the rate of water loss as well as solid gain increase. Owing to dehydration of the food, the osmotic solution suffers dilution which lowers the concentration gradient and the driving force to decreases mass transfer rates (Ispir and Toğrul, 2009). A suitable mass ratio of solid to solution seems to be around 1:20 in order to provide a uniform driving force during treatment (Heredia et al., 2007). Meanwhile, some studies typically used a ratio of 1:30 to eliminate dilution of osmotic agent (Azarpazhooh and Ramaswamy, 2010a; Azarpazhooh and Ramaswamy, 2010b; Tortoe, 2010). Despite the advantages, such ratios become a problem in industrial practice due to the high cost of osmotic solution used (Ciurzyńska et al., 2016). Therefore, the selection of suitable process parameters is important in order to make the process economically viable.

2.2.3 Osmotic Dehydration as a Pre-treatment Method Prior to Further Processes

Although water content of osmo-dehydrated product could be reduced by up to 50% of the initial mass, the water activity is still high enough for microbiological activity to occur which can, reduce the shelf life of products. Therefore, osmo-dehydrated fruits or vegetables must undergo further processing such as conventional drying, frying and freezing in order to lower their water activity and form microbiologically stable food products.

The benefits of osmotic dehydration as a pre-treatment have been widely explored in literature which is summarized in Table 2.2. Most studies report that the total processing time can be reduced in osmo-dehydrated products than untreated products, and this pre-treatment also results to energy saving mainly because the starting moisture contents of such products are anyway lower (Dermesonlouoglou, Chalkia and Taoukis, 2018; Demiray and Tulek, 2017; Utkucan and Kemal, 2016; Verma, Kaushik and Rao, 2014).

Abundant researches have highlighted the effect of osmotic pre-treatment on the quality characteristics of finished dehydrated products. For instance, osmotically dehydrated fruits exhibit better colour and flavour by minimizing thermally induced changes as well as enzymatic browning (Udomkun et al., 2014; Riva et al., 2005). Osmo-dehydrated strawberry and peach retained mechanical and structural properties of products (Prosapio and Norton, 2017; Lyu et al., 2017). Other authors demonstrated that the concentration of osmotic medium significantly enhanced the hardness and crispness of chips because the higher solid concentration led to a firmer structure, low porosity and loss in elasticity of products.

OD pre-treatment is a promising method to minimize oil uptake in fried products (Dehghannya and Abedpour, 2018; Ren et al., 2018; Krokida et al., 2001). The lower moisture content of osmo-dehydrated samples also reduces the frying time. According to Li et al. (2016) and Kassama and Ngadi (2007), crust is formed during frying owing to water loss but promotes oil diffusion in the pores. Low initial moisture content leads to the formation of less pores, which in turn reduces the oil uptake. Besides, OD pre-treatment also results in better colour, structures and sensory properties of fried products (Ren et al., 2018; Afjeh, Bassiri and Nafchi, 2014; Nunes and Moreira, 2009; Santis et al., 2007; Bunger, Moyano and Rioseco, 2003). In other studies (Wilde et al., 2008; Pedreschi et al., 2007; Sahin, Sumnu and Oztop, 2007), osmo-dehydrated fried product also gave lower acrylamide. Acrylamides are classified as being carcinogenic and are prone to formation at temperatures greater than 120 °C. Therefore, it is undesirable in the final product (Ismial, 2013).

Meanwhile, the application of osmotic dehydration prior to freezing process (also called as osmodehydro-freezing) has been critically reviewed by Ahmed, Qazi and Jamal (2016) and James, Purnell and James (2014). These authors have highlighted the benefits of osmotic dehydration prior to freezing and reported shorter freezing time and superior texture, colour and sensory properties. The effect of osmotic dehydration conditions on freezing of apple cubes was studied by Bunger et al. (2004). These authors found that the osmotic solution concentration significantly influenced the quality of frozen apple products, followed by temperature of the solution. They also reported that the high concentration of the osmotic medium increased firmness of the apple cubes, while increase in temperature preserved the colour by reducing enzymatic browning.

Improved quality characteristics of osmodehydro-frozen vegetables have also been reported in the case of green peas (Giannakourau and Taoukis, 2003), cucumbers

(Dermesonlouoglou, Pourgouri, and Taoukis, 2008) and tomatoes (Dermesonlouoglou, Giannakourou, and Taoukis, 2007). Similar results have also been reported by Garcia-noguera et al. (2014), Rincon and Kerr (2010), Marani and Agnelli (2007) and Maestrelli et al. (2001) in the case of fruit products such as strawberries, melons, apples and mangoes. Recently, Li et al. (2017) exploited novel process of combined osmo-dehydration with cryogenic freezing of tomato pieces. These authors found that this combined technique could produce high quality frozen vegetables with enhanced colour, reduced textural degradation and lower nutritional quality loss.

Table 2.2 The advantages of osmotic dehydration as pre-treatment prior to various further processes.

Products	**Post osmo-dehydration process**	**Advantages**	**References**
Strawberry halves	Hot air drying	Moisture effective diffusivity was higher and total drying time was shortened by 28%. The total phenolic content loss was also lower by 38% in comparison with fresh samples.	(Ezzeddine Amami et al., 2017)
Apple cubes	Hot air drying	Total drying time reduced by up to 39% compared with untreated samples.	(Assis, Morais, and Morais, 2017)
Pomegranates arils	Freeze drying	Quality of final products in term of rehydration rate, colour, antioxidant activity and sensory profiles were superior.	(Cano-lamadrid et al., 2017)
Kiwi slices	Vacuum frying	Colour change, texture rigidity and oil uptake decreased following pre-treatment.	(Afjeh et al., 2014)

Table 2.2 (Continued)

Products	Post osmo-dehydration process	Advantages	References
Carrot chips	Vacuum frying	Total yield increased by 25% compared to untreated samples and loss of vitamin C and carotenes could be prevented.	(Fan, Zhang, and Mujumdar, 2006)
French fries	Deep fat frying	Oil content reduced by 50% and the colour was retained.	(Krokida et al., 2001a)
Potato strips	Deep fat frying	Fried products had 50% lower oil content.	(Dehghannya and Abedpour, 2017)
Tomato cubes	Cryogenic-freezing	Osmotic pre-treatment improved colour, reduced nutritional quality loss and texture degradation after freezing.	(Juan Li et al., 2017)
Mango cubes	Freezing	Freezing time reduced by up to 45%. Also vitamin C and drip losses were lower.	(Zhao et al., 2014)
Mango slices	Freezing	Vitamin C retention and firmness improved.	(Rincon and Kerr, 2010)

2.2.4 Limitations of Osmotic Dehydration

Despite the advantages of osmotic dehydration, it suffers some drawbacks. Since fresh samples are continuously immersed in concentrated solution during treatment, a high amount of the osmotic solute, mainly sugar/salt diffuse into the final products. This poses major health problems and can severely alter organoleptic and nutritional characteristics of the products (Akbarian et al., 2014). Matuska, Lenart and Lazarides (2006) mentioned that solids accumulated inside the cell and lowered the water mobility. Furthermore, a large amount of solute incorporated into fresh sample caused the osmotic solution to become less concentrated which lowered the dewatering efficiency. The dewatering rate also depends on the concentration of osmotic agent, with higher concentration exhibiting better performance in moisture removal. The osmotic solution, which becomes diluted with use, may have to be disposed off which can be expensive (García-Martínez et al., 2002). Therefore, the solution is typically regenerated in order to make the process economic and environmental friendly (Valdez-Frugoso, Welti-Chancs, and Giroux, 1998). However, these techniques also contribute to operating cost due to energy required for evaporation as well as adding fresh solute.

During osmotic dehydration other food constituents such as aromas, pigments, acids and proteins leach out of the tissue. This can cause: 1) alteration of syrup solution such as pH, viscosity and water activity that can influence to the mass transfer kinetics; 2) modification of sensory properties such as flavour and colour; and 3) increase in microbial growth in the solution phase (Dalla Rosa and Giroux, 2001). For example, during the dehydration of apples, Valdez-Frugoso and Mujica-Paz (2002) observed that the osmotic solution rapidly underwent browning after two cycles of treatment due to pigments diffusing from the fruits. The diffusion of malic acid from the tissue also decreased the pH of syrup from 6.8 to 4 after reusing five times. Meanwhile, Peiro-Mena,

Camacho and Martinez-Navarrete (2007) reported the diffusion of mineral salts and organic acids from pineapple which contributed increased electricity conductivity of syrup over the dehydration cycle, while viscosity of syrup is increased owing to increases in pectin content. Recent studies also observed the modification of osmotic solution with reuse in the cases of guava and cranberry (Germer et al., 2016; Wray and Ramaswamy, 2016).

2.3 Frying Process

Frying is an ancient and most popular process in food preparation. It is a rapid dehydration method that uses hot oil in the range 150 – 200 °C as medium to remove water content of fruits and vegetables (Gertz, 2014). Due to its rapid speed and operational simplicity, frying is extensively practised in home, business sectors such as restaurants and fast food outlet as well as in industry. Although fried products are associated with the risks of suffering obesity, hypertension and diabetes due to high fat intake, it is still widely employed because fried products have desirable texture (crispness), colour, flavour and unique taste.

Broadly speaking, frying can be undertaken with the material being fully immersed in a relatively large volume of oil (deep fat frying) or with the material being partially submerged in a relatively small amount of oil (known as shallow or pan frying). While the former is generally practised industrially, the latter is widely practised at home and in the food service sector. When vegetables, meat, poultry and fish are deep or shallow fried, the protein, carbohydrates and mineral are retained in the product, while mineral contents can reduce by up to 50% during boiling and steaming processes. The total frying time is always based on physical appearance, especially when the product surface becomes golden brown (Prakash et al., 2016). However, in some cases, the end

point of frying may be defined in terms of the moisture content or internal temperature of products. For instance, French fries and potato strips are completely cooked when the moisture content is in the range of 40 to 50 %, while moisture content of potato chips should below 2 % in order to be considered as ready-to-eat product (Pedreschi, Kaack and Granby, 2006; Costa, Oliveira and Boutcheva, 2001). Meanwhile, the interior of the food must receive adequate heat to destroy microorganism especially foods that support pathogenic bacteria such as fish and meat products. Hence, the internal temperature of 71.1 °C is required for meat patties to be completely cooked (Ikediala and Correia, 1996).

Frying process is a complex phenomenon and involves simultaneous heat and mass transfer. Generally, frying process can be categorized into four stages namely (Koerten et al. 2017; Mujumdar, 2015):

1) Initial heating – heat transfer by natural convection between oil and surface of food until surface material temperature becomes similar and elevated from boiling point of water. There is no vaporization of water at the surface material during this process.
2) Surface boiling – water at surface material starts to evaporate. The steam bubbles created cause turbulence in oil, as a result of which forced convection takes over heat transfer. The crust is formed at surface due to dehydration and high temperature.
3) Falling rate – due to heat transfer, the internal core temperature rises slowly to the boiling point of water and crust layer thickness increases. During this stage, more internal moisture diffuses out but it cannot match the rate of surface evaporation, so the rate of water lass falls. In addition, starch gelatinization and protein denaturation also happens in this stage.

4) Bubble end point – when frying is extended to long time, the rate of moisture loss is reduced sue to decrease in moisture content of the product and a stage is reached when no more bubbles emit from product surface.

2.3.1 Operating Conditions in Quality of Fried Products

The operating conditions such as frying temperature and time become critical factors influencing the quality of fried products especially with regard to oil absorption. Basically, the frying time is related to the frying temperature, because the final product must attain the desired moisture content, thus, a lower frying temperature implies a longer frying time. The frying temperature for deep fat frying is commonly in the range 130 to 190 °C, but the most common range employed is 170 to 190 °C (Pedro Bouchon, 2009).

Frying at low temperature requires longer frying time and usually results in a higher oil uptake. A plausible reason for this is the low rate of water vapour release creates a less firm crust that can easily promote oil penetration into the food structure (Ziaiifar et al., 2008a). Moyano and Pedreschi (2006) studied the effect of frying temperature in the range of 120 to 180 ^{o}C for potato slices and found that frying at higher temperatures lead to lower oil content. For instance, the average value of oil content fell from 0.39 to 0.30 g/g dry basis when the temperature rose from 120 to 180°C. Moreira, Sun and Chen (1997), on the other hand, found that the effect of frying temperature was minimal between 140 to 190 °C.

The frying medium, namely the oil type, is yet another factor influencing the oil uptake, flavour, texture and nutritional effects of the final products due to the different chemical compositions of frying oil. Kita and Lisińska (2005) reported that the type of frying medium affects to the texture and oil absorption in French fries. They found that rapeseed oil produced the most delicate texture and lowest oil uptake, while sunflower

resulted in the highest amount of fat absorption. Meanwhile, other researchers demonstrated that French fries fried in peanut oil had significantly higher fat content (Parikh and Nelson, 2013). According to Ziaiifar et al. (2008), the oil absorption depends on oil viscosity. The oil draining rate from the product, after frying, is slower when products are fried using higher viscosity oil, which results in the product retaining higher amount of fat.

2.3.2 Frying Pre-treatment

2.3.2.1 Blanching Process

Blanching is a common cooking process most often associated with fruits and vegetables. It is a heat treatment of structural alterations in plant tissue with inactive enzymes and prevents microbial deterioration. Generally, blanching used before frying for colour and texture improvement (Graham-Acquaah et al., 2015; Sobukola et al., 2008). In addition, blanching can also reduce the sugar content and consequently, form a lower amount of acrylamide in the fried product (Sansano et al., 2015; Mestdagh et al., 2008; Pedreschi et al., 2004). These studies also reported that the use of a higher blanching temperature lowered the formation of acrylamide.

Nevertheless, the impact of blanching as a pre-treatment to reduce oil uptake by the fried product remains unclear. Paz-Gamboa et al. (2015) found that blanching significantly lowered the fat content up to 80% in the case of taro chips. Such a significant reduction is mainly noted when the oil content is expressed in relation to the total sample weight that includes the moisture content. It is known that blanching can promote the reduction of moisture content prior to frying and generally, the lower the amount of moisture removed from sample during frying, the lower is the oil absorbed. Meanwhile, other researchers suggest that blanching results in surface starch gelatinisation which

forms a thin layer preventing oil uptake (Ziaiifar et al., 2008; Fan, Zhang, and Mujumdar 2006).

On the other hand, several studies have found that blanching enhances oil uptake during frying (Moyano and Pedreschi 2006; Pedreschi and Moyano 2005b). Pedreschi et al. (2008) studied the effect of blanching followed by the use of different frying temperatures on oil absorption and distribution in the structure of potato slices. The results showed that blanching increased oil absorption at all frying temperature between 150 to 180 °C. Meanwhile, Al-Khusaibi and Niranjan (2012) reported that there was no significant difference in total fat content between blanched and unblanched samples, when the oil content was expressed on a fat free dry basis.

2.3.2.2 Pre-drying Prior to Frying

Drying by using either hot air, vacuum microwave or convection microwave lowers the initial moisture content of a product prior to frying. Some earlier studies reported that the total oil adsorbed during frying was affected by the total amount of water removed from the food (Moreira et al., 1997). Therefore, pre-drying lowered the amount of free moisture to remove during frying and consequently lowered the oil uptake. Meanwhile, some studies reported that pre-drying also modified the gelatinized starch on the product surface , creating a crust which acts as a barrier to oil penetration, (Garmakhany et al. 2010; Troncoso et al. 2009). Moyano and Pedreschi (2006) investigated the impact of blanching and blanching with drying of potato slices on oil uptake during frying. These authors found that pre-drying of blanched samples resulted in less fat content compared to blanching alone. Meanwhile, the combination of hot air drying and frying decreased oil uptake in the case of chicken nuggets (Martínez-Ávila, Vélez-Ruiz, and Sosa-Morales, 2010). Several researches also tried to use drying or

baking to prepare fat-free potato chips without deep frying process. Such samples invariably resulted in poor colour, undesirable texture and degradation of nutrition (Wang et al., 2010; Leeratanarak et al., 2006).

2.3.2.3 Coating

The application of coating is also employed as a pre-treatment before frying. The raw product is dipped in a coating suspension for a short time before frying. Normally, heat stabile hydrocolloids, which possess good water transfer properties, as well as good organoleptic and nutritional qualities are considered in this process. The most commonly used hydrocolloids are carboxyl methyl cellulose (CMC), guar gum, xanthan gum and tragacanth (Suyatma et al., 2015; Ziaiifar et al,. 2008).

Several studies reported the effectiveness of coating to reduce oil content of products such as fried potato chips, cereals and vegetables (Hua et al., 2015; Garmakhany et al., 2008; Akdeniz et al., 2006). The coated samples reduce surface porosity and create a barrier against oil absorption. Hydrocolloids can also decrease water evaporation during frying and in some cases improve the sensorial quality (Kilincceker and Hepsag, 2012). In addition, coating can also reduce acrylamide formation by up to 50% in fried potato strips (Zeng et al., 2010). Suyatma et al. (2015) found that coating banana chips with pectin could reduce acrylamide content by up to 33%. The results also reported synergistic effect of blanching and coating on acrylamide reduction by up to 91.9% which also improved the texture and sensory properties.

2.3.3 Deep-fat Frying

Deep-fat frying involves the total immersion of food materials in hot oil, which temperatures above the boiling point of water. This process is complex and consists of simultaneous heat and mass transfer between hot oil and the material. In addition, physical and chemical transformation also take place, such as shrinkage, crust formation, starch gelatinization, protein degradation, chemical reaction and pore formation (Bravo et al., 2009).

Even though deep fat frying is extensively employed in industrial practice, the absorption of oil is significant. In order to produce lower fat fried foods, many studies have been undertaken to understand the mechanism underpinning oil uptake, which have been critically reviewed by Ziaiifar et al. (2008). Figure 2.3 shows the simultaneous heat and mass transfer between food and oil during deep fat frying. Initially, the heat is transferred from hot oil to the surface of the product by convection and thereafter, to the core of product predominantly by conduction, and water is removed from the product as vapour. Heat and mass transfer during frying are controlled by the heat transfer at the surface of product and vaporisation rate is proportional to the temperature difference between oil and boiling point of water (Vitrac et al., 2002). Meanwhile, the lower thermal conductivity of the crust affects heat and mass transfer and decreases water loss. Several studies have shown that thermal conductivity of foods decrease with the moisture content which increases oil uptake (Wang and Brennan, 1992; Donsì, Ferrari and Nigro, 1996; Sablani and Rahman, 2003). Ziaiifar, Heyd, and Courtois (2009) measured the thermal conductivity of crust and core of potato during deep fat frying using a modified Lees method and found that the crust thermal conductivity was lower than the core due to lower moisture content and greater porosity. Ziaiifar, Courtois and Trystram (2010) also

revealed that the structure of crust was nearly six times more porous than the core, and therefore resulted high oil absorption.

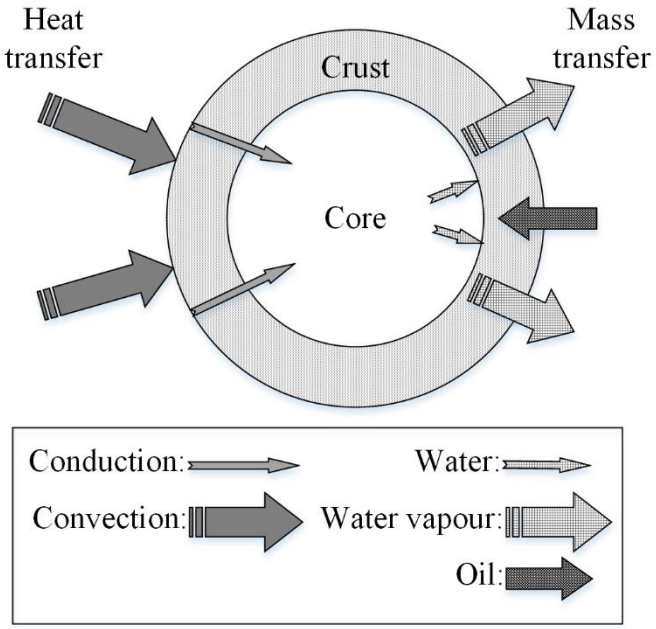

Figure 2.3 Schematic diagram of heat and mass transfer during deep fat frying (Pedro Bouchon, 2009)

2.3.3.1 Oil Absorption Mechanism

Generally, three possible mechanisms have been proposed to describe oil absorption phenomenon i.e. water replacement during frying, the effect of the cooling phase after frying and the effect of surface active agents present (Dana and Saguy, 2006). During frying, water evaporates rapidly due to a sharp temperature gradient between oil and food, which causes the outer surface to become dry and form a crust. Moisture in foods is converted to steam and escapes through cracks, defects and open capillaries. Due to water evaporation, the surface structure is changed and oil that adheres to the foods enters the voids. Therefore, the higher water removal from the foods, the greater is the oil absorbed. Several researchers have demonstrated that high initial moisture content of

foods results in high oil absorption (Martínez-Ávila, Vélez-Ruiz and Sosa-Morales, 2010; Song, Zhang and Mujumdar, 2007; Moyano and Pedreschi, 2006).

According to Bouchon, Aguilera and Pyle (2003), the total oil content of fried foods can be divided into three different oil fractions due to different oil uptake mechanisms; (1) structure oil, which is the oil absorbed during frying; (2) penetrated surface oil, which is the oil absorbed after frying (cooling period) and (3) surface oil, which is remaining oil that adhering on the surface (as shown in Figure 2.4). After foods are removed from the fryer, they start to cool which leads to water vapour condensation, and subsequently decrease in the internal pressure. Consequently, a 'vacuum suction effect' is created and oil that adheres on the surface is sucked into the product structures (Dana and Saguy, 2006). Several studies have claimed that significant oil uptake occurs during the cooling period. Durán et al. (2007) found that 65% of total oil content got absorbed into the structure, while 35% still remained on the surface when potato chips were fried at 180 °C. This finding is in agreement with Ziaiifar, Courtois and Trystram (2010), who studied the effect of porosity development on the oil uptake of French fries. But, the authors highlighted that at low frying temperatures, the oil entering the products during frying was due to water replacement which played an important role in the final oil content.

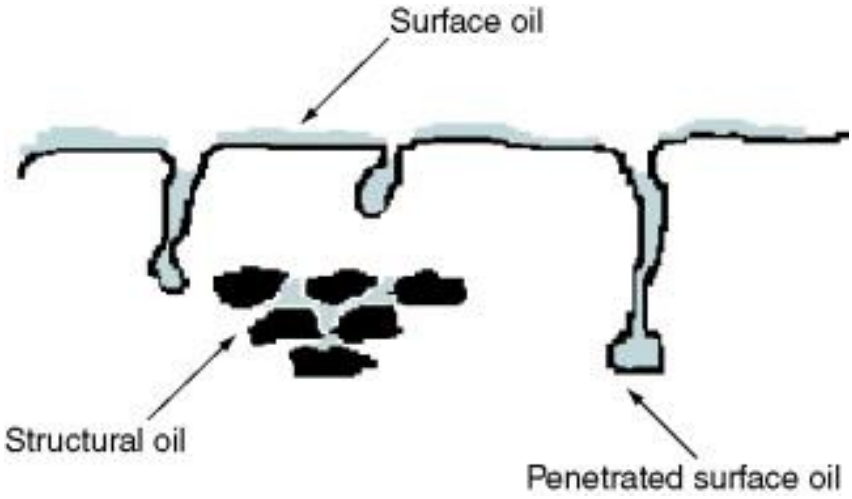

Figure 2.4 Diagram of different oil fraction absorbed after frying (Bouchon et al., 2003)

2.3.3.2 Fry-drying Approach

Since the moisture content of material can be rapidly removed via deep-fat frying, some studies have explored this process as an alternative drying method, which is called as fry-drying technique, e.g. in the case of drying industrial water sludge (Do et al., 2017; Ayol and Durak, 2013; Shin, Kim and Jang, 2011; Ohm et al., 2009). Fry-drying is a novel dehydration approach to convert dry sewage sludge into solid fuel in a relatively short time. It is noteworthy that the fried sludge has great potential as a bio combustible fuel due to its high energy value, ease of handling and odour-free burning (Chang et al., 2013). Silva, Rudolph and Taranto (2005) demonstrated that the heat of combustion of fried sludge increased with frying time due to the reduction in water content and increase in oil uptake. They also found that the heat of combustion of fried sludge was comparable to the other biomasses such as wood and sugarcane bagasse. This was in agreement with the study conducted by Wu et al. (2012), who stated that the heating value of solid fried sludge was in the range of 21.5 to 24 MJ/kg. Meanwhile, some studies also conducted

fry-drying to reduce moisture content of other products such as wood (Grenier et al., 2007) and low-rank coal (Ohm et al., 2012).

2.3.4 Shallow Frying

Shallow or pan frying is another frying technique that is usually practised in households to cook vegetables, meat, fish and other products. The process basically involves partial immersion of food into hot oil, which results in the heat transfer not being uniform across the entire surface of product. In fact, heat is transferred from oil to the immersed bottom surface of the food by convection and through the product mostly by conduction. It therefore takes much longer to fry than deep fat frying (Oke et al., 2018).

Oroszvari, Sjoholm and Tornberg (2005), Oroszvari et al., (2005) and Oroszvari et al., (2006) reported the influences of several factors such as the use of different raw materials, pan temperature and patty diameter on the heat and mass transfer through beef burgers during pan frying. According to these studies, the higher temperature of the pan and smaller the patty diameter, the faster was the heat transfer rate as one might expect. Consequently, water loss increased significantly. The authors also highlighted that the pressure-driven drip loss of water was dominant during frying of patty, and the drip loss was constant, regardless of the pan temperature used. Meanwhile, Ikediala et al. (1996) and Pan, Singh and Rumsey (2000) developed a model of heat and mass transfer of meat patties during single and double sided of pan frying. The product yield, temperature, crust formation and microorganism survival rate could be predicted by using this model.

Although shallow frying requires longer cooking time than deep fat frying, there are a number of advantages associated with shallow frying, such it inhibits 1) total iodine losses, which is around 40% (Rana and Raghuvanshi, 2013), 2) oil oxidation (Ghosh, Chatterjee, and Bhattacharjee, 2012) and 3) it is able to increase the nutritional value of

the product (Hrncirik and Zeelenberg 2014; Hrncirik 2010). Meanwhile, work done by Ghosh, Chatterjee and Bhattacharjee (2012) on oil uptake of potato wedges during shallow and deep fat frying shows that shallow-fried wedges absorbed less oil. Although operating time of shallow frying was two times longer than deep fat frying, the oil content was 28% lower. This was in agreement with a study conducted by Galoburda, Murniece and Karklina (2013) in the case of five different varieties of potato slices. These authors found that the oil content of shallow-fried potatoes were in the range of 6.86 – 16 g/100g of dry basis, while the deep fat fried product contained oil in the range 14.11 to 21.12 g/100g of dry basis. Recently, Lima et al. (2018) also reported that shallow fried foods contained lower oil when compared to deep fat fried foods. The authors claimed that a limited amount of oil is in contact with the food surface and therefore, less oil absorption took place under shallow frying. Further, the authors suggested that the use of paper towel absorption could significantly reduce oil uptake after frying, regardless of the frying type.

2.3.4.1 Chemical Reactions and Quality of Fried Food

As significant amount of oil is being absorbed in the fried food, great attention should be given to the oil quality to minimize its deterioration during frying. Prolonged exposure of oil to oxygen and moisture at high temperatures leads to complex reactions such as oxidation, hydrolysis and thermal decomposition (Choe and Min, 2007). Numerous studies investigated the effects of chemical reactions on frying oil quality during deep fat frying (Oke et al., 2018; Zhang et al., 2012; Kalogianni, Karastogiannidou and Karapantsios, 2009; Chung, Lee and Choe, 2004; Tompkins and Perkins, 2000). The findings highlighted that oil exposed to high temperature (150 – 190 °C) and repeatedly for prolonged times led to the degradation of polyunsaturated fatty acids (PUFA), formation of *trans* fatty acid (TFA), changes in the colour of oil and yield of unpleasant

volatiles. Therefore, several previous studies also investigated the degradation of different type of oils such as rapeseed, soybean, sunflower and canola oil during shallow frying l (Choo, Birch and Dufour, 2007; Soupas et al., 2007; Kiatsrichart et al., 2003; Soheili, Artz and Tippayawat, 2002). Soupas et al. (2007) demonstrated that shallow frying induced phytosterol oxidation initially but not after 10 mins of operation, regardless of the frying temperature applied. In addition, the interaction between iron pan and oil also contributed to the deterioration of oil. Similar observation has also been reported in a recent study by Raczyk et al. (2018), where the degradation of unsaturated fatty acids, phytosterol and vitamin-E-active compounds was found within 15 mins of shallow frying using margarines at 180 °C. About 50% of the phytosterols and almost all the vitamin E active compounds in margarines got degraded during at this period.

Moreover, the study by Grootveld, Rodado and Silwood (2014) showed that a shallow fry gives higher level of lipid oxidation than deep fat frying under the same conditions. The reason for this behaviour is that the higher surface area of frying medium exposed to air influenced to the stability of oil in the case of shallow fry. The relationship between oil layer height or specific oil surface (the ratio of the surface in contact with air on the weight of oil) and the thermal stability has been extensively studied by Kobyliński et al. (2016). According to these authors, lower height of the oil layer employed during shallow frying caused a noticeable deterioration in the oil quality. For instance, at an oil layer height at 0.5 cm reached 25% of total polar compound (TPC) in a relatively short time after 71.5 mins of frying, while it took 315.1 mins in the case of 2.5 cm of oil layer height.

In contrast, Ghosh, Chatterjee and Bhattacharjee (2012) demonstrated that highest oxidation occurred in deep fat frying followed by shallow and par-frying in the case of soybean oil. This finding might be due to the different frying temperature and time

applied for all frying types. In addition, the authors recommended to add soybean oil with citric acid based antioxidant of Butylated Hydroxy Toluene (BHT), to limit the degradation of oil during frying. This was in agreement with a study conducted by Hrncirik and Zeelenberg (2014) in the case of different oils and fat (sunflower oil, rapeseed oil, margarine and butter). The authors demonstrated that oil with high PUFA not to form significant amounts of undesirable compounds, and improved the nutritional value of the fried food. Although previous studies claimed that shallow frying causes considerably more oil deterioration than deep fat frying, but shallow frying only operates for a short time and the frying medium is typically not reused. Therefore, the thermal stress seems to have limited effect on the frying oil (Hrncirik, 2010).

Due to oil absorption, some of the components such as unsaturated fatty acid, vitamin E and polyphenols (in the case of olive oil) diffuses into fried food and thus increases the nutritive value of final product (Fillion and Henry, 1998). In fact, vegetable oils are among the richest sources of vitamin E, especially tocopherols and tocotrienols (Deiana et al., 2002), and many studies observed the retention and distribution of these compounds in fried foods. Chiou et al. (2009) and Kalogeropoulos et al. (2007) found that one portion (100 g) of French fries might provide 0.8, 1.2 and 3.3 mg tocopherols when fried using olive oil, palm oil and sunflower oil, respectively. Due to highest amount of total tocopherol content in fresh sunflower oil contributes to the considerate tocopherol retained in fried products.

Abundant studies reported the potential of spices, herbs, and leaf extracts as natural antioxidants for the enrichment of oil used in deep fat frying (Si et al., 2018; Alizadeh, Nayebzadeh and Mohammadi, 2016; Ammar, 2016; Banerjee, Ghosh and Ghosh, 2015; Horuz and Maskan, 2015; Abriana and Johannes, 2014). Meanwhile, in the case of shallow frying, some studies also reported the benefits to the oil medium when

supplemented with natural antioxidants to increase the nutritional quality of fried foods. In a study conducted by Chiou et al. (2007) and Chiou et al. (2009), the effect of different vegetable oils such as sunflower oil, olive oil and palm oil supplemented with polyphenol extract from olive leaves were evaluated on fried potato during shallow frying. The oils were supplemented with an extract polyphenols at 120 and 240 mg/kg of oil. According to the authors, French fries cooked in supplemented oils retained up to 31-, 1.4- and 2.2-fold of polyphenols, tocopherols and phytosterols as compared to French fries fried in the non-supplemented oils. In addition, the authors claimed that no changes were observed in terms of taste, colour, texture, flavour and crispiness of the French fries fried using supplemented oil.

