ASSESMENT OF PORE DEVELOPMENT, OIL AND MOISTURE DISTRIBUTION IN FRYING

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ABSTRACT

ASSESMENT OF PORE DEVELOPMENT, OIL AND MOISTURE DISTRIBUTION IN FRYING

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The main objective of this study was to evaluate the relationship between moisture content, oil uptake, pore development and shrinkage of the potatoes during frying and to investigate the effects of pretreatment on these quality parameters. Moreover, determination of the differences between crust and core region of potatoes during frying was aimed. It was also aimed to correlate Magnetic Resonance imaging (MRI) results with moisture and oil contents of the potatoes.

In the first part of this study, pretreatment effects on the quality of the potatoes were evaluated. Pre-drying and pre-coating with hydroxyprophylmethylcellulose was applied to potatoes as a pretreatment and potatoes were fried for 4, 8, 12, 16 and 20 min. Moisture content, oil content, porosity, shrinkage and MR images of the potatoes were evaluated. In the second part of the study, difference between crust and core region of the potatoes were evaluated in terms of moisture and oil content, porosity and pore size distribution.

As a result of the study, pretreatments decreased moisture and oil contents but increased shrinkage. Oil content of the crust was found to be higher while moisture content and porosity were lower as compared to core region. Oil content results were found to be correlated with moisture content and shrinkage. According to results of MRI, oil and moisture distribution was observed qualitatively and signal intensity results of the water suppression images were found to be correlated with oil contents of the potatoes quantitatively.

Keywords: Frying, potato, pre-coating, pre-drying, oil content

ÖZ

KIZARTMA SIRASINDA GÖZENEK OLUŞUMU, YAĞ, VE NEM DAĞILIMININ DEĞERLENDİRİLMESİ

Işık, Betül
Yüksek Lisans, Gıda Mühendisliği Bölümü
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Bu çalışmanın temel amacı, patateslerin kızartma işlemi sırasındaki nem kaybı, yağ emilimi, gözenek gelişimi ve büzülmesi arasındaki ilişkinin değerlendirilmesi ve ön işlemlerin bu kalite parametreleri üzerine olan etkilerinin araştırılmasıdır. Buna ek olarak, kabuk ve iç kısım arasındaki farkın belirlenmesi de amaçlar arasındadır. Ayrıca, patateslerin nem ve yağ içeriği ile Manyetik Rezonans Görüntüleme (MRG) sonuçları arasında bir ilişki olup olmadığının bulunması da amaçlanmıştır.

Çalışmanın ilk bölümünde, patates kalitesine ön işlemin etkileri değerlendirilmiştir. Ön işlem olarak patateslere ön kurutma ve hidroksipropil metil selüloz çözeltisi ile ön kaplama uygulanmıştır ve patatesler 4, 8, 12, 16 ve 20 dak kızartılmıştır. Patateslerin nem içeriği, yağ içeriği, gözeneklilik, hacimsel büzülme ve Manyetik Rezonans görüntüleri incelenmiştir. Çalışmanın ikinci bölümünde ise, kızarmış patateslerin kabuk ve iç kısımları arasındaki fark nem ve yağ içeriği, gözeneklilik ve gözenek boyutu dağılımı açısından değerlendirilmiştir.

Bu çalışmanın sonucunda, ön işlemlerin patateslerin nem ve yağ içeriğini azaltırken, büzülmesini arttırdığı gözlemlenmiştir. Ayrıca, patateslerin kabuk bölümünün iç bölümüne nazaran yağ içeriği yüksek iken nem içeriği ve gözenekliliği düşük bulunmuştur. Patateslerin, yağ içeriği ile nem içeriği ve büzülmesi arasında bir ilişki olduğu belirlenmiştir. MRG sonuçlarına göre, yağ ve nem dağılımı nitelik olarak gözlemlenmiştir ve su bastırma görüntüleri sinyal yoğunluğu ile patateslerin yağ içeriği arasında nicelik olarak ilişki olduğu bulunmuştur.

Anahtar Kelimeler: Kızartma, patates, ön kurutma, ön kaplama, yağ miktarı

To my family…

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INTRODUCTION

1.1 Potato

The potato (*Solanum tuberosum* L.) belongs to the family of *Solanaceae*. Tomatoes, pepper, eggplant and chilies are the other known plants in this family (Thomas, 1998). Potato is one of the most consumed agricultural crops in the world. The production of the potato comes from after wheat, maize and rice as a fourth rank in the world with the 375 million tons annually (FAOSTAT, 2013). The demand of the processed potato products was 0.7 million tons in 2010 and it is estimated to rise 7.3 million tons in 2050 (Saran & Chhabra, 2014).

The production of the potatoes does not need any quarrelling effort and they can be grown in places where daily temperature is in the range of 5°C to 21°C (Govindakrishan & Haverkort, 2006). Potatoes were grown in 149 countries on the 19.6 million hectares of land in 2006. China takes the first place in the production with 70 million tons/year and Russian Federation, India and the USA comes after China (Bradshaw & Ramsay, 2009).

The composition of the potato can be changed by growing conditions, soil type, cultivar, and storage conditions. Water content of the potatoes is generally about 80-82% in wet basis. Starch is the main dry component of the potatoes corresponding 70% of the dry solid. The content and characteristics of the starch affect quality of the potatoes and potato products. Moreover, potatoes are good source of protein, fiber and essential vitamins. Approximately 1-2% protein, 0.5% fiber and 30 mg vitamin C are found in the 100 g of potato tuber (Singh & Kaur, 2009). Furthermore, potatoes contain antioxidants like carotenoids and phenolics.

Antioxidant content of the potatoes can vary from cultivars to cultivars. For example, caretonoid content of the white-fleshed cultivar are about 100 µg while it is 2000 µg per 100 g fresh weight in the case of yellow-fleshed cultivar (Brown, 2005). Lipid content of the potato is nearly zero (fat free) and a medium size potato gives 110 kcal (Burlingame, Mouille, & Charrondiere, 2009). Contents of the potato make it nutritional vegetable and it is consumed at breakfast, lunch and dinner in the world.

Morphologically, potato tuber has an oval shape and brown skin. The internal structure of the potato tuber is composed of four distinguishable areas as periderm, parenchyma tissue, vascular bunds and medullar rays or pith. Lengthwise section of the potato tuber is indicated in the Fig 1.1 (Van Es & Hartmans, 1981).

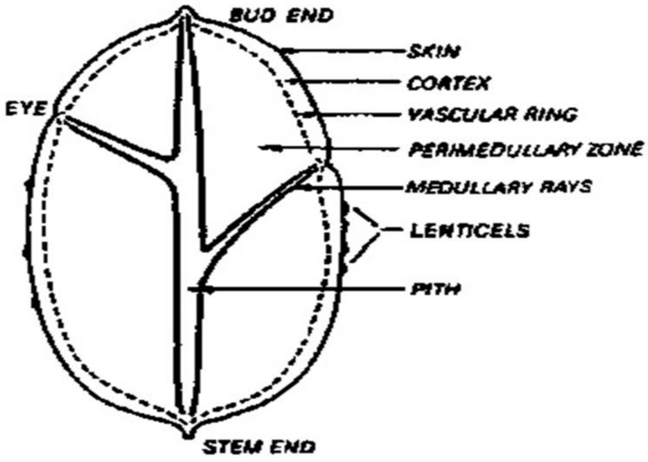

Figure 1. 1 Lengthwise section of the potato tuber.

Lenticels, eyes, bud and stem ends are in the periderm also known as skin part of the tuber. Periderm is composed of ring shaped suberized cell layers and number of the layers can change with different growing conditions and species. However, layers at the stem end are much more than bud end (Diop, 1998). Cortex and perimedullary zone are in the parenchyma and contains starch of the potato tuber. Dry matter content and reducing sugar content can show difference at different parts of the tuber. The researches on potato tuber indicates that dry matter content of the tuber decreases from stem end to bud end and also lowest at pith (Kumar & Ezekiel, 2004).

Ungelatinized potato starch is indigestible and cooking is needed for being edible (Burton, 1989). Thus, potato is one of the important raw materials in the food industry. Boiling, roasting, baking or frying are the main cooking processes of the potato production. In the United States, fried potato products takes 42 % of the total potato crop utilization (Miranda & Aguilera, 2006). Consequently, frying is the most preferred process and researches on potato frying become crucial in the processes of potato production.

1.2 Deep- fat Frying

Deep-fat frying is one of the oldest preparation methods of foods. It can be identified as a thermal process that drying and cooking take place simultaneously by immersing food into hot oil (Sahin, Sastry, & Bayindirli, 1999). The process of frying dates back to old times around sixth century BC (Morton, 1998). The consumers prefer fried products due to their unique flavor and texture integration. Moreover, frying is also fast cooking process and it is used widely in the snack food industry and in the United States about 65% of snack products are deep-fat fried (Chen & Moreira, 1997).

Deep- fat frying is a complex process which involves simultaneous heat and mass transfer. Heat transfer takes place by conduction inside the food and by convection between food and frying medium. During frying, food is cooked by the transfer of heat from hot oil. The temperature of the oil is decreased by addition of the cold food into hot oil and temperature of the food increases. The convective heat transfer rate increases due to the formation of water vapor bubbles providing turbulence in oil. High temperature difference between food and oil also leads to develop high heat transfer rates (Hubbard & Farkas, 1999). The development of high heat transfer rates creates formation of special features of fried products (Farkas, Singh, & Rumsey, 1996).

The mass transfer occurs between water inside the food and oil. When food is immersed into hot oil, water leaving the surface of the food starts to boil immediately and creates steam. As steam comes into existence and run away from the food, sponge-like network is formed by pores created from steam (McDonough, Gomez, Lee, Waniska, & Rooney, 1993). The surrounding oil penetrates the food through these pores. Moreover, the generated steam causes the formation of pressure gradient inside the food. This pressure gradient prohibits oil penetration and this continues until the frying is completed. During cooling period of the fried products, internal pressure is lowered by condensation of water vapor and oil penetrates into food as if vacuum is applied (Ufheil & Escher, 1996).

The rate of heat and mass transfer is affected by variations on physical and chemical properties of the food and oil. The geometric properties of the food, oil and food temperature and also applied pretreatments are the factors that influence heat and mass transfer during frying (Krokida, Oreopoulou, Maroulis, & Marinos-Kouris, 2001a). Moreover, thermal properties, porosity, geometry of the food and density of the food are changing during frying process as a result of change in moisture and oil content (Sumnu & Sahin, 2008). These alterations in food and oil bring on change in quality of the fried products.

Oil content, moisture content, shrinkage, porosity, color, acrylamide content and texture are important quality parameters in fried products. During deep-fat frying, many physical and chemical changes take place. Maillard reaction, starch gelatinization, protein denaturation, inactivation of enzymes, crust and pore formation are the main biochemical changes. Maillard reaction (non-enzymatic browning) is the reason of color change during frying. Temperature of the frying accelerates browning reactions due to rapid polymerization of Amodari products to melanoidins that give dark color (Navas Sánchez, 2005). Moreover, the amount of reducing sugar content of food is directly proportional to the development of color in fried products (Bordin, Kunitake, Aracava, & Trindade, 2013). High heat transfer rates lead to the formation of pores as a result of water evaporation. Water at the surface of the food is evaporated initially and this dehydration leads to the formation of crust and shrinkage (Mellema, 2003). Formation of crust during frying provides unique texture of fried products by acting as a barrier to water evaporation and oil uptake. The characteristic moist interior of the fried products is the result of crust formation. Starch gelatinization and protein denaturation can have an effect on the pore development since gelatinized starch is dispersed in the continuous phase. Gelatinized starch and denaturized protein league together and form an association of strands (Sumnu & Sahin, 2008).

Deep- fat frying also affects the nutritional properties of the foods. Oil absorption of foods during frying increases energy intake. Vitamin loss during frying is less than that observed in baking and boiling due to shorter process time of frying. Moreover, vitamin E content of foods increases after frying since vegetable oils used as a frying medium have significant amount of α-tocopherol (Vitamin E) (Saguy & Dana, 2003). Oil uptake of food can enrich vitamin E in fried products. However, moisture and air lead to chemical reactions in oil at high temperatures. Hydrolysis, oxidation and polymerization are the undesirable reactions that occur in oil. These reactions affect the quality of the fried products adversely. Therefore, the quality of the oil used as a frying medium should be controlled carefully.

Reduction of oil absorption during deep-fat frying is important in fried food products since consumer demands have been increasing to consume low fat foods. Consequently, researchers focus on decreasing the oil uptake during frying without loss of sensory properties. There are many ways to reduce oil absorption such as pre-drying, pre-coating, vacuum frying, microwave frying and osmotic pretreatment.

1.3 Reduction of oil uptake

New alternative ways are searched to reduce oil content of fried products because of health concerns. Alternative frying methods and alteration in the raw food composition by pretreatments can be used. Vacuum frying is one of the alternative frying methods. The principle in vacuum frying relies on decreasing boiling points of water and oil by providing pressure lower than atmospheric level. It provides to obtain fried products with low oil content, conserved natural color and flavors thanks to low frying temperature and oxygen content imposed during frying (Shyu, Hau, & Hwang, 1998). Microwave frying is another alternative method to deep-fat frying. Internal heat generation in foods is observed during microwave frying and this provides reduction in oil content by decreasing frying time (Oztop, Sahin, & Sumnu, 2007). Pretreatment prior to frying is another way to obtain low fat fried products.

There are many treatments applied to foods prior to frying. Blanching, osmotic dehydration, drying and coating are the main examples of pretreatments. Partial moisture removal or forming barrier to oil uptake are the basic principles of pretreatments. Blanching before frying leads to gelation of starch on the surface and provides reduction in oil uptake. However, some researchers found blanching prior to frying can increase oil absorption in fried products. Pedreschi, Cocio, Moyano, and Troncoso (2008) reported blanched potato chips absorb more oil compared to not blanched ones. Similarly, Alvarez, Morillo, and Canet (2000) indicated that high temperature short time blanching reduces firmness and increases oil absorption of potato strips. On the other hand, Califano and Calvelo (1988) stated that blanching develops better color and texture to fried products. Furthermore, fried products have low amount of acrylamide, which have potential carcinogenic effect, when blanching is applied as a pretreatment (Pedreschi, 2009).

Osmotic pretreatment is also applied in foods by immersing them into hypertonic solution. The amount of moisture inside the food is partially decreased by osmotic dehydration without phase change. There are many researches to evaluate osmotic pretreatment effect on oil content of fried product. For instance, potatoes, which are immersed into NaCl solutions prior to frying has lower oil contents (Bunger, Moyano, & Rioseco, 2003). Moreover, Karizaki, Sahin, Sumnu, Mosavian, and Luca (2013) studied effect of osmotic dehydration and ultrasound-assisted osmotic dehydration on quality of the fried potatoes. They reported that osmotic dehydration and ultrasound-assisted osmotic dehydration decreases oil uptake compared to untreated fried potatoes. Pre-drying and pre-coating are also important pretreatments applied for oil reduction in frying.

1.3.1 Pre-drying

Drying is a widely used preservation method in food industry. The underlying objective of the drying prior to frying is to decrease the initial moisture content of the foods. Moisture content of foods affects oil absorption during frying substantially. Water vapor creates pores and oil enters food through these pores. Consequently, higher initial moisture content of foods indicates formation of greater pores and more oil absorption during frying (Gamble, Rice & Selman, 1987a). Hot-air and microwave treatment can be used as pre-drying method in fried foods (Lamberg, Hallstroem, & Olsson, 1990).

Effects of pre-drying on reduction of oil uptake and quality parameters of fried products have been investigated in many researches. For instance, Krokida, Oreopoulou, Maroulis and Marinos-Kouris (2001b) investigated the effects of pre-drying duration on oil and moisture content of french fries. They indicated that increasing pre-drying time resulted in lower oil content in french fries. However, they also stated that quality of the french fries affected negatively when exposed to drying so much and appropriate drying time should be chosen for high quality french fries low in fat. Pedreschi and Moyano (2005) studied pre-drying effect on oil absorption and texture of the potato chips. They applied pre-drying after blanching of the potato chips and they stated pre-drying decreases oil absorption and also increases crispiness of the potato chips. Moreover, Song, Zhang, and Mujumdar (2007) investigated effect of vacuum microwave pre-drying on moisture, oil and color parameters of vacuum fried potato chips. They showed vacuum microwave pre-drying decreases moisture and oil content of the potato chips compared to untreated ones but lightness of the samples decreases.