2.4 Concluding Remarks

Dehydration is an important process in food industry in order to extend the shelf life of products, facilitate transportation and minimize storage space. Osmotic dehydration is one of the dehydration technique that involves natural process and low energy requirement. However, the problems of osmotic dehydration are high amounts of salt/sugar diffused into the products and osmotic solution management due to water and some food components such as aroma, pigments, acid and minerals being leached out from tissue. Therefore, a suitable operation is needed to overcome these drawbacks and find ways of enabling the water inside fresh samples to diffuse from tissue cell, but at the same time, not allow high levels of the osmotic solute to diffuse into the tissue.

On the other hand, frying is another dehydration method used for reducing water content in a relatively short time. Several previous studies have demonstrated the effectiveness of deep-fat frying in reduced water content of some products such as industrial waste sludge, coal, wood and food materials. Although numerous studies in the

literature have been devoted to the heat and mass transfer, oil absorption mechanism, frying factors and conditions, nutritional studies and effect of pre-treatment on the deep fat frying, but very few have focused on the shallow frying. Most of researches on shallow frying concentrate on the quality of the products and oil, and nutritional studies. Hence, there is limited information concerning the water loss mechanism and thermal profile development during shallow frying which is the main focus of this study.

CHAPTER 3

DEHYDRATION OF POTATO SLICES FOLLOWING BRIEF DIPPING IN OSMOTIC SOLUTIONS: EFFECT OF CONDITIONS AND UNDERSTANDING THE MECHANISM OF WATER LOSS

Abstract

A novel variant of osmotic dehydration, named here as post-dipping dehydration – where a material is dipped in a salt or sugar solution for a very short time followed by simple exposure to ambient conditions was explored with the aim of lowering water content of potato slices but at the same time not gain a high level of sugar/salt. The rate of water loss, which was rapid initially, was found to approach equilibrium. This study also explored whether the water loss process could subsequently be kick started once again, by employing a multi-stage process, where each stage consisted of osmotic solution dipping followed by ambient holding of the potato slices that had reached equilibrium in the earlier stage. Water loss values comparable to osmotic dehydration could be achieved thus, but with significantly lower overall solid gain (less than 50%) – which can potentially yield a significantly healthy product option.

**This work has been published in Drying Technology journal.*

3.1 Introduction

Hot air drying is an ancient and extensively employed process to reduce moisture content and increase the shelf life and stability of food products. The process involves simultaneous heat and mass transfer (Akbarian et al., 2014). A major drawback of hot air drying is quality deterioration of the products due to exposures to a high temperature for extended periods of time. Another drawback is that this technique requires the expenditure of high energy (Ochoa-Martinez et al., 2007). Therefore, a number of alternative energy efficient dehydration techniques have been developed resulting in better quality food products.

Osmotic dehydration eliminates water from materials without expending latent heat. It essentially involves immersion of materials such as fresh fruits or vegetables in a concentrated solution. Due to osmotic driving force generated between the hypertonic solution and tissue, three mass transfer phenomena occur i.e. i) water removal from tissue, ii) leaching out of other components from the tissue, and iii) influx of solute from the concentrated solution into the tissue (Chandra and Kumari 2015; Akbarian et al., 2014). This method of dehydration has yielded promising results for a variety of foods including potato (Eren and Kaymak-Ertekin 2007; Tortoe et al., 2007a), banana (Mercali et al., 2011; Tortoe et al., 2007b), yacon (Brochier et al., 2015), mango (Nagai et al., 2015; Madamba and Lopez 2002), berries(Yu et al., 2017) and pineapple (Filho et al., 2015; Corrêa et al., 2011). In addition to low energy consumption, this method also preserves some key sensory characteristics of the fruit and vegetable. Due to its simple and inexpensive operation, it has also been applied as a pre-processing step prior to operations such as conventional drying (Lyu et al., 2017; Prosapio and Norton, 2017; Fernandes and Rodrigues, 2008), freezing (Juan Li et al., 2017) and frying (Chavan and Amarowicz, 2012).

Despite the advantages of osmotic dehydration, it also suffers several limitations such as floating of fruit in solution, osmotic solution managements and the main ones being high solute uptake due to diffusion of solute towards tissue cell (Ebner Azuara, Flores, and Beristain, 2009), which can potentially pose major health issues and the leaching out of water and other nutritious components from the tissue, which not only affects the product but also dilutes the osmotic solution thereby adversely influencing the osmotic driving force (Sun, 2014). Wray and Ramaswamy (2015); Wray and Ramaswamy (2013); Azarpazhooh and Ramaswamy (2010b) and Azarpazhooh and Ramaswamy (2010a) were demonstrated a thin layer of osmotic solution by on the fruit surface by using spray mode in order to overcome this problem. However, a spray mode has potential in non-uniform distribution of solution on the entire fruit surface. Thus, there is an acute need to find ways of enabling the water from the tissue to diffuse into the osmotic solution, but at the same time, not allow high levels of the osmotic solute to diffuse into the tissue.

This study aims to achieve this objective by employing brief dipping of fresh material slices, in order to allow the osmotic medium to occlude to the surface of the slices, then hold the slice under ambient conditions, which allows the osmotic driving force generated between the surface of the slice and interior to expel water, which subsequently drips out or evaporates from the surface. Water loss can therefore, be achieved for as long as the osmotic driving force prevails between the surface and the interior of the slice, without expending any energy or even gaining significant levels of solid. This novel method of water loss has not been studied so far, and the specific objectives of the study are to: (1) investigate the effects of the concentration of the dip solution, dipping time and post-dipping holding time on the water loss and solid gain patterns; (2) compare the extents of water loss and solid gain with osmotic dehydration;

(3) understand the mechanism of water loss; and (4) explore whether a multi-stage process consisting of repeated dipping in osmotic solution followed by holding under ambient conditions, can be used as an alternative to osmotic dehydration.

3.2 Materials and Methods

3.2.1 Materials

Fresh potatoes (*Solanum tuberosum* L.) of Maris Piper variety were purchased from local store and kept in a refrigerator at 4 °C. Commercial sucrose and sodium chloride (NaCl) were purchased from local markets.

3.2.2 Preparation of Potato Slices and Osmotic Solutions

Potatoes were removed from the refrigerator and left out for at least 12 hrs to reach the ambient temperature before processing. Potatoes weighing around 170 – 230 g were selected for experiments. The potatoes were washed, peeled and horizontally sliced (perpendicular to the longer side) into 1.5 mm thick slices using an adjustable hand slicer (Mandoline slicer, Lakeland, UK). Subsequently, the potato slices were cut into disk shape (50 mm diameter) using a circular mould to ensure uniformly sized experimental slices. Potato slices were rinsed in running water (for 30 s) immediately after slicing in order to remove the excess starch adhering on the surface, and finally the surface water was eliminated using tissue paper and weighted. The osmotic solutions were obtained by dissolving commercial sucrose or NaCl in distilled water.

3.2.3 Single Stage Dip Dehydration and Osmotic Dehydration Treatments

For each experiment, 10 g of identical potato slices were dipped in osmotic solution (sucrose solution: 30, 40 and 50% w/v or NaCl: 5, 10 and 15% w/v) for short time at 0.5 or 1.5 min. These times were sufficient to ensure that the entire potato slices surfaces were occluded with osmotic solution and at the same time, to study the effect of dipping time on the mass transfer. The dip solution concentrations used were selected so as to result in water loss rates which were significant enough to validate our hypothesis. To be very specific, the water activity a_w of the dip solutions were: 0.983 ± 0.005, 0.956 ± 0.009 and 0.932 ± 0.004 for 30%, 40% and 50% sucrose solutions, and 0.976 ± 0.002, 0.924 ± 0.003 and 0.891 ± 0.010 for 5%, 10% and 15% NaCl solutions, respectively. Preliminary studies showed that the post-dipping water loss was very low when the dip solution concentration was less than 30% in the case of sucrose and 5% in the case of NaCl. Preliminary experiments also showed that there was no added benefit of raising the solution concentration above 50% in case of sucrose and 15% in case of NaCl, because the subsequent water loss kinetics were not significantly different from the highest concentrations used in this work. The mass ratio of the potato slices to the osmotic solution was kept at 1:30 and the dipping temperature was maintained between 20 – 22 °C.

After dipped for the stipulated time, the potato slices were taken out and then placed on a stainless steel mesh under ambient conditions (temperature: 20 – 22 °C) for dehydration to occur. At given total times, which is a combination of dipping and holding time at 5, 10, 20, 30, 40 and 60 mins, samples were very gently blotted with a tissue paper to eliminate the adhering osmotic solution on the potato surface and analysed.

Osmotic dehydration of similar potato slices was also carried out in sucrose 50% and NaCl 10% solutions in order to compare the water loss and solid gain values with dip dehydration process. Preliminary studies showed that these concentration of solution gave higher water loss. In this case, the potato slices were immersed in the osmotic solution, and samples were taken out after 5, 10, 20, 40, 60, 80, 120, 160, 200 and 240 mins (in sucrose) and 5, 10, 20, 30, 40, 50, 60, 70 and 80 mins (in NaCl) immersion, gently blotted with a tissue paper to remove the excess osmotic solution and analysed.

3.2.4 Multi-stage Dip Dehydration

Multi-stage dipping and holding was carried out in two ways. In treatment A, two osmotic solutions which are sucrose 50% and NaCl 10% were chosen. Potato slices were dipped for 0.5 min in the osmotic solution and held for dehydration to occur under ambient conditions for approximately 40 mins (in sucrose case) and 10 mins (in NaCl case) of total time, when the osmotic driving force between the surface of the slice and the interior was too low for dehydration to occur as observed on the single stage dip dehydration case. The slices were then again dipped in the same osmotic solution at the same dipping time and held under ambient conditions for another 40 mins (in sucrose case) and 10 mins (in NaCl case) of total time, and the process of dipping and holding were repeated 6 times (in sucrose case) and 8 times (in NaCl case) in order to achieve equilibrium of water loss rate. In another multi-stage treatment B, subsequent dipping involved brief immersion in progressive concentrated solutions. Table 3.1 summarises the osmotic solution concentrations and total times (combination of dipping and holding times) employed in this study. At every 40 mins (in sucrose case) and 10 mins (in NaCl case) of total time, replicate samples were blotted with tissue and analysed.

Table 3.1 List of the osmotic solution concentrations and total time employed in treatment B. All dipping time was employed at 0.5 min.

Sucrose case		NaCl case	
Total time (min)	Osmotic solution (w/v)	Total time (min)	Osmotic solution (w/v)
0 (Dip 1)	Sucrose 30%	0 (Dip 1)	NaCl 5%
40 (Dip 2)	Sucrose 40%	10 (Dip 2)	NaCl 10%
80 (Dip 3)	Sucrose 50%	20 (Dip 3)	NaCl 15%
120 (Dip 4)	Sucrose 60%	30 (Dip 4)	NaCl 20%
160 (Dip 5)	Sucrose 60%	40 (Dip 5)	NaCl 20%
200 (Dip 6)	Sucrose 60%	50 (Dip 6)	NaCl 20%
		60 (Dip 7)	NaCl 20%
		70 (Dip 8)	NaCl 20%

3.2.5 Water Activity and Moisture Content Determination

Water activity of osmotic solution and potato slices were analysed using HygroLab 3 (Rotronic, Sussex, U.K.). Meanwhile, for moisture content analyses, samples were weighed and dried at 105 °C in a convection oven (Weiss-Gallenkamp, Loughborough, U.K.) for approximately 24 hrs until a constant weight was achieve (AOAC, 2000). The moisture content wet basis and dry basis were determined from:

$$MC_{wet\ basis} = \frac{M_{wet} - M_{dry}}{M_{wet}} \tag{3.1}$$

$$MC_{dry\ basis} = \frac{M_{wet} - M_{dry}}{M_{dry}} \tag{3.2}$$

where M_{wet} is a mass of the wet sample (g) and M_{dry} is a mass of the solid content of the sample after drying to constant weight in an oven at 105 °C (g).

3.2.6 Water Loss (WL) and Solute Gain (SG) Determination

The WL and SG were calculated from the following equations (Li and Ramaswamy, 2006):

$$WL\left(\frac{g}{100g}of\ fresh\ sample\right) = \frac{(M_0x_0 - M_tx_t)}{M_0} \times 100 \quad (3.3)$$

$$SG\left(\frac{g}{100g}of\ fresh\ sample\right) = \frac{(M_ts_t - M_0s_0)}{M_0} \times 100 \quad (3.4)$$

where M_0 and M_t are the sample masses initially and at time, t respectively; x_0 and x_t are the moisture fractions (g/g wet basis) initially and at time, t; and s_0 and s_t are the dry solid fractions (g/g) initially and at time, t . The above equations assume that there is no solute transferred from the sample to the solution.

3.2.7 Determination of Remaining Total Solute Content of Osmotic Solution on Potato Slices

The remaining total sucrose or NaCl that occluded and diffused into the potatoes slices after dipped in osmotic solution over total time was determined by other experimental works. After potato slices were taken out from dipping solution and hold at the given total time of dip dehydration treatment, samples were dried in an oven until constant weight in order to determine the total sucrose or NaCl content on the potato slices. The total sucrose or NaCl content was calculated from the weight of difference between dipped and fresh samples and expressed as g/100g of the fresh sample.

3.2.8 Process Modelling

Three well-known empirical models (Table 3.2) were used to fit the water loss kinetics of dip dehydration and the fitting was performed using cftool in MATLAB (R2016b) software (The MathWorks, Inc., UK) in order to determine the model constants (Assis et al., 2016; Ochoa-Martinez et al., 2007; Azuara et al., 1992).

Table 3.2 Kinetic models used in modelling.

Model	Equation	Equation no.	Reference
Azuara	$WL_t = \frac{s_1 t(WL_\infty)}{1 + s_1 t}$	(3.5)	(Azuara et al., 1992)
Page	$WL_t = \exp(-At^B)$	(3.6)	(Ochoa-Martinez et al., 2007)
Peleg	$WL_t = \frac{t}{k_1 + k_2 t}$	(3.7)	(Assis et al., 2016)

WL_t= water loss at any time, *t*, WL_∞ = equilibrium water loss, s_1 = Azuara's constant, *A* and *B* = Page's constants, k_1 and k_2 = Peleg's constants.

The statistical parameters such as coefficient of determination (R^2), root mean square error (RMSE), average relative error (E) were used to compare the goodness of fit (Barbosa Júnior, Cordeiro Mancini, and Hubinger, 2013). The best model must possess the highest R^2, the least of RMSE and *E*, defined as follows (Ramya and Kumar, 2015):

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{N} (WL_i - WL_{pre,i}) . (\sum_{i=1}^{N} (WL_i - WL_{exp,i})}{\sqrt{\left[\sum_{i=1}^{N} (WL_i - WL_{pre,i})^2\right] . \left[\sum_{i=1}^{N} (WL_i - WL_{exp,i})^2\right]}} \right] \quad (3.8)$$

$$RMSE = \sqrt{\left[\frac{\sum_{i=1}^{N} (WL_{pre,i} - WL_{exp,i})^2}{N} \right]} \quad (3.9)$$

$$E = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{Experimental\ value - Predicted\ value}{Experimental\ value} \right| \quad (3.10)$$

3.2.9 Statistical Analysis

Two batches of each experiment were performed and potato samples were collected from each batch in triplicate for analysed. All experimental data reported in figures and tables are the mean and standard deviation values that calculated by using Microsoft Office Excel 2013 and were evaluated using Minitab 17 Statistical Software. A t-test was used to determine the significant difference involving two samples (each sample with replication data), while a one-way analysis of variance (ANOVA) with Tukey's test was used to determine the significant difference involving more than two samples (each sample with replication data) at 95% confidence level.

3.3 Results and Discussion

3.3.1 Effect of Process Parameters and Nature of Osmotic Solutions on Single Stage of Dipping Dehydration Water Loss

Figure 3.1 depicts WL as a function of total time (i.e. expressed as a combination of dipping and holding times). The potato samples were dipped in sucrose (30 to 50%) and NaCl (5 to 15%) solutions for 0.5 and 1.5 min, withdrawn, and left to dehydrate. Figure 3.1 clearly demonstrates high initial water loss (WL) which becomes progressively slower in all cases. This patterns of water loss is similar to osmotic dehydration (Tortoe et al., 2007b; Mayor et al., 2007; El-Aouar et al., 2006). Based on statistical analysis, the value of WL significantly increased with total time for 10 mins (P<0.05) in the case of NaCl and for 40 mins in the case of sucrose solutions, after which the values of WL increased at a much slower rate. It can be postulated that the initial increase in WL is more pronounced due to the existence of a greater osmotic driving force between the fresh sample and concentrated solution which adheres to the surface of the sample.

Subsequently, water diffusion rate from interior to the surface becomes slower as the osmotic agent adhering to the potato surface, becomes diluted by the water that has already diffused from the interior. Figure 3.1 shows that there is no significant (P>0.05) effect of dipping time on WL in all cases. This is because the dipping times are relatively short and insufficient either for the sugar/salt to penetrate, or for the water to leave the tissue. Hence, the dipping time of 0.5 min was chosen for performing further experiments. Figure 3.1 also shows that the WL curve for sucrose and NaCl solutions follow similar trend, and as expected, the WL values are higher when the samples are dipped in solutions having greater concentrations.

Figure 3.1 also shows that WL increased with the concentration of the dip solution (P<0.05) for both sucrose and NaCl solution. For example, the maximum WL value for samples dipped in 50% sucrose at 0.5 min is 31.09 ± 0.74 g/100 g whereas it is only 22.86 ± 0.51 g/100 g for samples dipped in 30% sucrose solution. Likewise, in the case of NaCl solution, the maximum WL value for 10% solution is 18.76 ± 0.76 g/100 g whereas for the 5% solution, it is 16.56 ± 0.42 g/100 g. It is also interesting to note that the increase in WL with dip solution concentration tapers off in the case of NaCl because there is no significant difference between the WL values between 10 and 15% solutions. These observations on the effects of dip solution concentrations are similar to those in osmotic dehydration. For example, (Brochier et al., 2015; Nagai et al., 2015; Luchese et al., 2015; Pan et al., 2003) observed that WL increases with osmotic solution concentrations. (Manafi et al., 2010; Wang et al., 2010) have also reported in the case of apricot and potato that WL does not change dramatically at high osmotic solution concentration, which these authors attribute to "case hardening" caused by high concentrations of infuse salt. It is necessary to note that even though the trends in variation of WL with solution concentrations are similar to osmotic dehydration, the solute concentration in the tissue are significantly lower (Table 3.5).

It is also interesting to compare the above WL values obtained after dipping the potato sample in various solutions, with the values for identical samples which are not subjected to any dipping process (control), and samples subjected to osmotic dehydration treatment. For untreated samples, the dewatering is due to natural evaporation. It is obvious that the dipped slices gave significant higher water loss (P<0.05) according to Figure 3.1. The results show that the non-dipped control sample attained a WL value of only 10.75 ± 0.45 g/100 g after 60 mins whereas the samples dipped in sucrose attained

three times this value. In the case of osmo-dehydrated samples, the WL value is four times higher than control sample at 42.86 ± 1.61 g/100 g of fresh sample.

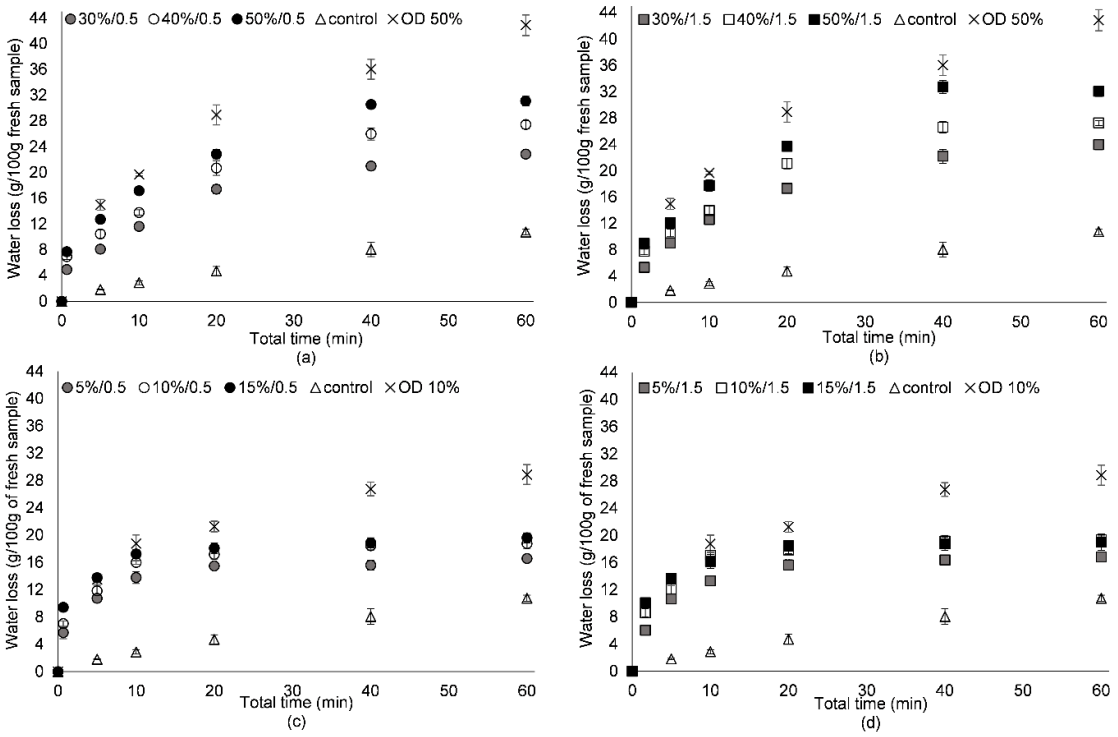

Figure 3.1 The variation of water loss as a function of time for post-dipping and osmotic dehydration treatments, and control samples in the case of (a) sucrose at 0.5 min of dipping time; (b) sucrose at 1.5 min of dipping time; (c) NaCl at 0.5 min of dipping time and (d) NaCl at 1.5 min of dipping time. The concentration of the solution and dipping time is mins are shown in figure. (OD = osmotic dehydration).

In order to demonstrate the practical benefits of post-dip dehydration, it is illustrative to compare the actual moisture content of the various samples (Table 3.3). The average initial moisture content (dry basis) of samples was 4.75 ± 0.47 g/g of dry matter, which, after 60 mins reduced to 2.26 ± 0.15 g/g of dry matter in the case of post-sugar-dip water loss, 1.76 ± 0.14 g/g of dry matter in the case of osmotic dehydration in the same solution, and 3.92 ± 0.07 g/g of dry matter in the case of ambient air drying. It

is obvious that post-dip moisture loss is significantly closer to osmotic dehydration than to air drying. Of course, the moisture loss in the case of osmotic dehydration is higher, which can simply be attributed to the higher sugar/salt concentrations. It is also for this very reason that osmotically dehydrated samples lose water continuously while the dipped samples attain constant moisture content values. Table 3.3 also lists the water activity for all cases. According to (Mathlouthi, 2001), water activity is good indicator to determine the shelf life of food products. Table 3.3 shows that the water activity decreased over time for dip-dehydrated samples due to decrease water loss as discussed before. Generally, further process such as drying and frying is operate to minimize water activity of osmo-dehydrated samples at desired value to prevent any microbial activity.

Table 3.3 Moisture content (dry basis) and water activity, a_w of potatoes after withdrawn from dip solution at 0.5 min of dipping time, potatoes for osmotic dehydration and control samples.

Moisture content (g/g of dry matter)					
Total time (min)	Post-dipping dehydration		Osmotic dehydration		Control
	Sucrose 50%	NaCl 10%	Sucrose 50%	NaCl 10%	
0	$4.75 \pm 0.47^{a,A}$	$4.75 \pm 0.47^{a,A}$	$4.75 \pm 0.47^{a,A}$	$4.75 \pm 0.47^{a,A}$	$4.75 \pm 0.47^{a,A}$
5	$3.55 \pm 0.46^{b,B}$	$3.52 \pm 0.30^{b,B}$	$3.47 \pm 0.12^{b,B}$	$3.49 \pm 0.11^{b,B}$	$4.65 \pm 0.21^{a,A}$
10	$3.01 \pm 0.21^{c,B}$	$3.11 \pm 0.15^{bc,B}$	$2.79 \pm 0.05^{c,B}$	$2.88 \pm 0.15^{c,B}$	$4.53 \pm 0.24^{ab,A}$
20	$2.66 \pm 0.13^{cd,C}$	$2.97 \pm 0.20^{c,B}$	$2.33 \pm 0.09^{d,D}$	$2.73 \pm 0.14^{c,BC}$	$4.43 \pm 0.08^{ab,A}$
40	$2.25 \pm 0.07^{d,C}$	$2.95 \pm 0.34^{c,B}$	$1.98 \pm 0.07^{e,D}$	$2.30 \pm 0.11^{d,C}$	$4.27 \pm 0.37^{bc,A}$
60	$2.26 \pm 0.15^{d,C}$	$2.92 \pm 0.23^{c,B}$	$1.76 \pm 0.14^{f,D}$	$2.25 \pm 0.14^{d,C}$	$3.92 \pm 0.07^{c,A}$
a_w					
Total time (min)	Post-dipping dehydration		Osmotic dehydration		Control
	Sucrose 50%	NaCl 10%	Sucrose 50%	NaCl 10%	
0	$0.992 \pm 0.004^{a,A}$	$0.992 \pm 0.004^{a,A}$	$0.992 \pm 0.004^{a,A}$	$0.992 \pm 0.004^{a,A}$	$0.992 \pm 0.004^{a,A}$
5	$0.988 \pm 0.003^{a,A}$	$0.987 \pm 0.007^{a,A}$	$0.988 \pm 0.002^{a,A}$	$0.986 \pm 0.001^{a,A}$	$0.991 \pm 0.005^{a,A}$
10	$0.986 \pm 0.001^{a,A}$	$0.984 \pm 0.001^{a,A}$	$0.981 \pm 0.005^{a,A}$	$0.982 \pm 0.002^{ab,A}$	$0.988 \pm 0.004^{a,A}$
20	$0.977 \pm 0.007^{ab,A}$	$0.977 \pm 0.007^{ab,A}$	$0.967 \pm 0.005^{b,B}$	$0.977 \pm 0.008^{ab,A}$	$0.987 \pm 0.005^{a,A}$
40	$0.969 \pm 0.008^{b,B}$	$0.977 \pm 0.003^{ab,B}$	$0.962 \pm 0.005^{b,BC}$	$0.976 \pm 0.012^{ab,A}$	$0.987 \pm 0.006^{a,A}$
60	$0.968 \pm 0.005^{b,BC}$	$0.977 \pm 0.001^{b,B}$	$0.961 \pm 0.001^{b,C}$	$0.969 \pm 0.004^{b,B}$	$0.985 \pm 0.002^{a,A}$

$^{a-f}$ different letters within in the same column indicate the comparison with different time of the same treatment that differ significantly at $P<0.05$.

$^{A-D}$ different letters within in the same row indicate the comparison with different treatments of the same time that differ significantly at $P<0.05$.

3.3.2 Mechanism of Dip Dehydration Water Loss

When the sample is withdrawn from the dip solution, a layer of the dip solution gets occluded to the surface, and a concentration driving force results between the bulk and the surface of the potato sample, which moves the water from the interior towards the surface. At the surface, the water can evaporate or the solution can drain out of the sample. The concentration of the solute at the surface does not reach a steady state and therefore the commonly assumed quasi-steady state surface concentration does not apply. The osmotic gradient between the tissue cells and the surface is also unsteady and therefore the rate of water loss from the tissue remains unsteady. Figure 3.2 illustrates the rate of water loss in the case of samples dipped in 50% sucrose and 10% NaCl solutions, and compares these rates with the values observed in non-dipped samples. It may be noted that the rates in Figure 3.2 essentially represents the local gradients of WL versus time data shown in Figure 3.1. It is evident from Figure 3.2 that the dehydration rate generally decreases with time in all cases. For the untreated sample, the initial dehydration rate is 0.37 g/(100g.min) and decreases steadily to less than 0.13 g/(100g.min) in later stages. Water loss from the surface sample is essentially by evaporation, and since all samples are dehydrating under the same ambient conditions the rates of evaporation would be expected to be the same. It is clear from Figure 3.2 that after 10 min, the control sample is dehydrating at the rate of 0.21 g/(100g.min), which may be assumed to represent the rate of evaporation. At the same time, the salt and sucrose dipped samples are losing water at a much higher rate. The difference between the two rates can be assumed to indicate the rate at which the water drains from the sample in the liquid state taking with it some solute.

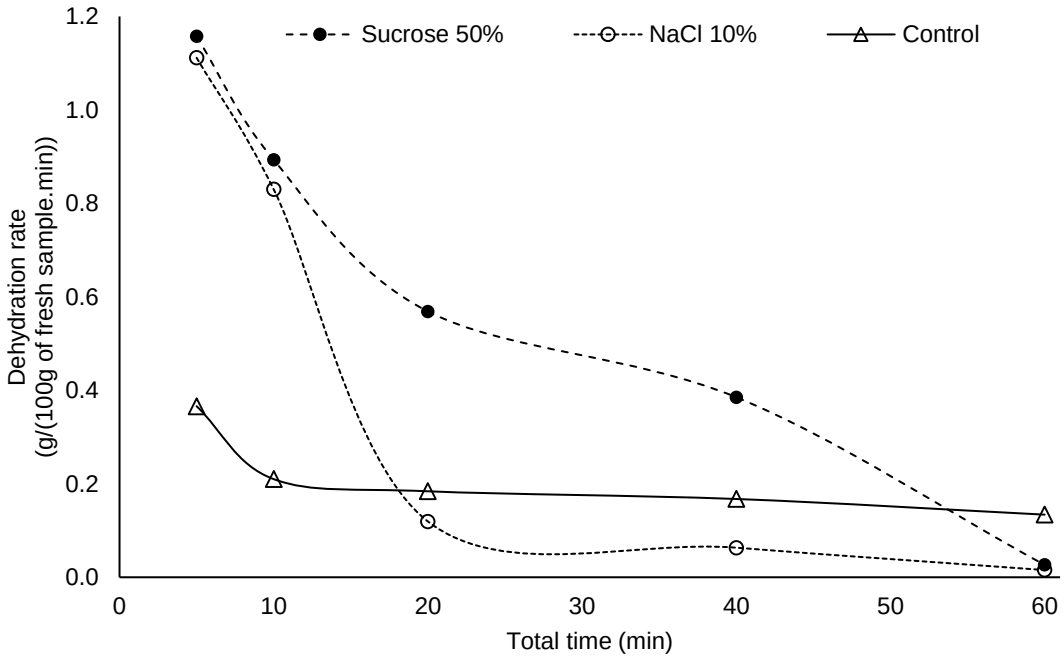

Figure 3.2 Dehydration rate curve of single stage of post-dipping treatment for sucrose 50% and NaCl 10%, and control samples.

3.3.3 Kinetics in Water Loss

The water loss data shown in Figure 3.1 can be fitted to three selected empirical models, which are commonly used in dehydration literature: Azuara (Azuara et al., 1992), Page (Ochoa-Martinez et al., 2007) and Peleg (Assis et al., 2016). The values of the model parameters and relevant statistical data are given in Table 3.4, which shows that R^2 for all models are greater than 0.91 with low RMSE values (<0.024). However, it was found that Peleg model satisfactorily described the dehydration behaviours with the highest R^2 (>0.98) and lowest RMSE (<0.018).

Table 3.4 Fitting of water loss data shown in Fig. 1 to Azuara model: $WL_t = \frac{s_1 t(WL_\infty)}{1+ s_1 t}$, Page model: $WL_t = \exp(-At^B)$ and Peleg model: $WL_t = \frac{t}{k_1 + k_2 t}$.

Model	Parameter	Osmotic solution					
		Sucrose 30%	Sucrose 40%	Sucrose 50%	NaCl 5%	NaCl 10%	NaCl 15%
Page	*A*	3.372	3.489	3.005	2.610	2.441	2.226
	B	-0.209	-0.253	-0.233	-0.096	-0.098	-0.081
	R^2	0.984	0.987	0.965	0.971	0.979	0.987
	RMSE	0.012	0.013	0.024	0.012	0.011	0.009
	E	0.117	0.134	0.120	0.085	0.065	0.046
Peleg	k_1	49.400	42.730	35.650	10.540	16.390	11.840
	k_2	3.406	2.806	2.541	6.132	5.056	4.921
	R^2	0.987	0.984	0.981	0.977	0.982	0.982
	RMSE	0.011	0.015	0.018	0.010	0.010	0.010
	E	0.138	0.154	0.157	0.068	0.115	0.115
Azuara	WL_∞ (g/g)	0.270	0.320	0.350	0.170	0.190	0.200
	s_1 (min^{-1})	0.100	0.103	0.120	0.478	0.499	0.517
	R^2	0.971	0.938	0.959	0.980	0.954	0.919
	RMSE	0.014	0.024	0.024	0.008	0.014	0.019
	E	0.167	0.178	0.172	0.076	0.118	0.112

3.3.4 Solute Gain (SG) Behaviour

The solute gain estimated from Eq. 3.4 is given in Table 3.5. It may be noted that the solute gain is expressed in g solid per 100g fresh sample. Table 3.5 shows that there are significant increases in solute gain values with total time for both dip dehydration and osmotic dehydration in sucrose and NaCl solutions, but osmotic dehydration always exhibits higher solute gain value than dip dehydration samples. For example, solute gain in the case of osmotic dehydration were 7.06 ± 0.44 g/100g for sucrose 50% and 5.00 ± 0.48 g/100g for NaCl 10% after 60 mins of osmotic dehydration. These values are nearly twice the value of the solid gain in the case of dip dehydration. Thus, by employing dip dehydration, we can achieve osmotic water loss with considerably reduced solid gain, which is potentially health beneficial.

Table 3.5 Solute gain (in g/100g of fresh sample) of potatoes after withdrawn from dip solution at 0.5 min of dipping time and potatoes for osmotic dehydration.

Total time (min)	Sucrose solution			
	Single stage dip dehydration			Osmotic dehydration
	30%	40%	50%	50%
5	$1.52 \pm 0.17^{a,a}$	$2.41 \pm 0.24^{a,b}$	$2.53 \pm 0.42^{a,b}$	$3.62 \pm 0.45^{a,c}$
10	$1.60 \pm 0.30^{ab,a}$	$2.65 \pm 0.20^{a,b}$	$2.73 \pm 0.41^{ab,b}$	$5.59 \pm 0.49^{b,c}$
20	$1.89 \pm 0.22^{ab,a}$	$2.77 \pm 0.24^{a,b}$	$3.32 \pm 0.30^{bc,c}$	$6.48 \pm 0.43^{bc,d}$
40	$1.90 \pm 0.20^{ab,a}$	$2.87 \pm 0.66^{a,b}$	$3.48 \pm 0.35^{c,b}$	$6.67 \pm 0.17^{c,c}$
60	$1.95 \pm 0.25^{b,a}$	$2.91 \pm 0.55^{a,b}$	$3.52 \pm 0.33^{c,b}$	$7.06 \pm 0.44^{c,c}$

[a-c] different at first letter within in the same column indicate the comparison with different time of the same treatment that differ significantly at $P<0.05$.
[a-d] different at second letter within in the same row indicate the comparison with different treatments of the same time that differ significantly at $P<0.05$.

Table 3.5 (Continued)

Total time (min)	NaCl solution			
	Single stage dip dehydration			Osmotic dehydration
	5%	10%	15%	10%
5	$0.74 \pm 0.15^{A,A}$	$1.07 \pm 0.09^{A,A}$	$1.82 \pm 0.34^{A,B}$	$3.06 \pm 0.55^{A,C}$
10	$0.86 \pm 0.25^{A,A}$	$1.53 \pm 0.38^{AB,AB}$	$1.98 \pm 0.40^{A,B}$	$3.40 \pm 0.85^{A,C}$
20	$1.01 \pm 0.20^{AB,A}$	$1.92 \pm 0.38^{BC,B}$	$2.27 \pm 0.30^{A,B}$	$4.26 \pm 0.98^{AB,C}$
40	$1.35 \pm 0.32^{BC,A}$	$2.04 \pm 0.18^{BC,B}$	$3.18 \pm 0.58^{B,C}$	$4.99 \pm 0.55^{B,D}$
60	$1.54 \pm 0.32^{C,A}$	$2.15 \pm 0.49^{C,A}$	$3.16 \pm 0.69^{B,B}$	$5.00 \pm 0.48^{B,C}$

$^{a-f}$ different letters within in the same column indicate the comparison with different time of the same treatment that differ significantly at $P<0.05$.

$^{A-D}$ different letters within in the same row indicate the comparison with different treatments of the same time that differ significantly at $P<0.05$.

Table 3.6 shows the values of process efficiency index (WL/SG) for both dip and osmotic dehydration of potato slices. This ratio of water loss/solid gain is an important indicator to evaluate the efficiency of osmotic dehydration technique (García et al., 2010). It was observed, in general, the dipped samples presented higher value of efficiency index as compared with osmo-dehydrated samples. The advantage of dip dehydration treatment which lowers solid gain substantially, is the main factor contributing to the higher WL/SG values. Thus, these results indicate the superiority of dip dehydration over the osmotic dehydration treatment with respect to the lower solid gain.

Table 3.6 Process efficiency index (WL/SG) of potatoes under dip dehydration and osmotic dehydration treatments.

Total Time	Single stage dip dehydration		Osmotic dehydration	
(min)	Sucrose 50%	NaCl 10%	Sucrose 50%	NaCl 10%
5	$5.13 \pm 0.91^{a,A}$	$11.13 \pm 1.35^{a,B}$	$4.17 \pm 0.35^{ab,A}$	$4.52 \pm 0.86^{a,A}$
10	$6.42 \pm 1.04^{ab,B}$	$11.05 \pm 2.82^{a,C}$	$3.54 \pm 0.35^{a,A}$	$5.76 \pm 1.33^{a,B}$
20	$6.92 \pm 0.53^{b,B}$	$9.23 \pm 1.65^{a,C}$	$4.48 \pm 0.28^{b,A}$	$5.15 \pm 0.92^{a,A}$
40	$8.84 \pm 0.86^{c,B}$	$9.08 \pm 0.55^{a,B}$	$5.40 \pm 0.29^{c,A}$	$5.39 \pm 0.54^{a,A}$
60	$8.88 \pm 0.72^{c,B}$	$9.11 \pm 1.98^{a,B}$	$6.10 \pm 0.52^{c,A}$	$5.79 \pm 0.34^{a,A}$

$^{a-c}$ different letters within in the same column indicate the comparison with different time of the same treatment that differ significantly at $P<0.05$.

$^{A-C}$ different letters within in the same row indicate the comparison with different treatments of the same time that differ significantly at $P<0.05$.

Figure 3.3 shows the variation in remaining total sucrose and NaCl, which amount of solute gain and occluded on slices, expressed as the g of solute per 100g of fresh sample, as a function of time. It is clear that the mass of solute in the potato decreases for sucrose (for the first 20 mins) as well as NaCl (for the first 10 mins) and then remains constant. The loss of solute in the initial stage is due to the solution draining from the surface. We can postulate that the water diffusing towards the surface under the osmotic gradient, dissolves the solute present near the surface, and leaches it out with the draining solution. It clearly seen from Figure 3.3 that solute content decreased from 13.31 g/100g to 7.39 g/100g of fresh sample after 20 mins in the case of sucrose, and from 4.38 g/100g to 2.58 g/100g in the case of NaCl after 10 mins. This reduction in solute content also lowers the osmotic gradient, which in turn lowers the rate of water loss; this is clearly seen in Figure 3.2. Thus the dewatering process due to osmotic dehydration becomes less

effective over the period of time and ceases to occur; any water loss from surface occurring thereafter is mainly due to natural evaporation.

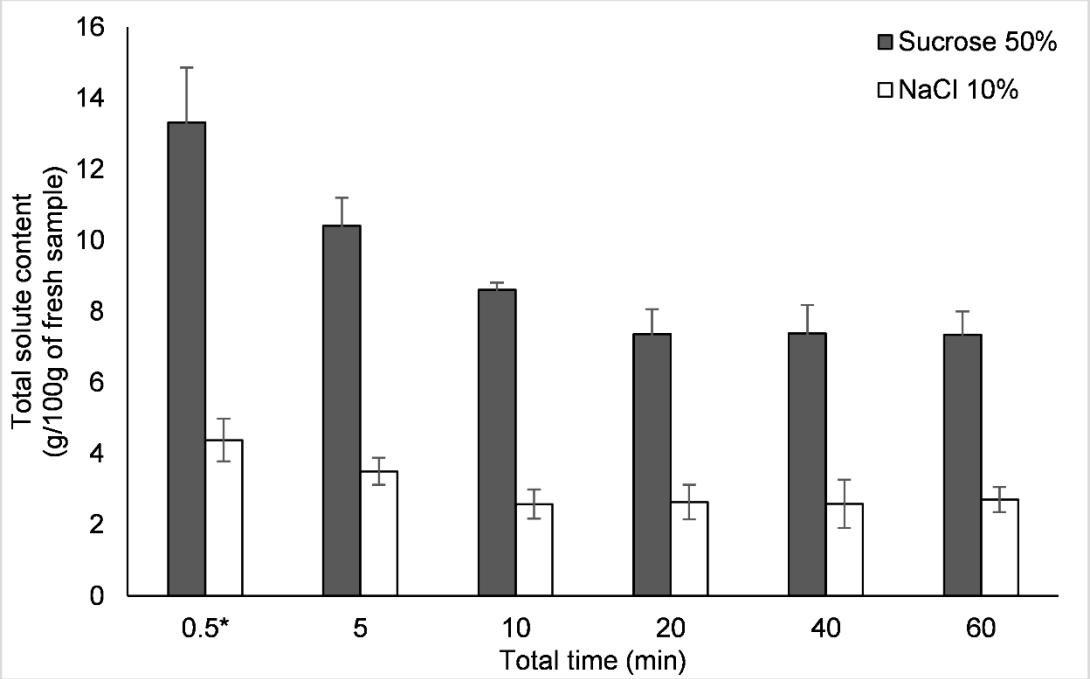

Figure 3.3 Variation in sucrose and NaCl content (g/100 g fresh sample weight) on the sample with total time. (0.5* is the time after sample withdrawn from the osmotic solution and immediately measured the solute content, which is at 0 min of holding time).

3.3.5 Multi-stage Dip Dehydration

As discussed in the previous section, the WL after the first dip in osmotic solution becomes constant after 40 mins in the case of sucrose and 10 mins in the case of NaCl, due to decreases in the osmotic driving force. It was therefore thought desirable to find out whether the dehydration process could, once again, be re-started by dipping the partially dehydrated product, once again, in the osmotic solution. It is true that we are re-exposing the product to more water, but, given the short dipping time, the amount of water and salt taken up thus, will be very low. If dehydration could be successfully re-started, it was also thought desirable to explore whether water loss comparable to osmotic dehydration could be achieved by a series of repeated dipping and holding processes, in other words, multi-stage dipping and dehydration. As mentioned earlier, two approaches were considered: repeated dipping in the same concentrated solution (treatment A) and dipping in progressively concentrated solution (treatment B).

Figure 3.4 shows the transient WL values for multi-stage dipping and compares the data with the water loss observed in the case of osmotic dehydration in the same solution. It is clear that the water loss patterns for the multi-stage process is similar to osmotic dehydration, i.e. the rate WL values increase rapidly soon after dipping, but slow down in the later stages. It is clear from Figure 3.4 that initially, the water loss values for dip dehydration is lower than osmotic dehydration in the same dip solution, which is naturally expected; this is indeed a key disadvantage of the process in relation to osmotic dehydration. The water loss for treatment B appears to be lower than treatment A, but this is simply because the first dip solution had a lower concentration. In the case of sucrose solution, it is clearly seen that the value of WL does not significantly change (P>0.05) for all treatments after 240 mins. Although the potato slices underwent dipping in progressively higher concentrated sucrose solution up to 60% (treatment B), the WL

values did not continually rise. This is due to the decrease in chemical potential of water between the tissue and solution over the process time, and the high viscosity of concentrated sucrose solution that adheres to the potato surfaces. (Phisut, 2012) also mentioned that the increasing sucrose concentration leads to a high viscosity of solution which creates external resistance to the water transfer rate.

It is interesting to note that even though the water loss values achieved in dip dehydration is comparable to osmotic dehydration, the solute gain (SG) is significantly lower and the process efficiency index (WL/SG) values for dip dehydration is significantly higher (Table 3.7).

In the case of NaCl, the most effective method was found to be treatment B which achieved a maximum value of WL of 37 g/100g of fresh sample after 80 mins, whereas the WL value for treatment A and OD was around 30 g/100g of fresh sample. However, it may be noted that there is no significant different in SG values between treatment B and OD after 50 mins, thus resulting in treatment B giving lower WL/SG value than treatment A, but still higher than OD as shown in Table 3.7. Furthermore, the lower molecular weight of NaCl (58.4 g/mol) than sucrose (342 g/mol) enables the solute to diffuse more easily into the tissue (Akbarian et al., 2014).

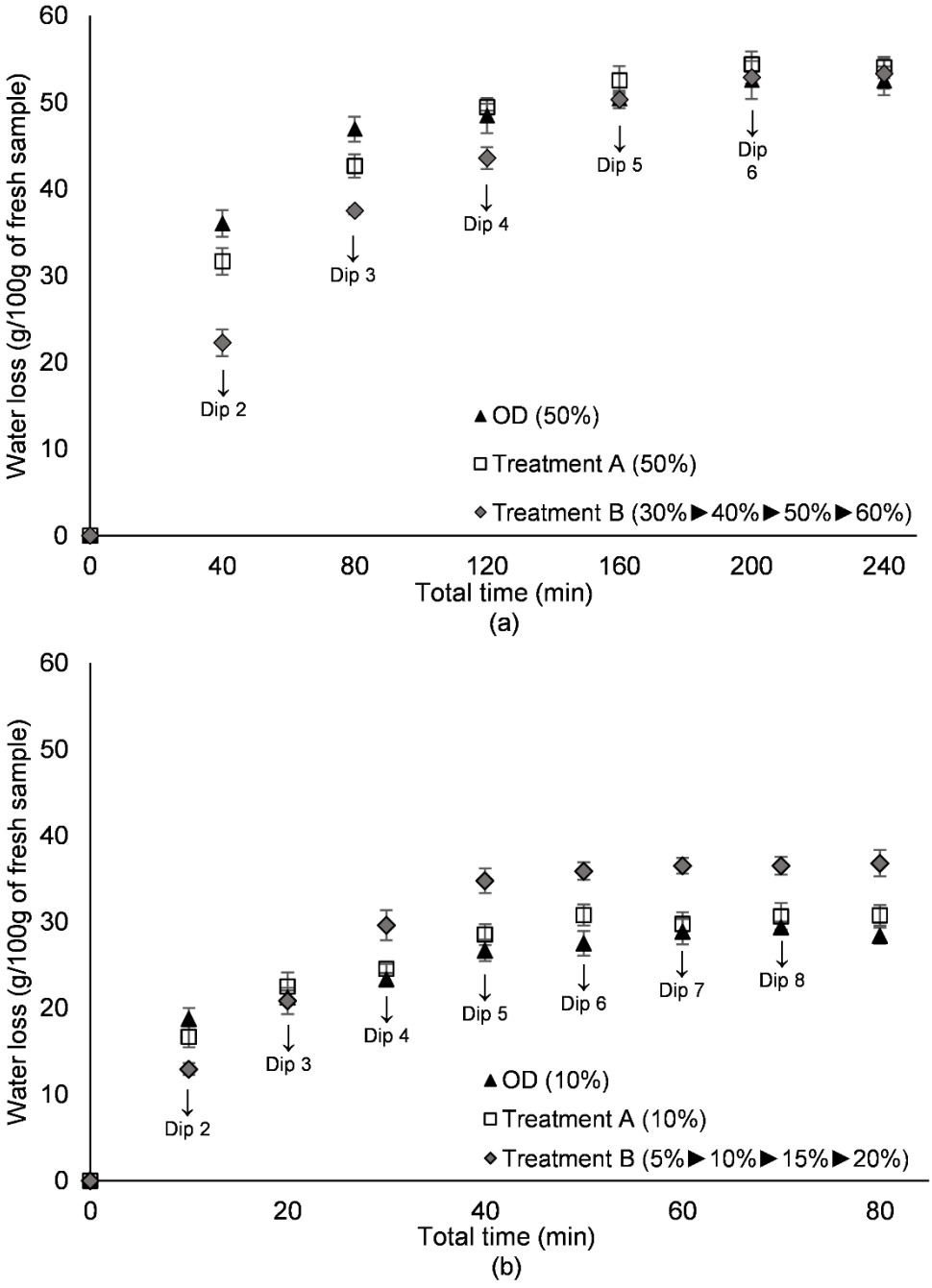

Figure 3.4. The variation of WL as a function of time (a) sucrose; (b) NaCl solutions for osmotic dehydration, (OD), multi stage dipping and dehydration in same solution (treatment A) and multi stage dipping and dehydration in progressively solution (treatment B). The concentrations of the dip solution employed are stated in the figure. (↓ shows the time which the redipping occurred. In treatment A, samples were re-dipped in same solution as shown in figure, while in treatment B, samples were redipped in progressive concentrated solutions based on Table 3.1).

Table 3.7 Comparison of solute gain (in g/100g of fresh sample) and process efficiency index (WL/SG) of potato samples under different treatment conditions: osmotic dehydration (OD), multi-stage dip dehydration in same solution (treatment A) and multi-stage dip dehydration in progressively concentrated solution (treatment B). The concentrations of the solutions employed are stated in the table.

Time (min)	Sucrose solution					
	SG (g/100g of fresh sample)			WL/SG		
	OD (50%)	Treatment A (50%)	Treatment B (30%►40%►50%►60%)	OD (50%)	Treatment A (50%)	Treatment B (30%►40%►50%►60%)
40	$6.67 \pm 0.17^{a,c}$	$3.07 \pm 0.55^{a,b}$	$2.18 \pm 0.07^{a,a}$	$5.40 \pm 0.29^{a,a}$	$10.58 \pm 2.07^{ab,b}$	$10.22 \pm 0.82^{b,b}$
80	$7.72 \pm 0.67^{a,b}$	$3.29 \pm 0.80^{a,a}$	$2.79 \pm 0.20^{ab,a}$	$6.11 \pm 0615^{a,a}$	$13.48 \pm 2.89^{a,b}$	$13.65 \pm 0.97^{c,b}$
120	$8.45 \pm 0.68^{ab,b}$	$4.34 \pm 0.47^{ab,a}$	$3.84 \pm 0.32^{bc,a}$	$5.77 \pm 0.57^{a,a}$	$11.49 \pm 1.15^{ab,b}$	$11.39 \pm 1.01^{bc,b}$
160	$9.87 \pm 1.36^{abc,b}$	$5.03 \pm 0.59^{bc,a}$	$4.84 \pm 0.65^{c,a}$	$5.17 \pm 0.60^{a,a}$	$10.51 \pm 0.91^{ab,b}$	$10.58 \pm 1.86^{b,b}$
200	$11.16 \pm 1.97^{bc,b}$	$6.10 \pm 0.48^{cd,a}$	$7.28 \pm 0.86^{d,a}$	$4.84 \pm 0.98^{a,a}$	$8.96 \pm 0.78^{a,b}$	$7.35 \pm 0.98^{a,b}$
240	$11.97 \pm 2.34^{c,b}$	$6.73 \pm 0.89^{d,a}$	$7.14 \pm 0.43^{d,a}$	$4.53 \pm 0.99^{a,a}$	$8.12 \pm 1.00^{a,b}$	$7.49 \pm 0.54^{a,b}$

[a-d] different at first letter within in the same column indicate the comparison with different time of the same treatment that differ significantly at $P<0.05$.

[a-c] different at second letter within in the same row indicate the comparison with different treatments of the same time that differ significantly at $P<0.05$.

Table 3.7 (Continued)

Time (min)	NaCl solution					
	SG (g/100g of fresh sample)			WL/SG		
	OD (10%)	Treatment A (10%)	Treatment B (5%►10%►15%►20%)	OD (10%)	Treatment A (10%)	Treatment B (5%►10%►15%►20%)
10	$3.40 \pm 0.85^{A,B}$	$1.41 \pm 0.18^{A,A}$	$1.10 \pm 0.35^{A,A}$	$5.76 \pm 1.33^{A,A}$	$11.96 \pm 1.13^{AB,B}$	$12.72 \pm 3.94^{AB,B}$
20	$4.26 \pm 0.98^{AB,B}$	$2.14 \pm 0.75^{A,A}$	$1.61 \pm 0.44^{AB,A}$	$5.15 \pm 0.92^{A,A}$	$11.33 \pm 3.31^{AB,B}$	$13.90 \pm 4.94^{B,B}$
30	$4.56 \pm 0.74^{ABC,B}$	$1.75 \pm 0.35^{A,A}$	$2.36 \pm 0.33^{BC,A}$	$5.20 \pm 0.72^{A,A}$	$14.50 \pm 3.23^{AB,B}$	$12.83 \pm 2.55^{AB,B}$
40	$4.99 \pm 0.55^{BC,C}$	$1.93 \pm 0.20^{A,A}$	$3.21 \pm 0.55^{CD,B}$	$5.39 \pm 0.54^{A,A}$	$14.93 \pm 1.60^{B,C}$	$11.11 \pm 2.25^{AB,B}$
50	$5.17 \pm 0.68^{BC,B}$	$2.34 \pm 0.28^{AB,A}$	$4.20 \pm 0.57^{DE,B}$	$5.37 \pm 0.51^{A,A}$	$13.28 \pm 1.01^{AB,C}$	$8.66 \pm 1.10^{AB,B}$
60	$5.00 \pm 0.48^{BC,B}$	$2.45 \pm 0.57^{AB,A}$	$5.33 \pm 0.20^{E,B}$	$5.79 \pm 0.34^{A,A}$	$12.73 \pm 3.30^{AB,B}$	$6.86 \pm 0.23^{A,A}$
70	$5.89 \pm 0.40^{C,B}$	$3.20 \pm 0.33^{B,A}$	$5.11 \pm 0.81^{E,B}$	$4.99 \pm 0.24^{A,A}$	$9.64 \pm 1.00^{A,C}$	$7.26 \pm 1.01^{A,B}$
80	$6.05 \pm 0.54^{C,B}$	$3.32 \pm 0.56^{B,A}$	$5.24 \pm 0.34^{E,B}$	$4.73 \pm 0.49^{A,A}$	$9.43 \pm 1.29^{A,C}$	$7.04 \pm 0.55^{A,B}$

$^{A-E}$ different at first letter within in the same column indicate the comparison with different time of the same treatment that differ significantly at $P<0.05$.

$^{A-C}$ different at second letter within in the same row indicate the comparison with different treatments of the same time that differ significantly at $P<0.05$.

3.4 Conclusion

In this chapter, dehydration of potato slices was explored after dipping the slices briefly in concentrated sugar (30-50%) and salt solutions (5-15%), and leaving the slices to lose water under ambient conditions. The absorption of sugar and salt resulted in the movement of water towards the surface of the slices under osmotic gradients, which was subsequently lost from the slices by a combination of evaporation and draining. Initially, the loss of water by draining was more significant, but later on evaporation tended to dominate. The moisture content (dry basis) of the slices could be reduced thus from 4.75 ± 0.47 g/g of dry matter to 2.26 ± 0.15 g/g of dry matter in an hour, without any significant expenditure of energy and the water loss was three times higher when compared to natural air drying. It was also found that dipped potato slices gained much lower amount of sugar/salt, which could be half or even lower than the value gained during osmotic dehydration in the same solution, thus yielding higher effectiveness index (WL/SG). This technique was further extended by investigating repeated dipping in the same concentration solution (treatment A) or by dipping in progressively concentrated solutions (treatment B). It was found that the water loss in multi-stage dip dehydration was comparable to osmotic dehydration but with significantly lower solid gain. The process efficiency index (WL/SG) was also higher for multi-stage dip dehydration. Thus, dip dehydration can be used instead of osmotic dehydration to achieve the same levels of water loss but with substantially lower solid gain.

CHAPTER 4

EFFECTS OF DIP DEHYDRATION AS A PRE-TREATMENT TO LOWER OIL UPTAKE IN FRIED POTATO CHIPS

Abstract

The removal of some water from potatoes by osmotic dehydration prior to frying is known to reduce the oil content of fried potato chips. However, this process introduces significant amounts of salt in the products. Our previous chapter proposed a novel variant of osmotic dehydration (called multi dip dehydration), which involves dipping the potatoes in a salt solution briefly and allowing the water to be lost by dripping or ambient air dehydration, can result in a product comparable to the osmotically dehydrated potato but with significantly lower salt content. This study aims to investigate the effect of multi dip dehydration, prior to the frying of potato chips, on the characteristics of the chips. In particular, the moisture and oil contents, colour and texture of the fried potato chips obtained with different pre-treatments, were measured and compared. The potato slices were subjected to three different pre-treatments i.e. hot water blanching at 65 °C for 5 mins (control), multi dip dehydration in NaCl (10% solution) lasting 40 mins and osmotic dehydration with NaCl 10% for 40 mins. The samples were then fried at 170 °C for 3 mins before moisture, salt and oil contents, colour and texture were analysed. In order to attain a final moisture content of ~0.02 g/g of dry matter, the results showed that multi dip and osmotic dehydration pre-treatments reduced frying time from 2.75 mins to 2 mins, decreased the oil content by about 17% and also improved the colour of the fried product. Further, the samples treated by multiple dipping contained around 50% lower

salt content than osmo-dehydrated samples, and thus can potentially yield a more health-positive product option.

4.1 Introduction

Frying is extensively employed in food preparations: 1) at home, 2) in business sectors such as restaurants and fast food outlet, and 3) in industrial practice. The process essentially involves simultaneous transfer of mass and heat between the food product and the frying medium which is normally hot oil. Fried products, in general, are in high demand from consumers because of their desirable texture (crispness), colour, flavour and taste characteristics (Gertz, 2014).

Potato chips (also known as potato crisps) is one of the most popular salty snacks consumed in many countries. However, this snack also contains a significantly higher oil content than other fried products (Ziaiifar et al., 2008a; Kita, Lisińska, and Gołubowska, 2007). Consequently, its shelf life is affected and its frequent consumption is also linked to the risk of obesity related health conditions (Su et al., 2018). It is therefore desirable to find methods to lower the fat content fried products.

Numerous research publications have reported on the relationship between oil uptake and water evaporation during frying, and concluded that a higher initial moisture content leads to a higher oil content in the fried products (Ren et al., 2018; Dehghannya and Abedpour 2017; Karizaki et al., 2013). One possible explanation for this observation is that the water escaping from food during frying promotes the pore formation, which subsequently provides pathways for oil absorption in the fried products during the cooling period following frying (Kassama and Ngadi, 2007). Therefore various dehydration methods have been proposed to reduce the initial moisture content prior to frying (Martínez-Ávila, Vélez-Ruiz, and Sosa-Morales 2010; Garmakhany et al., 2010).

However, conventional dehydration results in higher overall energy consumption and significant quality changes in the final product. Therefore, osmotic dehydration, which is generally considered to be less energy intensive than other dehydration methods, was proposed as an alternative pre-treatment to reduce the initial moisture content and some studies have demonstrated the effectiveness of this pre-treatment process in lowering the oil content of the fried chips (Karizaki et al., 2013; Bunger, Moyano, and Rioseco, 2003b; Krokida, et al., 2001b). However, the main limitation of osmotic dehydration is the high solute uptake (normally common salt), which is undesirable because of adverse sensory and longer term health effects. An earlier chapter proposed multi-stage dip-dehydration as a novel variant of osmotic dehydration, which resulted in a lower salt containing dehydrated product. Dip-dehydration process involves dipping potato slices in an osmotic solution briefly and allowing the water to be lost by dripping, or ambient air dehydration, either once or a number of times.

In this chapter, we hypothesise that repeated or multi-stage dip-dehydration can lower the water content of potato slices prior to frying without taking up significant levels of salt, which can potentially result in a lower oil and salt containing fried potato chip. In addition to verifying this hypothesis, this study also reports on the product characteristics which include its moisture and oil content, texture and colour. This chapter also compares these product characteristics with chips obtained by frying conventionally blanched or osmotically dehydrated potato slices.

4.2 Materials and Methods

4.2.1 Raw Material and Sample Preparation

Maris Piper potatoes, ranging in weight between 170 – 230 g, were purchased locally and stored in refrigerator at 4 °C until 12 h prior to use, while commercial salt was purchased from a local supplier. Analytical grade petroleum ether (boiling point of 40 °C to 60 °C) and cellulose extraction thimbles were purchased from Sigma-Aldrich, Dorset, UK. The potatoes were peeled and sliced to 1.5 mm thickness using an adjustable hand slicer (Mandoline slicer, Lakeland, UK), and then, were cut into disk shape (50 mm diameter) using a circular mould to ensure uniformly sized experimental slices. Potato slices were rinsed in running water (for 30 s) to eliminate surface starch, and blotted using tissue paper for 1 min.

4.2.2 Pre-treatment Procedure

The process flow employed for sample preparation, pre-treatment, frying and analysis is illustrated in Figure 4.1. Different pre-treatments were employed i.e. hot-water blanching as control, multi dip dehydration (MD) and osmotic dehydration (OD).

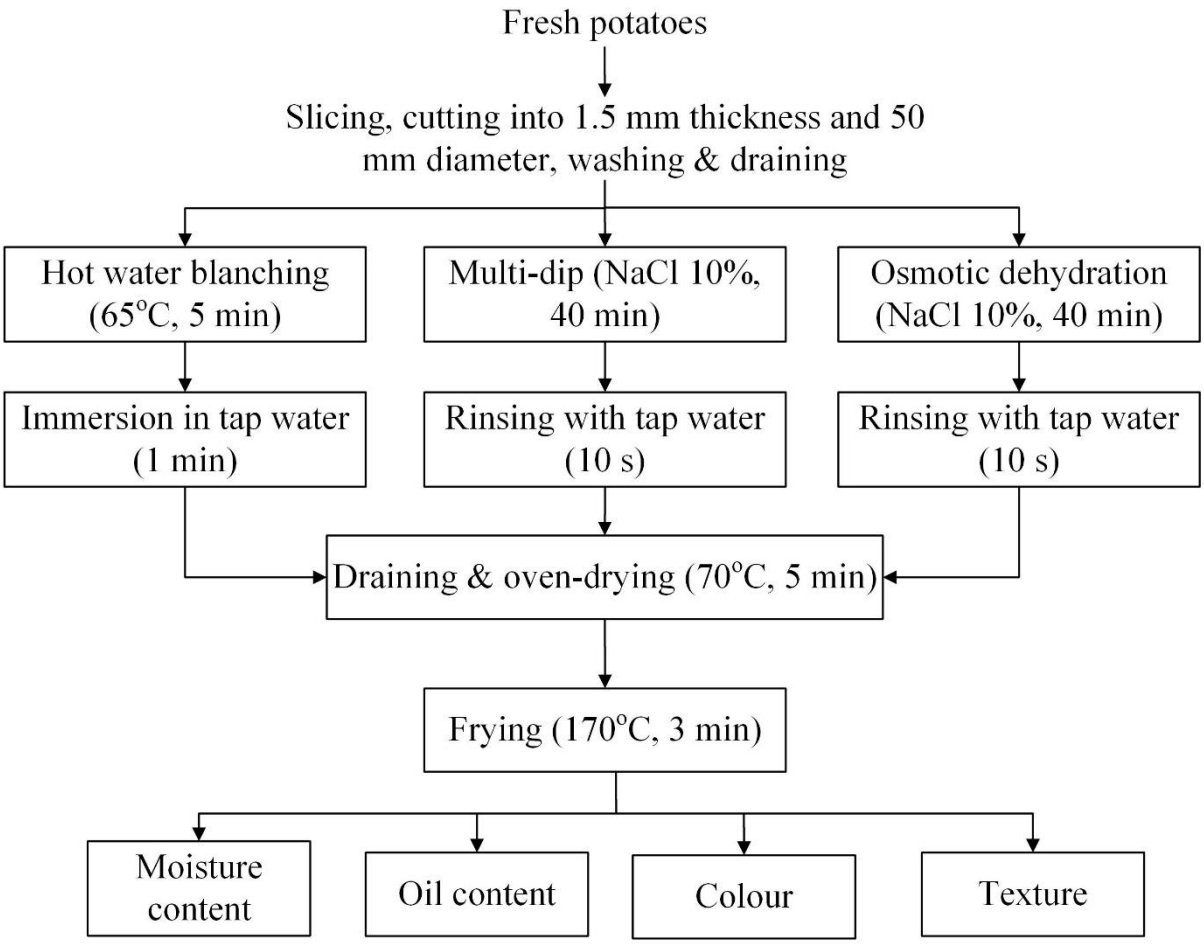

Figure 4.1 Process flow for the preparation of potato slices and treatment prior to frying.