1.3.2 Pre-coating

Coating before frying brings about surface treatment to foods. Most of the oil is absorbed from surface of the food after frying process during cooling (Bouchon, Aguilera, & Pyle, 2003). Mellema (2003) indicated the application of a coating as an assuring way to reduce oil content of fried potatoes. There are many coating materials used in fried products such as pectin, gellan gum, sodium alginate, and corn zein and cellulose derivatives (García et al., 2004). All of them form film on the surface of the food and inhibits oil uptake and at the same time provides moisture retention during frying.

Cellulose derivatives, which are methylcellulose (MC) and hydroxyprophylmethylcellulose (HPMC), show gelation properties when their suspensions are heated (García, Ferrero, Bértola, Martino, & Zaritzky, 2002). The solution of the cellulose derivatives are hydrated and increase in temperature of the solution leads to lose hydration water and viscous property. When the gelation temperature is reached, polymer to polymer interactions become dominant and cause to gelation of solution. However, this process is reversible and temperature of the solution reduced to lower than gelation point, the process start to reverse (Sanz, Salvador, & Fiszman, 2004). Thus, foods, coated with MC or HPMC solution prior to frying, form film when they are immersed into hot oil. Entrance of oil to the food and loss of moisture from the food is limited by gelation at the surface of the food.

Balasubramaniam, Chinnan, Mallikarjunan, and Phillips (1997) studied the effectiveness of HPMC coating on oil absorption and moisture retention of the chicken balls during frying. They stated that oil absorption of the coated chicken balls reduced by 33.7% and moisture retention by 16.4%. In addition, the effect of hydrocolloid addition to batter formulation of fried carrot slices were studied by Akdeniz, Sahin, and Sumnu (2006). They researched effects of HPMC, guar gum, xanthan gum and guar-xanthan combination addition to batter on moisture content and oil content and reported that guar-xanthan combination shows best reduction in oil content and also HPMC addition reduces the oil content compared to xanthan gum added ones. Moreover, Mallikarjunan, Chinnan, Balasubramaniam, and Phillips (1997) indicated the effect of pre-coating on mashed potato balls. They analyzed moisture loss and oil uptake of uncoated and coated samples with MC, corn zein and HPMC solution. As a result of their investigations, moisture loss and oil uptake of HPMC coated potatoes reduced by 21.9% and 61.4%, respectively compared to uncoated potatoes. Consequently, HPMC is chosen in this study as a pre-coating material.

1.4 Quality Parameters

The quality of the fried products should be utilized according to their structural, optical, textural, nutritional and sensorial properties. Color, texture, porosity, flavor, moisture content and oil content of the fried products are the main concerns in the food industry. Thus, fried products need to fulfill health and sensory aspects of the consumers.

1.4.1 Oil Content and Moisture Content

Consumption of low fat foods has been increasing in recent years. Consumers demand healthier products in their diets and high amount of oil in fried foods leads to prefer keeping away consumers from fried products. Therefore, decreasing oil content of fried foods without undesirable quality change becomes crucial in food industry.

Mechanism of oil uptake during frying should be understood for production of fried products with lower oil content. Water replacement, condensation effect (cooling phase) and effect of surface active agents are the main reasons of oil uptake (Dana & Saguy, 2006). The principle of water replacement relies on evaporation of water. Water evaporation creates large pores inside foods and oil penetrates into food with these pores. Condensation effect on oil absorption is observed during cooling period. Formation of crust at the surface of the food inhibits escaping of vapor and this creates overpressure inside pores. When food is removed from fryer, temperature starts to decrease and overpressure turns to under-pressure. Vapor inside the pores starts to condensate and oil penetrates into food. The effects of surface active agents on oil absorption become important at prolonged frying times. When frying time is prolonged, oil degradation starts and surface active agents such as diglycerides, monoglycerides, free fatty acids and glycerol are formed (O'brien, 2008). As a consequence of the formation of these surfactants, contacts of food and oil increases, which results in increase in oil absorption.

There are many researches to understand mechanisms of oil uptake during frying and cooling. For example, Gamble, Rice and Selman (1987b) indicated higher amount of oil penetrated after frying process due to vacuum effect of condensation. Similarly, most of the oil is penetrated to food during cooling period according to research of Moreira, Sun and Chen (1997). They found that 20% of total oil content is penetrated during frying and the rest are remained on the surface. Consequently, cooling period is more important on oil contents of fried products and convenient draining and shaking can be useful for reduction of oil absorption after frying.

Moisture loss during frying is also important in fried foods. Moisture loss and oil uptake are interrelated phenomena in frying. Gamble, Rice and Selman (1987b) indicated that oil uptake higher at portions of food that more moisture loss observed. Moreover, Pinthus, Weinberg, and Saguy (1993) suggested that oil uptake and moisture loss are equal to each other in mass balance. Furthermore, there are many models to determine water diffusion during frying. Krokida, Oreopoulou, and Maroulis (2000b) stated that square root of the frying time is proportional to moisture diffusion. Fick's law of diffusion was also used in moisture diffusion model (Kozempel, Tomasula, & Craig, 1991). Even though moisture loss and oil uptake are related to each other, they are out of synchronized since higher oil absorption occurs during cooling period (Bouchon et al., 2003).

Frying time and temperature are the two important process parameters affecting oil absorption and moisture loss. Increasing frying time leads to increase in oil uptake and moisture loss. Moreover, there is an inverse relationship between frying temperature and oil uptake. When frying temperature is raised, frying ends up at shorter times and crust is formed quickly. Crust formation and short frying inhibits oil absorption (Pinthus, Weinberg, & Saguy, 1995). In addition, shape and size of the food have an effect on oil and moisture contents of the fried products. Research on potato strips showed that oil uptake of thick potato samples have low amount of oil (Krokida et al., 2001a).

Oil content of the foods can be analyzed by different methods. Soxhlet extraction is a widely used method in determination of oil content. Organic solvents such as hexane, ethanol are used for extraction of oil. In addition, supercritical fluid extraction (SFE) can be used for oil content determination of foods. Supercritical fluid is used as a solvent instead of toxic and flammable fluids used in soxhlet extraction (Devineni, Mallikarjunan, Chinnan, & Phillips, 1997). Baumann and Escher (1995) performed refractometric methods for oil content determination of potatoes. Moreover, Differential scanning calorimetry (DSC) is also used for oil content determination. Determination of oil with DSC does not need organic solvents and peak area (enthalpy) is used for calculation of oil content (Aguilera & Gloria, 1997). Nuclear magnetic resonance (NMR) is an alternative way for determination of oil and moisture contents of foods (MacMillan, Hickey, Newling, Ramesh, & Balcom, 2008).

1.4.2 Porosity and Shrinkage

Porosity is one of the important structural properties of fried products. Porosity is related with voids inside material and can be defined as fraction of the void. It can be found by equation (1.1):

$$\varphi = 1 - \frac{\rho_b}{\rho_s} = 1 - \frac{V_s}{V_b} \tag{1.1}$$

where, ρ_b is bulk density (total density), ρ_s is solid density. Bulk density is calculated with material mass and volume of total solid whereas solid volume taken after excluding volume of pores (Sumnu & Sahin, 2008). Mercury intrusion porosimetry is common method to determine porosity and pore size distribution of the materials. Pore size distribution of the materials obtained by fitting intruded volume of mercury and pressure to Washburn equation (1.2) (Kassama, 2003).

$$D = -\left(\frac{1}{P}\right) 4\gamma\ cos\Phi \tag{1.2}$$

Porosity of the foods is changing during frying process due to water evaporation and oil uptake. Diffusion of water during frying creates capillary pores. Relationship between water loss and porosity has been investigated by many researchers (McDonald & Sun, 2001; Rahman & Potluri, 1990). As a result of their investigations, they concluded that decreasing water content increase porosity of samples. Moreover, parameters of frying such as temperature and time have also effect on porosity. For example, increasing frying temperature leads to increase in porosity (Krokida et al., 2001a). Furthermore, shrinkage and density change during frying also affect pore size of the fried products (Kassama & Ngadi, 2004). Therefore, shrinkage is another important phenomenon that should be evaluated carefully to achieve quality.

Shrinkage, characterized with volume change, is also another structural phenomena occurring during frying. There are two types of shrinkage as isotropic and anisotropic. Anisotropic shrinkage generally observed foods have muscles like fish and meat since muscle change direction of the shrinkage (Rahman, 2007). In fruits and vegetables isotropic shrinkage is observed.

Evaporation of water during frying and condensation after frying trigger collapsing of foods. The collapse phenomenon leads to increase in shrinkage, decrease in porosity and breaking down of structure (Levi & Karel, 1995). Consequently, moisture loss is the main reason of shrinkage. Moreira and Sereno (2003) reported that moisture content change of samples could be an indication of volumetric shrinkage. Moreover, initial moisture content, size and composition of foods and frying conditions have an impact on shrinkage and shrinkage also affects pore size change during frying process (Rahman, 2001). Therefore, shrinkage and porosity are linked properties and they are important parameters to ensure structural quality of fried products.

1.5 Microstructural Changes

Deep-fat frying is a complex process as a result of many structural changes such as starch gelatinization, protein denaturation and pore development during frying. Therefore, microstructural analysis is also important in fried foods. Electron microscopy (EM), light microscopy (LM), confocal laser scanning microscopy (CLSM) are the major methods to understand microstructural changes in fried products (Sumnu & Sahin, 2008).

Scanning electron microscope was used in many researches to emphasize microstructural changes. For example, Pedreschi et al. (2008) used SEM images for determination of oil distribution and surface morphology of the potato slices. Moreover, Khalil (1999) took advantage of SEM images to support results of oil and moisture contents of french fried potatoes. Consequently, SEM and other microscopic techniques can be used to examine structure visually at microscopic level.

1.6 Magnetic Resonance Imaging (MRI)

Magnetic resonance imaging (MRI) is a technique that provides images of the internal structure of the samples based on proton distribution and commonly used in medical field. Moreover, the utilization of MRI in food science has been increasing in recent years. The increasing tendency of usage of MRI is the result of its non-invasive and nondestructive features. The principle of MRI relies on magnetic behavior of nuclei in sample under external magnetic field while being exposed to radio frequency pulses (Ruan, Chang, Chen, Fulcher, & Bastian, 1998). Longitudinal relaxation time (T_1) and spin-spin relaxation time (T_2) are two important terms for assessment of images. The efficiency of magnetic energy transfer between $_1H$ protons and neighboring lattice is represented with T_1 and T_2 indicates effectiveness of the magnetic energy transfer between surrounding spins (Kirtil & Oztop, 2015). Water has long T_1 and T_2 relaxation times compared to oil and solids. Large difference between T1 and T2 relaxation time values of water and oil provides determination of oil and moisture contents of foods. The variation in T_1, T_2 relaxation time and density of protons in the sample provides contrast in the images. The effect of T_1, T_2 and proton density on the image can be controllable by changing the repetition time (TR) and echo delay time (TE) parameters of the sequence. The change in these parameters affects signal intensity. The signal intensity can be calculated by (Bernstein, King, & Zhou, 2004) :

$$S = M_0\left(1 - 2e^{-(TR-TE/2)/T_1} + e^{-TR/T_1}\right)e^{-TE/T_2} \tag{1.3}$$

where S represents signal intensity and M_0 is the initial magnetization. As can be seen in equation (1.3), the increase in TR leads to decrease T_1 effect on the signal intensity of the image. Similarly, the decrease in the TE causes to obtain images with reduction in the T_2 weighting. Moreover, proton density weighted images can be obtained by higher TR and lower TE values. Consequently, these features make MRI excellent tool for fried foods in evaluation of oil and moisture contents.

Another advantage of MRI is determination of oil and moisture contents of the foods simultaneously on the same sample. Therefore, its usage in researches on fried products has been increasing. For example, Oztop et. al (2014) evaluated moisture and oil distribution in fried chicken nuggets. They concluded that MRI can be an alternative method to quantify moisture and oil distribution. Moreover, Horigane, Motoi, Irie and Yoshida (2003) used MRI in tempura, typical Japanese coated fried food. They indicated MRI as an efficient way for visualizing oil and moisture transfer in fried foods. In addition, Macmillan and others (2008) evaluated T_2 values to determine resolved oil and moisture contents of french fries. Determination of oil and moisture contents of fried foods in MRI is also rapid process. The non-invasive, nondestructive, simultaneous oil and water content determination and fastness are the main advantages of MRI and reasons of usage in frying studies.

1.7 Aim of the Study

Potato is one of the most important agricultural crops consumed commonly in the world. Consumers prefer deep fat frying process for preparation of potatoes due to the development of unique flavor and texture. However, consumers’ demand for consumption of low fat foods has been increasing in recent years. Therefore, researchers investigate new methods for reducing oil content of foods to meet the demands of consumers. Hence, frying process should be examined carefully for reduction of oil content. The relationship between moisture loss, oil uptake, pore development and shrinkage during frying should be analyzed to understand the mechanism. However, there are limited studies on this subject in the literature. Therefore, it is aimed to investigate the relationship between pore development, shrinkage and diffusion of oil and moisture during frying in this study. The effect of pre-drying and pre-coating was also considered in evaluating the relationship between quality parameters. Furthermore, studying different pretreatments will be helpful to obtain additional data to study this relationship. Moisture is lost, pores are created and oil penetrates the food through these pores during frying. Moisture, oil and pores are not uniformly distributed within the fried samples. These parameters show differences at the crust and core parts of the samples. This study also aims to show distribution of oil, moisture and pores within the fried potato sample.

Magnetic resonance imaging (MRI) is an excellent way to visualize internal structures and moisture and oil distribution of fried foods. In this study, it is also aimed to investigate whether this method can be used to analyze moisture and oil content quantitatively as well as qualitatively. The signal intensity of the images and spin-spin relaxation times (T_2) of the samples give information about moisture and oil contents of fried products. MRI method is assessed for determination of oil and moisture contents by investigating longitudinal relaxation time (T_1) weighted and water suppression images and also T_2 of the fried potatoes.

CHAPTER 2

MATERIALS AND METHODS

2.1 Materials

Potatoes were the main raw material of the study and purchased from the local market in Ankara, Turkey. The oil chosen for frying was sunflower oil (Komili, Istanbul, Turkey), a type of oil used in the frying industry.

(Hydroxypropyl) methyl cellulose, coating material, was purchased from Sigma Aldrich Chemical Co. (St. Louis, MO, USA). The viscosity of the solution prepared with 2 % distilled water is in the range of 2.600-5.600 cP at 20°C.

n-Hexane, extracting solvent used in soxhlet extraction, was acquired from Sigma Aldrich Chemical Co. (St. Louis, MO, USA).

2.2 Preparation of potato slices

Potatoes were removed from their skins, washed and cut into cylindrical pieces. Manually operating circular cutting mold was used to obtain potato pieces of 58.0 mm in diameter and 20.0 mm in thickness. Caliper (Mitutoyo, CD-15D, Japan) was used for controlling the size of the slices. Then, the slices were rinsed with distilled water for 30 s to remove free starch on the surface. Paper towel was used for blotting potatoes prior to frying to remove excess free water.

2.2.1 Pretreatments

Initial moisture content of potatoes was 80±2 % (g/100g wet sample). Initial moisture content of the potatoes was lowered to 70 % (g/100g wet sample) by pre-drying in a convection oven (Memmert, Schwabach, Germany) at 103 ^{0}C for 1 hour and allowed to reach room temperature for 10 min in order to study the effect of pre-drying on moisture content, oil content, pore development and shrinkage of fried potatoes.

The effect of pre-coating on these physical and chemical properties was also studied. For this purpose, potato slices were soaked into aqueous solution of hydroxyprophyl methyl cellulose (1% w/w) at 30 °C for 2 min. The samples were then dried at 150 °C for 5 min.

2.3 Frying

Frying was carried out in a temperature controlled deep-fat fryer (King, DF 21R Fritt, Istanbul, Turkey). The capacity of the fryer was 1.2 L of oil. The oil was pre-heated and temperature of the frying media was measured by thermocouple (Nel, Ankara, Turkey). Only one potato slice was placed into the center of the fryer with the help of wire basket, providing uniform heating.