For control sample, the potato slices were blanched in hot water for 5 mins at 65 °C using a water bath fitted with temperature control. The ratio of potato to water was 1:20 (w/v). The time-temperature combination was sufficient to gelatinize all of the starch (Al-Khusaibi and Niranjan, 2012), whilst minimising the loss of nutrients and vitamins (Mukherjee and Chattopadhyay, 2007). After blanching, the potato slices were immediately cooled to ambient temperature (around 22 °C) within a minute, drained and placed in an oven at 70 °C for 5 mins to eliminate the water adhering to the surface and to preserve the colour of potato slices (Bingol et al., 2014; Queiroz et al., 2008).

The salt solution 10% (w/v) used for multiple dip-dehydration (MD) treatment was prepared by dissolving commercial salt in distilled water. The potato slices were dipped for 0.5 min in the osmotic solution and placed on a wire mesh for 10 mins for dehydration to occur under ambient conditions. Then slices were again dipped in same solution and similarly held under ambient conditions for another 10 mins, and these processes were repeated four times taking 40 mins overall. After MD, samples were rinsed in tap water for 10 s to remove surface salt, drained and placed in an oven at 70 °C for 5 mins, as before. The selected conditions and operating times for MD were chosen to give the highest water loss to solids gain ratio, based on the results of our previous chapter (Chapter 3). The conditions employed for osmotic dehydration pre-treatment, i.e. concentration of the osmotic solution, immersion time, potato slices to osmotic solution ratio and sample preparation were similar to MD treatment.

4.2.3 Frying

Pre-treated potato slices were fried using a domestic deep fat fryer (VonShef 13/183, Manchester, U.K.), oil capacity of 3 litre set to a frying temperature of 170 °C. A batch of potato slices (40 g) was placed in the frying basket and covered with wire mesh grid to prevent the slices from floating on the oil. Slices were then fried for different time intervals up to 3 mins by lowering and immersing the basket in the oil. After frying, the basket was removed from oil to allow some of the surface oil drain back into the bulk and then allowed to cool at room temperature for 10 mins. Subsequently, the slices were removed from the basket and gently wrapped with tissue paper for 1 min to remove loosely adhering oil on the surface and stored in polythene bags for further analysis. Moisture and oil contents, colour and texture were measured for all operating times, while the salt content was only measured for the final fried products.

4.2.4 Moisture and Oil Contents

The moisture and oil contents of samples in this experiment were measured according to the Official Method of Analysis of AOAC International (AOAC, 2000). The samples were dried at 105 °C in an oven (Weiss-Gallenkamp, Loughborough, U.K.) until attaining a constant weight for moisture content determination. Meanwhile in oil content determination, dried samples were ground and extracted with petroleum ether for 4 hrs using Quickfit Soxhlet extraction system. Then, the solvent was removed under vacuum at 50 °C by using a rotary evaporator (Buchi Rotavapor RE 111, Flawil, Switzerland) and the flask containing oil was dried to constant weight in an oven at 90 °C. Both moisture and oil contents were expressed as dry basis.

4.2.5 Salt Content

Salt content of the samples was determined according to Mercali et al., (2011) by using electrical conductivity meter (Accumet AET30, Fisherbrand, Leicestershire) with slight modification. About 3 g of sample were heated in 50 ml of deionized water for 30 mins at 90 °C. The mixture was centrifuged at 5000 rpm for 15 mins and then cooled until achieved ambient temperature before the conductivity of the solution was measured. The standard curve was prepared by measured conductivity of standard solutions at 0.1 – 1.0 (mg/ml) concentration.

4.2.6 Colour Measurement

Colour of samples was measured using HunterLab colorimeter (Color-Quest, Hunter Assn. Laboratory, Reston, U.S.A.). The instrument was warmed up 2 hrs before analysis, and calibrated with white and grey standards. The colour measurements were expressed in terms of L^*, a^* and b^* values. Before colour measurement, the slices were

ground using a coffee grinder to obtain homogenous sample from all slices and to reduce the reading error (Nunes and Moreira, 2009).

4.2.7 Texture Analysis

The texture of potato chips was measured in terms of hardness (a maximum breaking force) at ambient temperature by using Brookfield texture analyser (CT3, Brookfield Engineering Laboratories, Middleborough, U.S.A.). A cylindrical probe (2 mm diameter) was fitted to the instrument and a compression test was carried out at a test speed at 1 mm/s. Each slice was punctured at the centre and data obtained were analysed by the software (TexturePro CT v1.2 software) provided by the supplier.

4.2.8 Statistical Analysis

Duplicate batches of frying experiments were performed for each pre-treatment and frying condition. Three samples taken from each batch were analysed for moisture, salt and oil contents, texture and colour as described above. All experimental data reported in the figures and tables are the mean and standard deviation values calculated by using Microsoft Office Excel 2013. The differences between means were evaluated by one-way analysis of variance using Minitab 17 Statistical Software.

4.3 Results and Discussion

4.3.1 Moisture content

The moisture content variation during deep-frying of pre-treated potato chips is illustrated in Figure 4.2. The initial moisture content of pre-treated potato slices prior to frying decreased from 4.75 ± 0.47 g/g of dry matter (fresh potato sample) to 2.77 ± 0.27 following MD treatment and to 2.65 ± 0.14 in the case of OD treatment, whereas the

initial moisture content increased to 5.15 ± 0.17 g/g of dry matter in the case of hot water blanching, as expected.

With regard to the frying times, it is clearly seen in Figure 4.2 that blanched potato chips took longer (2.75 mins) to reach the desired final moisture content of ~0.02 g/g of dry matter, which is generally final moisture content of commercially sold chips (Costa et al., 2001). But MD and OD pre-treated chips required a shorter time of 2 mins to reach the same final moisture content which suggests that both these pre-treatments are promising.

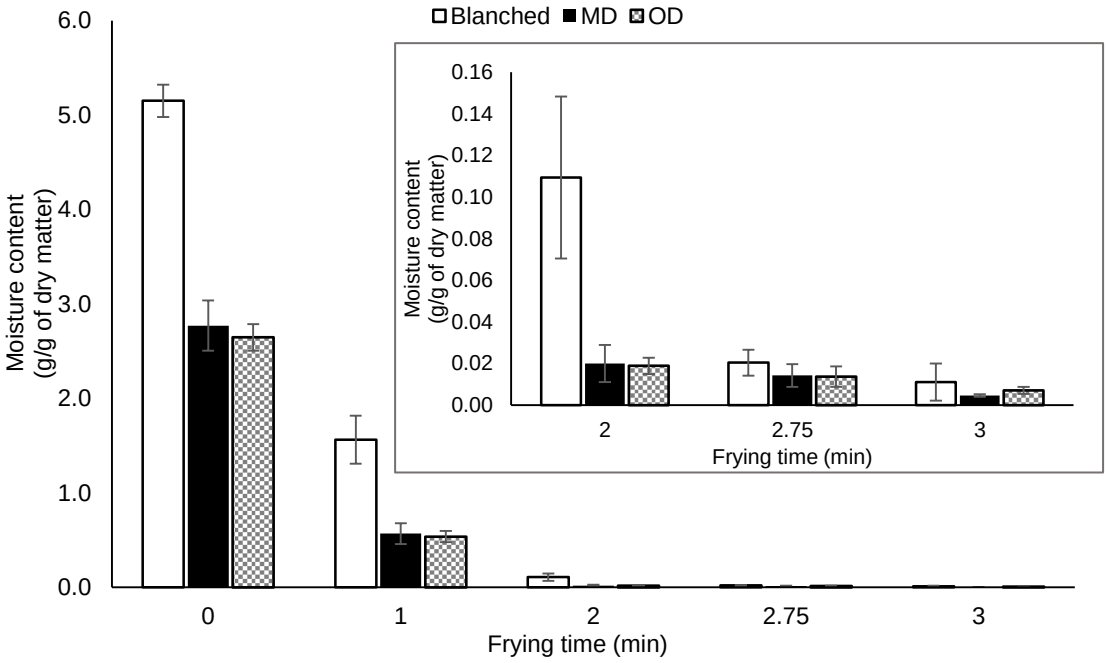

Figure 4.2 Transient moisture content in potato chips subjected to different pre-treatments. The moisture content at 2 mins and greater, can be read from magnified section. (MD = multi dip dehydration, OD = osmotic dehydration).

4.3.2 Oil content

Figure 4.3 shows the amount of oil absorbed by the potato chips made by employing different pre-treatments. It is clear that the oil content, in all cases, increased markedly in the first 2 mins of frying, after which, the increased more gradually. This observation is in agreement with earlier research, e.g. Ren et al. (2018); Bingol et al. (2012), who studied shiitake mushroom chips and French fries with blanching and osmotic dehydration as the pre-treatment methods. The blanched product resulted in the highest final oil uptake (0.41 ± 0.02 g/g of dry matter) compared to products treated under MD (0.33 ± 0.02 g/g of dry matter) and OD (0.34 ± 0.02 g/g of dry matter) to reach the same moisture content of ~0.02 g/g of dry matter. Although some studies showed that hot water blanching is able to reduce oil content of fried products by gelatinization of the surface starch (Ngobese, Workneh, and Siwela, 2017), the present study clearly shows that the blanched slices absorbed significantly more oil ($P<0.05$) compared to samples pre-treated by MD and OD treatments. Statistical analysis also showed that there was no significant difference ($P>0.05$) between the final oil content of samples pre-treated by MD and OD.

According to Ziaiifar et al. (2008), the initial moisture content is the main factor affecting the oil uptake, and in general, a higher initial moisture content leads to higher oil uptake by the fried products. As we can see in Figure 4.2, the blanched samples had the highest initial moisture content and correspondingly lost more water by evaporation during frying, which resulted in a more porous structure that facilitated oil absorption. Pre-treating the potato slices by OD and MD enables initial moisture content reduction without changing the structure significantly, and consequently results in lower final oil contents.

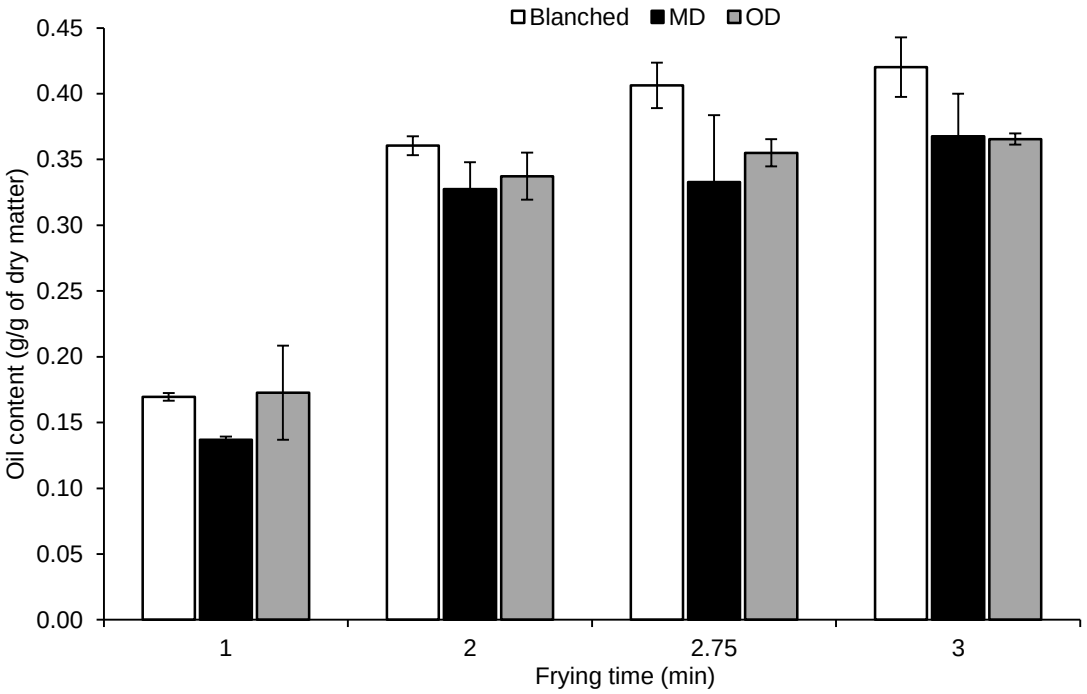

Figure 4.3 Oil content in potato chips subjected to different pre-treatments as a function of frying times. (MD = multi dip dehydration, OD = osmotic dehydration).

4.3.3 Texture analysis

The crust formation is very crucial in potato chips and it accounts for the crispiness, which is a key parameter in characterising its sensory quality. According to Miranda and Aguilera (2006), the moisture adsorption from humid air tends to soften the texture of chips during the cooling. Therefore, in this study, the chips were cooled to room temperature after frying and immediately packaged in airtight containers. This reduces the possibility of moisture uptake during storage, which also contributes to texture softening.

Figure 4.4 illustrates the hardness values, which refers to the maximum force needed to break the chips by probe penetration. These values indicate the crispiness of potato chips subjected to different pre-treatments. In general, the hardness increased progressively with frying time. Ziaiifar, Courtois, and Trystram (2010) studied the crust

thickness formation in French fries as a function of frying time and noted that the crust thickness significantly increased. Similar observations were also made in the case of tortilla chips (Moreira, 2007). Costa et al. (2001) found that the crust thickness increased linearly with the square root of frying time. The finding of the present study shows that the blanched potato chips had the lowest hardness value of 168 ± 11 g, followed by MD chips at 207 ± 21 g and OD chips at 253 ± 21 g when the final moisture content of ~0.02 kg H_2O/kg of dry matter was reached. According to Ren et al. (2018), a higher hardness corresponded to lower crispiness of the product. The highest hardness of OD chips may be due to the higher salt content than MD and blanched chips; see Table 4.1. Lagnika et al. (2018) noted that the hardness of a product increased with salt uptake due to the formation of a firmer structure, which accounts for the highest hardness of the OD pre-treated chips, with the MD pre-treated chip possessing relatively lower hardness.

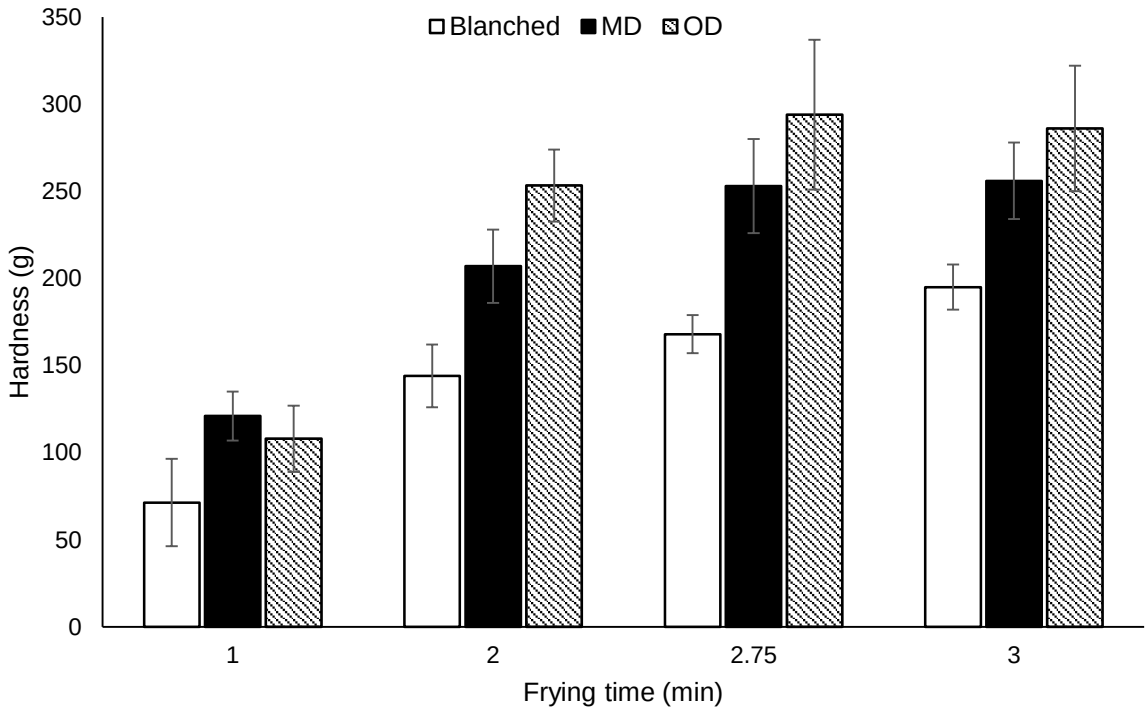

Figure 4.4 Effects of different pre-treatments on the texture of the fried potato slices.

4.3.4 Colour analysis

Colour is one of the most important criteria determining consumer acceptability. As mentioned earlier, the potato chips were ground before colour measurement, to reduce errors caused by the presence of isolated dark and brown spots on the surface resulting from natural defects or injuries to the fresh potatoes during sample preparation. In the present study, the colour values of potato chips ranged from 38.29 to 64.10 for L*, -0.76 to 9.67 for a* and 1.51 to 9.86 for b*. The parameters of L*, a*and b* are associated with lightness, redness and yellowness of samples. It is noted that the L* value decreased while the a* and b* values increased as frying progressed for all potato chips. This pattern of colour parameter variation shows that the potato chips become darker (overall) with frying, which also happens in the case of other products such as French fries (Krokida et al., 2001a).

It is interesting to compare the colour parameters values for all pre-treated potato chips when the final moisture content reaches ~0.02 g/g of dry matter. As listed in Table 4.1, the lowest values of L* and highest value of a* were observed in blanched chips at 39.71 ± 1.57 and 7.13 ± 0.51, respectively. Based on the statistical analysis, there is no significant difference (P>0.05) between all colour parameters for MD and OD pre-treated potato chips. In general, higher a* value is due to Maillard reaction caused by browning. The fried potato chips made from MD and OD pre-treatments exhibited least browning and gave higher brightness as indicated by greater values of L* and lower values of a* as shown in Figure 4.5.

Table 4.1 Colour parameters and salt content of fried potato chips made from different pre-treatments.

Treatment	Frying time (min)	Colour value[a]		
		L*	a*	b*
Blanched	1	64.10 ± 1.00^{c}	-0.76 ± 0.36^{a}	4.76 ± 1.30^{a}
	2	55.81 ± 1.63^{b}	4.15 ± 0.39^{b}	4.75 ± 0.93^{a}
	2.75	39.71 ± 1.57^{a}	7.13 ± 0.51^{c}	7.43 ± 0.78^{ab}
	3	38.29 ± 2.73^{a}	8.00 ± 0.62^{c}	8.00 ± 0.62^{b}
MD	1	55.12 ± 1.29^{c}	2.43 ± 0.30^{a}	2.62 ± 0.76^{a}
	2	50.24 ± 3.18^{ab}	6.61 ± 0.51^{b}	7.06 ± 0.58^{b}
	2.75	51.82 ± 2.41^{bc}	9.09 ± 1.28^{b}	7.47 ± 0.55^{b}
	3	45.98 ± 1.06^{a}	9.67 ± 0.39^{bc}	9.86 ± 0.51^{c}
OD	1	57.00 ± 0.70^{c}	1.37 ± 0.08^{a}	1.56 ± 0.39^{a}
	2	52.59 ± 1.78^{b}	7.00 ± 0.47^{b}	6.86 ± 1.10^{b}
	2.75	45.29 ± 1.09^{a}	9.13 ± 0.10^{c}	7.50 ± 1.23^{b}
	3	45.15 ± 0.63^{a}	9.06 ± 0.28^{c}	7.57 ± 0.33^{b}

Salt content (mg/g of dry matter)[b]		
Blanched	MD	OD
0.72 ± 0.12^{a}	36.58 ± 2.95^{b}	61.78 ± 4.25^{c}

[a] Means within the column for each colour parameters between frying time marked with the same first letters do not differ significantly at $P< 0.05$.

[b] Salt content of potato chips at moisture content of ~0.02 g/g of dry matter. Means with the row with the same first letters do not differ significantly at $P< 0.05$.

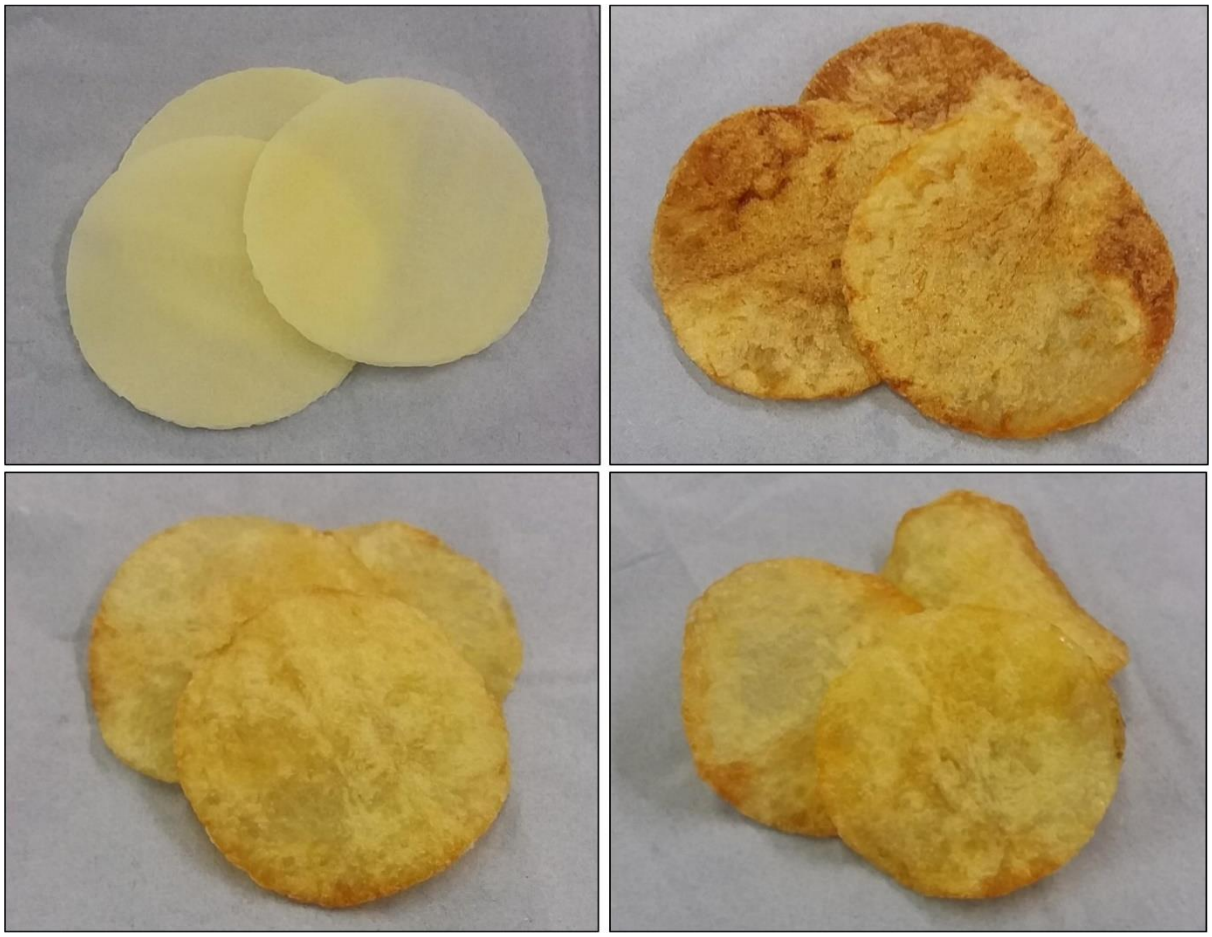

Figure 4.5 Appearance of potato chips (a) fresh sample, (b) fried blanched sample at a final moisture content of ~0.02 g/g of dry matter, (c) fried MD pre-treated sample at the same final moisture content and (d) fried OD pre-treated sample, also at the same final moisture content.

4.4 Conclusion

In this chapter, the influence of multi-dip dehydration pre-treatment prior to frying of potato chips in lowering oil content was investigated, and the findings were compared with other pre-treatments such as hot-water blanching and osmotic dehydration. The oil content of potato chips significantly reduced by about 17%, when the potato slices were subjected to dip dehydration prior to frying. Colour analysis revealed that multi-dip pre-treated chips developed a similar colour to that of osmo-dehydrated chips, but suffered less browning than blanched chips at a final moisture content of ~0.02 g/g of dry matter. Both osmotically dehydrated and multi dip dehydrated products had slightly higher hardness possibly due to salt uptake from the osmotic solution, but the salt content of the multi-dip pre-treated chips was lower. These findings indicate the benefit of multi-dip dehydration as a possible approach to produce healthier fried products, containing lower amounts of oil and salt. Furthermore, this technique also decreased the frying time by about 27%.

CHAPTER 5

SHALLOW FRYING OF POTATO AND CHICKEN CUBES: WATER LOSS, OIL GAIN, TEMPERATURE PROFILES AND TEXTURE DEVELOPMENT

Abstract

Unlike deep fat frying, where the product to be fried is completely immersed in 5-6 times its own mass of oil, the mechanism of water loss and thermal behaviour during shallow frying has not been systematically studied so far. Using potato and chicken cubes as illustrative products, this study reports on the water loss and oil gain occurring during the process as well as the transient variations in the temperature of frying medium and products. Shallow frying was conducted at two initial oil temperatures 150 °C and 180 °C with the initial mass of product to oil set at 10:1. Under similar frying temperatures, both products displayed different dehydration behaviour. It was found that the chicken cubes suffered two-fold higher water loss than potato due to evaporation and dripping occurring simultaneously. Due to excessive water lost, the frying medium became an oil-in-water emulsion - which was also confirmed by recording an increase in the electrical conductivity value. Surface hardness of the product increased with crust formation and this was noted to occur after the water had completely evaporated from the frying medium and the temperature increased well above 100 °C. The effects of regularly turning over the products during shallow frying were also investigated, and a lower turn-over frequency resulted in a harder fried chicken cubes.

**Part of this work has been submitted to Journal of Food Science.*

5.1 Introduction

Frying is an ancient process and one of crucial unit operations in food preparation. It is essentially a worthwhile dehydration process because of its ability to reduce moisture content in a significantly shorter time compared to other methods such as the use of convective air (Gertz, 2014). In conventional deep fat frying, the food is immersed in hot oil maintained at 150 to 200 °C and subjected simultaneous mass (mainly represented by water loss and oil intake) and heat transfer, which also changes the physical and chemical properties of the products and the oil (Hosseini et al., 2016; Ahmad Tarmizi et al., 2013). Due to its simplicity, it is extensively used in domestic and industrial practices as well as in business sectors such as restaurants and fast food outlets. Even though fried foods have significant fat content which can potentially lead to the health problems (Nayak et al., 2016; Dana and Saguy 2001), it still popular amongst consumers because the products possess desirable flavour, colour and crispy texture (Farinu and Baik, 2005).

In addition to deep fat frying, there are other types of frying which include shallow, pan and stir frying, which vary in terms of the amount of oil used in relation to the product being fried, the frying times, and the equipment used (Chiou et al., 2012). Shallow or pan frying is extensively employed in domestic as well as small business sectors. Shallow frying basically involves partial immersion of food material in hot oil, and therefore requires lesser amount of oil than deep fat frying. Although this method requires longer cooking times compared to deep frying, but it has many advantages. In addition to the product containing lesser oil, this process has been reported to increase nutritional value of prepared foods (Hrncirik and Zeelenberg, 2014; Hrncirik, 2010), inhibit total iodine loss (Rana and Raghuvanshi, 2013), and lower oil oxidation (Ghosh et al., 2012). Despite its widespread use, earlier research on this culinary practice only focused on the impact of the process on the quality of the products or the nutritional

properties of oil (Oria et al., 2017; Lu et al., 2016; Aniołowska et al., 2016; Hrncirik, 2010; Kalogeropoulos et al., 2007; Sioen et al., 2006), but there is very limited investigation on heat and mass transfer characteristics. There is only one significant study that evaluated the heat and mass transfer during contact heating of model foods (Cernela et al., 2015). A specially designed contact heating device was used in this study, and the results reported may differ with the domestic equipment employed. Furthermore, this study only heated model foods and did not consider turning-over or flipping of the product, which is common practice in shallow frying. By understanding the mechanism underpinning water loss and thermal profile and their relationships to various parameters, we will have vital information for scale-up and optimization of this process, and for designing energy efficient equipment (Safari et al., 2018; Neethu et al., 2016; Gertz, 2014). Besides, we will also be able to undertake modelling and simulation studies (Sandhu et al., 2016) to predict the quality of shallow fried foods.

Using chicken and potato as illustrative products, the aim of this chapter is to explore the dehydration behaviour and thermal profile during shallow frying, by measuring the transient temperature and the moisture and oil contents. In addition, the effect of turn-over frequency during frying, on water loss phenomena and product quality have also been determined. These food products have been chosen because they are the extensively shallow fried both at home and in food service outlets.

5.2 Materials and Methods

5.2.1 Raw Materials

Chicken breast without skin and potatoes (*Solanum tuberosum L.*) of *Maris Piper* variety were purchased from local store and stored in a refrigerator at 4 °C prior to use. Commercial rapeseed oil was purchased from local market in Reading UK. Sudan III dye,

petroleum ether (boiling point 40 °C to 60 °C) and cellulose extraction thimbles were obtained from Sigma-Aldrich, Dorset, UK.

5.2.2 Sample Preparation

Refrigerated chicken breasts were taken out of storage and diced manually into cubes, approximately 1.5 x 1.5 x 1.5 cm pieces. Due to the irregular nature of the breast pieces, it was difficult to obtain precisely sized cubes; consequently, the size dimension varied by approximately ± 0.3 cm. Meanwhile, potato tubers were washed, peeled and cut into similar cubes (1.5 x 1.5 x 1.5 cm) using a domestic dicer (Kitchen Craft, Birmingham, UK). The initial temperature before frying for both food samples was 10 °C ± 2 °C.

5.2.3 Domestic Shallow Frying Experiment

The shallow frying experiments were carried out in the same manner as in a household cooking process. A round shaped non-stick frying pan made of Teflon-coated aluminium (George Home, UK) with dimension 7 cm high and 20 cm inside diameter was used in this study. This frying pan was heated by a portable electrical hot plate cooker hob equipped with temperature control dials (Caterlite GG567, Bristol, UK).

Frying temperature was set by using a temperature control dial, and experiments at two different temperatures: 150 °C (knob position at 4) and 180 °C (knob position at 5), were performed. In each frying session, 15 g of oil was introduced into the pan fryer, which was heated and maintained at the desired temperature for 10 mins. About 150 g of food samples were fried for 25 mins and these were turned over every 5 mins to fry on the opposite sides (Turn-over A). At the end of frying, the fried samples were taken out from the oil and placed on absorbent paper to remove the excess oil and cooled at room

temperature for 10 mins. Then, the samples were used for subsequent analyses. After each frying operation, the frying pan was cleaned, and the used oil was discharged and replaced with fresh oil for the next frying session.

The effect of product turn over intervals during shallow frying was observed by conducting further experiments, where the product was flipped every 10 mins (Turn-over B), whilst maintaining the same frying temperature and sample cubes to oil ratio as Turn-over A.

5.2.4 Moisture Content and Water Loss Rate Determination

Moisture contents of the fried samples collected after 5 mins intervals were determined using dry-oven. The samples were crushed in a mortar, weighed and then dried at 105 °C in a convection oven (Weiss-Gallenkamp) for approximately 24 hrs until a constant weight was achieved (AOAC, 2000). The moisture content was expressed as g/g of dry matter. The total water loss was calculated using the following equation (Li and Ramaswamy, 2006):

$$WL\left(\frac{g}{100g}of\ fresh\ sample\right) = \frac{(M_0x_0 - M_tx_t)}{M_0} \times 100 \qquad (5.1)$$

where M_0 and M_t are the sample masses initially and at time, t respectively; x_0 and x_t are the moisture fractions (g/g wet basis) initially and at time, t. Total water loss data over the frying times were fitted with non-linear polynomial equation and the gradients of the curve were used to estimate the water loss rate.

5.2.5 Oil Content Determination

The oil content was determined by Soxhlet method, according to the Official Method of Analysis of AOAC International (AOAC, 2000). After the sample was dried by using an oven, the samples were ground and extracted with petroleum ether for 4 hrs

using Quickfit Soxhlet extraction system. Then, the solvent was evaporated from the extracted oil under vacuum at 50 °C by using a rotary evaporator (Buchi Rotavapor RE 111, Flawil, Switzerland), followed by drying the flask that contained the oil in an oven at 90 °C to constant weight. The difference between the initial (empty) and final weights of the flask gave the oil content (on a dry basis) and all experiments were performed in duplicate.

5.2.6 Temperature Measurement

Temperatures were recorded every 10 s using a 3-Channel K-thermocouple temperature data logger (Extech SD200, United State). A set of K-type thermocouples (0.1 mm of diameter) was used to record the temperatures at various locations in the samples: one thermocouple was placed approximately at the centre of the cube; two other thermocouples were inserted in such a way that these recorded the temperatures of the opposite faces of the cubes (less 1 mm from surfaces); and finally, one thermocouple also recorded the oil temperature real time as illustrated in Figure 5.1. The bottom temperature (T_b) and top temperature (T_t) refer, respectively, to the temperature of the cube face in contact with the oil and the surface exposed to air at the start of frying. After frying, the cubes were cut to ensure that the thermocouples were still located at the desired positions by using a digital calliper. All temperature measurements were performed in quadruplicates to check for reproducibility.

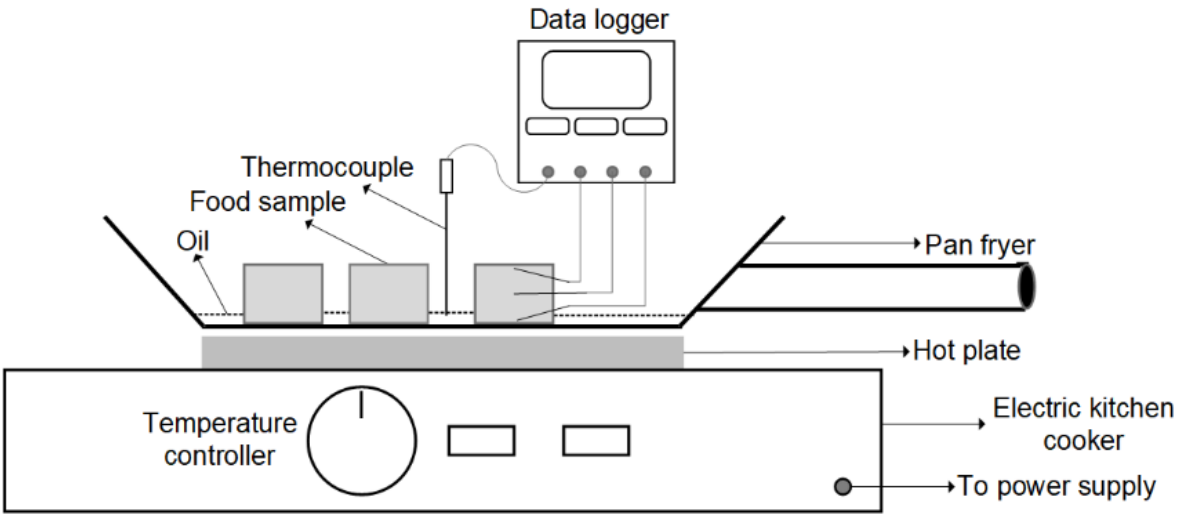

Figure 5.1 Schematic diagram of shallow frying equipment indicating the positions of the thermocouples.

5.2.7 Distribution of Water in Frying Oil

Electrical conductivity of the frying medium was measured to indicate the extent of water diffusing out of the sample during frying. Oil samples were collected after each 2.5 mins interval and placed in a glass beaker. The conductivity was measured by Accumet AET30 Conductivity Tester (Fisherbrand, Leicestershire, U.K.) at room temperature.

The appearance composition of the frying medium (containing oil and water) was observed by undertaking experiments in oil mixed with thermostable fat soluble Sudan red III dye. Dyed oil was prepared by dissolving 2 g of Sudan red III in 1 L of oil and then heated to 60 °C to make a uniform solution (Lalam et al., 2013). Then, frying was performed at desired temperature and the oil containing the water diffused from the samples was collected at different time intervals for up to 25 mins of frying. Oil was transferred to a bottle tube and the images of layer separation between oil and water with time were captured.

5.2.8 Texture Measurement

The texture of the fried product was measured using a Brookfield texture analyser fitted with 25 kg loading cell (CT3, Brookfield Engineering Laboratories, Middleborough, U.S.A.). A probe (2 mm diameter) was fitted to the instrument and a puncture test was carried out at a test speed of 1 mm/s at room temperature. The penetration depth was set to 2 mm in order to study the crust formation. The puncture test was carried out at two different surface positions and data obtained were analysed by software (TexturePro CT v1.2 software) provided by the instrument supplier.

5.2.9 Statistical Analysis

The frying experiments were performed in duplicate batches and samples were collected in triplicates from each batch. All experimental data reported in figures are the mean and standard deviation values calculated using Microsoft Office Excel 2013 and evaluated using Minitab 18 Statistical Software. A one-way analysis of variance (ANOVA) with Tukey's test was used to determine the significant difference involving more than two samples (each sample with replication data) at 95% confidence level.

5.3 Results and Discussion

5.3.1 Moisture Loss and Dehydration Rate

Figure 5.2 shows the moisture content (expressed as g/g of dry matter) and total water loss (expressed as g/100 g of fresh sample) of potato and chicken cubes at initial oil temperatures of 150 °C and 180 °C for up to 25 mins of frying time. As expected, the moisture content decreased significantly with time (P<0.05) for all cases and this trend is similar to deep fat and air frying (Teruel et al., 2015; Farinu and Baik, 2007).

It may be noted that the use of a higher frying temperature for a given time would result in consistently lower moisture content. For example, the moisture content of potato and chicken cubes at 150 °C only attained at 3.25 ± 0.18 g/g of dry matter and 2 ± 0.06 g/g of dry matter respectively, after 10 mins of frying, whereas frying at 180 °C for 10 mins reduced the moisture content to 2.73 ± 0.41 g/g of dry matter in the case potato and 1.45 ± 0.12 g/g of dry matter in the case of chicken. The higher rates of water loss at the higher frying temperature may be attributed to higher rates of heat transfer.

Figure 5.2 also shows that total water loss increases significantly (P<0.05) with the frying time for both the products, and frying at higher temperature also results in more water loss. It may be noted that the water loss data were calculated according to Equation 5.1. It is also interesting to note that the total water loss was always significantly higher in the case of chicken as compared with potato cubes, regardless of the frying temperature. Figure 5.2 clearly shows that the total water loss in chicken was nearly two times greater than in potato cubes after 10 mins frying at both temperatures. This finding seems surprising since the initial moisture content of potato (4.5 ± 0.08 g/g of dry matter) was significantly higher than chicken (3.22 ± 0.04 g/g of dry matter). Danowska-oziewicz and Karpin (2007) also reported similar results when they compared the effect of cooking on the chemical compositions of meat and vegetables. Although vegetable products (potato and carrot) contain higher moisture content, these authors noted that the loss of water from all meat products such as pork chops, fish fillets and chicken quarters were significantly higher than from vegetable products when cooked in a combi-oven under otherwise similar conditions.

According to Bayod et al. (2005), meat loses moisture in two ways: i) evaporation and ii) liquid dripping. These authors reported that water loss by dripping was dominant when meat is cooked at temperatures up to 100 °C. They also reported that, even at high

temperatures such as 175 °C, almost 80% of total water loss occurred through dripping, which occurs when i) fat in meat melts and leaves the structure by taking along with it some water and ii) water is squeezed out of the meat fibrous structure, due to the shrinkage occurring when proteins get denatured. The latter mechanism constitutes pressure driven removal of water, especially the water present in the interstitial spaces (Goñi and Salvadori, 2010). In contrast, water removal from vegetable structures is largely driven by mass transfer which occurs as a result of water concentration gradient developing between the surface and interior of the product. Such mass transfer controlled processes are inherently slow because of the compact structure of vegetable tissues (Tortoe et al., 2007a), and get even slower when biochemical reactions occur, such as starch gelatinization in potatoes, which, especially in the initial stages, involves significant swelling of starch granules following water absorption (Ratnayake and Jackson, 2008). Furthermore Ziaiifar, Heyd and Courtois (2009) reported that most existing pores of potato disappeared during starch gelatinization, which further reduced the tissue porosity and internal mass transfer coefficients.

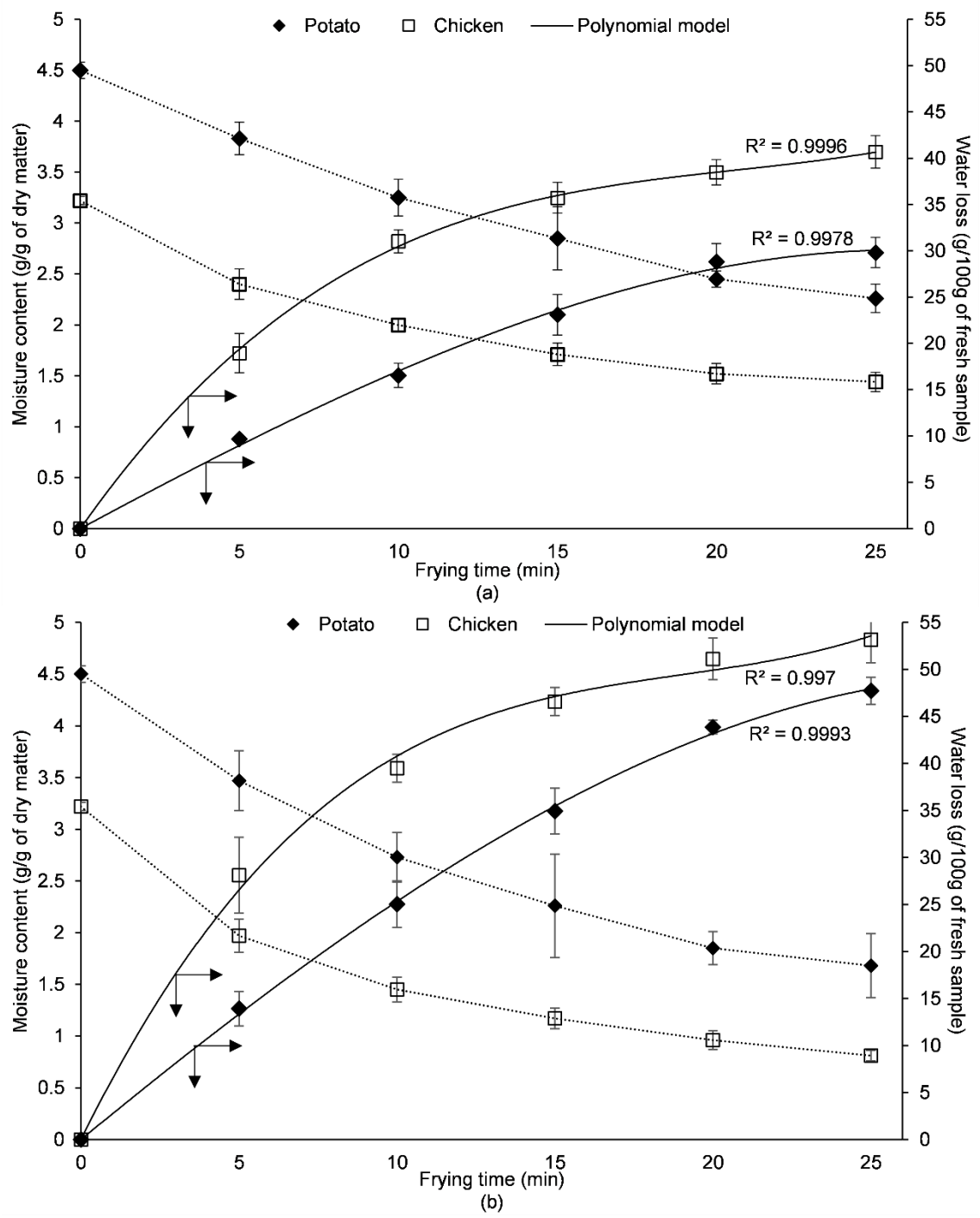

Figure 5.2 Moisture content and water loss variation of potato and chicken cubes at initial oil temperature of (a) 150 °C and (b) 180 °C of shallow frying. The turn-over of food samples during frying at 5, 10, 15 and 20 mins. Water loss data were fitted with third degree polynomial with $R^2 \geq 0.997$.

Water loss rate during frying was obtained by fitting the moisture content data shown in Figure 5.2(a) and Figure 5.2(b) to a third degree polynomial ($R^2 \geq 0.99$ for all cases) and subsequently evaluating the gradient as described detail by (Kemp et al., 2001). Figure 5.3 shows the rate of water loss as a function of frying time. It is clear from Figure 5.3 that the water loss rate falls with time (and the moisture content). This pattern appears to be similar to earlier studies on deep fat frying (Farkas and Hubbard 2000), vacuum frying (Yagua and Moreira, 2011) and conventional drying process (Wang et al., 2017; Chemkhi et al., 2005), and is commonly known as the falling rate dehydration. It is however interesting to note from Figure 5.3 that the water loss rate falls gradually in the case of potato and mimics conventional drying process, whereas it falls very sharply in the case of chicken. The difference in water loss rates between the two materials is attributable to the differences in water loss mechanisms discussed above. The high initial rate of water loss during frying is due to the high initial moisture content as well as due to the high initial temperature difference between the oil and the product (which will be discussed later). Based on the fact that the material temperatures rarely exceed 100 °C suggest that the water is predominantly moving in the liquid state. The slower rates of water loss during the latter stages of frying are due to the water having to diffuse from the interior of the product prior to exiting from the materials. In addition, the formation of crust also contributes to the reduction in water loss rate (Ziaiifar et al., 2009; Ziaiifar et al., 2008). The similar principles also applied in deep fat frying (Isik et al., 2016; Farinu and Baik, 2007).

Regardless of the frying temperature, Figure 5.3 shows that the water loss rate of chicken was significantly higher than potato, especially during the initial stages of frying. Accordingly, the maximum value of water loss rate registered for chicken at 180 °C was around 6.5 g/(100g.min) and 4.66 g/(100g.min) at 150 °C, whereas it was found to be

around 2.75 g/(100g.min) and 1.84 g/(100g.min) in potato cubes at 180 °C and 150 °C, respectively. As mentioned earlier, the main reason for higher water loss in the case of chicken is dripping. Persson et al. (2002) reported that protein denaturation also tended to exaggerate dripping loss. Another obvious observation is that higher rates of dehydration were observed for each material at a higher temperature.

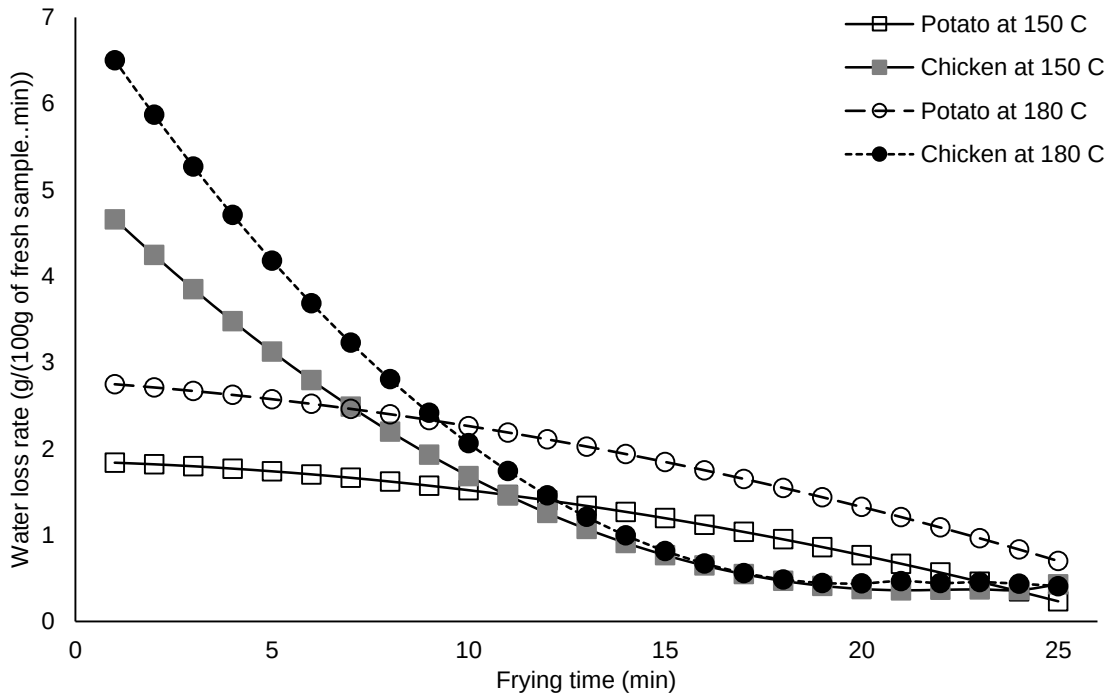

Figure 5.3 Water loss rate curve of fried potato and chicken cubes under different initial oil temperatures.

5.3.2 Oil Content

The oil contents of potato and chicken cubes during shallow frying are shown in Figure 5.4. It is interesting to note that the potato and chicken cubes exhibited a different trend of oil content variation with frying time. The oil content of potato cubes increased progressively with the frying time at both the frying temperatures. This observation is in agreement with most earlier studies on the deep fat frying (Teruel et al., 2015; Bingol et

al., 2012) and vacuum frying (Su et al., 2018; Yagua and Moreira, 2011). The increase in oil uptake with time occurs through the crust which is porous and allows oil to be absorbed, especially as the product cools after frying. Ziaiifar et al. (2010) also noted that the thickness of the crust increased with frying time and facilitated oil absorption due to its highly porous structure.

On the other hand, the oil content of chicken cubes which was initially 0.073 g /g of dry matter, dropped during the early stages of frying due to dripping which released both fat and water. Similar observations were also reported by (Rahimi et al., 2018) and (Sheridan and Shilton, 2002) in the cases of cooking chicken nugget and beef burger patties. After about 10 mins of frying at 180 °C, and 15 mins of frying at 150 °C, the net fat content began to progressively increase due to a combination of reduced dripping and increased oil uptake the crust formed.

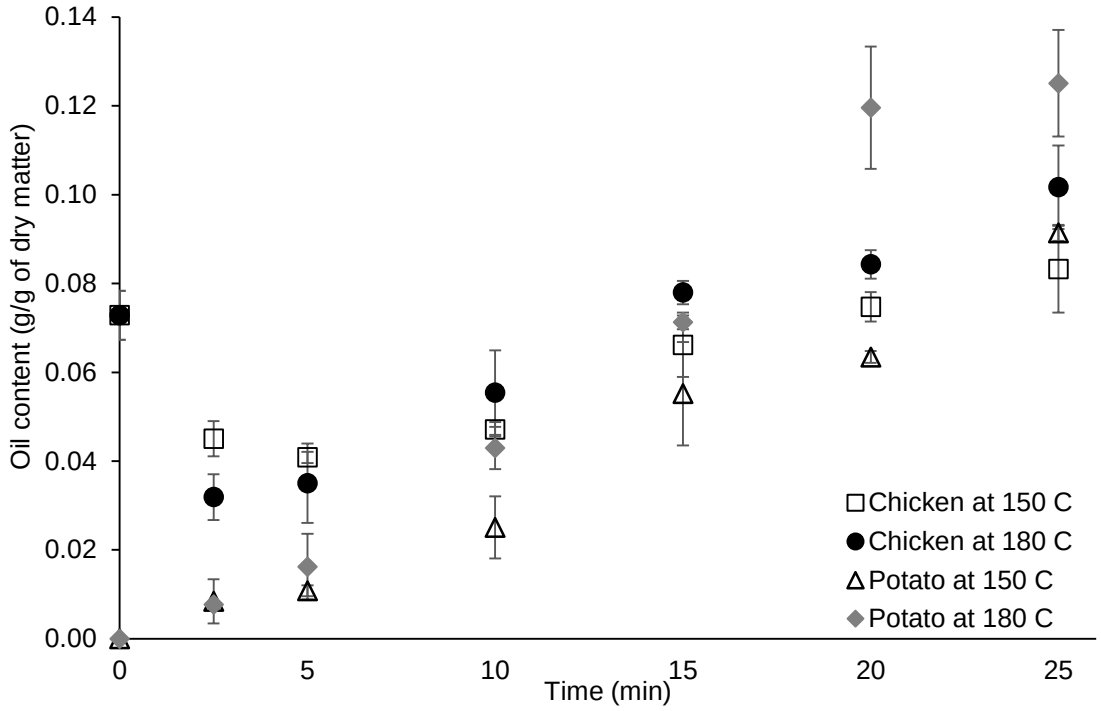

Figure 5.4 Oil content variation of potato and chicken cubes at initial oil temperature of 150 °C and 180 °C during shallow frying.

5.3.3 Temperature Profiles

Figures 5.5 and 5.6 show the temperature profiles of oil, core (i.e. the centre of the cube) and the top (T_t) and bottom (T_b) surfaces of a typical cube during shallow frying at 150 °C and 180 °C. The temperature variation patterns appear similar in all cases. The oil temperature drops substantially below the set frying temperature when the cubes are introduced into the pan because the oil mass relatively low in relation to the mass of cubes being fried (Koerten et al., 2017). The temperature then increases gradually with frying time but does not reach the initial temperature during the process. In the case of chicken cubes, the oil temperature drops to a value that is very close to the boiling point of water and rises rather gradually. At this stage, water evaporation not only occurs from the product surface but also from the oil-water emulsion formed by the dripping liquid (Goñi and Salvadori, 2010). As long as water escapes from the emulsion, the so-called oil

temperature remains close to the boiling point of water and this stage is also known as the evaporation zone (Persson et al., 2002). The oil temperature begins to increase more sharply after all the water in the emulsion has evaporated. This trend contrasts the observation in deep fat frying where the oil temperature is more or less constant due to the relatively high mass of oil being taken relative to the product (Lalam et al., 2013; Erdogdu and Dejmek, 2010; Segnini et al., 1999).

As one might expect, with each turnover of the product, the temperature of the cube that is in contact with the oil drops while that of the opposite surface increases. But the temperature at the core progressively increases regardless of the turnover. The present observation is generally in agreement with Persson et al. (2002) and Ikediala et al. (1996) who pan-fried chicken breast and beef patties. As mentioned earlier, T_t and T_b are the surface temperature of product exposed to air and oil at the start of the frying process, respectively. The variation of T_t and T_b are both sinusoidal except out of phase with each other.

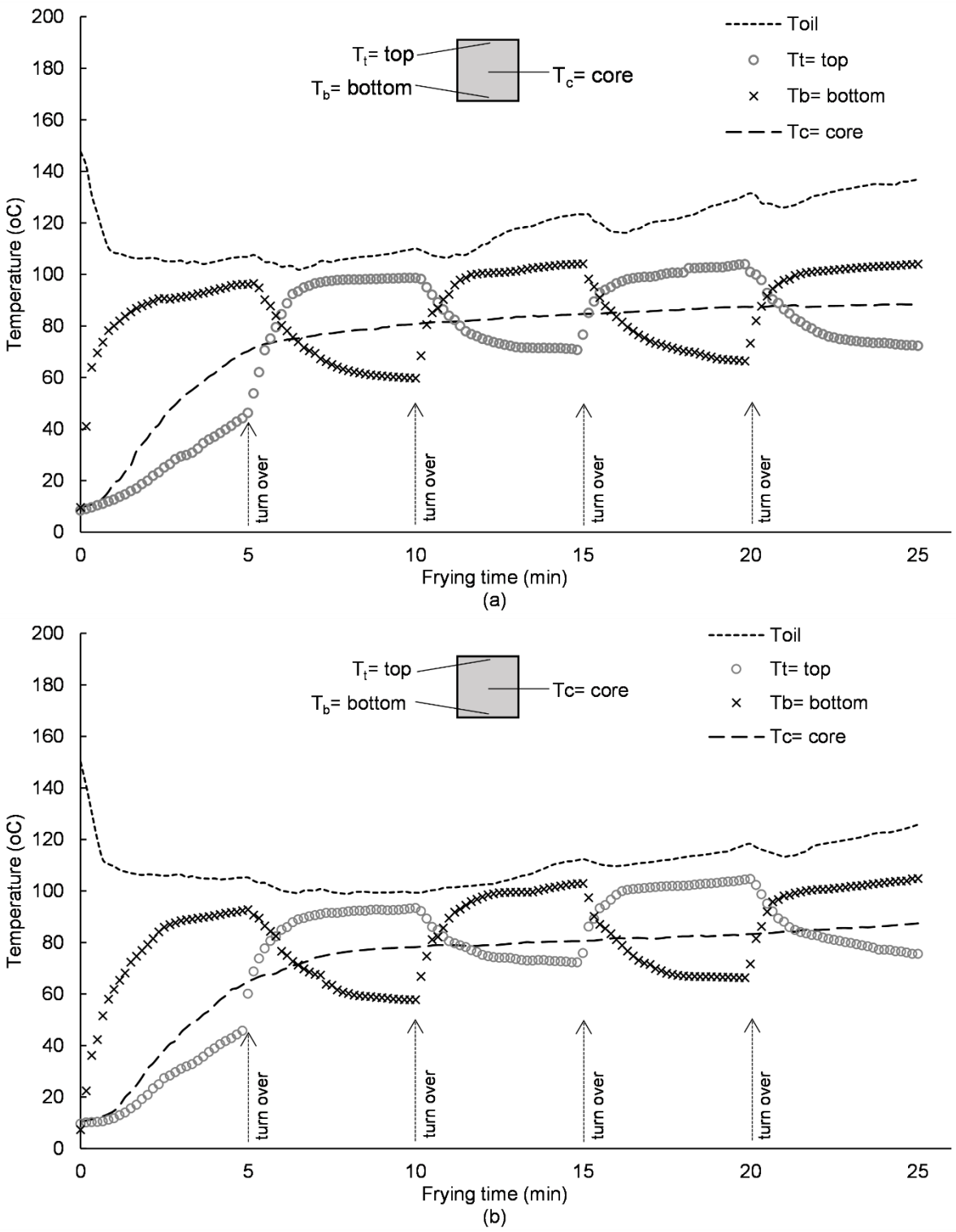

Figure 5.5 Temperature profiles of oil, core, and top and bottom surfaces of (a) potato and (b) chicken cubes at initial oil temperature of 150 °C during shallow frying.

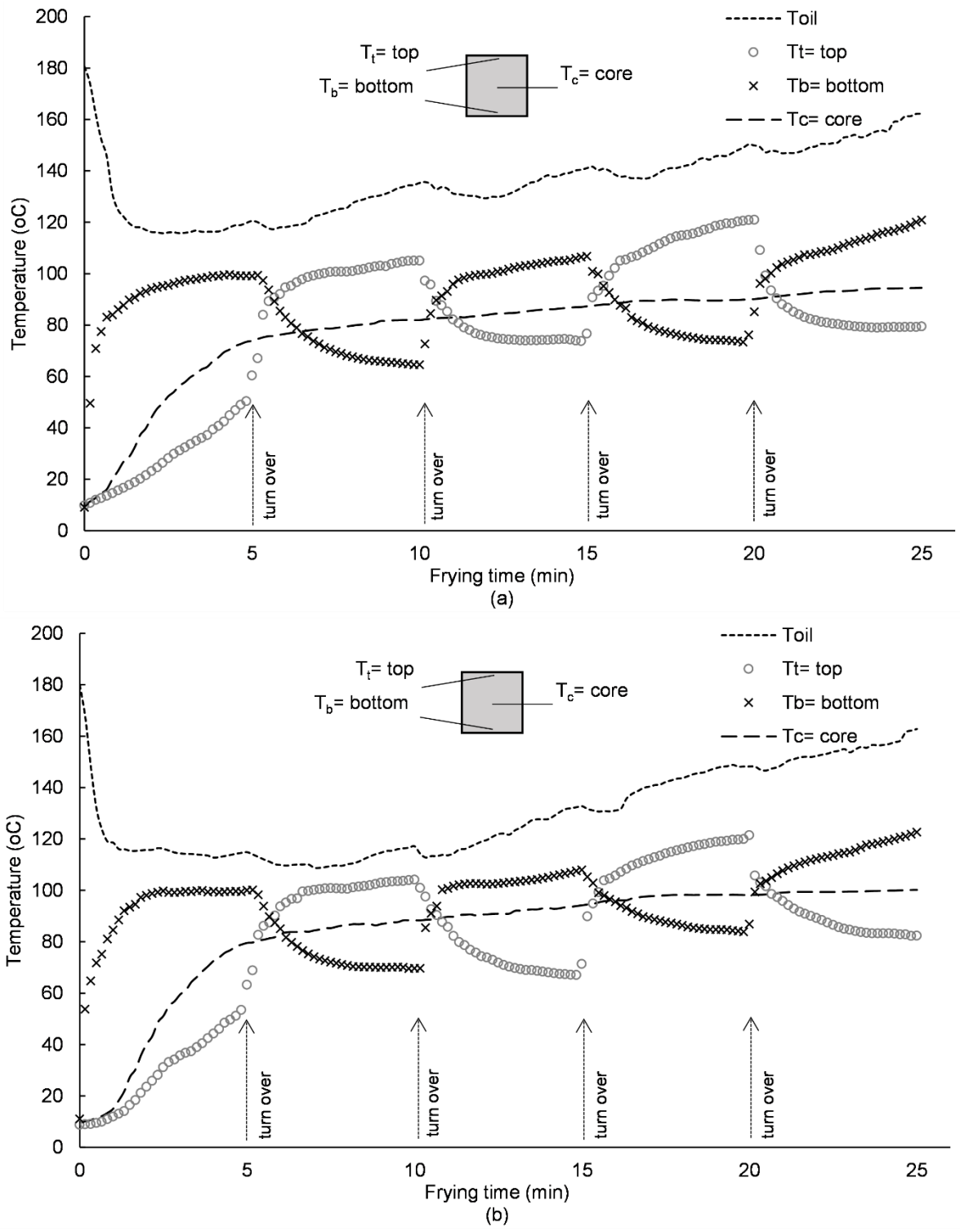

Figure 5.6 Temperature profiles of oil, core, and top and bottom surfaces of (a) potato and (b) chicken cubes at initial oil temperature of 180 °C during shallow frying.