The potatoes were fried at 180 ^{0}C ± 10 ^{0}C and potato to oil ratio was kept constant at 0.042 (w/v). After each frying, the oil level was controlled and ratio of sample to oil was ensured. The oil was thrown out after 2h frying time.

The potatoes were fried at five different times as 4.0, 8.0, 12.0, 16.0, and 20.0 min. After frying of potatoes, they were kept for 2 min on the wire basket to drain over excess oil on the surface and allowed to cool to room temperature before analyses.

2.4 Analysis

Analyses of untreated potatoes and the potatoes fried after pre-coating or pre-drying were performed using whole sample. On the other hand, fried potatoes without any pretreatment were also analyzed for moisture, oil and pore size distribution. The sample was separated into two parts as crust and core and these parts were analyzed separately. Crust part was obtained by peeling disc like pieces of 2.0 mm thickness from the upper and lower surfaces of the potato slices. The remaining piece of the fried samples constituted the core part.

2.4.1 Moisture content measurement

Moisture contents of the fried samples were determined by drying up to the establishment of constant weight in a convection oven at 103^0C (Memmert, Schwabach, Germany). After the establishment of constant weight, weighing was performed with the electronic scale with a precision of 0.01g (Adventurer, Ohaus Corporation, Parsippany, China).

Moisture content was calculated on % wet basis (g moisture/ g wet solid). All measurements of moisture content were done in triplicate.

2.4.2 Oil content measurement

Soxhlet extraction method was used for oil content measurement. After temperature of the fried potatoes reached to room temperature, extraction was applied by using n-hexane as a solvent. Soxhlet extraction was performed for 5h. n-Hexane was removed by distillation .The concentrated mixture was transferred to a beaker and further evaporated under fume hood; then dried in the oven at 105°C until constant weight was achieved. The extracted oil was weighed by electronic balance (Denver Instrument, Bohemia, Germany) with a precision of 0.0001g. Oil content was calculated on the basis of wet sample (g oil/ g wet solid). All measurements were done in triplicate.

2.4.3 Porosity measurement

Porosity of the pre-dried, pre-coated, crust and core region of the untreated potatoes was determined by mercury porosimeter (Poremaster 60, Quantichrome Corp., Florida, USA). Moreover, pore size distribution of the crust and core parts of the potatoes were analyzed also by mercury porosimeter. Furthermore, helium pycnometer (Ultrapycnometer 1000, Quantichrome Corp., Florida, USA) was used for bulk density determination of the samples.

The oil inside the fried potatoes was removed by soaking in the n-hexane for 30 min. Then the untreated potatoes were separated into two parts as crust and core. Potatoes were fast frozen before freeze drying by immersing into liquid nitrogen and freeze dried in a laboratory scale freeze dryer (Christ, Alpha 1-2 LD plus, Osterode am Harz, Germany) for 48 hour. About 0.2g of freeze dried samples were placed into sample cell then put into the mercury porosimeter. Porosity (φ) is defined as fraction of the air in the sample and was determined by equation (2.1) (Sumnu & Sahin, 2008):

$$\varphi = 1 - \frac{\rho_b}{\rho_s} \tag{2.1}$$

where, ρ_b: bulk density (g/ cm^3)

ρ_s : solid density (g/ cm^3)

Pore size distributions of the crust and core region of the fried potatoes were analyzed with relationship between pressure, intruded volume and pore diameter.

Washburn equation (2.2) was used for pore size distribution modeling (Kassama, 2003).

$$D = -\left(\frac{1}{P}\right) 4\gamma\ cos\Phi \tag{2.2}$$

where, D: pore diameter

P: applied pressure

γ: surface tension of mercury

Φ: contact angle.

The maximum applied pressure was set to 340 MPa. Contact angle of mercury on samples was 140° and surface tension of mercury was 480 erg/cm^2.

2.4.4 Shrinkage measurement

Shrinkage of the samples were evaluated by volume ratio of the fried and raw potatoes. Volume of the samples was calculated from the measured dimensions (thickness and diameter) of the sample by caliper (Mitutoyo, CD-15D, Illinois, United States). Measurements were done in four different places of each sample and all measurements were made in triplicate. Volumetric shrinkage of the samples were determined with equation (2.3) (Kawas & Moreira, 2001).

$$S_V = \left(\frac{V_0 - V(t)}{V_0}\right) 100 \tag{2.3}$$

where, V_0 is original volume of the raw potato (cm^3) and V(t) is the volume of the fried potato (cm^3) at time t frying.

2.4.5 Scanning electron microscopy analysis

The fried potatoes were fast frozen by using liquid nitrogen and crushed into small pieces and then freeze dried with freeze dryer (Christ, Alpha 1-2 LD plus, Germany). The freeze dried samples were covered with gold and attached to the aluminum plate by conductive adhesive on the lateral section of the samples. SEM images of the samples were achieved by using a scanning electron nanomicroscope (JSM-6400-NORAN, Tokyo, Japan) at 20kV. 400× and 800× magnifications were used for obtaining SEM images.

2.4.6 Magnetic resonance imaging analysis

Magnetic resonance images of fried potatoes were practiced by NMR spectrometer (Siemens, Magnetom Trio 3 T, Germany). Longitudinal relaxation time (T_1) weighted images and water suppression images were obtained by spin echo sequence (SE). The parameters of the sequence were repetition time (TR), echo time space (TE), field of view set as 1000 ms, 12 ms and 170 mm, respectively. The signal intensity measurements of the images were analyzed.

Spin-spin relaxation times (T_2) of the fried potatoes were obtained by using multi-slice-multi-echo (MSME) pulse sequence results. The parameters of the MSME sequence set repetition time (TR) as 2000 ms, echo time space (TE) to 13.8 ms and , field of view to 170 mm. Three slices images with 3 mm slice thickness were obtained and mid slices were chosen for T_2 analysis. Relaxation time distributions of samples were obtained from an image by manually selecting all regions of the potatoes. Coronal images were analyzed and all MR imaging experiments of the fried potatoes were done in replicate.

2.5 Statistical analysis

The effects of pretreatments were determined by analysis of variance (ANOVA) ($p \leq 0.05$). Moreover, the difference between crust and core regions of the potatoes in terms of their moisture content, oil content and porosity, were analyzed with ANOVA. In addition, effect of frying time on moisture content, oil content, porosity and shrinkage of samples were analyzed by ANOVA to understand if there was a significant difference between the samples. Tukey's Comparison Test ($p \leq 0.05$) was applied to results when a significant difference was found. Furthermore, variation in the signal intensity values of the T_1 weighted images, water suppression images and also spin-spin relaxation time (T_2) was analyzed to show the effect of pretreatments and frying time. All statistical analysis, Pearson correlation and coefficients were determined by Minitab program (Minitab, Version 15, Minitab Inc., State College, Pa., USA).

CHAPTER 3

RESULTS AND DISCUSSION

3.1 Moisture Content

3.1.1 Effect of pretreatments on moisture content

Moisture content of fried potatoes is an important quality parameter since consumers prefer to consume these products that are crisp on the outside and moist on the inner side. The initial moisture content of potatoes was almost 80±2 % in wet basis (w.b). The moisture content of the untreated, pre-dried and pre-coated potatoes during frying was examined. The variation of the moisture contents of deep-fat fried potatoes with frying is shown in Fig. 3.1.

As shown in Fig. 3.1, moisture content of deep-fat fried potatoes decreased with increasing frying time. The highest moisture content was obtained for untreated potatoes at the shortest frying time (4.0 min). Moisture content of pre-dried potatoes decreased gradually as compared to untreated and pre-coated ones. This may be explained by the less amount of free moisture content in pre-dried potatoes.

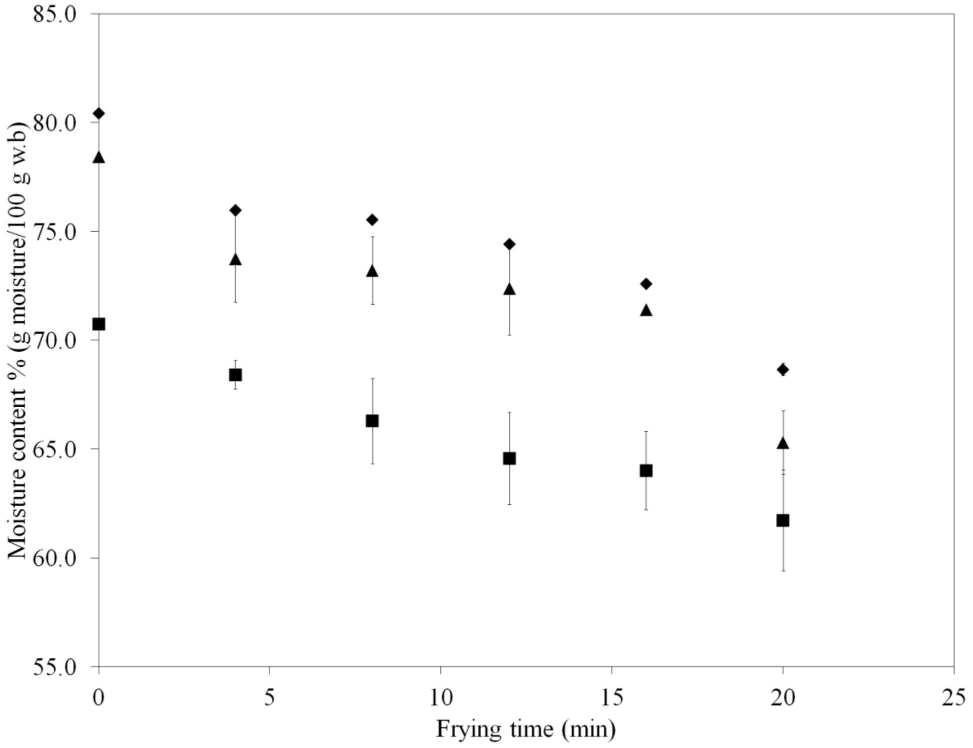

Figure 3.1 Effect of frying time on moisture content of deep-fat fried potatoes prepared with different pretreatments. (♦): untreated[a], (■): pre-dried[c] and (▲): pre-coated[b]. Different letters indicate significant difference ($p \leq 0.05$).

The pretreatments and frying time affected moisture content significantly ($p \leq 0.05$) according to the ANOVA result (Table A.1 in Appendix). Untreated potatoes had higher moisture content through the whole frying period. When Tukey test applied to moisture content results, it was seen that untreated, pre-dried and pre-coated potatoes were found to be significantly different. The reduction in the initial moisture content to 78±2 % and to 70±2 % in wet basis for pre-coated and pre-dried potatoes as a result of the drying applied during preparing could be the main reason for this difference.

3.1.2 Moisture content distribution

Distribution of moisture in the structure of deep-fat fried potatoes was examined by separating crust and core part of the samples. The effect of frying time on moisture content of crust and core region of the deep-fat fried potatoes is represented in Fig.3.2.

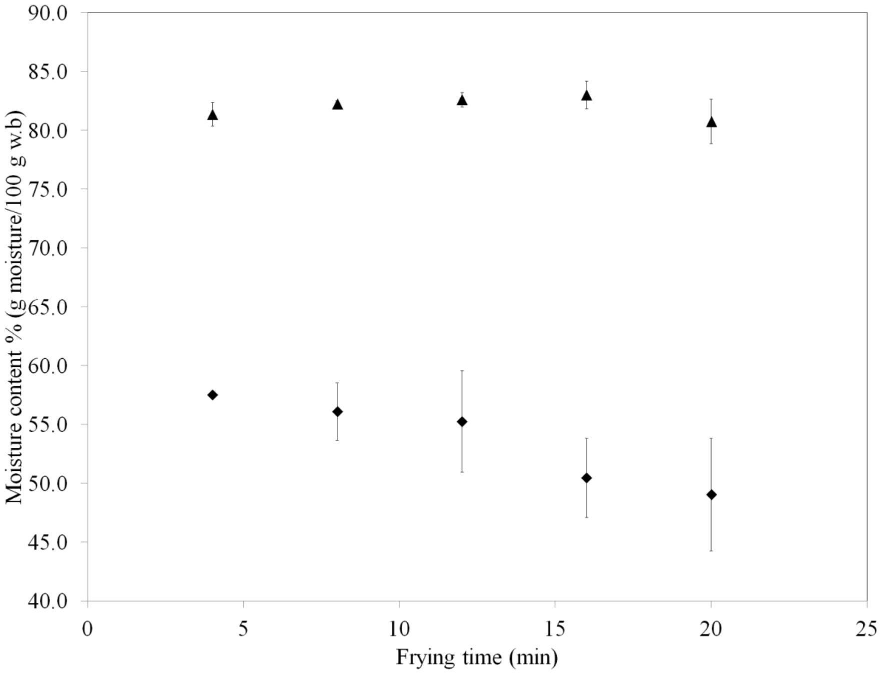

Figure 3.2 Variation on the distribution of moisture content in the structure of the potato samples with frying time. (▲): core^a and (♦): crust^b. Different letters indicate significant difference ($p \leq 0.05$).

When the ANOVA results represented in Table A.2 in Appendix was examined, frying time had no significant effect ($p>0.05$) but the moisture contents of crust and core parts of fried potatoes were significantly different ($p \leq 0.05$). As represented in Fig. 3.2, the moisture content of core region was higher than crust. This could be explained by conduction mechanism. The surface temperature of the samples started to increase as soon as they were immersed into hot oil and the surface temperature reached evaporation temperature of the water faster as compared to inner parts of the samples. Thus, water evaporation started first at the surface. Then, water is supplied to the surface from the inner part of solid sample. However, supply of water to the surface may not be as fast as it evaporates. This dehydration of the surface led to formation of crust region. The formation of crust acted as a barrier to moisture loss and as a result moisture loss of the core region was lower than crust region of the potatoes.

3.2 Oil Content

3.2.1 Effect of pretreatments on oil content

The increasing demand of consumption of fried products with low oil content increases the importance of oil content measurements in fried products. Therefore, oil content of fried samples is one of the most important quality parameter. Pretreatments were applied to reduce oil content and to achieve the desired quality of fried samples. That is why pre-drying and pre-coating were applied in this study.

Oil contents of deep-fat fried potato slices during frying process are represented in Fig.3.3. The results show that untreated, pre-dried and pre-coated fried potatoes were found to be significantly different ($p \leq 0.05$) with respect to oil content (Table A.3). The oil content of potatoes having no pretreatment was changed between 2.23-3.29% while it was in the range of 1.92- 3.19% for pre-dried and 2.19- 2.90 % in wet basis for pre-coated. Oil uptake increased with increasing frying time for all potato samples. This can be explained by replacement of moisture by oil during frying. The amount of evaporated water increases with increasing frying time and more oil enters to potato. In agreement with several researches (Southern, Chen, Farid, Howard, & Eyres, 2000; Ufheil & Escher, 1996; Ziaiifar, Courtois, & Trystram, 2010), the longer the sample remained in the frying medium, the more oil was penetrated into the fried sample.

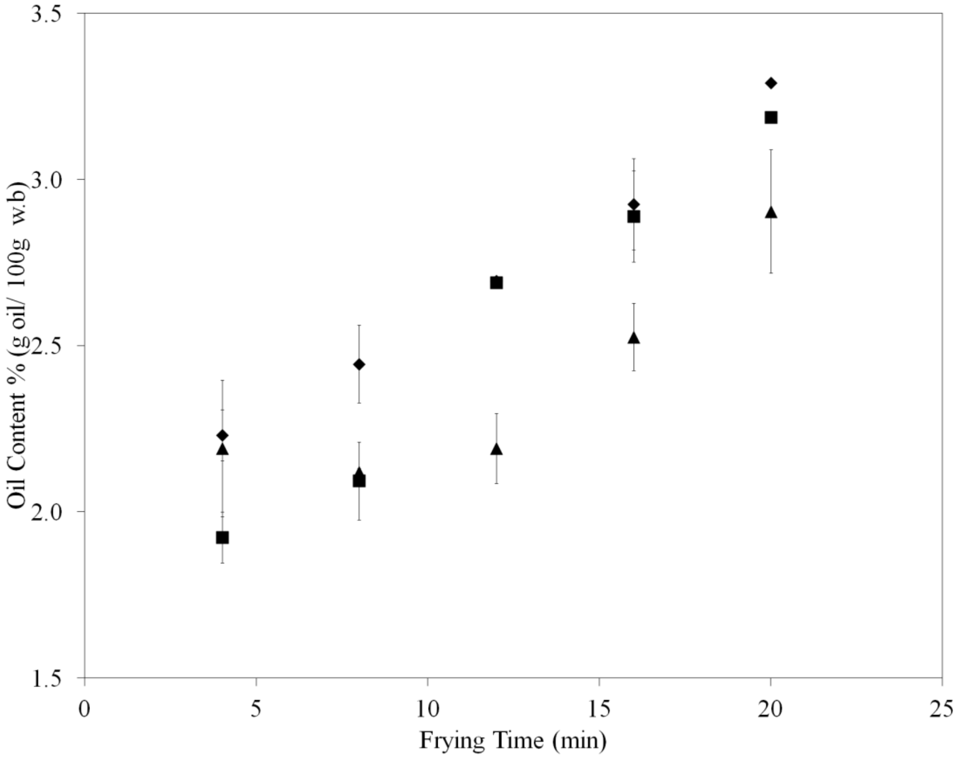

Figure 3.3 Effect of frying time on oil content of deep-fat fried potatoes prepared with different pretreatments. (♦): untreated[a], (■): pre-dried[b] and (▲): pre-coated[c]. Different letters indicate significant difference ($p \leq 0.05$).