5.3.4 Water Loss Mechanism during Shallow Frying

In order to observe the nature of the emulsion formed by dripping from the chicken and the oil used, the electrical conductivity of the shallow frying medium was measured and the data are shown in Figure 5.7. It is interesting to note that the initial electrical conductivity as well as in the later stages of frying is virtually zero, which indicates the dominance of oil in the frying medium. As the water is lost from the product especially by dripping, the frying medium becomes an oil-in-water emulsion and the electrical conductivity values increases sharply between 5 and 10 mins of frying at both the starting temperatures (150 and 180 °C). The conductivity then again drops to zero as the water evaporates and oil dominates the frying medium. In order to observe the nature of the frying medium at different temperatures, frying experiments were carried out in oil containing Sudan red III dye. It is clear from Figure 5.8 that a significant amount of water is observed after phase separation between 5 and 10 mins of frying which accounts for the high electrical conductivity values noted.

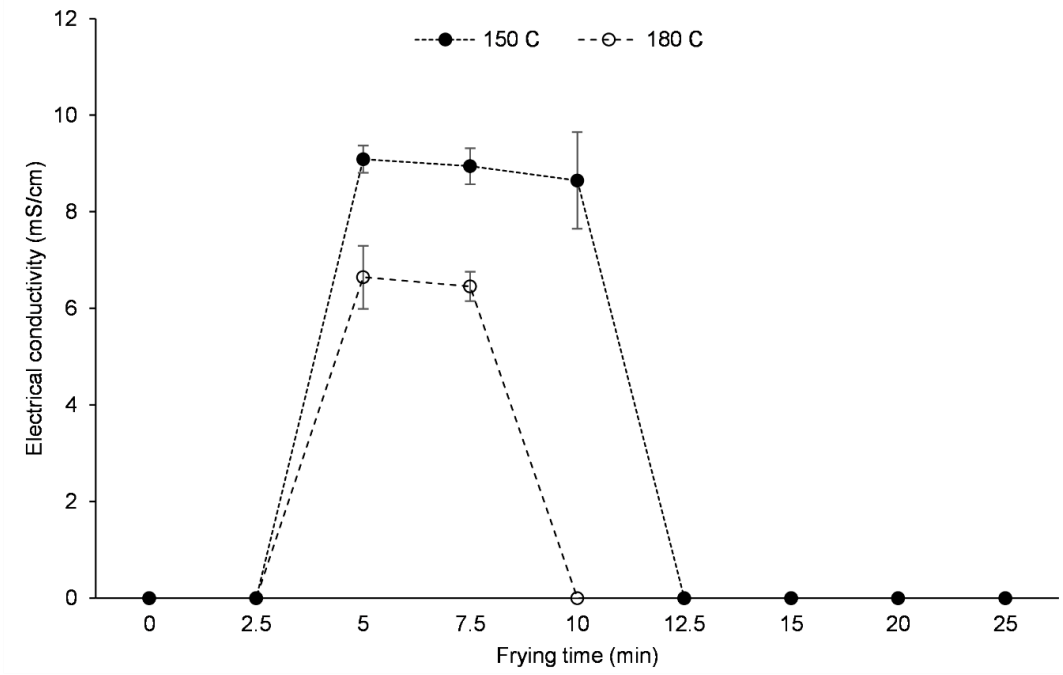

Figure 5.7 Electrical conductivity of the chicken frying medium (initial temperature of 150 °C and 180 °C.

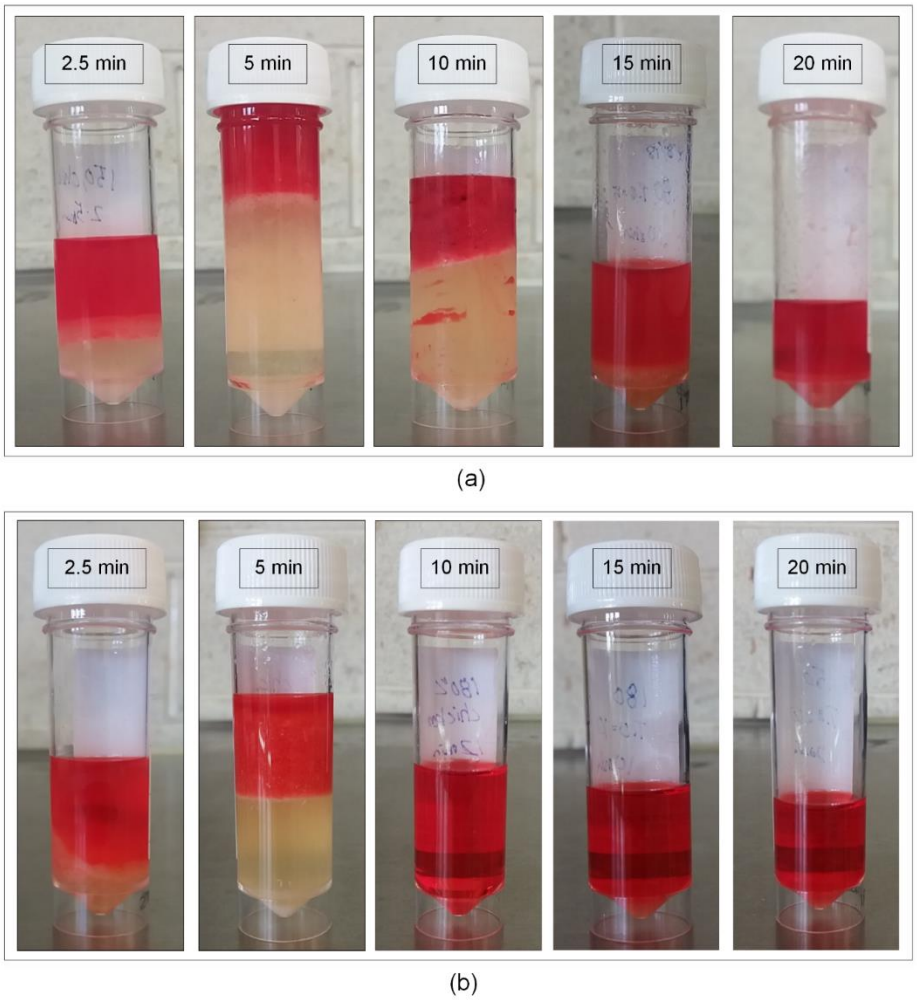

Figure 5.8 Appearance of oil medium composition during frying at initial of temperature of (a) 150 °C and (b) 180 °C of chicken cubes. Red layer is dyed oil, while colourless layer is water drip from chicken cubes.

5.3.5 Product Texture Development

Since frying leads to changes in quality attributes, especially in texture development due to crust formation, the hardness of the surface was measured in the case of chicken cubes at different frying times, and the results are given in Figure 5.9. It is clear from the figure that the hardness values remain more or less unchanged in the early stages of frying, but increase significantly after 15 mins when frying commences at 150 °C and after 10 mins when frying commences at 180 °C. The increasing hardness can be

attributed to crust formation. It is also interesting to note from Figure 5.7 that 10 mins after starting to fry at 180 °C, and 15 mins after starting to fry at 150 °C, corresponds to the electrical conductivity becoming virtually zero. In other words, texture development coincides with the loss of water and dominance of oil in the frying medium. It also coincides with a sharper increase in the product surface temperatures. Costa et al. (2001) reported that the crust formation commenced when the surface temperature of products reached 103 °C and the crust thickness increased with the square root of frying time.

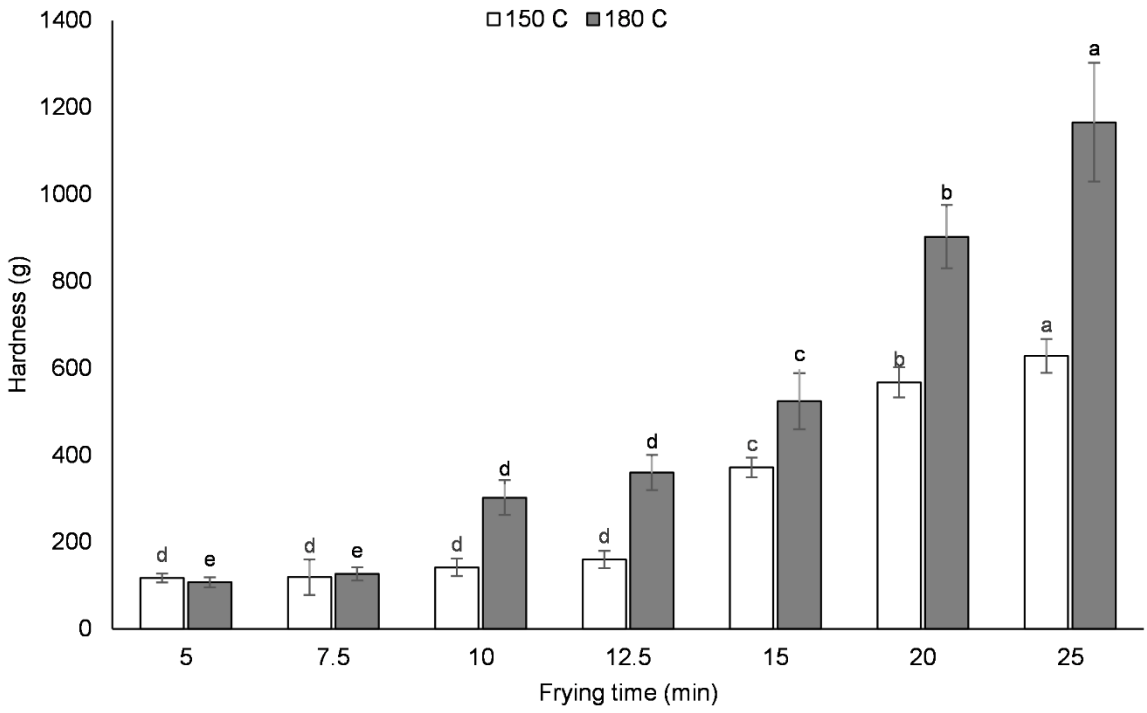

Figure 5.9 Hardness values profile of fried surface chicken cubes as a function of frying time (initial oil temperature at the start of frying 150 °C and 180 °C). Hardness value followed by the different letters are significantly different of each frying time (P<0.05).

5.3.6 Effect of Product Turn Over

As discussed in the previous section, the oil temperature briefly dropped (as shown in Figures 5.5 and 5.6) when the product was turned over, which can potentially slow down the water evaporation rate during frying and increase the liquid water content of the frying medium in the case of chicken cubes. Therefore, we tried to find out whether changing the turn-over frequency could influence the distribution of water in oil. Thus, an additional experiment was carried out at 180 °C with turn-over occurring every 10 mins (referred to as Turn-over B in Figures 5.10 and onwards) instead of every 5 mins (known as Turn-over A in Figures 5.10 and onwards).

Roughly similar oil temperature kinetics were observed at the start of frying, but significantly different trends were revealed later, after 5 mins of operation as compared to both cases involving turn-over as shown in Figure 5.10. Due to product turn-over, the oil temperature dropped at 5 mins in case of Turn-over A, while Turn-over B exhibited contrasting result, where the oil temperature increased steadily before slightly dropping after the chicken was flipped at 10 mins. These temperature kinetics may contribute to the changes in conductivity values which corresponded to the distribution of water dispersed in oil during frying under Turn-over B as illustrated in Figures 5.11 and 5.12. It is clear from Figure 5.10 that the oil temperature for Turn-over B is above that observed for Turn-over A. As a result, Figure 5.11 shows that the electrical conductivity only drops very briefly in the case of Turn-over B as compared to Turn-over A, and the texture is also harder (Figure 5.13).

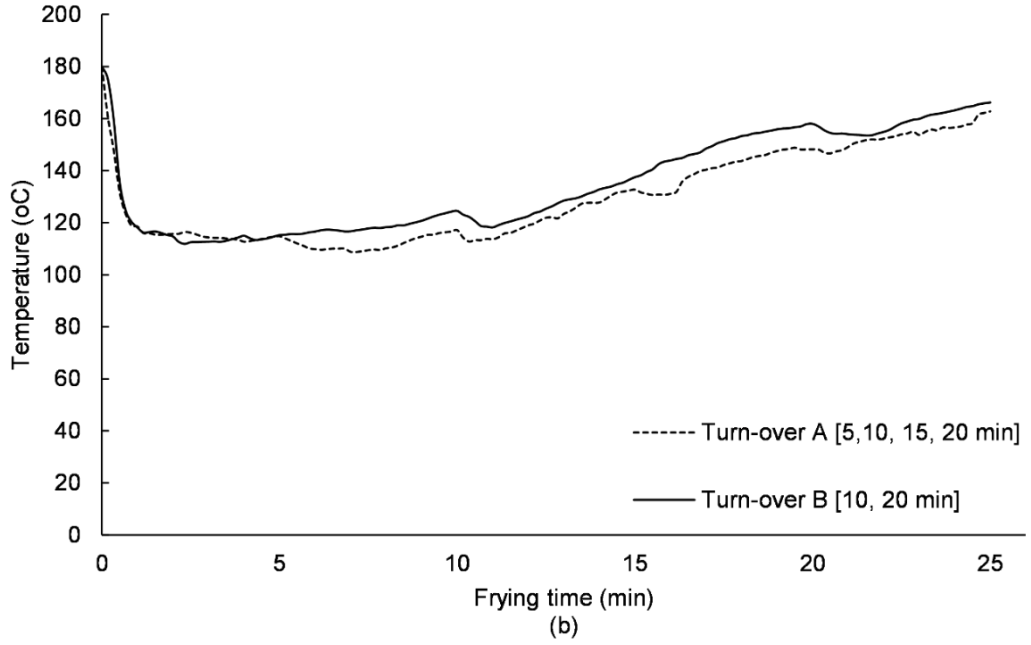

Figure 5.10 Variation in oil temperatures during frying at initial oil temperature of 180 °C when chicken cubes were flipped at Turn-over A and Turn-over B.

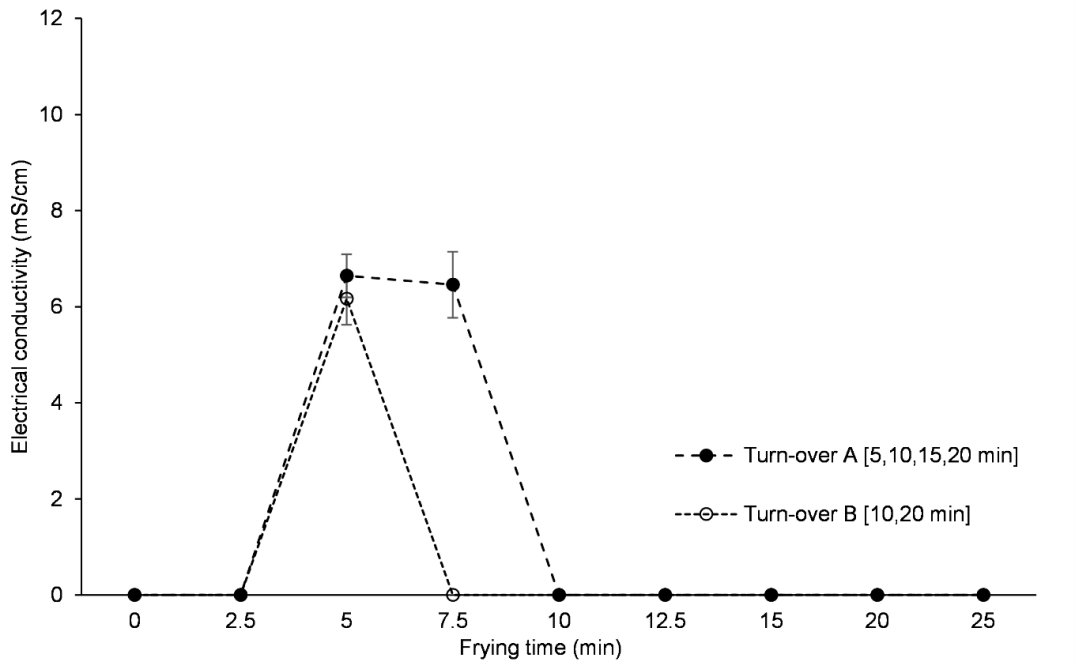

Figure 5.11 Electrical conductivity of oil medium during frying process at initial oil temperature of 180 °C when chicken cubes were flipped at Turn-over A and Turn-over B.

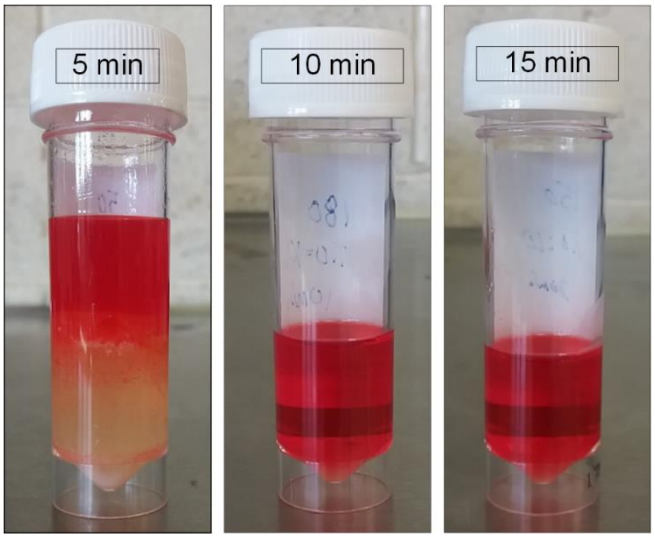

Figure 5.12 Appearance of oil medium composition during frying at initial oil temperature of 180 °C of chicken cubes subjected to Turn-over B. Red layer is dyed oil, while colourless layer is water drip from chicken cubes.

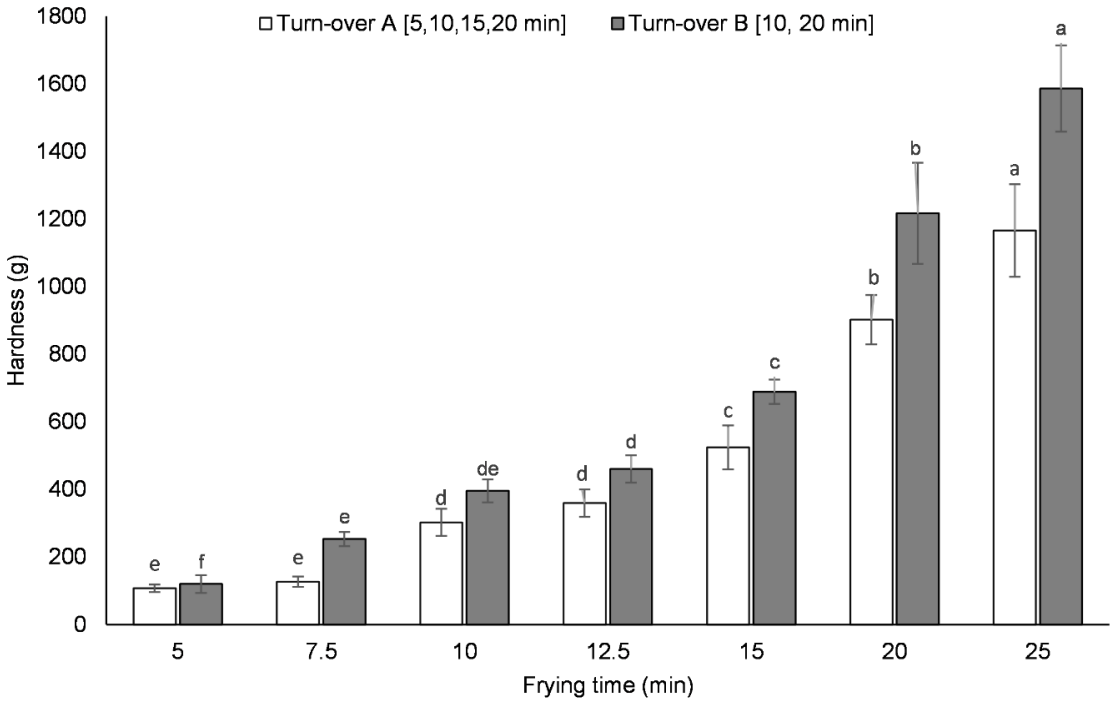

Figure 5.13 Hardness values profile of fried surface chicken cubes as a function of frying time at initial oil temperature of 180 °C when chicken cubes were flipped at Turn-over A and Turn-over B. Hardness value followed by the different letters are significantly different on each frying time (P<0.05).

5.4 Conclusions

1. This study explores the water loss mechanism and temperature profiles during domestic shallow frying of potato and chicken cubes at initial oil temperature of 150 and 180 °C. The higher initial oil temperature, as expected, resulted in a greater decrease in moisture content of both the products in a given time.
2. Chicken cubes were found to dehydrate by evaporation as well as dripping and therefore, resulted in a two-fold higher water loss in a given time when compared to potato. The oil content of chicken first decreased at the start of frying due to fat release during dripping, but subsequently, the oil content steadily increased as the crust formed.
3. The oil temperature dropped considerably when the products were introduced into pan and remained close to the boiling point of water (known as the evaporation zone) in the case of chicken cube. The water released from the products being fried turned the frying medium into an oil-in-water emulsion, which progressively lost water by evaporation. After water present in frying medium completely evaporated, the oil temperature began to increase, which also resulted in the formation of crust on the product accompanied by surface hardness. Meanwhile, the core product temperature steadily increased regardless of whether the products were turned over or not during frying. The temperatures of top and bottom surfaces of product exhibited periodic rise and fall depending on the product turn over frequency.
4. Electrical conductivity values of the frying medium were high during the initial 5 to 10 mins of frying indicating a dominant presence of water in frying medium to form an oil-in-water emulsion, as stated above. With prolonged frying, the water evaporated to result in a phase inversion and the formation of a water in oil emulsion.

5. When food products were regularly turned over during frying, a lower turn-over frequency resulted in a reduced period of frying in oil-in-water emulsion to form a harder texture in the case of chicken cubes.

CHAPTER 6

CONCLUDING REMARKS

6.1 Conclusion

6.1.1 Dehydration of Potato Slices Following Brief Dipping In Osmotic Solutions

In dip dehydration, potato slices were dipped in concentrated sugar (30 – 50 %) and salt solutions (5 – 15%) for a very short time and then left under ambient conditions to lose moisture. The water loss did not depend on the dipping time but increased with the concentration of the dipping solution. In terms of kinetics, a statistical analysis indicated that the total water loss significantly increased for 10 mins of operation when dipping was undertaken in NaCl solution. In the case of sucrose solution, the water loss continued for 40 mins due a greater osmotic driving force operating. The dehydration rate generally decreased in the later stage due to dilution of the osmotic solution that adhered on the material surface. Peleg model seemed to be adequate to describe the dehydration behaviours with the R^2 >0.98 and RMSE <0.018 in all cases. Multi-stage dipping, either in same concentration solution (treatment A) or in progressively concentrated solutions (treatment B), was undertaken and water loss monitored. The water loss values in multi dip dehydration were comparable to the values observed in osmotically dehydration, but the sugar/salt uptake were significantly lower. Thus, the dipped samples presented higher process efficiency index (ratio of moisture loss/solid gain) which is an important indicator of the quality of osmotic dehydration products.

6.1.2 Effects of Dip Dehydration as a Pre-Treatment for Frying Potato Chips

Multi stage dipping dehydration was used as a pre-treatment prior to frying potato chips with the aim of lowering oil content. The potato chips treated under multi dip pre-treatment (in NaCl 10%) were compared with other pre-treatment techniques i.e. osmotic dehydration (in NaCl 10%) and hot water blanching at 65 °C for 5 mins (control), which is typically used in the industry. Multi-dipped and osmo-dehydrated samples resulted in a statistically significant decrease in the frying time to reach the same final moisture content, i.e. from 2.75 mins to 2 mins, in comparison to blanched samples. Moreover, both pre-treatments resulted in the samples taking up 17 % less oil and gave better colour, exhibiting lower browning and higher brightness. However, osmo-dehydrated samples contained about 50% higher salt content than multi-dipped samples which led to a greater hardness value and low crispness of chips.

6.1.3 Shallow Frying of Potato and Chicken Cubes

By considering chicken and potato cubes as illustrative examples, the water loss mechanism and thermal behaviour during shallow frying, which is essentially practiced as a culinary operation, were studied. Although chicken had lower initial moisture content, it appeared to suffer two-fold higher water loss in a given time as compared to potato due to two mechanisms operating, i.e. evaporation and dripping, while potato cubes only lost water by evaporative mass transfer. Due to the excessive water released from the products, the frying medium turned into an oil-in-water emulsion soon after the commencement of frying and this was confirmed by measuring the electrical conductivity. The conductivity value was high during the initial 5 to 10 mins of frying indicating a dominant presence of water in frying medium to form an oil-in-water emulsion, as stated above. With time, the water subsequently evaporated completely, and

the frying medium temperature increased progressively and the crust began to be formed on the product accompanied by surface hardness. Meanwhile, the core product temperature steadily increased regardless of whether the products were turned over or not during frying. This chapter also reports on the effect of regularly turning over the products during shallow frying, and found that a lower turn-over frequency resulted in a significantly reduced period of frying in oil-in-water emulsion and also tended to form a product possessing a hard texture.

Based on the results of this research, dip dehydration can be used as an alternative to the osmotic dehydration in lowering moisture content of food sample, but at the same time reduces the sugar or salt uptake. Additionally, this method has potential as a frying pre-treatment to reduce the frying time and oil content of fried potato chips which yield a healthier product option. Lastly, the physical and engineering science underpinning shallow frying was explored in detail, and it found that water loss mechanism and thermal behaviour during shallow frying is depending on the type of raw food products. Moreover, turnover frequency during frying also affected to the quality of the fried products.

6.2 Recommendations for Future Work

- In this study, dip dehydration has only been established in the case of potato slices. It would be illustrative to repeat similar experiments with other fruits and vegetables to explore the performance of this technique.
- The potential of new pre-treatments such as ultrasound, high pressure processing (HPP), and vacuum application to increase the water loss rate during osmotic dehydration process have been widely reported in literature. It would be desirable

to investigate the effects of such techniques prior to multi-stage dip dehydration to find out if there are synergies possible by using such combinations.

- The potential of dip dehydration as pre-treatment has been studied here in the case of frying chips. The use of dip dehydration as pre-treatment prior to subsequent further processes such as conventional drying, freeze drying seems worth investigating.
- This research has focused on oil uptake and water loss occurring during shallow frying. It would be useful to develop mathematical models which include heat and mass transfer coefficients to simulate transport phenomena occurring and relate these to the product quality.
- During shallow frying, the oil temperature was found to drop considerably when the food products are introduced into the oil. It is therefore worth exploring frying approaches which minimize oil temperature reduction and reduce the period of frying in oil-in-water emulsion as well as the overall frying time.

REFERENCES

Abbasi Souraki, B., Ghaffari, A., & Bayat, Y. (2012). Mathematical modeling of moisture and solute diffusion in the cylindrical green bean during osmotic dehydration in salt solution. *Food and Bioproducts Processing*, *90*(1), 64–71.

Abriana, A., & Johannes, E. (2014). Turmeric extract as an antioxidant in repeatedly used cooking oil. *International Journal of Scientific & Technology Research*, *3*(12), 347–350.

Afjeh, F. A., Bassiri, A., & Nafchi, A. M. (2014). Optimization of vacuum frying parameters in combination with osmotic dehydration of kiwi slices to produce healthy product. *Journal of Chemical Health Risks*, *4*(1), 13–22.

Agustinelli, S. P., Menchón, D., Agüería, D., Sanzano, P., & Yeannes, M. I. (2014). Osmotic dehydration dynamic of common carp (cyprinus carpio) fillets using binary and ternary solutions. *Journal of Aquatic Food Product Technology*, *23*(2), 115–128.

Ahmad Tarmizi, A. H., Niranjan, K., & Gordon, M. (2013). Physico-chemical changes occurring in oil when atmospheric frying is combined with post-frying vacuum application. *Food Chemistry*, *136*, 902–908.

Ahmed, I., Qazi, I. M., & Jamal, S. (2016). Developments in osmotic dehydration technique for the preservation of fruits and vegetables. *Innovative Food Science and Emerging Technologies*, *34*, 29–43.

Akbarian, M., Ghasemkhani, N., & Moayedi, F. (2014). Osmotic dehydration of fruits in food industrial: A review. *International Journal of Bioscience*, *4*(1), 42–57.

Akdeniz, N., Sahin, S., & Sumnu, G. (2006). Functionality of batters containing different gums for deep-fat frying of carrot slices. *Journal of Food Engineering*, *75*(4), 522–526.

Al-Khusaibi, M. K., & Niranjan, K. (2012). The impact of blanching and high-pressure pretreatments on oil uptake of fried potato slices. *Food and Bioprocess Technology*, *5*, 2392–2400.

Alizadeh, L., Nayebzadeh, K., & Mohammadi, A. (2016). A comparative study on the in vitro antioxidant activity of tocopherol and extracts from rosemary and Ferulago angulata on oil oxidation during deep frying of potato slices. *Journal of Food Science and Technology*, *53*, 611–620.

Almeida, J. A. R., Mussi, L. P., Oliveira, D. B., & Pereira, N. R. (2015). Effect of temperature and sucrose concentration on the retention of polyphenol compounds and antioxidant activity of osmotically dehydrated bananas. *Journal of Food Processing and Preservation*, *39*, 1061–1069.

Alves, D. G., Barbosa, J. L., Antonio, G. C., & Murr, F. E. X. (2005). Osmotic dehydration of acerola fruit (Malpighia punicifolia L.). *Journal of Food Engineering*, *68*(1), 99–103.

Amami, E., Khezami, L., Jemai, A. B., & Vorobiev, E. (2014). Osmotic dehydration of some agro-food tissue pre-treated by pulsed electric field: Impact of impeller's Reynolds number on mass transfer and color. *Journal of King Saud University - Engineering Sciences*, *26*, 93–102.

Amami, Ezzeddine, Khezami, W., Mezrigui, S., Badwaik, L. S., Kammoun, A., Tellez, C., & Kechaou, N. (2017). Effect of ultrasound-assisted osmotic dehydration pretreatment on the convective drying of strawberry. *Ultrasonics - Sonochemistry*, *36*, 286–300.

Ammar, M. S. (2016). A comparative study on the antioxidant activity of tbhq and extracts from rosemary and oregano on oxidative stability of palm olein during deep fat frying of beef meatballs. *Middle East Journal of Applied Sciences*, *6*(4),

671–681.

Aniołowska, M., Zahran, H., & Kita, A. (2016). The effect of pan frying on thermooxidative stability of refined rapeseed oil and professional blend. *Journal of Food Science and Technology*, *53*(1), 712–720.

Antonio, G. C., Azoubel, P. M., Elizabeth, F., Murr, X., & Park, K. J. (2008). Osmotic dehydration of sweet potato (Ipomoea batatas) in ternary solutions. *Ciência e Tecnologia de Alimentos*, *28*(3), 696–701.

AOAC. (2000). *Official Method of Analysis of AOAC International*.

Assis, F. R., Morais, R. M. S. C., & Morais, A. M. M. B. (2016). Mass transfer in osmotic dehydration of food products: comparison between mathematical models. *Food Engineering Reviews*, *8*(2), 116–133.

Assis, F. R., Morais, R. M. S. C., & Morais, A. M. M. B. (2017). Osmotic dehydration with sorbitol combined with hot air convective drying of apple cubes. *Journal of Food Science and Technology*, *54*(10), 3152–3160.

Ayol, A., & Durak, G. (2013). Fate and effects of fry-drying application on municipal dewatered sludge. *Drying Technology*, *31*, 350–358.

Azarpazhooh, E., & Ramaswamy, H. S. (2010a). Evaluation of diffusion and azuara models for mass transfer kinetics during microwave-osmotic dehydration of apples under continuous flow medium-spray conditions. *Drying Technology*, *28*, 57–67.

Azarpazhooh, E., & Ramaswamy, H. S. (2010b). Microwave-osmotic dehydration of apples under continuous flow medium spray conditions: comparison with other methods. *Drying Technology*, *28*, 49–56.

Azoubel, P. M., & Murr, F. E. X. (2004). Mass transfer kinetics of osmotic dehydration of cherry tomato. *Journal of Food Engineering*, *61*(3), 291–295.

Azuara, E, Cortes, R., Garcia, H. S., & Beristain, C. I. (1992). Kinetic model for

osmotic dehydration and its relationship with Fick's second law. *International Journal of Food Science and Technology*, *27*, 409–418.

Azuara, Ebner, Flores, E., & Beristain, C. I. (2009). Water diffusion and concentration profiles during osmodehydration and storage of apple tissue. *Food and Bioprocess Technology*, *2*(4), 361–367.

Banerjee, A., Ghosh, S., & Ghosh, M. (2015). Anti-oxidative effect of turmeric on frying characteristics of soybean oil. *Journal of Food Science and Technology*, *52*(March), 1760–1765.

Barat, J. M., Fito, P., & Chiralt, A. (2001). Modeling of simultaneous mass transfer and structural changes in fruit tissues. *Journal of Food Engineering*, *49*(2–3), 77–85.

Barbosa Júnior, J. L., Cordeiro Mancini, M., & Hubinger, M. D. (2013). Mass transfer kinetics and mathematical modelling of the osmotic dehydration of orange-fleshed honeydew melon in corn syrup and sucrose solutions. *International Journal of Food Science and Technology*, *48*(12), 2463–2473.

Behsnilian, D., & Spiess, W. E. L. (2006). Osmotic dehydration of fruits and vegetable. In *13th World Congress of Food Science & Technology* (pp. 1857–1869).

Bingol, G., Wang, B., Zhang, A., Pan, Z., & McHugh, T. H. (2014). Comparison of water and infrared blanching methods for processing performance and final product quality of French fries. *Journal of Food Engineering*, *121*, 135–142.

Bingol, G., Zhang, A., Pan, Z., & McHugh, T. H. (2012). Producing lower-calorie deep fat fried French fries using infrared dry-blanching as pretreatment. *Food Chemistry*, *132*, 686–692.

Bouchon, P., Aguilera, J. M. M., & Pyle, D. L. L. (2003). Structure oil – absorption relationships during deep-fat frying. *Journal of Food Science*, *68*, 2711–2716.

Bouchon, Pedro. (2009). *Chapter 5 Understanding Oil Absorption During Deep-Fat*

Frying. *Advances in Food and Nutrition Research* (1st ed., Vol. 57). Elsevier Inc.

Bravo, J., Sanjuán, N., Ruales, J., & Mulet, A. (2009). Modeling the dehydration of apple slices by deep fat frying. *Drying Technology*, *27*(6), 782–786.

Brochier, B., Marczak, L. D. F., & Noreña, C. P. Z. (2015). Osmotic dehydration of yacon using glycerol and sorbitol as solutes: water effective diffusitivity evaluation. *Food and Bioprocess Technology*, *8*(3), 623–636.

Bunger, A, Moyano, P. C., Vega, R. E., Guerrero, P., & Osorio, F. (2004). Osmotic dehydration and freezing as combined processes on apple preservation. *Food Science and Technology International*, *10*(3), 163–170.

Bunger, Andrea, Moyano, P., & Rioseco, V. (2003a). NaCl soaking treatment for improving the quality of french-fried potatoes. *Food Research International*, *36*, 161–166.

Bunger, Andrea, Moyano, P., & Rioseco, V. (2003b). NaCl soaking treatment for improving the quality of french-fried potatoes. *Food Research International*, *36*(2), 161–166.

Cano-lamadrid, M., Lech, K., Michalska, A., Wasilewska, M., Figiel, A., Wojdyło, A., & Carbonell-barrachina, Á. A. (2017). Influence of osmotic dehydration pre-treatment and combined drying method on physico-chemical and sensory properties of pomegranate arils, cultivar Mollar de Elche. *Food Chemistry*, *232*, 306–315.

Cernela, J., Heyd, B., Keller, S., Bailleul, J. L., Maillard, M. N., Bonazzi, C., & Broyart, B. (2015). Experimental study of heat and mass transfer phenomena during the contact heating of solid food models. *Journal of Food Engineering*, *146*, 99–106.

Chandra, S., & Kumari, D. (2015). Recent development in osmotic dehydration of fruit

and vegetables: a review. *Critical Reviews in Food Science and Nutrition*, *55*, 552–561.

Chang, F. C., Ko, C. H., Wu, J. Y., Wang, H. P., & Chen, W. S. (2013). Resource recovery of organic sludge as refuse derived fuel by fry-drying process. *Bioresource Technology*, *141*, 240–244.

Chavan, U. D., & Amarowicz, R. (2012). Osmotic dehydration process for preservation of fruits and vegetables. *Journal of Food Research*, *1*(2), 202–209.

Chemkhi, S., Zagrouba, F., & Bellagi, A. (2005). Modelling and simulation of drying phenomena with rheological behaviour. *Brazilian Journal of Chemical Engineering*, *22*(2), 153–163.

Chiou, A., Salta, F. N., Kalogeropoulos, N., Mylona, A., Ntalla, I., & Andrikopoulos, N. K. (2007). Retention and distribution of polyphenols after pan-frying of French fries in oils enriched with olive leaf extract. *Journal of Food Science*, *72*(8), 574–584.

Chiou, Antonia, Kalogeropoulos, N., Boskou, G., & Salta, F. N. (2012). Migration of health promoting microconstituents from frying vegetable oils to French fries. *Food Chemistry*, *133*(4), 1255–1263.

Chiou, Antonia, Kalogeropoulos, N., Salta, F. N., Efstathiou, P., & Andrikopoulos, N. K. (2009). Pan-frying of French fries in three different edible oils enriched with olive leaf extract: oxidative stability and fate of microconstituents. *LWT - Food Science and Technology*, *42*(6), 1090–1097.

Choe, E., & Min, D. B. (2007). Chemistry of deep-fat frying oils. *Journal of Food Science*, *72*(5), 77–86.

Choo, W. S., Birch, E. J., & Dufour, J. P. (2007). Physicochemical and stability characteristics of flaxseed oils during pan-heating. *Journal of the American Oil*

Chemists' Society, *84*(8), 735–740.

Chung, J., Lee, J., & Choe, E. (2004). Oxidative stability of soybean and sesame. *Journal of Food Science*, *69*(7), 574–578.

Chwastek, A. (2014). Methods to increase the rate of mass transfer during osmotic dehydration of foods. *ACTA Scientiarum Polonorum Technologia Alimentaria*, *13*(4), 341–350.

Ciurzyńska, A., Kowalska, H., Czajkowska, K., & Lenart, A. (2016). Osmotic dehydration in production of sustainable and healthy food. *Trends in Food Science and Technology*, *50*, 186–192.

Corrêa, J. L. G., Dev, S. R. S., Gariepy, Y., & Raghavan, G. S. V. (2011). Drying of pineapple by microwave-vacuum with osmotic pretreatment. *Drying Technology*, *29*, 1556–1561.

Cortellino, G., Pani, P., & Torreggiani, D. (2011). Crispy air-dried pineapple rings: optimization of processing parameters. *Procedia Food Science*, *1*, 1324–1330.

Costa, R. M., Oliveira, F. A. R., & Boutcheva, G. (2001). Structural changes and shrinkage of potato during frying. *International Journal of Food Science and Technology*, *36*(1), 11–23.

Dalla Rosa, M., & Giroux, F. (2001). Osmotic treatments and problems related to the solution management. *Journal of Food Engineering*, *49*(2–3), 223–236.

Dana, D., & Saguy, I. S. (2001). Frying of nutritious foods: obstacles and feasibility. *Food Science and Technology Research*, *7*(4), 265–279.

Dana, D., & Saguy, I. S. (2006). Review: mechanism of oil uptake during deep-fat frying and the surfactant effect-theory and myth. *Advances in Colloid and Interface Science*, *128–130*, 267–272.

Danowska-oziewicz, M., & Karpin, M. (2007). The effect of cooking in a steam-

convection oven on the quality of selected dishes. *Journal of Food Service, 18*, 187–197.

Dehghannya, J., & Abedpour, L. (2017). Influence of a three stage hybrid ultrasound – osmotic – frying process on production of low-fat fried potato strips. *Journal of the Science of Food and Agriculture*.

Dehghannya, J., & Abedpour, L. (2018). Influence of a three stage hybrid ultrasound–osmotic–frying process on production of low-fat fried potato strips. *Journal of the Science of Food and Agriculture*, *98*(4), 1485–1491.

Deiana, M., Rosa, A., Cao, C. F., Pirisi, F. M., Bandino, G., & Dessi, M. A. (2002). Novel approach to study oxidative stability of extra virgin olive oils: importance of α-tocopherol concentration. *Journal of Agricultural and Food Chemistry*, *50*(15), 4342–4346.

Demiray, E., & Tulek, Y. (2017). The effect of pretreatments on air drying characteristics of persimmons. *Heat and Mass Transfer*, *53*(1), 99–106.

Dermesonlouoglou, E., Chalkia, A., & Taoukis, P. (2018). Application of osmotic dehydration to improve the quality of dried goji berry. *Journal of Food Engineering*, *232*, 36–43.

Dermesonlouoglou, E. K., Giannakourou, M. C., & Taoukis, P. (2007). Stability of dehydrofrozen tomatoes pretreated with alternative osmotic solutes. *Journal of Food Engineering*, *78*, 272–280.

Dermesonlouoglou, E. K., Pourgouri, S., & Taoukis, P. S. (2008). Kinetic study of the effect of the osmotic dehydration pre-treatment to the shelf life of frozen cucumber. *Innovative Food Science & Emerging Technologies*, *9*, 542–549.

Devic, E., Guyot, S., Daudin, J. D., & Bonazzi, C. (2010). Effect of temperature and cultivar on polyphenol retention and mass transfer during osmotic dehydration of

apples. *Journal of Agricultural and Food Chemistry*, *58*(1), 606–614.

Do, T. X., Lim, Y., Cho, H., Shim, J., Yoo, J., Rho, K., Park, B.-Y. (2017). Process modeling and energy consumption of fry-drying and torrefaction of organic solid waste. *Drying Technology*, *35*(6), 754–765.

Donsì, G., Ferrari, G., & Nigro, R. (1996). Experimental determination of thermal conductivity of apple and potato at different moisture contents. *Journal of Food Engineering*, *30*(3–4), 263–268.

Doymaz, I. (2004). Pretreatment effect on sun drying of mulberry fruits (Morus alba L.). *Journal of Food Engineering*, *65*(2), 205–209.

Durán, M., Pedreschi, F., Moyano, P., & Troncoso, E. (2007). Oil partition in pre-treated potato slices during frying and cooling. *Journal of Food Engineering*, *81*, 257–265.

El-Aouar, Â. A., Azoubel, P. M., Barbosa, J. L., & Xidieh Murr, F. E. (2006). Influence of the osmotic agent on the osmotic dehydration of papaya (Carica papaya L.). *Journal of Food Engineering*, *75*(2), 267–274.

Erdogdu, F., & Dejmek, P. (2010). Determination of heat transfer coefficient during high pressure frying of potatoes. *Journal of Food Engineering*, *96*(4), 528–532.

Eren, I., & Kaymak-Ertekin, F. (2007). Optimization of osmotic dehydration of potato using response surface methodology. *Journal of Food Engineering*, *79*, 344–352.

Eroglu, E., & Yildiz, H. (2010). Recent developments in osmotic dehydration. *Academic Food Journal*, *8*(6), 24–28.

Falade, K. O., & Igbeka, J. C. (2017). Osmotic dehydration of tropical fruits and vegetables. *Food Reviews International*, *23*(4), 373–405.

Fan, L., Zhang, M., & Mujumdar, A. S. (2006). Effect of various pretreatments on the quality of vacuum-fried carrot chips. *Drying Technology*, *24*(11), 1481–1486.

Farinu, A., & Baik, O. (2005). Deep fat frying of foods — transport phenomena. *Food Reviews International*, *21*, 389–410.

Farinu, A., & Baik, O. D. (2007). Heat transfer coefficients during deep fat frying of sweetpotato:effects of product size and oil temperature. *Food Research International*, *40*, 989–994.

Farkas, B. E., & Hubbard, L. J. (2000). Analysis of convective heat transfer during immersion frying. *Drying Technology*, *18*(6), 1269–1285.

Fernandes, F. A. N., & Rodrigues, S. (2008). Application of ultrasound and ultrasound-assisted osmotic dehydration in drying of fruits. *Drying Technology*, *26*, 1509–1516.

Ferrari, C. C., Carmello-Guerreiro, S. M., Bolini, H. M. A., & Hubinger, M. D. (2010). Structural changes, mechanical properties and sensory preference of osmodehydrated melon pieces with sucrose and calcium lactate solutions. *International Journal of Food Properties*, *13*(1), 112–130.

Ferrari, C. C., & Hubinger, M. D. (2008). Evaluation of the mechanical properties and diffusion coefficients of osmodehydrated melon cubes. *International Journal of Food Science and Technology*, *43*, 2065–2074.

Filho, R. S. F., Gusmão, R. P. de, Silva, Wi. P. da, Gomes, J. P., Filho, E. V. C., & El-Aouar, Â. A. (2015). Osmotic dehydration of pineapple stems in hypertonic sucrose solutions. *Agricultural Sciences*, *6*, 916–924.

Filipovic, V., Biljana, C., Nic, M., & Filipovic, J. (2017). The effects of technological parameters on chicken meat osmotic dehydration process efficiency. *Journal of Food Processing and Preservation*, *41*, 1–7.

Fillion, L., & Henry, C. J. K. (1998). Nutrient losses and gains during frying: a review. *International Journal of Food Sciences and Nutrition*, *49*(2), 157–168.

Galoburda, R., Murniece, I., & Karklina, D. (2013). The amount of fat absorbed by non-stored and stored potatoes after frying and roasting. *International Journal of Bioscience, Biochemistry and Bioinformatics*, *3*(4), 345–348.

García-Martínez, E., Martínez-Monzó, J., Camacho, M. M., & Martínez-Navarrete, N. (2002). Characterisation of reused osmotic solution as ingredient in new product formulation. *Food Research International*, *35*(2–3), 307–313.

Garcia-noguera, J., Oliveira, F. I. P., Weller, C. L., Rodrigues, S., & Fernandes, F. A. N. (2014). Effect of ultrasonic and osmotic dehydration pre-treatments on the colour of freeze dried strawberries. *Journal of Food Science and Technology*, *51*(9), 2222–2227.

García, M., Díaz, R., Martínez, Y., & Casariego, A. (2010). Effects of chitosan coating on mass transfer during osmotic dehydration of papaya. *Food Research International*, *43*, 1656–1660.

Garmakhany, AD Daraei, Mirzaei, H. O., Maghsoudlou, Y., Kashaninejad, M., & Jafari, S. M. (2010). Influence of partial drying on oil uptake & quality attributes of french fries. *Journal of Agricultural, Science and Technology*, *4*(1), 41–46.

Garmakhany, Amir Daraei, Mirzaei, H. O., Nejad, M. K., & Maghsudlo, Y. (2008). Study of oil uptake and some quality attributes of potato chips affected by hydrocolloids. *European Journal of Lipid Science and Technology*, *110*(11), 1045–1049.

Germer, S. P. M., Morgano, M. A., Da Silva, M. G., Silveira, N. F. de A., & Souza, E. de C. G. (2016). Effect of reconditioning and reuse of sucrose syrup in quality properties and retention of nutrients in osmotic dehydration of guava. *Drying Technology*, *34*(8), 997–1008.

Gertz, C. (2014). Fundamentals of the frying process. *European Journal of Lipid Science and Technology*, *116*(6), 669–674.

Ghosh, P. K., Chatterjee, D., & Bhattacharjee, P. (2012). Alternative methods of frying and antioxidant stability in soybean oil. *Advance Journal of Food Science and Technology*, *4*(1), 26–33.

Giannakourau, M. C., & Taoukis, P. S. (2003). Stability of dehydrofrozen green peas pretreated with nonconventional osmotic agents. *Food Engineering and Physical Properties*, *68*(6), 2002–2010.

Giovanelli, G., Brambilla, A., Rizzolo, A., & Sinelli, N. (2012). Effects of blanching pre-treatment and sugar composition of the osmotic solution on physico-chemical, morphological and antioxidant characteristics of osmodehydrated blueberries (Vaccinium corymbosum L.). *Food Research International*, *49*(1), 263–271.

Giraldo, G., Talens, P., Fito, P., & Chiralt, A. (2003). Influence of sucrose solution concentration on kinetics and yield during osmotic dehydration of mango. *Journal of Food Engineering*, *58*(1), 33–43.

Goñi, S. M., & Salvadori, V. O. (2010). Prediction of cooking times and weight losses during meat roasting. *Journal of Food Engineering*, *100*(1), 1–11.

Graham-Acquaah, S., Ayernor, G. S., Bediako-Amoa, B., Saalia, F. S., Afoakwa, E. O., & Abbey, L. (2015). Effect of blanching and frying on textural profile and appearance of yam (Dioscorea rotundata) french fries. *Journal of Food Processing and Preservation*, *39*(1), 19–29.

Grenier, D., Bohuon, P., Meot, J. M., Lecomte, D., & Bailleres, H. (2007). Heat and mass transfer in fry drying of wood. *Drying Technology*, *25*(1–3), 511–518.

Grootveld, M., Rodado, V. R., & Silwood, C. J. L. (2014). Detection, monitoring, and deleterious health effects of lipid oxidation products generated in culinary oils during thermal stressing episodes. *INFORM*, *25*(10), 614–624.

Halder, A., Dhall, A., & Datta, A. K. Ã. (2007). An improved, easily implementable,

porous media based model for deep-fat frying part i: model development and input parameters. *Food and Bioproducts Processing*, *85*, 209–219.

Heredia, a., Barrera, C., & Andrés, a. (2007). Drying of cherry tomato by a combination of different dehydration techniques. Comparison of kinetics and other related properties. *Journal of Food Engineering*, *80*, 111–118.

Horuz, T. I., & Maskan, M. (2015). Effect of the phytochemicals curcumin , cinnamaldehyde , thymol and carvacrol on the oxidative stability of corn and palm oils at frying temperatures. *Journal of Food Science and Technology*, *52*(12), 8041–8049.

Hosseini, H., Ghorbani, M., & Meshginfar, N. (2016). A review on frying : procedure, fat, deterioration progress and health hazards. *Journal of the American Oil Chemists' Society*, *93*(4), 445–466.

Hrncirik, K. (2010). Stability of fat-soluble vitamins and PUFA in simulated shallow-frying. *Lipid Technology*, *22*(5), 107–109.

Hrncirik, K., & Zeelenberg, M. (2014). Stability of essential fatty acids and formation of nutritionally undesirable compounds in baking and shallow frying. *Journal of the American Oil Chemists' Society*, *91*, 591–598.

Hua, X., Wang, K., Yang, R., Kang, J., & Yang, H. (2015). Edible coatings from sunflower head pectin to reduce lipid uptake in fried potato chips. *LWT - Food Science and Technology*, *62*, 1220–1225.

Ikediala, J., & Correia, L. (1996). Finite element modeling of heat transfer in meat patties during single-sided pan-frying. *Journal of Food Science*, *61*(4), 796–802.

Ikediala, J., Correia, L., Fenton, G., & Ben-abdallah, N. (1996). Finite element modeling of heat transfer in meat patties during single-sided pan-frying. *Journal of Food Science*, *61*(4), 796–802.

Isik, B., Sahin, S., & Sumnu, G. (2016). Pore development, oil and moisture distribution in crust and core regions of potatoes during frying. *Food and Bioprocess Technology*, 1–8.

Ismial. (2013). Impact of pre-treatments on the acrylamide formation and organoleptic evolution of fried potato chips. *American Journal of Biochemistry and Biotechnology*, *9*(2), 90–101.

Ispir, A., & Toğrul, I. T. (2009). Osmotic dehydration of apricot: kinetics and the effect of process parameters. *Chemical Engineering Research and Design*, *87*(2), 166–180.

James, C., Purnell, G., & James, S. J. (2014). A critical review of dehydrofreezing of fruits and vegetables. *Food and Bioprocess Technology*, *7*, 1219–1234.

Kalogeropoulos, N., Mylona, A., Chiou, A., Ioannou, M. S., & Andrikopoulos, N. K. (2007). Retention and distribution of natural antioxidants (tocopherol, polyphenols and terpenic acids) after shallow frying of vegetables in virgin olive oil. *LWT - Food Science and Technology*, *40*, 1008–1017.

Kalogianni, E. P., Karastogiannidou, C., & Karapantsios, T. D. (2009). Effect of the presence and absence of potatoes under repeated frying conditions on the composition of palm oil. *Journal of the American Oil Chemists' Society*, *86*(6), 561–571.

Karizaki, V. M., Sahin, S., Sumnu, G., Mosavian, M. T. H., & Luca, A. (2013). Effect of ultrasound-assisted osmotic dehydration as a pretreatment on deep fat frying of potatoes. *Food and Bioprocess Technology*, *6*, 3554–3563.

Kassama, L. S., & Ngadi, M. O. (2007). Pore development and moisture transfer in chicken meat during deep-fat frying. *Drying Technology*, *23*, 907–923.

Kaymak-Ertekin, F., & Sultanoglu, M. (2000). Modelling of mass transfer during osmotic

dehydration of apples. *Journal of Food Engineering*, *46*(4), 243–250.

Kemp, I. C., Fyhr, B. C., Laurent, S., Roques, M. A., Groenewold, E., Tsotsas, E., Kind, M. (2001). Methods for processing experimental drying kinetics data. *Drying Technology*, *19*(1), 15–34.

Khin, M. M., Zhou, W., & Perera, C. O. (2007). Impact of process conditions and coatings on the dehydration efficiency and cellular structure of apple tissue during osmotic dehydration. *Journal of Food Engineering*, *79*, 817–827.

Kiatsrichart, S., Brewer, M. S., Cadwallader, K. R., & Artz, W. E. (2003). Pan-frying stability of nusun oil, a mid-oleic sunflower oil. *Journal of the American Oil Chemists' Society*, *80*(5), 479–483.

Kilincceker, O., & Hepsag, F. (2012). Edible coating effects on fried potato balls. *Food and Bioprocess Technology*, *5*, 1349–1354.

Kita, A., Lisińska, G., & Gołubowska, G. (2007). The effects of oils and frying temperatures on the texture and fat content of potato crisps. *Food Chemistry*, *102*(1), 1–5.

Kita, Agnieszka, & Lisińska, G. (2005). The influence of oil type and frying temperatures on the texture and oil content of French fries. *Journal of the Science of Food and Agriculture*, *85*(15), 2600–2604.

Kobyliński, J. P., Krygier, K., Karlovits, G., & Szydłowska-Czerniak, A. (2016). Effect of specific oil surface area on the thermal stressing of rapeseed oil during heating in an electric frying pan. *Journal of the American Oil Chemists' Society*, *93*(2), 237–242.

Koerten, K. N. Van, Somsen, D., Boom, R. M., & Schutyser, M. A. I. (2017). Modelling water evaporation during frying with an evaporation dependent heat transfer coefficient. *Journal of Food Engineering*, *197*, 60–67.

Krokida, M. ., Oreopoulou, V., Maroulis, Z. ., & Marinos-Kouris, D. (2001a). Effect of osmotic dedydration pretreatment on quality of french fries. *Journal of Food Engineering*, *49*(4), 339–345.

Krokida, M. K., Oreopoulou, V., Maroulis, Z. B., & Marinos-Kouris, D. (2001b). Deep fat frying of potato strips—quality issues. *Drying Technology*, *19*(5), 879–935.

Lagnika, C., Huang, J., Jiang, N., Li, D., Liu, C., Song, J., Zhang, M. (2018). Ultrasound-assisted osmotic process on quality of microwave vacuum drying sweet potato. *Drying Technology*, *0*(0), 1–13.

Lakshmishri Roy, D. B. (2015). Osmotic dehydration of litchi using sucrose solution: effect of mass transfer. *Journal of Food Processing & Technology*, *6*(7), 1–7.

Lalam, S., Sandhu, J. S., Takhar, P. S., Thompson, L. D., & Alvarado, C. (2013). Experimental study on transport mechanisms during deep fat frying of chicken nuggets. *LWT - Food Science and Technology*.

Leeratanarak, N., Devahastin, S., & Chiewchan, N. (2006). Drying kinetics and quality of potato chips undergoing different drying techniques. *Journal of Food Engineering*, *77*(3), 635–643.

Li, H., & Ramaswamy, H. S. (2006). Osmotic dehydration of apple cylinders: I. conventional batch processing conditions. *Drying Technology*, *24*(5), 619–630.

Li, Jinwei, Zhang, T., Liu, Y., & Fan, L. (2016). Effects of initial moisture content on the oil absorption behavior of potato chips during frying process. *Journal of Oleo Science*, *65*(4), 303–310.

Li, Juan, Chotiko, A., Kyereh, E., Zhang, J. I. E., Liu, C., Vandeker, V., Sathivel, S. (2017). Development of a combined osmotic dehydration and cryogenic freezing process for minimizing quality changes during freezing with application to fruits and vegetables. *Journal of Food Processing and Preservation*, *41*(1), 1–8.

Lima, K. C. M. de, Barros, H. D. de F., Passos, T. S., & Maciel, B. L. L. (2019). The effect of using different oils and paper towel in vegetable oil absorption of fried recipes. *Journal of Culinary Science and Technology*, *17(4)*, 373–384.

Lu, R., Yang, Z., Song, H., Zhang, Y., Zheng, S., Chen, Y., & Zhou, N. (2016). The aroma-active compound, acrylamide and ascorbic acid contents of pan-fried potato slices cooked by different temperature and time. *Journal of Food Processing and Preservation*, *40*, 183–191.

Luchese, C. L., Gurak, P. D., & Marczak, L. D. F. (2015). Osmotic dehydration of physalis (Physalis peruviana L.): evaluation of water loss and sucrose incorporation and the quantification of carotenoids. *LWT - Food Science and Technology*, *63*(2), 1128–1136.

Lyu, J., Yi, J., Bi, J., Chen, Q., Zhou, L., & Liu, X. (2017). Effect of sucrose concentration of osmotic dehydration pretreatment on drying characteristics and texture of peach chips dried by infrared drying coupled with explosion puffing drying. *Drying Technology*, *35*(15), 1887–1896.

Maciel, R. D. A., Manoel, A., & Pena, S. (2016). Influence of the process parameters on osmotic dehydration of mapara (Hypophthalmus edentatus) fillet. *Journal of Food Science and Technology*, *53*(1), 676–684.

Madamba, P. S., & Lopez, R. I. (2002). Optimization of the osmotic dehydration of mango (Mangifera Indica L.) slices. *Drying Technology*, *20*(6), 1227–1242.

Maestrelli, A., Scalzo, R. Lo, Lupi, D., Bertolo, G., & Torreggiani, D. (2001). Partial removal of water before freezing:cultivar and pre-treatments as quality factors of frozen muskmelon (Cucumis melo, cv reticulatus Naud.). *Journal of Food Engineering*, *49*, 255–260.

Manafi, M., Hesari, J., Peighambardoust, H., & Khoyi, M. R. (2010). Osmotic

dehydration of apricot using salt-sucrose solutions. *International Journal of Biological, Biomolecular, Agricultural, Food and Biotechnological Engineering*, *4*(8), 574–577.

Marani, C. M., & Agnelli, M. E. (2007). Osmo-frozen fruits: mass transfer and quality evaluation. *Journal of Food Engineering*, *79*, 1122–1130.

Martínez-Ávila, M., Vélez-Ruiz, J. F., & Sosa-Morales, M. E. (2010). Combination of hot air drying and deep-fat frying to reduce the oil content in chicken nuggets. *International Journal of Food Science and Technology*, *45*(10), 2101–2107.

Mathlouthi, M. (2001). Water content, water activity, water structure and the stability of foodstuffs. *Food Control*, *12*, 409–417.

Matusek, A., Czukor, B., & Merész, P. (2008). Comparison of sucrose and fructo-oligosaccharides as osmotic agents in apple. *Innovative Food Science and Emerging Technologies*, *9*(3), 365–373.

Matuska, M., Lenart, A., & Lazarides, H. N. (2006). On the use of edible coatings to monitor osmotic dehydration kinetics for minimal solids uptake. *Journal of Food Engineering*, *72*(1), 85–91.

Mayor, L., Moreira, R., Chenlo, F., & Sereno, A. M. (2007). Osmotic dehydration kinetics of pumpkin fruits using ternary solutions of sodium chloride and sucrose. *Drying Technology*, *25*, 1749–1758.

Md Salim, N. S., Garièpy, Y., Raghavan, V., & Yildiz, F. (2016). Effects of operating factors on osmotic dehydration of broccoli stalk slices. *Cogent Food & Agriculture*, *2*(1), 1134025.

Medina-vivanco, M., Sobral, P. J. A., & Hubinger, M. D. (2002). Osmotic dehydration of tilapia fillets in limited volume of ternary solutions. *Chemical Engineering Journal*, *86*, 199–205.

Mercali, G. D., Ferreira Marczak, L. D., Tessaro, I. C., & Zapata Noreña, C. P. (2011). Evaluation of water, sucrose and NaCl effective diffusivities during osmotic dehydration of banana (Musa sapientum, shum.). *LWT - Food Science and Technology*, *44*, 82–91.

Mercali, G. D., Marczak, L. D. F., Tessaro, I. C., & Noreña, C. P. Z. (2012). Osmotic dehydration of bananas (Musa sapientum, shum.) in ternary aqueous solutions of sucrose and sodium chloride. *Journal of Food Process Engineering*, *35*(1), 149–165.

Mestdagh, F., De Wilde, T., Fraselle, S., Govaert, Y., Ooghe, W., Degroodt, J.-M., De Meulenaer, B. (2008). Optimization of the blanching process to reduce acrylamide in fried potatoes. *LWT - Food Science and Technology*, *41*(9), 1648–1654.

Miranda, M. L., & Aguilera, J. M. (2006). Structure and texture properties of fried potato products. *Food Reviews International*, *22*(2), 173–201.

Mišljenović, N. M., Koprivica, G. B., Pezo, L. L., Kuljanin, T. A., Solarov, B. S., & Filipĉev, B. V. (2011). Application of peleg model to study mass transfer during osmotic dehydration of apple in sugar beet molasses. *Acta Periodica Technologica*, *42*, 91–100.

Moreira, R G. (2007). Chapter 7: Deep-fat frying. In *Heat Transfer in Food Processing*, 13, 209–237.

Moreira, Rosana G., Sun, X., & Chen, Y. (1997). Factors affecting oil uptake in tortilla chips in deep-fat frying. *Journal of Food Engineering*, *31*(4), 485–498.

Moyano, P. C., & Pedreschi, F. (2006). Kinetics of oil uptake during frying of potato slices: Effect of pre-treatments. *LWT - Food Science and Technology*, *39*(3), 285–291.

Mukherjee, S., & Chattopadhyay, P. K. (2007). Whirling bed blanching of potato cubes

and its effects on product quality. *Journal of Food Engineering*, *78*, 52–60.

Mundada, M., Hathan, B. S., & Maske, S. (2011). Mass transfer kinetics during osmotic dehydration of pomegranate arils. *Journal of Food Science*, *76*(1), 31–39.