As can be seen from Fig. 3.3, the untreated fried potatoes had the highest oil content through the whole frying period. During the initial period of frying (4 min and 8 min), the oil content of the pre-dried potato samples were lower than untreated and pre-coated ones. However, oil content of pre-dried potatoes increased and pre-coated samples had the lowest oil content at longer frying times (12 min, 16 min and 20 min). This can be explained by crust formation during pre-drying. While pre-drying was applied to potato samples, moisture at the surface of the potato decreased leading to a dry outer layer. The dry outer layer acted as a surfactant and this increased resistance to oil uptake. Similarly, pre-coating with HPMC reduced oil contents of potatoes. HPMC is a food hydrocolloid and it has a thermal gelling thickening property. When the pre-coated potatoes were immersed into hot oil, HPMC led to external crust formation which inhibited oil absorption. A similar result was observed by Garcia, Ferrero, Bertola, Martino and Zaritzky (2002) who studied fried potato strips and dough discs coated with methyl cellulose (MC) and HPMC.

3.2.2 Oil Content Distribution

The oil content of crust and core parts of the fried potatoes gave information about distribution of the oil inside the sample. Fig.3.4 shows how oil content change during frying at crust parts of the potatoes. As represented in Fig 3.4, frying time had significant effect ($p \leq 0.05$) on oil content of crust region (Table A.4).

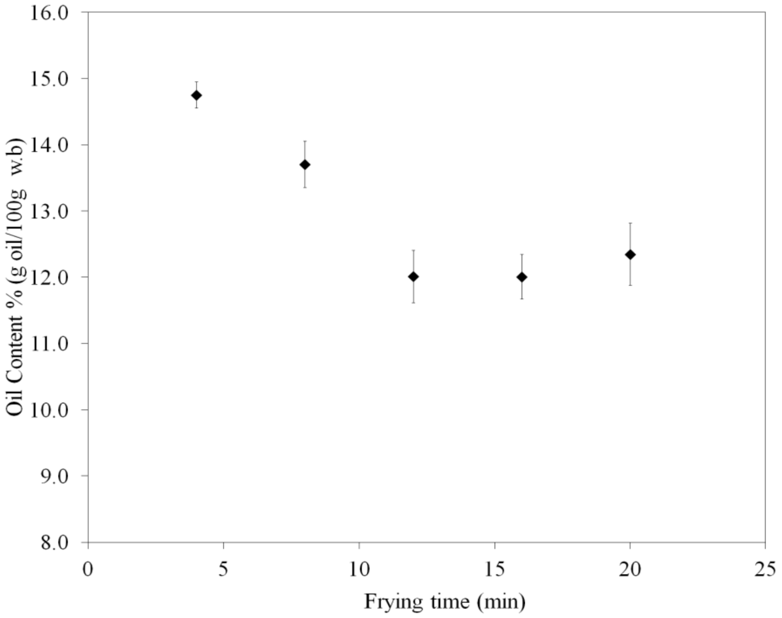

Figure 3.4 Variation of oil content in the crust part of the potato samples with frying time.

The oil content of the crust region decreased slightly up to 12 min and then remained constant. As mentioned in introduction part, water replacement, condensation effect and surface active agent impact are main principles lying behind oil absorption. The decrease in the oil content of the crust with frying can be explained with condensation effect (Bouchon et al., 2001). During the initial part of the frying, crust was formed and escaping of water vapor from potato was restricted with crust formation. Therefore, pressure inside potato increased until frying was ended up. When frying finished, pressure started to decrease and condensation took place inside potato. The oil at the crust was suctioned into the core part by the help of vacuum effect created by condensation. As a result, oil at the crust decreased with increasing frying time and at the same time oil content of the core part was increased (Figure 3.5).

The oil content of core part was very low as compared to crust part and variation of the oil content in core part during frying could not be observed when it was plotted together with that of crust part so it was represented in Fig. 3.5 separately. The oil content of crust and core region was found to be significantly different ($p \leq 0.05$) according to Table A.4 in Appendix.

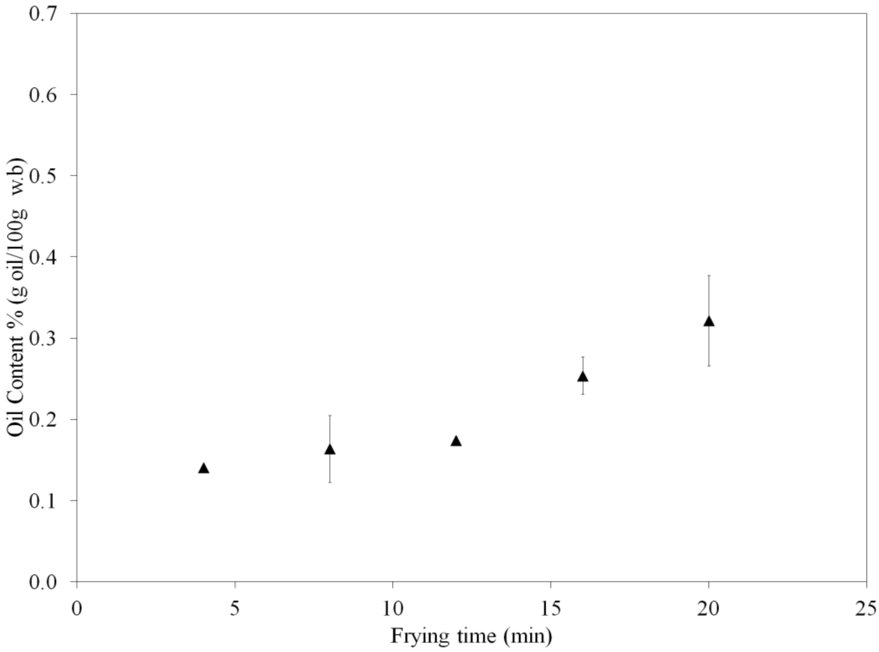

Figure 3.5 Variation in the oil content of core part of the untreated fried potatoes.

The oil content of the core part was not changed significantly with frying. The oil uptake on the core part of fried potatoes after 4 min frying was about 0.14% in wet basis. This low value of oil content pointed out that oil could not enter into the potato at initial frying times. When frying was continued for 20 min, the oil content of the core part increased to 0.32% in wet basis. However, there was no significant effect ($p>0.05$) of frying time on oil content of the core part of the fried potatoes in statistically (Table A.4). As a result of the statistical analysis, oil content of the crust region decreased and remained constant and that of core region did not changed with increasing frying time. On the other hand, oil content of the untreated potatoes increased with frying time significantly (Fig. 3.3 and Table A.3). This might be explained by higher fraction of the core region as compared to crust region in potato slice. Therefore, slight increase in oil content of core region might have more impact on increasing oil content of the whole potato although oil content of the crust region decreased with frying.

3.3 Shrinkage

Shrinkage is the volume change and it depends on moisture loss, oil uptake and pore size alteration. The profile of the volumetric shrinkage of the untreated, pre-dried and pre-coated potatoes is represented in the Fig. 3.6. The results of the ANOVA is represented in the Table A.5 in Appendix and ANOVA results showed that shrinkage changed significantly with pretreatments and frying time ($p\leq0.05$).

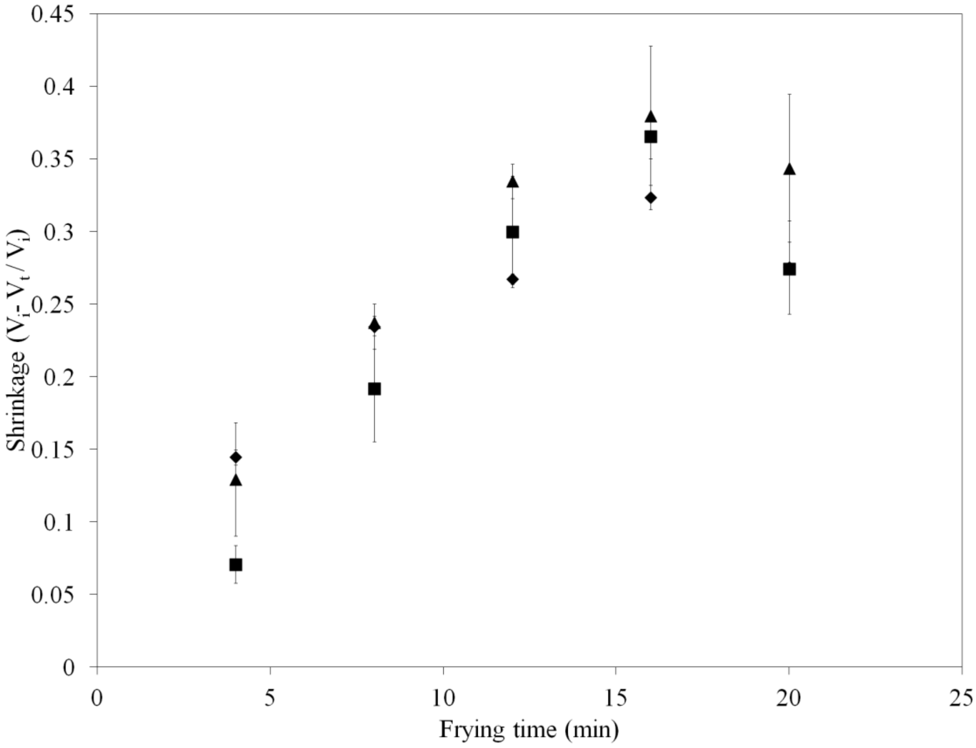

Figure 3.6 Variation in the volumetric shrinkage of the potatoes during frying in sunflower oil at 180 °C. (♦): untreated^{b}, (■): pre-dried^{b} and (▲): pre-coated^{a}. Different letters indicate significant difference ($p \leq 0.05$).

The untreated and pre-dried potatoes showed similar volumetric shrinkage during frying. The pre-coated potatoes showed more shrinkage. Yamsaengsung and Moreira (2002) stated that shrinkage started at the surface and then moved inward with increasing frying time. The HPMC coating on the surface of the potatoes developed crust behavior and could cause generation of higher pressure inside potatoes. The formation of higher pressure might enhance collapsing during cooling of the potatoes and increased volumetric shrinkage. Moreover, the oil uptake of the pre-coated potatoes was significantly lower than untreated and pre-dried samples (Figure 3.3 and Table B.1). The low amount of oil absorption could increase volumetric shrinkage since absorbed oil filled the voids inside samples.

As shown in Fig. 3.6 volumetric shrinkage of the potatoes increased with frying time and reached maximum value at 16 min frying time and then decreased. The volumetric shrinkage of untreated, pre-dried and pre-coated potatoes changed from 0.14 to 0.28, from 0.07 to 0.27 and from 0.13 to 0.34 during 4min to 20 min frying time. The maximum volumetric shrinkage of the untreated, pre-dried and pre-coated potatoes at 16 min was 0.32, 0.36 and 0.37 respectively. Moisture loss is the main reason of the increase in the volumetric shrinkage. Wang, Ngadi, and Adedeji (2010) reported linear relationship between moisture loss and volumetric shrinkage of the deep-fat fried chicken nuggets with R^2 values ranging between 0.90 and 0.94. The experimental results of the study showed reduction in the volumetric shrinkage at the longest frying time (20 min) and this behavior disabled linear relationship. Similarly, Taiwo and Baik (2007) reported an increase in the volumetric shrinkage of sweet potatoes at initial times of the frying and then observed reduction or leveling off. The separation of the cells can be observed at prolonged frying times. Costa, Oliveira, and Boutcheva (2001) expressed that accumulation of the water vapor inside food during frying resulted in cell separation and increase in volume of the samples. Thus, volumetric shrinkage of the potatoes at 20 min might be the result of the cell separation. Nonetheless, these results showed that 16 min is the crucial duration for untreated, pre-dried and pre-coated potatoes having similar dimensions.

3.4 Porosity

3.4.1 Pretreatment effect on porosity

Porosity is an important quality parameter in fried foods as it directly affects other physical properties such as thermal and mass diffusivity and textural properties. Thus, porosity of the potatoes was analyzed and the correlation between porosity and oil content were determined. Porosity of the whole sample was evaluated only in pretreated samples. For the untreated sample, pore developments were analysed in the crust and core parts separately. Fig. 3.7 represents porosity change of pre-dried and pre-coated potatoes with frying.

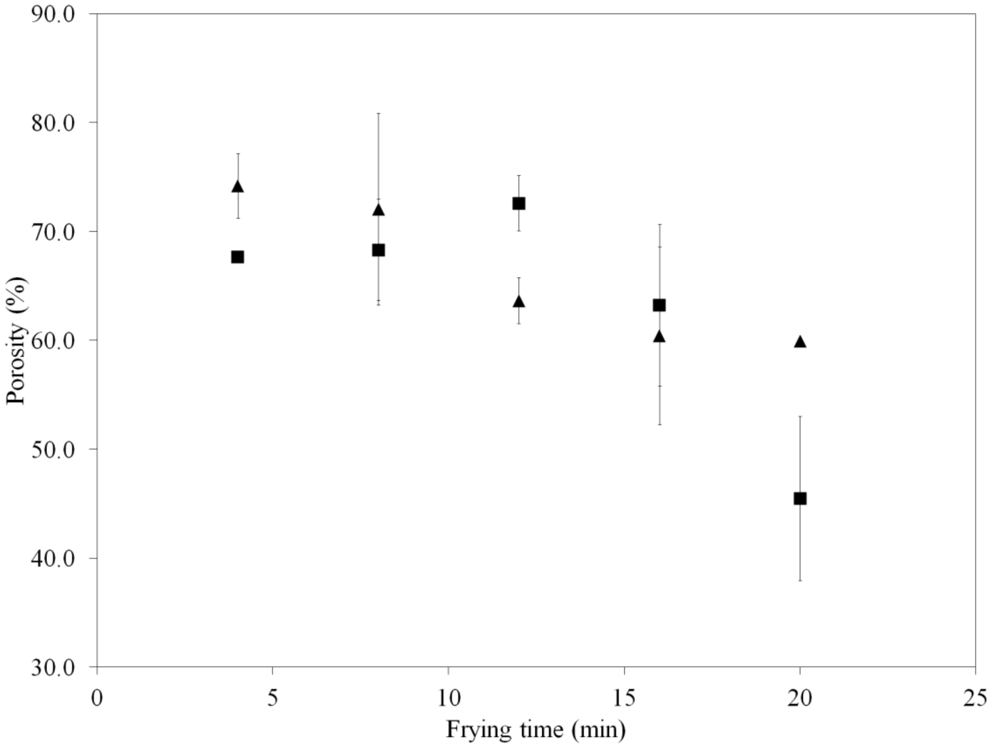

Figure 3.7 Variation in the porosity of the potatoes with increasing frying time. (■): pre-dried[a], (▲): pre-coated[a]. Different letters indicate significant difference ($p \leq 0.05$).

There was no significant difference ($p > 0.05$) between porosity values of pre-dried and pre-coated potatoes, when analysis of variance (ANOVA) was performed (Table A.6). On the other hand, frying time had significant effect on porosity of potatoes ($p \leq 0.05$). However, their variation trend was different as can be seen from Fig. 3.7. The porosity of the pre-dried potatoes increased and then started to decrease. It reached maximum value of 72% at 12 min frying time and then decreased to 45% at 20 min frying time. This was an expected behavior. As indicated by Kawas and Moreira (2001), Krokida, Oreopoulou, and Maroulis (2000a) and Ziaiifar et al. (2010) in their study, these results can be explained by moisture loss, collapse and oil uptake phenomena. The evaporation of water during frying creates bubbles and open pores are generated. The decrease in moisture content brought about an increase in porosity up to 12 min. After that time, oil absorption into potato and shrinkage became dominant and porosity started to decrease. On the other hand, porosity of the pre-coated fried potatoes decreased to 59% from 74% with increasing frying time. This was the unexpected result since moisture loss during frying was observed which created pores inside potatoes. This situation may be explained by the rapid and strong crust formation at pre-coated potatoes. The formation of crust prevented moisture escape and caused generation of large pores which enhanced collapse in potatoes. This collapse inside potatoes could be linked to volumetric shrinkage of the potatoes. Shrinkage may be the reason of the decreasing trend of porosity in pre-coated fried potatoes. There are researches that record decreasing trend in porosity. For example, Kassama and Ngadi (2005) reported that agglomeration of protein, shrinkage and oil uptake can be the reason of decrease in porosity of chicken meat. Moreover, Pinthus et al. (1995) also studied porosity on crust region of the potato products. They reported that porosity of the restructured potato crust decreased as a result of lower gel strength.

The change in porosity and oil content of the pre-dried and pre-coated fried potatoes is represented in Fig. 3.8. As represented in Fig. 3.8, the increase in the oil content decreased porosity of the potatoes.

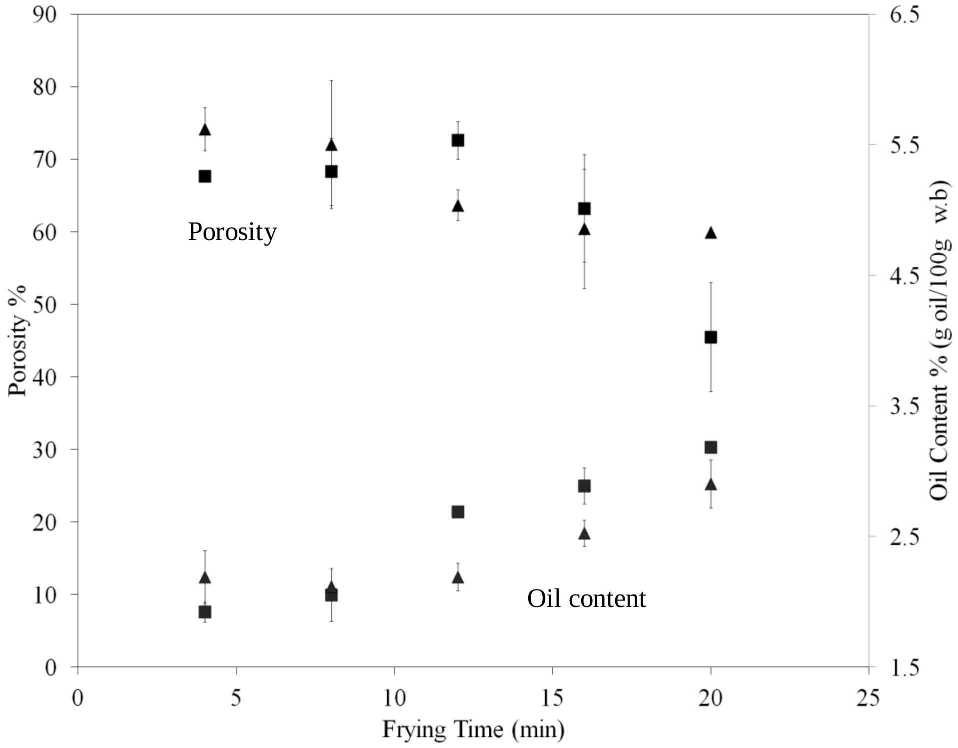

Figure 3.8 Change in porosity and oil content of pre-dried (■) and pre-coated(▲) fried potatoes at 180°C with increasing frying time.

3.4.2 Pore development at crust and core

Crust and core parts were two different distinguishable regions of the fried potatoes. The formation of crust is important in fried products due to its influences on physical properties and mass transfer mechanism of fried products. Porosity is one of the main differences between crust and core. The change in the porosity of the crust and core part of the untreated potatoes during frying is represented in Fig. 3.9.

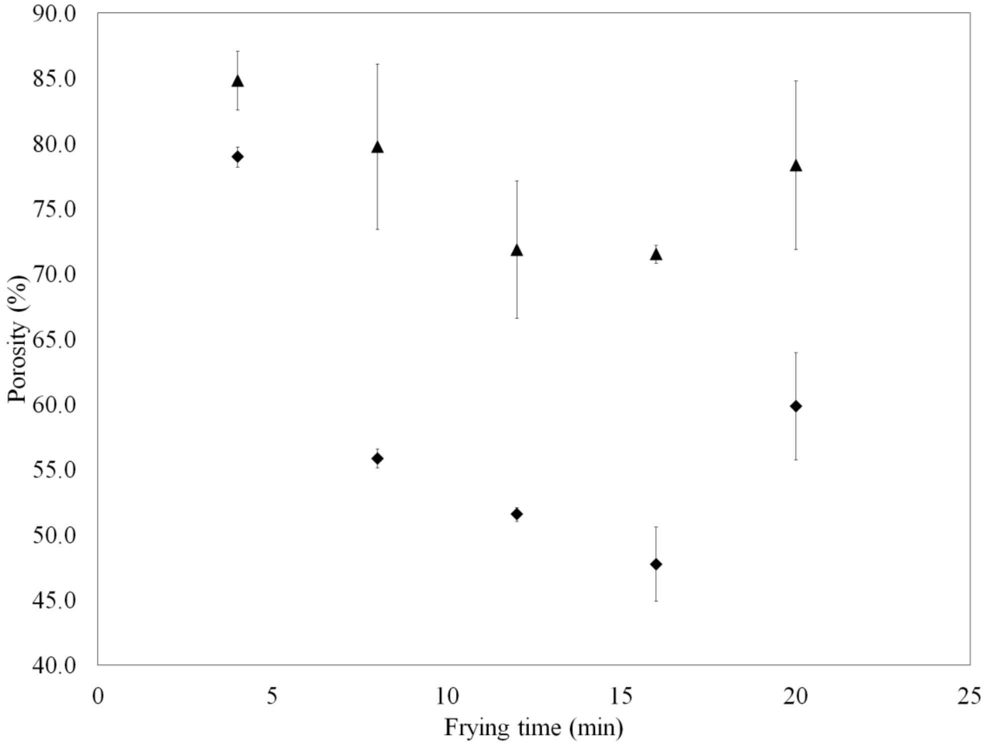

Figure 3.9 Variation in the porosity of crust and core parts of the untreated fried potatoes. (▲): core[a] and (♦): crust[b]. Different letters indicate significant difference ($p \leq 0.05$).

The result of the analysis of variance (ANOVA) was represented in Table A.7 in Appendix. As a result of the ANOVA, there was significant difference ($p \leq 0.05$) between crust and core part of the potatoes in terms of their porosity. Moreover, porosity of the crust and core was significantly affected with frying time ($p \leq 0.05$).

Porosity of the crust region was lower than core region for the whole frying period. It is known that water at the crust was evaporated quickly and more rapid generation of pores and canals were observed as compared to core. However, oil was penetrated into potatoes from these pores at the same time. Aguilera and Gloria-Hernandez (2000) specified the location of the absorbed oil was in pores and canals of the crust. As represented in the Table B.1, oil content of the crust was significantly higher than core. The high amount of oil content at crust part resulted in lower porosity in the crust. This was an expected result since oil filled the pores.

Both in the crust and core regions, porosity decreased up to 16 min frying time and then increased. The decrease in the shrinkage at 20 min may be the reason of this behavior (Figure 3.6). Porosity of the crust and core region decreased to 47% and 71% from 78% and 84% and then increased to 59%, 78%, respectively.

3.4.2.1 Pore size distribution

Pore size distributions of the crust and core region of the fried potatoes were analyzed by Washburn equation. The applied pressure was converted to pore radius and pore size distribution function can be defined by equation (3.1) ;

$$D_V = \left(\frac{P}{r}\right) \times \left(\frac{dV}{dP}\right) \tag{3.1}$$

where, P represents pressure (Pa) and D_V represents volume pore size distribution function and identified as volume of pore at unit interval of pore radius (cc g^{-1} μm^{-1}). The intruded volume was defined as dV and dV/ dP was found by slope of the intruded volume versus pressure graph. There are few studies on pore size distribution of fried foods in the literature. Kawas and Moreira (2001) showed the effect of frying time on pore size distribution of the tortilla chips. They indicated that increasing frying time led to greater amount of larger pores.

The pore size distribution curves of the core region of the untreated fried potatoes for different frying times are given in Figures 3.10- 3.14.

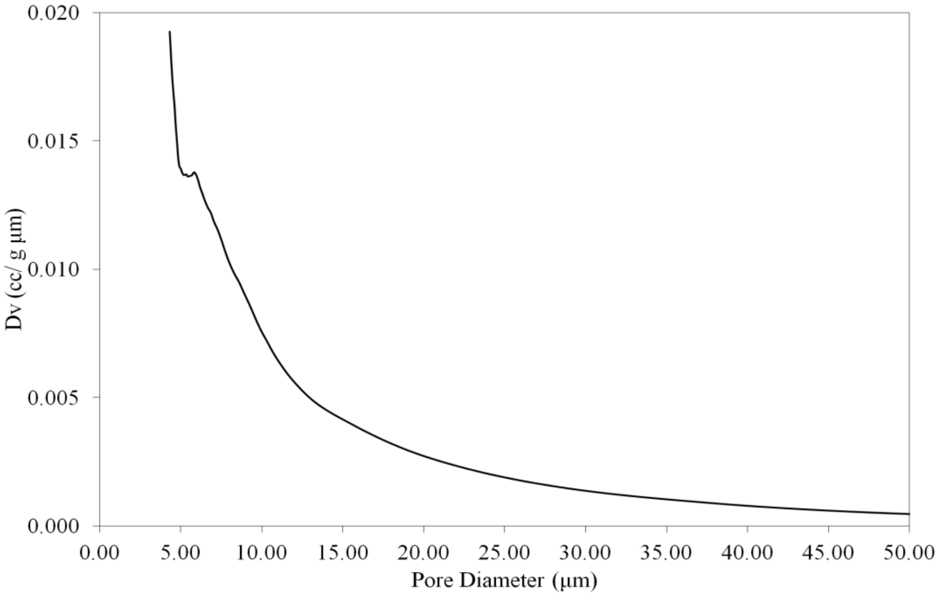

Figure 3.10 Pore size distribution curve for the core region of potatoes after 4 min frying.

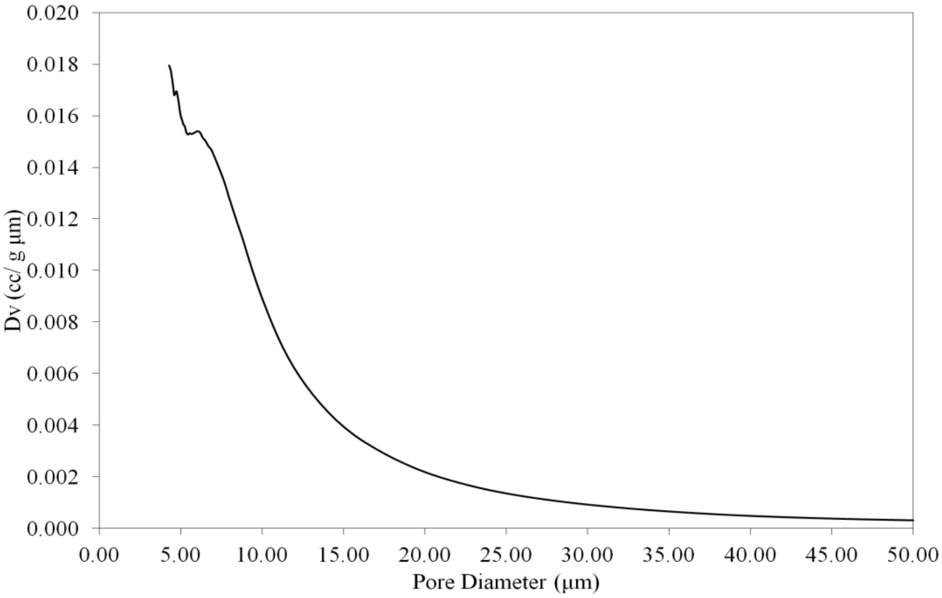

Figure 3.11 Pore size distribution curve for the core region of potatoes after 8 min frying.

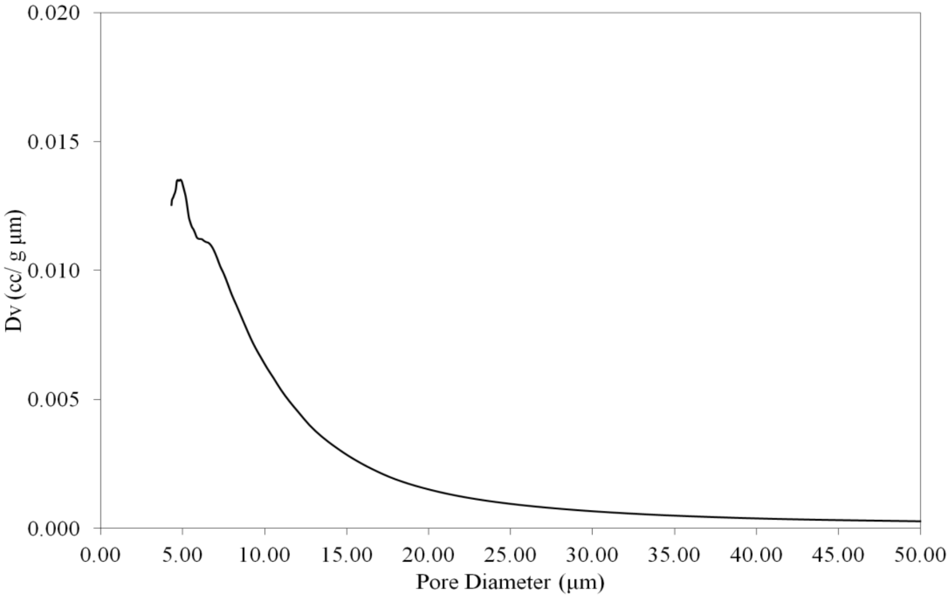

Figure 3.12 Pore size distribution curve for the core region of potatoes after 12 min frying.

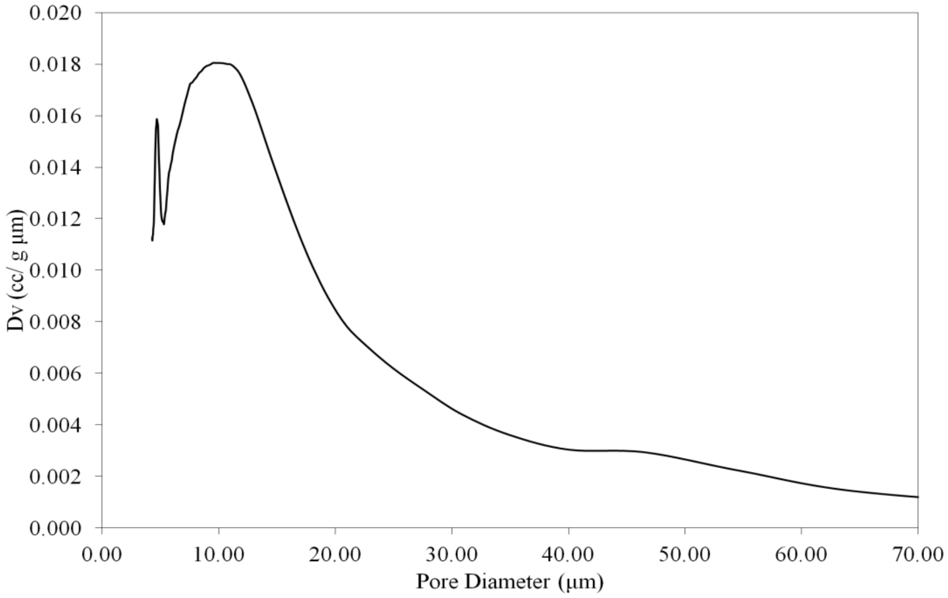

Figure 3.13 Pore size distribution curve for the core region of potatoes after 16 min frying.