Nagai, L. Y., Santos, A. B., Faria, F. A., Boscolo, M., & Mauro, M. A. (2015). Osmotic dehydration of mango with ascorbic acid impregnation: influence of process variables. *Journal of Food Processing and Preservation*, *39*, 384–393.

Naknean, P., Maneyam, R., & Kam-Onsri, A. (2013). Effect of different osmotic agents on the physical, chemical and sensory properties of osmo-dried cantaloupe. *Chiang Mai Journal of Science*, *40*(3), 427–439.

Nayak, P. K., Dash, U. M. A., Rayaguru, K., & Krishnan, K. R. (2016). Physio-chemical changes during repeated frying of cooked oil: a review. *Journal of Food Biochemistry*, *40*, 371–390.

Neethu, K. C., Sharma, A. K., Pushpadass, H. A., Eljeeva, F. M., & Manjunatha, M. (2016). Prediction of convective heat transfer coef fi cient during deep-fat frying of pantoa using neurocomputing approaches. *Innovative Food Science and Emerging Technologies*, *34*, 275–284.

Ngobese, N. Z., Workneh, T. S., & Siwela, M. (2017). Effect of low-temperature long-time and high-temperature short-time blanching and frying treatments on the French fry quality of six Irish potato cultivars. *Journal of Food Science and Technology*, *54*(2), 507–517.

Nunes, Y., & Moreira, R. G. (2009). Effect of osmotic dehydration and vacuum-frying parameters to produce high-quality mango chips. *Journal of Food Science*, *74*(7), 355-362.

Ochoa-Martinez, C. I., Ramaswamy, H. S., & Ayala-Aponte, A. A. (2007). A comparison of some mathematical models used for the prediction of mass transfer kinetics in

osmotic dehydration of fruits. *Drying Technology*, *25*, 1613–1620.

Ohm, T. I., Chae, J. S., Kim, J. E., Kim, H. kyum, & Moon, S. H. (2009). A study on the dewatering of industrial waste sludge by fry-drying technology. *Journal of Hazardous Materials*, *168*(1), 445–450.

Ohm, T. I., Chae, J. S., Lim, J. H., & Moon, S. H. (2012). Evaluation of a hot oil immersion drying method for the upgrading of crushed low-rank coal. *Journal of Mechanical Science and Technology*, *26*(4), 1299–1303.

Oke, E. K., Idowu, M. A., Sobukola, O. P., Adeyeye, S. A. O., & Akinsola, A. O. (2018). Frying of food: a critical review. *Journal of Culinary Science and Technology*, *16*(2), 107–127.

Oladejo, A. O., Ma, H., Qu, W., Zhou, C., Wu, B., Uzoejinwa, B., & Onwude, I. (2018). Application of pretreatment methods on agricultural products prior to frying: a review. *Journal of the Science of Food and Agriculture*, *98*, 456-466.

Olayemi, A., Ma, H., Qu, W., Zhou, C., Wu, B., Yang, X., & Onwude, D. I. (2017). Effects of ultrasound pretreatments on the kinetics of moisture loss and oil uptake during deep fat frying of sweet potato (Ipomea batatas). *Innovative Food Science and Emerging Technologies*, *43*, 7–17.

Oria, R., Salvador, M. L., Martorell, I., Corrales, A., & Granby, K. (2017). Effectiveness of a temperature control system in home induction hobs to reduce acrylamide formation during pan frying. *Italian Journal of Food Science*, *29*, 443–453.

Oroszvari, B. K., Bayod, E., Sjo, I., & Tornberg, E. (2005). The mechanisms controlling heat and mass transfer on frying of beefburgers . Part 2: The influence of the pan temperature and patty diameter. *Journal of Food Engineering*, *71*, 18–27.

Oroszvari, B. K., Bayod, E., Sjo, I., & Tornberg, E. (2006). The mechanisms controlling heat and mass transfer on frying of beefburgers. III. Mass transfer evolution during

frying. *Journal of Food Engineering*, *76*, 169–178.

Oroszvari, B. K., Sjoholm, I., & Tornberg, E. (2005). The mechanisms controlling heat and mass transfer on frying of beefburgers. I. the influence of the composition and comminution of meat raw material. *Journal of Food Engineering*, *67*(4), 499–506.

Pan, Y. K., Zhao, L. J., Zhang, Y., Chen, G., & Mujumdar, A. S. (2003). Osmotic dehydration pretreatment in drying of fruits and vegetables. *Drying Technology*, *21*(6), 1101–1114.

Pan, Z., Singh, R. P., & Rumsey, T. R. (2000). Predictive modeling of contact-heating process for cooking a hamburger patty. *Journal of Food Engineering*, *46*, 9–19.

Panades, G., Castro, D., Chiralt, A., Fito, P., Nuñez, M., & Jimenez, R. (2008). Mass transfer mechanisms occurring in osmotic dehydration of guava. *Journal of Food Engineering*, *87*(3), 386–390.

Parikh, A. A., & Nelson, D. C. (2013). Fat absorption in commercial french fries depending on oil type and coating. *Hospitality Review*, *30*(2), 1–13.

Paula, A. P. M., Barbosa, M. I. M. J., & Junior, J. L. B. (2016). Influence of osmotic dehydration on bioactive compounds , antioxidant capacity , color and texture of fruits and vegetables : a review. *Ciência Rural*, *46*(10), 1714–1722.

Paz-Gamboa, E., Ramírez-Figueroa, E., Vivar-Vera, M. A., Bravo-Delgado, H. R., Cortés-Zavaleta, O., Ruiz-Espinosa, H., & Ruiz-López, I. I. (2015). Study of oil uptake during deep-fat frying of Taro (Colocasia esculenta) chips. *CyTA - Journal of Food*, *13*(4), 506–511.

Pedreschi, F., Bustos, O., Mery, D., Moyano, P., Kaack, K., & Granby, K. (2007). Color kinetics and acrylamide formation in NaCl soaked potato chips. *Journal of Food Engineering*, *79*, 989–997.

Pedreschi, F., Cocio, C., Moyano, P., & Troncoso, E. (2008). Oil distribution in potato

slices during frying. *Journal of Food Engineering*, *87*, 200–212.

Pedreschi, F., Hernandez, P., Figueroa, C., & Moyano, P. (2005). Modeling water loss during frying of potato slices. *International Journal of Food Properties*, *8*(2), 289–299.

Pedreschi, F., Kaack, K., & Granby, K. (2004). Reduction of acrylamide formation in potato slices during frying. *LWT - Food Science and Technology*, *37*(6), 679–685.

Pedreschi, F., Kaack, K., & Granby, K. (2006). Acrylamide content and color development in fried potato strips, *39*, 40–46.

Pedreschi, F., & Moyano, P. (2005). Oil uptake and texture development in fried potato slices. *Journal of Food Engineering*, *70*(4), 557–563.

Peiro-Mena, R., Camacho, M. M., & Martinez-Navarrete, N. (2007). Compositional and physicochemical changes associated to successive osmodehydration cycles of pineapple (Ananas comosus). *Journal of Food Engineering*, *79*(3), 842–849.

Pereira, L. M., Ferrari, C. C., Mastrantonio, S. D. S., Rodrigues, a. C. C., & Hubinger, M. D. (2006). Kinetic aspects, texture, and color evaluation of some tropical fruits during osmotic dehydration. *Drying Technology*, *24*(4), 475–484.

Persson, E., Sjöholm, I., & Skog, K. (2002). Heat and mass transfer in chicken breasts - Effect on PhIP formation. *European Food Research and Technology*, *214*(6), 455–459.

Phisut, N. (2012). Factors affecting mass transfer during osmotic dehydration of fruits. *International Food Research Journal*, *19*(1), 7–18.

Prosapio, V., & Norton, I. (2017). Influence of osmotic dehydration pre-treatment on oven drying and freeze drying performance. *LWT - Food Science and Technology*, *80*, 401–408.

Queiroz, C., Mendes Lopes, M. L., Fialho, E., & Valente-Mesquita, V. L. (2008).

Polyphenol oxidase: Characteristics and mechanisms of browning control. *Food Reviews International*, *24*(4), 361–375.

Raczyk, M., Bonte, A., Matthäus, B., & Rudzińska, M. (2018). Impact of added phytosteryl/phytostanyl fatty acid esters on chemical parameters of margarines upon heating and pan-frying. *European Journal of Lipid Science and Technology*, *120*(2), 1–11.

Rahimi, D., Kashaninejad, M., Ziaiifar, A. M., & Mahoonak, A. S. (2018). Effect of infrared final cooking on some physico-chemical and engineering properties of partially fried chicken nugget. *Innovative Food Science and Emerging Technologies*, *47*(July 2017), 1–8.

Rahman, N., Bee, T., Hanisah, X., & Fazilah, K. (2018). Effects of osmotic dehydration treatment on volatile compound (Myristicin) content and antioxidants property of nutmeg (Myristica fragrans) pericarp. *Journal of Food Science and Technology*, *55*(1), 183–189.

Ramya, H. G., & Kumar, S. (2015). Evaluation of mass transfer kinetics for osmotic dehydration of oyster mushrooms (pleurotus sajor-caju) in salt-sugar solution. *Proceedings of the National Academy of Sciences India Section B - Biological Sciences*, *85*(2), 517–525.

Rana, R., & Raghuvanshi, R. S. (2013). Effect of different cooking methods on iodine losses. *Journal of Food Science and Technology*.

Raoult-Wack, a. . (1994). Recent advances in the osmotic dehydration of foods. *Trends in Food Science & Technology*, *5*, 255–260.

Ratnayake, W. S., & Jackson, D. S. (2008). Chapter 5 Starch Gelatinization. *Advances in Food and Nutrition Research*, *55*(08), 221–268.

Ren, A., Pan, S., Li, W., Chen, G., & Duan, X. (2018). Effect of various pretreatments

on quality attributes of vacuum-fried shiitake mushroom chips. *Journal of Food Quality, 2018*, 1–7.

Rincon, A., & Kerr, W. L. (2010). Influence of osmotic dehydration, ripeness and frozen storage on physicochemical properties of mango. *Journal of Food Processing and Preservation*, *34*, 887–903.

Riva, M., Campolongo, S., Leva, A. A., Maestrelli, A., & Torreggiani, D. (2005). Structure-property relationships in osmo-air-dehydrated apricot cubes. *Food Research International*, *38*(5), 533–542.

Rizzolo, A., Gerli, F., Prinzivalli, C., Buratti, S., & Torreggiani, D. (2007). Headspace volatile compounds during osmotic dehydration of strawberries (cv Camarosa): Influence of osmotic solution composition and processing time. *LWT - Food Science and Technology*, *40*, 529–535.

Rodrigues, S., & Fernandes, F. A. N. (2007). Dehydration of melons in a ternary system followed by air-drying. *Journal of Food Engineering*, *80*(2), 678–687.

Ruiz-López, I. I., Ruiz-Espinosa, H., Herman-Lara, E., & Zárate-Castillo, G. (2011). Modeling of kinetics, equilibrium and distribution data of osmotically dehydrated carambola (Averrhoa carambola L.) in sugar solutions. *Journal of Food Engineering*, *104*(2), 218–226.

Sablani, S. S., & Rahman, M. S. (2003). Using neural networks to predict thermal conductivity of food as a function of moisture content, temperature and apparent porosity. *Food Research International*, *36*(6), 617–623.

Safari, A., Salamat, R., & Baik, O. (2018). A review on heat and mass transfer coefficients during deep-fat frying: Determination methods and influencing factors. *Journal of Food Engineering*, *230*, 114–123.

Sahin, S., Sumnu, G., & Oztop, H. M. (2007). Effect of osmotic pretreatment and

microwae frying on acylamide formation in potato strips. *Journal of the Science of Food and Agriculture*, *87*, 2830–2836.

Salvatori, D., Andrés, A., Chiralt, A., & Fito, P. (1999). Osmotic dehydration progression in apple tissue. I: Spatial distribution of solutes and moisture content. *Journal of Food Engineering*, *42*(3), 125–132.

Sandhu, J., Parikh, A., & Takhar, P. S. (2016). Experimental determination of convective heat transfer coeffi cient during controlled frying of potato discs. *LWT - Food Science and Technology*, *65*, 180–184.

Sansano, M., Juan-Borrás, M., Escriche, I., Andrés, A., & Heredia, A. (2015). Effect of pretreatments and air-frying, a novel technology, on acrylamide generation in fried potatoes. *Journal of Food Science*, *80*(5), 1120–1128.

Santis, N., Mendoza, F., Moyano, P., Pedreschi, F., & Dejmek, P. (2007). Soaking in a NaCl solution produce paler potato chips. *LWT - Food Science and Technology*, *40*, 307–312.

Saputra, D. (2008). Osmotic dehydration of pineapple. *Indian Journal of Natural Products and Resources*, *7*(3), 241–242.

Segnini, S., Dejmek, P., & Öste, R. (1999). Reproducible texture analysis of potato chips. *Journal of Food Science*, *64*(2), 309–312.

Segui, L., Fito, P. J., & Fito, P. (2010). Analysis of structure-property relationships in isolated cells during OD treatments. Effect of initial structure on the cell behaviour. *Journal of Food Engineering*, *99*(4), 417–423.

Sheridan, P. S., & Shilton, N. C. (2002). Analysis of yield while cooking beefburger patties using far infrared radiation. *Journal of Food Engineering*, *51*(1), 3–11.

Shi, J., & Le Maguer, M. (2002). Osmotic dehydration of foods: mass transfer and modeling aspects. *Food Reviews International*, *18*(4), 305–335.

Shin, M., Kim, H., & Jang, D. (2011). Novel fry-drying method for the treatment of sewage sludge. *Journal of Material Cycles and Waste Management*, *13*, 232–239.

Si, W., Ping, Y., Zhang, J., Chen, Z., & Yin, H. (2018). Antioxidant activities of ginger extract and its constituents toward lipids. *Food Chemistry*, *239*, 1117–1125.

Silva, D. P., Rudolph, V., & Taranto, O. P. (2005). The drying of sewage sludge by immersion frying. *Brazilian Journal of Chemical Engineering*, *22*(2), 271–276.

Silva, K. S., Fernandes, M. a., & Mauro, M. a. (2014). Effect of calcium on the osmotic dehydration kinetics and quality of pineapple. *Journal of Food Engineering*, *134*, 37–44.

Singh, B., Panesar, P. S., Nanda, V., & Kennedy, J. F. (2010). Optimisation of osmotic dehydration process of carrot cubes in mixtures of sucrose and sodium chloride solutions. *Food Chemistry*, *123*(3), 590–600.

Sioen, I., Haak, L., Raes, K., Hermans, C., Henauw, S. De, Smet, S. De, & Camp, J. Van. (2006). Effects of pan-frying in margarine and olive oil on the fatty acid composition of cod and salmon. *Food Chemistry*, *98*, 609–617.

Sobukola, O. P., Awonorin, S. O., Sanni, L. O., & Bamiro, F. O. (2008). Optimization of blanching conditions prior to deep fat frying of yam slices. *International Journal of Food Properties*, *11*, 379–391.

Soheili, K. C., Artz, W. E., & Tippayawat, P. (2002). Pan-heating of low-linolenic acid and partially hydrogenated soybean oils. *Journal of the American Oil Chemists' Society*, *79*(3), 287–290.

Song, X., Zhang, M., & Mujumdar, A. S. (2007). Optimization of vacuum microwave predrying and vacuum frying conditions to produce fried potato chips. *Drying Technology*, *25*, 2027–2034.

Soquetta, M. B., Schmaltz, S., Wesz, F., Salvalaggio, R., & Marsillac, L. De. (2018).

Effects of pretreatment ultrasound bath and ultrasonic probe, in osmotic dehydration , in the kinetics of oven drying and the physicochemical properties of beet snacks. *Journal of Food Processing and Preservation*, 1–9.

Soupas, L., Huikko, L., Lampi, A., & Piironen, V. (2007). Pan-frying may induce phytosterol oxidation. *Food Chemistry*, *101*, 286–297.

Su, Y., Zhang, M., Zhang, W., Liu, C., & Bhandari, B. (2018). Low oil content potato chips produced by infrared vacuum pre-drying and microwave-assisted vacuum frying. *Drying Technology*, *36*(3), 294–306.

Sun, D.-W. (2014). *Emerging Technologies for Food Processing*. United States of America: Academia Press.

Suyatma, N. E., Ulfah, K., Prangdimurti, E., & Ishikawa, Y. (2015). Effect of blanching and pectin coating as pre-frying treatments to reduce acrylamide formation in banana chips. *International Food Research Journal*, *22*(3), 936–942.

Telis, V. R. N., Murari, R. C. B. D. L., & Yamashita, F. (2004). Diffusion coefficients during osmotic dehydration of tomatoes in ternary solutions. *Journal of Food Engineering*, *61*(2), 253–259.

Teruel, M. D. R., Gordon, M., Linares, M. B., Garrido, M. D., Ahromrit, A., & Niranjan, K. (2015). A comparative study of the characteristics of French fries produced by deep fat frying and air frying. *Journal of Food Science*, *80*(2), 349–358.

Tompkins, C., & Perkins, E. G. (2000). Frying performance of no-trans, low-linolenic acid soybean oils. *Journal of the American Oil Chemists' Society*, *77*(3), 223–229.

Tonon, R. V., Baroni, A. F., & Hubinger, M. D. (2007). Osmotic dehydration of tomato in ternary solutions: Influence of process variables on mass transfer kinetics and an evaluation of the retention of carotenoids. *Journal of Food Engineering*, *82*(4), 509–517.

Torreggiani, D. (1993). Osmotic dehydration in fruit and vegetable processing. *Food Research International*, *26*(1), 59–68.

Tortoe, C. (2010). A review of osmodehydration for food industry. *African Journal of Food Science*, *4*(6), 303–324.

Tortoe, C., Orchard, J., & Beezer, A. (2007a). Comparative behaviour of cellulosic andstarchy plant materials during osmoticdehydration. *Journal of the Science of Food and Agriculture*, *87*(7), 1284–1291.

Tortoe, C., Orchard, J., & Beezer, A. (2007b). Osmotic dehydration kinetics of apple, banana and potato. *International Journal of Food Science & Technology*, *42*, 312–318.

Troncoso, E., Pedreschi, F., & Zúñiga, R. N. (2009). Comparative study of physical and sensory properties of pre-treated potato slices during vacuum and atmospheric frying. *LWT - Food Science and Technology*, *42*, 187–195.

Tsamo, C. V. P., Bilame, A. F., Ndjouenkeu, R., & Nono, Y. J. (2005). Study of material transfer during osmotic dehydration of onion slices (Allium cepa) and tomato fruits (Lycopersicon esculentum). *LWT - Food Science and Technology*, *38*(5), 495–500.

Uddin, M. B., Ainsworth, P., & İbanoğlu, Ş. (2004). Evaluation of mass exchange during osmotic dehydration of carrots using response surface methodology. *Journal of Food Engineering*, *65*(4), 473–477.

Udomkun, P., Mahayothee, B., Nagle, M., & Müller, J. (2014). Effects of calcium chloride and calcium lactate applications with osmotic pretreatment on physicochemical aspects and consumer acceptances of dried papaya. *International Journal of Food Science and Technology*, *49*(4), 1122–1131.

Utkucan, Ş., & Kemal, H. (2016). Effects of pulsed vacuum osmotic dehydration (PVOD) on drying kinetics of figs (Ficus carica L). *Innovative Food Science & Emerging*

Technologies, *36*, 104–111.

Valdez-Frugoso, A., & Mujica-Paz, H. (2002). Reuse of sucrose syrup in pilot-scale osmotic dehydration of apple cubes. *Journal of Food Process Engineering*, *25*, 125–139.

Valdez-Frugoso, A., Welti-Chancs, J., & Giroux, F. (1998). Properties of a sucrose solution reused in osmotic dehydration of apples. *Drying Technology*, *16*(7), 1429–1445.

Verma, D., Kaushik, N., & Rao, P. S. (2014). Application of high hydrostatic pressure as a pretreatment for osmotic dehydration of banana slices (musa cavendishii) finish-dried by dehumidified air drying. *Food and Bioprocess Technology*, *7*, 1281–1297.

Vitrac, O., Dufour, D., Trystram, G., & Raoult-Wack, A. L. (2002). Characterization of heat and mass transfer during deep-fat frying and its effect on cassava chip quality. *Journal of Food Engineering*, *53*, 161–176.

Wan Mokhtar, W. M. F., Ghawi, S. K., & Niranjan, K. (2019). Dehydration of potato slices following brief dipping in osmotic solutions: Effect of conditions and understanding the mechanism of water loss. *Drying Technology*, *37*(7), 885–895.

Wang, H., Wang, F., & Liang, Y. (2017). Thermal drying dehydration and moisture migration in anthracite. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, *39*(14), 1518–1524.

Wang, N., & Brennan, J. G. (1992). Thermal conductivity of potato as a function of moisture content. *Journal of Food Engineering*, *17*(2), 153–160.

Wang, R., Zhang, M., & Mujumdar, A. S. (2010). Effect of osmotic dehydration on microwave freeze-drying characteristics and quality of potato chips. *Drying Technology*, *28*, 798–806.

Wang, S. M., Yu, D. J., & Song, K. Bin. (2011). Quality characteristics of purple sweet

potato (Ipomoea batatas) slices dehydrated by the addition of maltodextrin. *Horticulture Environment and Biotechnology*, *52*(4), 435–441.

Wilde, T. De, Delporte, K., Peteghem, C. Van, & Meulenaer, B. De. (2008). Impact of chemical pre-treatments on the acrylamide formation and sensorial quality of potato crisps. *Food Chemistry*, *106*, 914–922.

Wray, D., & Ramaswamy, H. S. (2013). Microwave-osmotic dehydration of cranberries under continuous flow medium spray conditions. *International Journal of Microwave Science and Technology*, *2013*, 1–11.

Wray, D., & Ramaswamy, H. S. (2015). Development of a microwave – vacuum- based dehydration technique for fresh and microwave – osmotic (MWODS) Pretreated whole cranberries (Vaccinium macrocarpon). *Drying Technology*, *33*, 796–807.

Wray, D., & Ramaswamy, H. S. (2016). Recycling of osmotic solutions in microwave-osmotic dehydration: Product quality and potential for creation of a novel product. *Journal of the Science of Food and Agriculture*, *96*, 3515–3523.

Wu, Z., Zhang, J., Li, Z., Xie, J., & Mujumdar, A. S. (2012). Production of a solid fuel using sewage sludge and spent cooking oil by immersion frying. *Journal of Hazardous Materials*, *243*, 357–363.

Yadav, A. K., & Singh, S. V. (2014). Osmotic dehydration of fruits and vegetables: a review. *Journal of Food Science and Technology*, *51*(9), 1654–1673.

Yagua, C. V, & Moreira, R. G. (2011). Physical and thermal properties of potato chips during vacuum frying. *Journal of Food Engineering*, *104*(2), 272–283.

Yu, Y., Jin, T. Z., Fan, X., & Xu, Y. (2017). Osmotic dehydration of blueberries pretreated with pulsed electric fields : Effects on dehydration kinetics , and microbiological and nutritional qualities. *Drying Technology*, *35*(13), 1543–1551.

Yuan, Y., Tan, L., Xu, Y., Dong, J., Zhao, Y., & Yuan, Y. (2018). Optimization of

processing parameters for lettuce vacuum osmotic dehydration using response surface methodology. *Polish Journal of Food and Nutritional Sciences*, *68*(1).

Zeng, X., Cheng, K.-W., Du, Y., Kong, R., Lo, C., Chu, I. K., Wang, M. (2010). Activities of hydrocolloids as inhibitors of acrylamide formation in model systems and fried potato strips. *Food Chemistry*, *121*(2), 424–428.

Zhang, Q., Saleh, A. S. M., Chen, J., & Shen, Q. (2012). Chemical alterations taken place during deep-fat frying based on certain reaction products: a review. *Chemistry and Physics of Lipids*, *165*(6), 662–681.

Zhao, J., Hu, R., Xiao, H., Yang, Y., Liu, F., & Gan, Z. (2014). Osmotic dehydration pretreatment for improving the quality attributes of frozen mango: effects of different osmotic solutes and concentrations on the samples. *International Journal of Food Science and Technology*, *49*, 960–968.

Ziaiifar, A. M., Achir, N., Courtois, F., Trezzani, I., & Trystram, G. (2008a). Review of mechanisms, conditions, and factors involved in the oil uptake phenomenon during the deep-fat frying process. *International Journal of Food Science and Technology*, *43*, 1410–1423.

Ziaiifar, A. M., Achir, N., Courtois, F., Trezzani, I., & Trystram, G. (2008b). Review of mechanisms, conditions, and factors involved in the oil uptake phenomenon during the deep-fat frying process. *International Journal of Food Science and Technology*, *43*, 1410–1423.

Ziaiifar, A. M., Courtois, F., & Trystram, G. (2010). Porosity development and its effect on oil uptake during frying process. *Journal of Food Process Engineering*, *33*, 191–212.

Ziaiifar, A. M., Heyd, B., & Courtois, F. (2009). Investigation of effective thermal conductivity kinetics of crust and core regions of potato during deep-fat frying using

a modified Lees method. *Journal of Food Engineering, 95*, 373–378.

APPENDICES

Appendix 1. Chapter 3 in this thesis has been published as "Wan Mokhtar, Ghawi, & Niranjan, (2019), Dehydration of potato slices following brief dipping in osmotic solutions: Effect of conditions and understanding the mechanism of water loss, *Drying Technology*, 37 (7), 885 – 895.

DRYING TECHNOLOGY
2019, VOL. 37, NO. 7, 885–895
https://doi.org/10.1080/07373937.2018.1473418

Taylor & Francis
Taylor & Francis Group

Check for updates

Dehydration of potato slices following brief dipping in osmotic solutions: Effect of conditions and understanding the mechanism of water loss

Wan Mohd Fadli Wan Mokhtar[a,b], Sameer Khalil Ghawi[a], and Keshavan Niranjan[a]

[a]Department of Food and Nutritional Sciences, University of Reading, Whiteknights, RG6 6AP, Reading, United Kingdom; [b]School of Food Industry, Faculty of Bioresources and Food Industry, Universiti Sultan Zainal Abidin, Terengganu, Malaysia

ABSTRACT

A novel variant of osmotic dehydration, named here as postdipping dehydration—where a material is dipped in a salt or sugar solution for a very short time followed by simple exposure to ambient conditions was explored with the aim of lowering water content of potato slices but at the same time not gain a high level of sugar/salt. The rate of water loss, which was rapid initially, was found to approach equilibrium. This article also explored whether the water loss process could subsequently be kick started once again, by employing a multistage process, where each stage consisted of osmotic solution dipping followed by ambient holding of the potato slices that had reached equilibrium in the earlier stage. Water loss values comparable to conventional osmotic dehydration could be achieved thus, but with significantly lower overall solid gain (<50%)—which can potentially yield a significantly healthy product option.

ARTICLE HISTORY
Received 5 October 2017
Revised 15 February 2018
Accepted 2 May 2018

KEYWORDS
Multistage dehydration; osmotic dehydration; postdipping dehydration; process efficiency index; solid gain

Introduction

Hot air drying is an ancient and extensively employed process to reduce moisture content and increase the shelf life and stability of food products. The process involves simultaneous heat and mass transfer.[1] A major drawback of hot air drying is quality deterioration of the products due to exposures to a high temperature for extended periods of time. Another drawback is that this technique requires the expenditure of high energy.[2] Therefore, a number of alternative energy efficient dehydration techniques have been developed resulting in better quality food products.

Osmotic dehydration eliminates water from materials without expending latent heat. It essentially involves immersion of materials such as fresh fruits or including potato,[5,6] banana,[7,8] yacon,[9] mango,[10,11] berries,[12] and pineapple.[13,14] In addition to low energy consumption, this method also preserves some key sensory characteristics of the fruit and vegetable. Because of its simple and inexpensive operation, it has also been applied as a preprocessing step prior to operations such as conventional drying,[15–17] freezing,[18] and frying.[19]

Despite the advantages of osmotic dehydration, it also suffers several limitations such as floating of fruit in solution, osmotic solution managements, and the main ones being high solute uptake due to diffusion of solute toward tissue cell,[20] which can potentially pose major health issues and the leaching out of water and other nutritious components from the tissue, which not only affects the product but also dilutes the osmotic solution thereby adversely influencing the

Appendix 2. Acceptance letter for a poster presentation in the International Congress on Food Technology, 10-12 October 2018, Cappadocia, Turkey.

3. INTERNATIONAL CONGRESS on FOOD TECHNOLOGY

October 10-12, 2018 **CAPPADOCIA** TURKEY

May 26, 2018, Ankara

Subject: ICFT3 Acceptance letter

No: GD ICFT3 375

Dear Wan Mohd Fadli Wan Mokhtar

On behalf of the Organizing Committee, we have the pleasure to inform you that the Scientific Committee evaluated and accepted your abstract entitled as "SHALLOW FRYING OF POTATO STRIPS: EFFECT OF SALT ADDITION ON MASS TRANSFER, COLOUR AND TEXTURE DEVELOPMENT" at the 3rd International Congress on Food Technology organized by the Association of Food Technology-Turkey with the support of Nevşehir Hacı Bektaş University. The Congress will be held at the Congress Room of Nevşehir Hacı Bektaş University in Cappadocia - Turkey from 10 to 12 October 2018. Please use the heading ICFT3 375 in future e-mail correspondence.

The Scientific Committee of the Congress has left the Congress Organizing Committee to choose whether to present your work as an oral or poster paper. The Congress Organizing Committee has found it preferable to leave this choice to the authors of the abstracts. ***Please promptly notify us about your choice of your ICFT3 375 numbered abstract as a poster or oral presentation***. The Congress Organizing Committee will evaluate the oral requests as much as possible, but not all oral presentation demands are guaranteed. Oral presentations should be of interest to the most of the participants of the Congress.

Please note that this letter cannot be regarded as a commitment on behalf of the Organizing Committee regarding funding for participation. Please also consider to register to the Congress and arrange an accommodation to any of the hotel in Cappadocia in order to find an available room for you since Cappadocia is a tourist area. We remind all participants that they have to do transportation and accommodation organizations by themselves. The registration fee table is given below: You should submit your paper summary as soon as possible in MS Word.doc file, as provided in the attached sample file and, if necessary, with updating it. Congress language is English.

Please note that this letter cannot be regarded as a commitment on behalf of the Organizing Committee regarding funding for participation. Please also consider to register to the Congress and arrange an accommodation to any of the hotel in Cappadocia in order to find an available room for you since Cappadocia is a tourist area. We remind all participants that they have to do transportation and accommodation organizations by themselves.

Appendix 3. Acceptance letter for a poster presentation in the Global Food Science Student Competition, 14-18 November 2018, Wuxi, China.

江南大学

JIANGNAN UNIVERSITY

LETTER OF INVITATION

August 27, 2018
WAN MOHD FADLI BIN WAN MOKHTAR

Dear Mr. WAN MOHD FADLI BIN WAN MOKHTAR,

We are glad to inform you that your abstract has been selected as poster presentation in the 2018 Global Food Science Student Competition, which will be held at Jiangnan University, Wuxi, China during November 14-18, 2018.

Jiangnan University is very pleased to host the event which aims to encourage academic exchange and strengthen friendship between students who are majoring or interested in Food Science all over the world. The competition provides a unique forum to present original research, exchange latest results, share stories and make friends.

Jiangnan University will be responsible to cover your round international travelling expenses, accommodation (Jiangnan Four Seasons Hotel, No. 100, Jinxi Road, Wuxi) and meals during the event on campus.

We look forward to meeting with you at Jiangnan University. Should you have any questions, please feel free to contact me at bjiang@jiangnan.edu.cn.

Best wishes!

Dr. Bo Jiang
Director of International Office
Jiangnan University
Tel: +86-510-85328307
Fax: +86-510-85913622
Email:

Appendix 4. Calibration curve for salt concentration using conductivity measurement