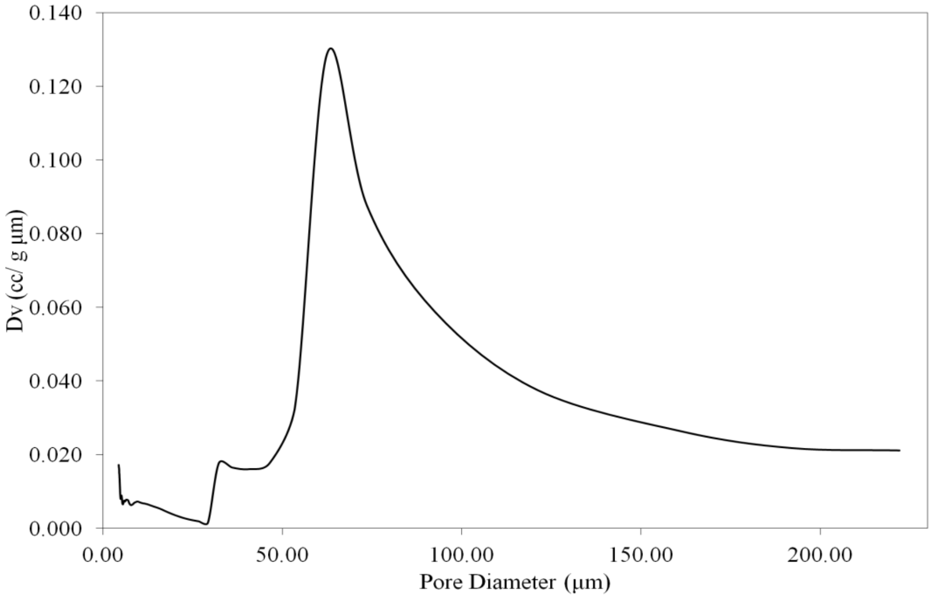

Figure 3.14 Pore size distribution curve for the core region of potatoes after 20 min frying.

The pore size distribution curve was obtained by drawing Dv versus pore diameter data. The curve was characterized by the number, shape and size of the peaks. The meaning of the large peaks is the existence of the pores mostly in that size range. Moreover, sharp peak shows extent of similarity at that pore diameter (Rahman, 2009). As shown from Figures 3.10-3.12, core region of the fried potatoes showed one sharp peak at 5.82 µm, 6.33 µm and 6.73 µm when fried 4 min, 8 min and 12 min, respectively. On the other hand, two sharp peaks were observed at 4.83 µm and 10.4 µm, 36.1 µm and 73.5 µm when frying time was 16 min and 20 min, respectively. The results showed that increasing frying time caused to obtain pores at two different size ranges. Besides, as frying time increased, curves were skewed to the right (to higher pore diameter).

The variation in the pore size distribution curves for the crust region of the fried potatoes is given in Figures 3.15- 3.19. Two sharp peaks at 5.29 µm and 8.11 µm pore diameter were obtained for crust region of the potatoes fried for 4 min and the height of the first peak was higher than the second peak. The number of the peak was increased to four at 8 min and no peak was observed at 12 min fried potatoes. This can be explained by the formation of cracks and channels in potatoes. The cracks can lead to eliminate similar size pores and formation of various size pores. Two sharp peaks at 5.7 μm and 7.84 μm in pore size distribution curve of the 16 min fried potatoes were observed and the heights of the peaks were lower than the peaks observed in earlier frying periods. Thus, lower amount and smaller size pores were formed at the later stages of frying. The effect of shrinkage on pores might be the reason for obtaining smaller pores. In addition, one sharp peak and wider peak were observed at 20 min fried potatoes. This is an expected result since the result of volumetric shrinkage at 20 min was lower than 16 min and this decrease might result in cause to observe wider peak at higher pore diameter.

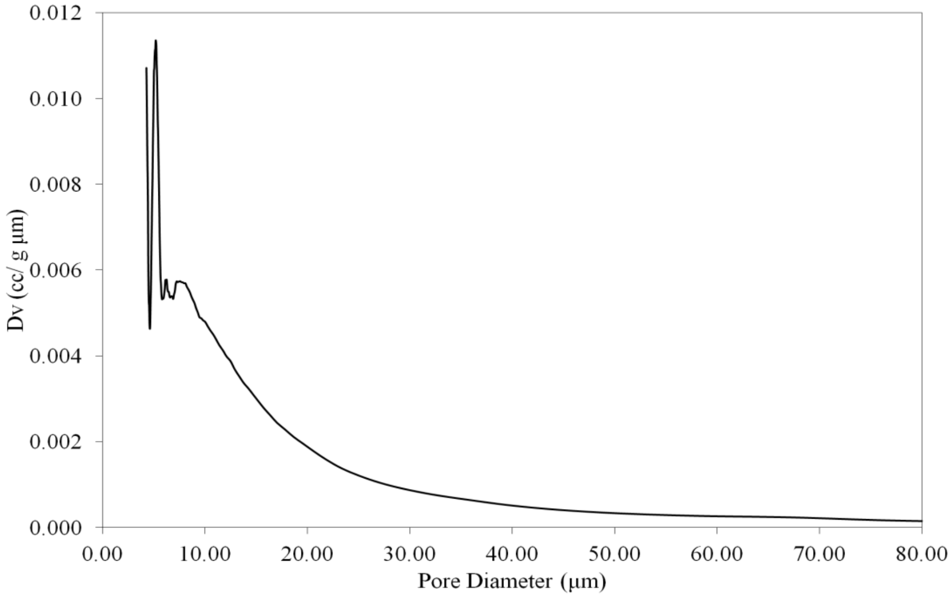

Figure 3.15 Pore size distribution curve for the crust region of potatoes after 4 min frying.

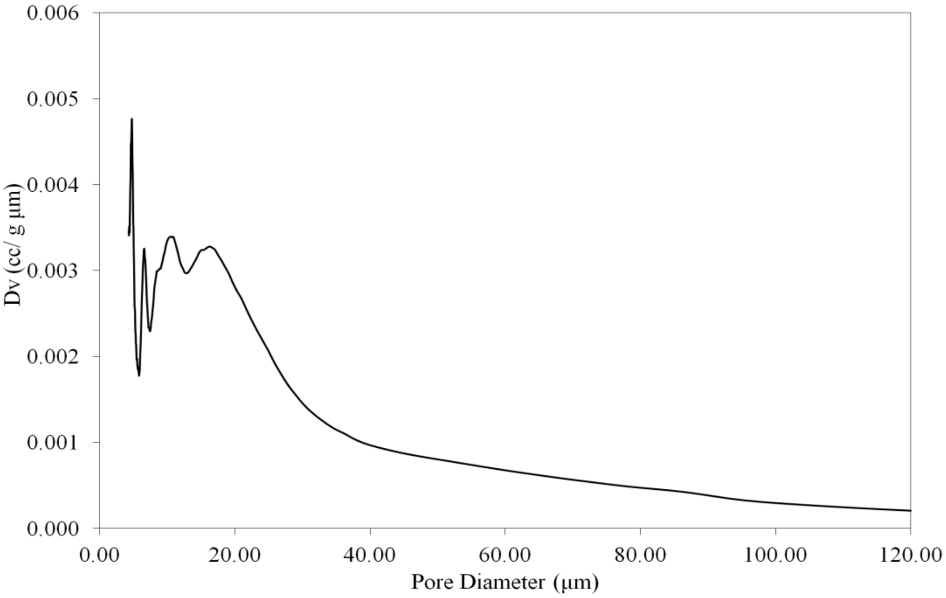

Figure 3.16 Pore size distribution curve for the crust region of potatoes after 8 min frying.

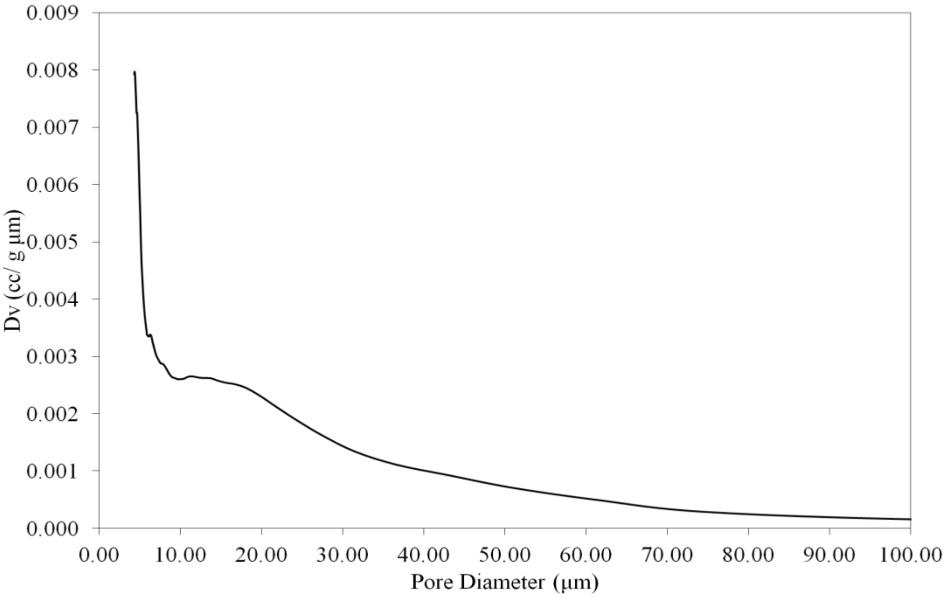

Figure 3.17 Pore size distribution curve for the crust region of potatoes after 12 min frying.

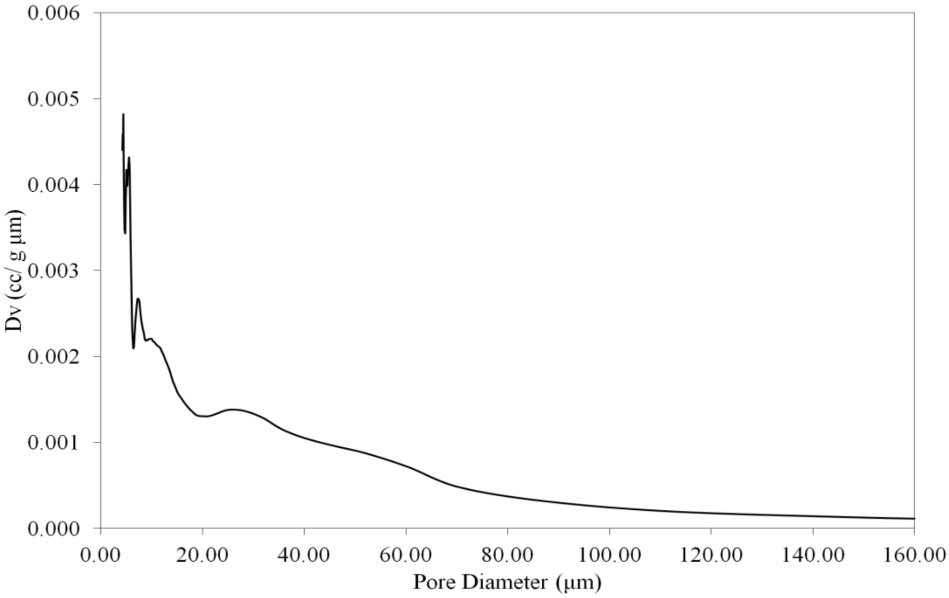

Figure 3.18 Pore size distribution curve for the crust region of potatoes after 16 min frying.

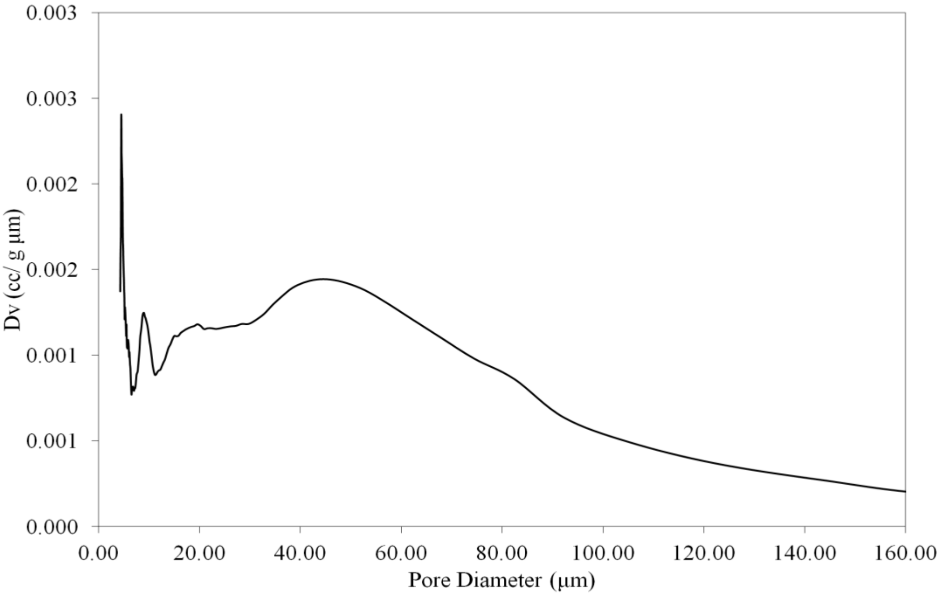

Figure 3.19 Pore size distribution curve for the crust region of potatoes after 20 min frying.

There was difference between pore size distributions of core and crust region of the fried potatoes when they were compared at same frying time. Size of pores at the core region was more similar and there was gradual increase in diameter of the pores with increasing frying time. on the other hand, the change in pore size with frying was less observable as compared to core region. In addition, smaller pores were observed at crust region which was in accordance with porosity results (Figure 3.9).

3.4.2.2 Microstructural Analyses

Scanning electron microscopic (SEM) analyses was applied to show the effect of frying time on the crust and core region of the fried potatoes on microscopic level. The SEM image of the raw potato is represented in Fig. 3.20. The starch granules and cell wall can be easily distinguished on the SEM images of the raw potato.

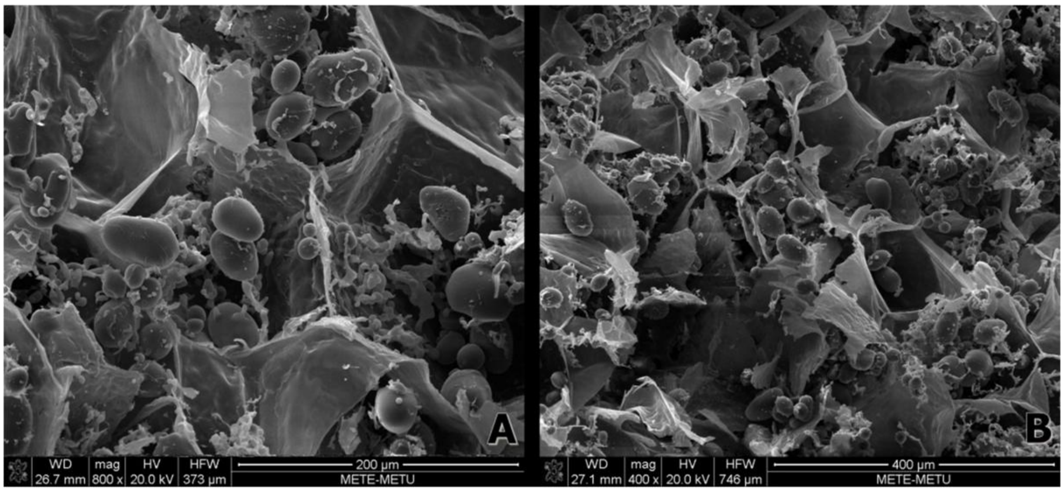

Figure 3.20 SEM images of the raw potato (A: 800x magnification, B: 400x magnification).

The SEM images of the crust and core region of the 4 min and 20 min fried potatoes are represented in Figures 3.21 and 3.22, respectively. The images of the fried potatoes were quite different as compared to raw potato image. As can be seen in Fig. 3.21, the starch granules were deformed and became fragmented as a result of starch gelatinization. Moreover, shrinkage of the cells and small pores can be observed at 4 min fried potatoes both in the crust and core region. When the SEM images of the 20 min fried potatoes (Figure 3.22) were examined, the formation of larger pores was observed. This result was correlated with increase in porosity of crust and core regions after 16 min frying (Figure 3.9). The breakage of the cell wall and appearance of gelatinized matrix can be shown in Fig. 3.22 more clearly. Kawas and Moreira (2001) reported similar results on research of the fried tortilla chips. They indicated that size and number of pores increased during frying and starch matrix surrounded them.

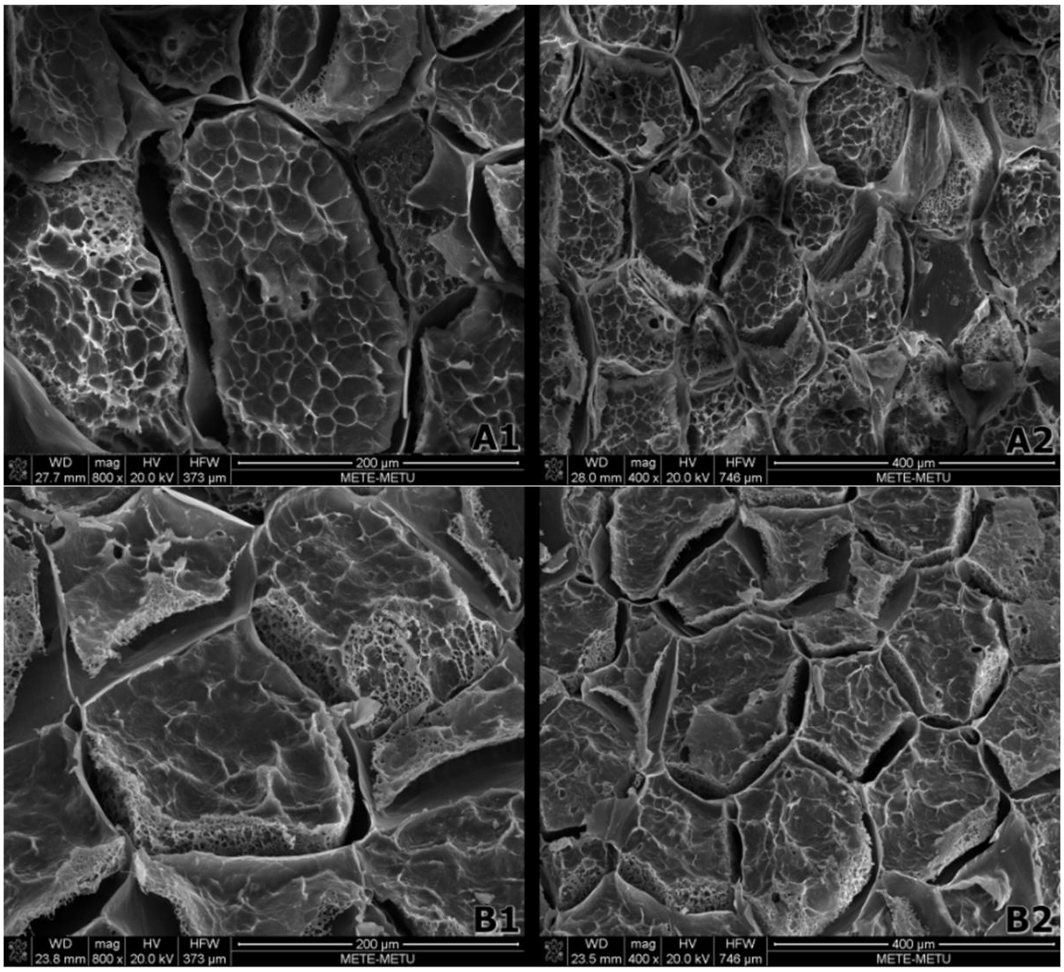

Figure 3.21 SEM images of the crust region (A1: 800x, A2: 400x magnification), core region (B1: 800x, B2: 400x magnification) of potatoes after 4 min frying.

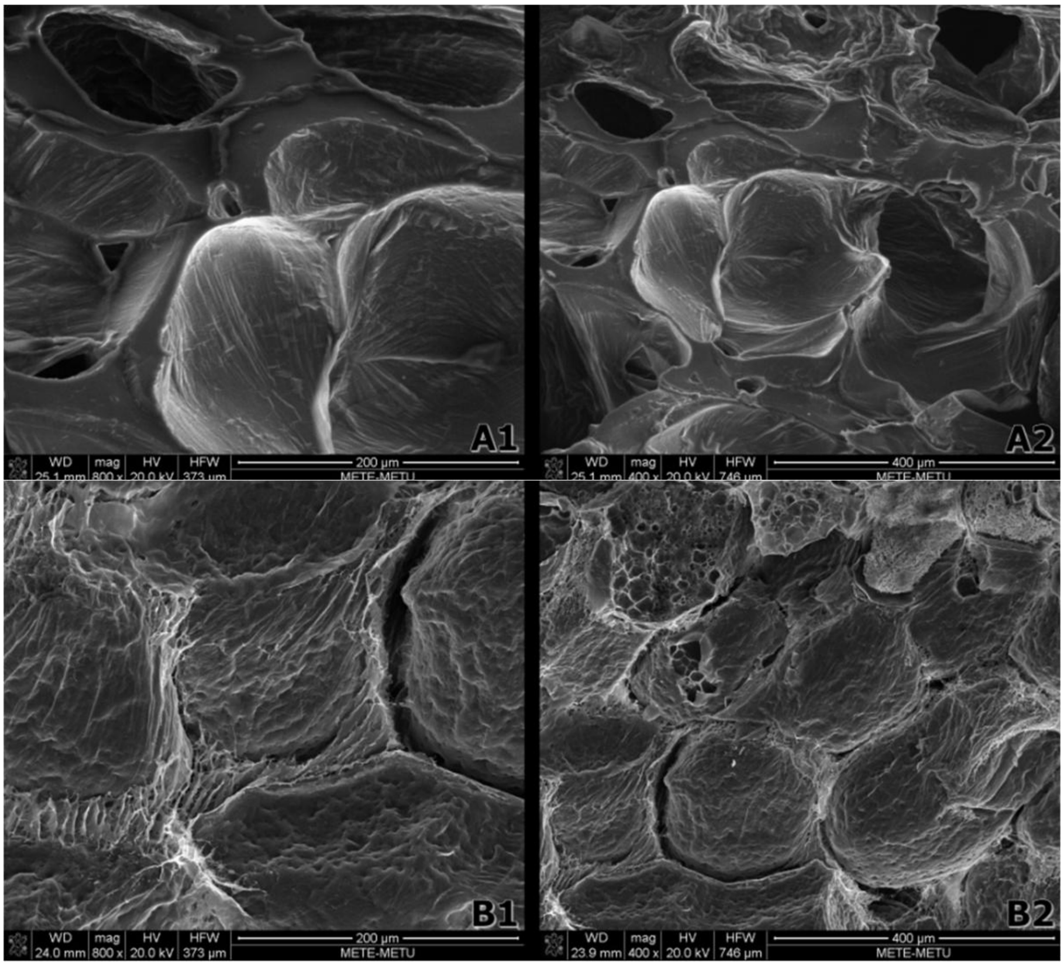

Figure 3. 22 SEM images of the crust region (A1: 800x, A2: 400x magnification), core region (B1: 800x, B2: 400x magnification) of potatoes after 20 min frying.

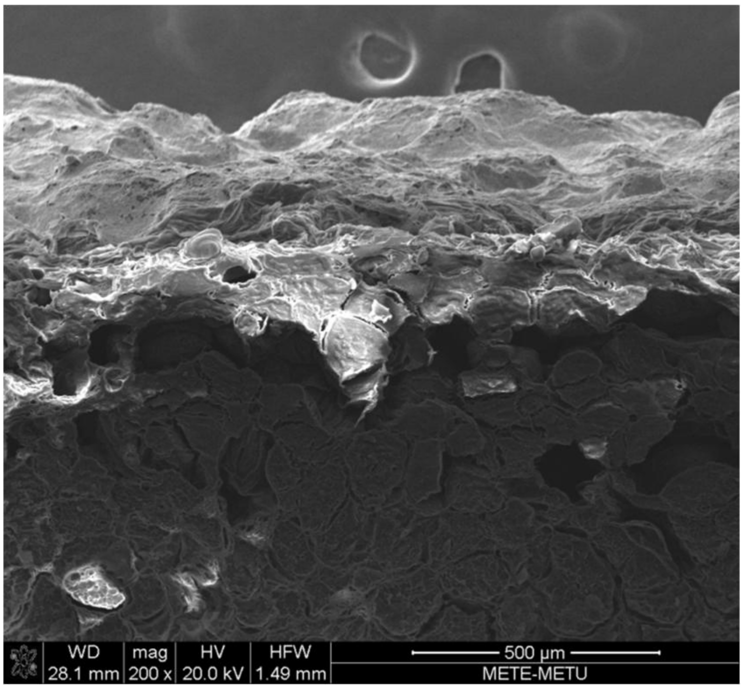

Figure 3.23 SEM image of the crust and core region of potato (200x magnification) after 4 min frying.

As shown in Fig. 3.23, SEM images showed differences between crust and core region of the potatoes. The breakage of cell wall and smaller size pores were observed in crust region. On the other hand, larger pores were observed and cell structure was distinguishable in core region. Furthermore, pores were accumulated between crust and core region and formed channel like structure between them.

3.5 Correlations between physical and chemical properties of potatoes

As explained before, moisture content, oil uptake, porosity and shrinkage of the potatoes were shown to be related to each other. Therefore, Pearson correlation was performed to find the relation between these parameters and correlation coefficient matrix was given in the Table 3.1.

Table 3.1 Pearson correlation coefficients matrix for moisture content, oil content, porosity and shrinkage results of the fried potatoes.

	Moisture Content	Shrinkage	Porosity
Shrinkage	-0.739^*		
	p=0.015		
Porosity	0.519	-0.207	
	p=0.124	p=0.566	
Oil Content	-0.813^*	0.786^*	-0.589
	p=0.004	p=0.007	p=0.073

(*) indicates significant correlation with $p\leq 0.05$.

As represented in Table 3.1, moisture content was negatively correlated with oil content and shrinkage results of the samples ($p\leq 0.05$). In other words, the increase in moisture content decreased oil content and shrinkage of fried potatoes.

Moreover, a correlation between results of oil content and shrinkage was detected with a correlation coefficient of 0.786. The strongest linear correlation was detected between moisture content and oil content of the samples with a coefficient of -0.813. The porosity results had no correlation with moisture content, oil content and shrinkage results.

3.6 Magnetic Resonance Imaging (MRI)

3.6.1 T_1 Weighted Magnetic Resonance Images

The equation for analyzing MR signal intensity for spin-echo sequence is given by equation (3.2) (Bernstein et al., 2004);

$$S = M_0\left(1 - 2e^{-(TR - TE/2)/T_1} + e^{-TR/T_1}\right)e^{-TE/T_2} \tag{3.2}$$

where, M_0 represents initial magnetization, TR is repetition time, TE is the echo time and T_1 and T_2 are the representation of longitudinal relaxation time and spin-spin relaxation time, respectively. When the repetition time (TR) which is the time between RF pulses is set to lower value than T_1 of the sample, T_1 weighted images is obtained. Similarly, when the echo delay time (TE) is lower than T_2 of the sample, T_1 effect on the images is enhanced. The effect of the T_1 on the images was enhanced by setting TR to 1000 ms in this study. Thus, the higher signal intensity shows short T_1 value and brighter color indicates higher signal intensity in the MR images. T_1 weighting images of the fried potatoes can give information about its moisture and oil distributions since T_1 provides information about how water is structurally bound in the tissues (Otero & Prestamo, 2009). Representative coronal MR images of the untreated, pre-dried and pre-coated fried potatoes after 4 min and 16 min frying times were indicated in the Fig. 3.24.

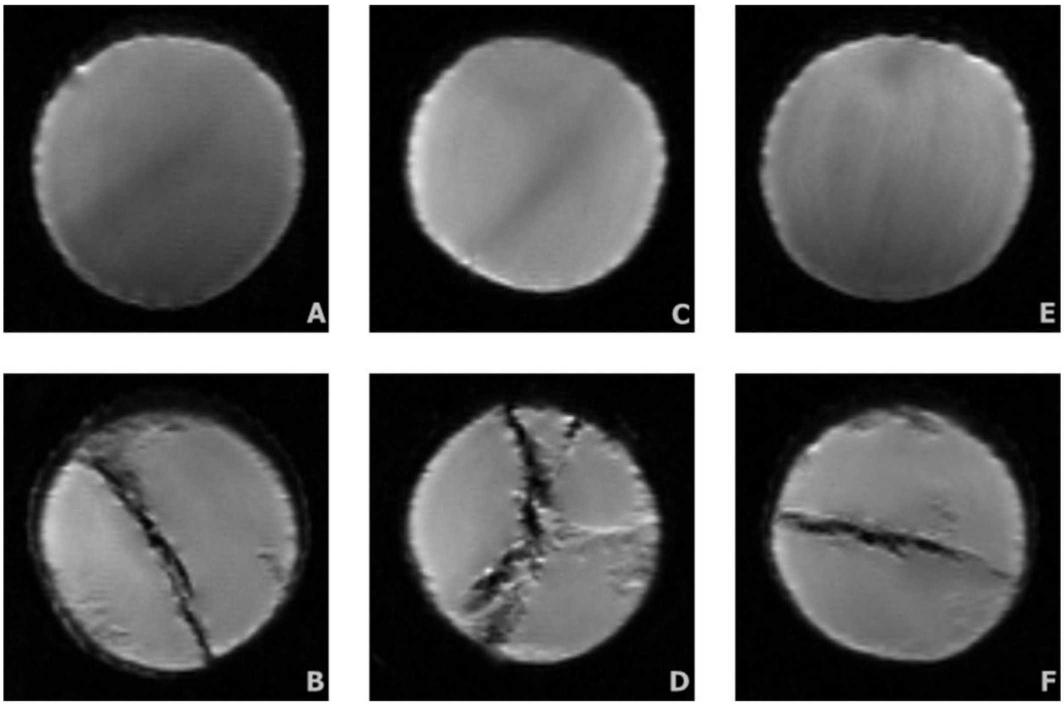

Figure 3.24 Representative T_1 weighted coronal magnetic resonance images (MRI) of the untreated (A: 4 min, B: 16 min fried), pre-dried (C: 4 min, D: 16 min fried) and pre-coated (E: 4 min, F: 16 min fried) potatoes fried in sunflower oil at 180°C.

As can be seen in Fig. 3.24, the pores around the pith of the potatoes were created with increasing frying time and dark color was observed at pith. The difference at pith of the potato can also be observed in Fig. C.1, Fig. C.2 and Fig. C.3 in Appendix. Moreover, signal intensity values are represented in Fig. 3.25. Frying time had significant effect ($p \leq 0.05$) and pretreatments had no significant impact ($p > 0.05$) on the signal intensity values (Table A.8). In addition, the interaction between frying time and pretreatment was significant ($p \leq 0.05$).

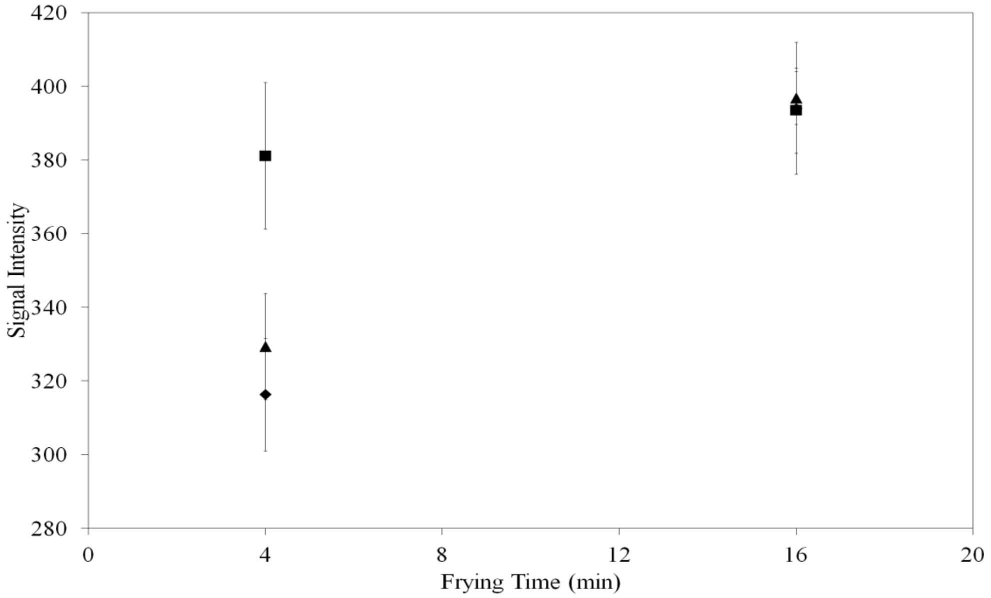

Figure 3.25 Variation in the signal intensities of the fried potatoes with frying. (♦): untreated[a], (■): pre-dried[a] and (▲): pre-coated[a]. Different letters indicate significant difference ($p \leq 0.05$).

As the frying time increased, signal intensity increased since moisture content of the potatoes reduced. As expected, the lowest signal intensity was obtained on the untreated 4 min fried potatoes which had the highest moisture content value. The signal intensity increased by 24.6%, 3.2% and 20.5% for untreated, pre-dried and pre-coated when frying time increased to 16 min from 4 min, respectively. The change in the signal intensity of the pre-dried potatoes with frying was lower than that of untreated and pre-coated potatoes. This can be explained by the lower moisture content of the pre-dried potatoes as compared to others. Moreover, oil content of fried potatoes which increased at 16 min might affect the signal intensity by reducing T_1. Furthermore, signal intensity and moisture content results of the potatoes were correlated (R= 0.98) for 4 min fried potatoes. On the contrary, there was no correlation for 16 min fried potatoes. As indicated in the Fig. 3.24, the formation of the pores around the pith might be the reason since pores could decrease signal intensity values. Similar results were obtained by Altan, Oztop, McCarthy, and McCarthy (2011). They reported a decrease in the signal intensity with increasing brining time of the feta cheese as water in the cheese diffused out and salt penetrated into cheese.

3.6.2 Water Suppression Images

Water suppression image provides information about oil distribution of the foods by suppressing signals coming from water. Water suppression spin echo sequence was used to obtain images. The water suppression images of the untreated, pre-dried and pre-coated potatoes fried at 4 min and 16 min are represented in Fig. 3.26.

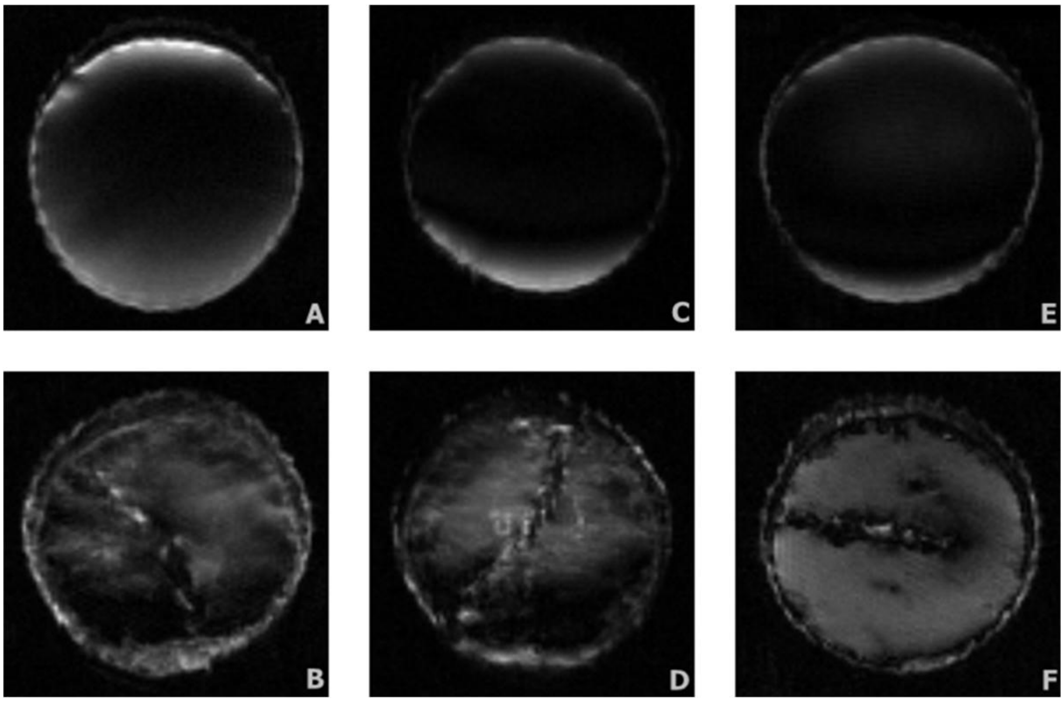

Figure 3.26 Representative water suppression coronal magnetic resonance images (MRI) of the untreated (A: 4 min, B: 16 min fried), pre-dried (C: 4 min, D: 16 min fried) and pre-coated (E: 4 min, F: 16 min fried) potatoes fried in sunflower oil at 180°C.

The oil is represented brighter in the water suppression images. At 4 min fried potatoes, the border regions were brighter and core regions were darker. This was an expected result since time was not sufficient for oil penetration through core region and evaporation of water at border region was also higher as compared to that in core region. Moreover, the result of the moisture and oil content as given in Fig. 3.1 and Fig. 3.3 supported water suppression images. Moisture content of the core region was higher and oil content was lower compared to crust region. On the other hand, oil was located at border and also penetrated to core region especially throughout formed pores around pith of the potatoes for 16 min fried potatoes. Kumar and Ezekiel (2004) showed that dry matter content of the pith was the lowest compared to other parts of the potato and the highest at stem end. Thus, high amount of water at pith might be the reason of the formation of pores as a result of water evaporation at pith. In addition, it is possible to observe more uniform oil distribution at pre-coated potatoes fried for 16 min based on uniform brightness at core region. Kirtil and Oztop (2015) stated that oil distribution can be indicated with water suppression images in the cakes prepared with peanut and raisin. The difference in the oil content of the raisin and peanut provided to obtain brightness at peanut in water suppression images.

The change in the signal intensity of the water suppression images are given in Fig 3.27. The signal intensity of the potatoes increased as frying time increased. When ANOVA was performed, frying time effect was to be significant ($p \leq 0.05$) whereas pretreatment and also the interaction between pretreatment and frying time had no significant effect ($p>0.05$) on the signal intensity of the water suppression images (Table A.9). Pearson correlation was performed on the results of oil content and signal intensity of the water suppression images. As a result of the Pearson correlation, significant correlation was determined between them with a correlation coefficient of 0.698.

The lowest signal intensity was obtained for 4 min pre-dried potatoes and the highest one was for 16 min untreated fried potatoes. Similar results were obtained in the oil content results with lowest for 4 min frying of pre-dried and highest for

16 min frying of untreated potatoes (Fig. 3.3). However, there was a significant difference between untreated, pre-dried and pre-coated potatoes in terms of oil content according to ANOVA results (Table A.3). The inconsistency between oil content and signal intensity values of water suppression images might be explained by close and low values of the oil contents of untreated, pre-dried and pre-coated potatoes. Therefore, these close values could not affect signal intensity significantly. This inconsistency showed correlation coefficient was not high for determination of oil content of the potatoes with water suppression images of the magnetic resonance images without any analytical method.

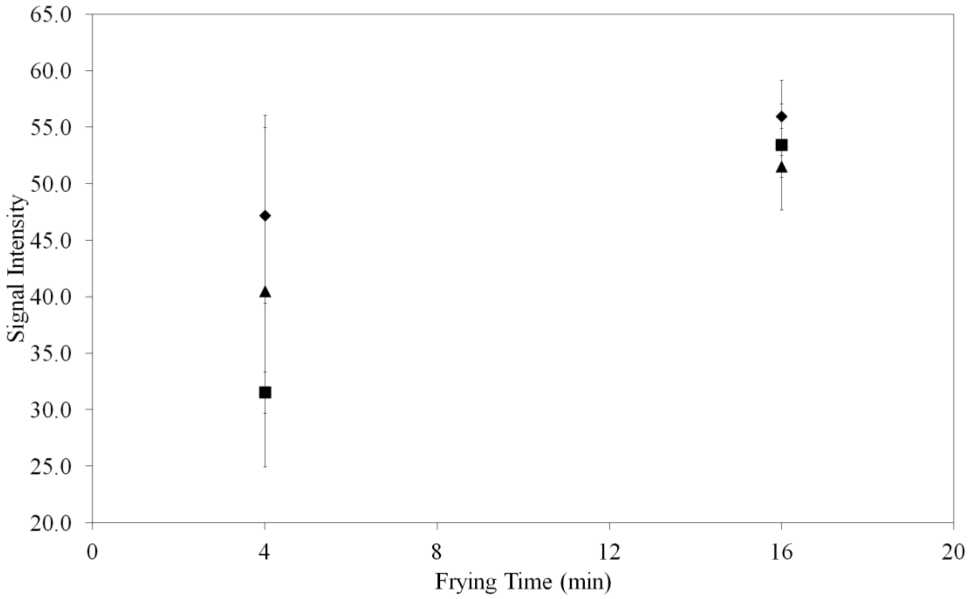

Figure 3.27 Variation in the signal intensity of water suppression images of the fried potatoes with frying. (♦): untreated[a], (■): pre-dried[a] and (▲): pre-coated[a]. Different letters indicate significant difference ($p \leq 0.05$).

3.6.3 Spin- Spin Relaxation Time (T_2)

The spin-spin relaxation time, T_2, is the rate of decaying of M_{xy} component of the magnetization vector in the transverse plane and it includes interactions between surrounding nuclear spins (Williams, Oztop, McCarthy, McCarthy, & Lo, 2011). The effect of molecular mobility on T_2 leads to differentiation of water and oil proton species (Hickey et al., 2006). T_2 distributions of the fried potato samples were obtained by multi-slice-multi-image sequence (MSME). T_2 values of the untreated, pre-dried and pre-coated fried potatoes, obtained with monoexponential fitting, are given in the Fig 3.28.

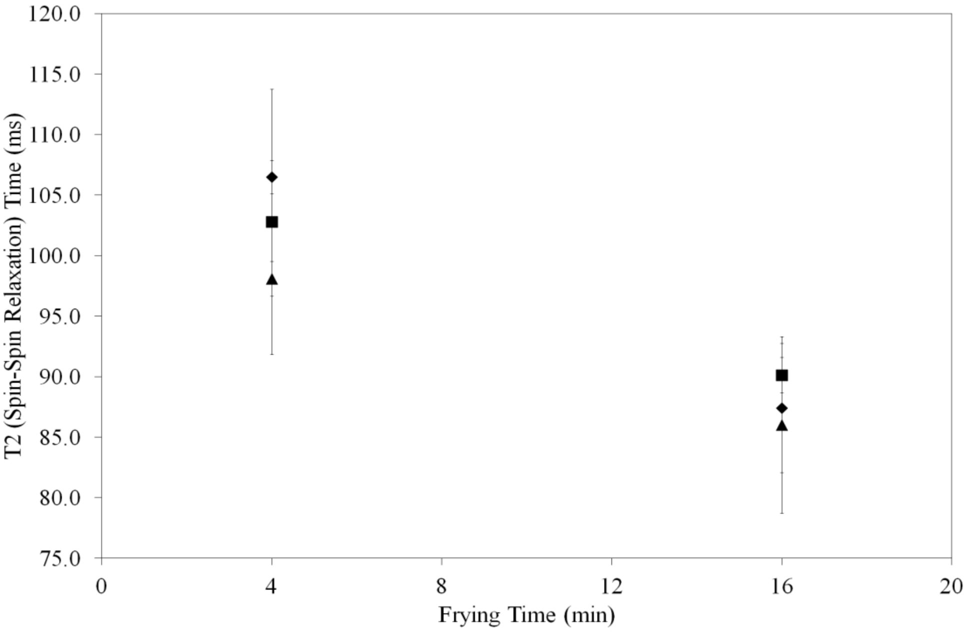

Figure 3.28 Variation in T_2 (spin-spin relaxation) times of the fried potatoes with frying. (♦): untreated[a], (■): pre-dried[a] and (▲): pre-coated[a]. Different letters indicate significant difference ($p \leq 0.05$).

T2 value of oil and water are different (~2.5 s for water and ~120ms for fat) and different oil and moisture contents of the samples cause difference between T_2 values (Oztop, Bansal, Takhar, McCarthy, & McCarthy, 2014). There was a significant difference ($p \leq 0.05$) between 4 min fried and 16 min fried potatoes in terms of T_2 (spin-spin relaxation) times (Table A.10). However, T_2 values of the untreated, pre-dried and pre-coated potatoes were not significantly different ($p > 0.05$). As expected, T_2 of the potatoes decreased with increasing frying time. As frying time increased, water inside potato continued to evaporate and oil also penetrated into the potatoes so more moisture loss and oil uptake took place at 16 min fried potatoes. Therefore, T_2 was expected to decrease as a result of reduction in water content and increase in oil content.

CHAPTER 4

CONCLUSION AND RECOMMENDATIONS

In this study, the effect of the pretreatments on quality of the deep-fat fried potatoes was studied. Pre-drying and pre-coating decreased oil content and moisture content of the potatoes as compared to untreated potatoes. The lowest oil uptake was determined on the pre-coated potatoes. However, the volumetric shrinkage of the pre-coated potatoes was the highest. In addition, no significant difference was observed between pre-dried and pre-coated potatoes in terms of porosity results. Frying time was found to be significant in affecting the change in the moisture content, oil content, porosity and shrinkage of the potatoes.

Crust and core region of the untreated potatoes were examined for determining moisture, oil and pore size distribution within the structure of the samples. The moisture content and porosity of the core region was higher and oil content was lower as compared to crust region. Porosity of crust and core regions of potatoes was affected significantly with frying time and the lowest porosity was detected at 16 min frying time for both crust and core region. Pore size distribution curves also showed difference for crust and core region in accordance with porosity results. The SEM images showed how microstructure of the potatoes was changed with frying. The gelatinization of starch, breakage of the cell wall and formation of pores inside potatoes were also observed with SEM images.

When magnetic resonance images of the untreated, pre-dried and pre-coated potatoes were analyzed, signal intensity of the T_1 weighted and water suppression images was increased with increasing frying time. The signal intensity values of the T_1 weighted images were in accordance with moisture content results. Furthermore, oil content and signal intensity of the water suppression images were found to be correlated. However, pretreatment effect on signal intensity was not observed while it had an effect on oil contents of the potatoes. T_2 relaxation times of the potatoes were decreased with frying.

For further research, crust and core region of the pre-dried and pre-coated potatoes can be evaluated for determination of effects of pretreatments on crust and core region of the potatoes. Also the effect of sample size on distribution of oil, moisture and porosity and different frying methods like vacuum and microwave frying can be analyzed.

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APPENDIX A

STATISTICAL ANALYSES

Table A.1 Two way ANOVA and Tukey' s comparison test results for moisture content of deep-fat fried untreated, pre-dried and pre-coated potatoes at 4, 8, 12, 16 and 20 min frying time.

Factor	Levels	Values
Frying time	5	4; 8; 12; 16; 20
Pretreatments	3	Pre-coated; Pre-dried; Untreated

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Frying time	4	200,941	200,941	50,235	24,660	0,000
Pretreatment	2	382,594	382,594	191,297	93,900	0,000
Frying time*Pretreatment	8	13,357	13,357	1,670	0,820	0,598
Error	15	30,559	30,559	2,037		
Total	29	627,451				

Table A.1 (continued)

Grouping information was made by using Tukey method and 95.0 % confidence

Pretreatments	Mean	Grouping		
Untreated	73,4	A		
Pre-coated	71,2		B	
Pre-dried	65,0			C

Frying time	Mean	Grouping		
4	72,7	A		
8	71,7	A	B	
12	70,5	A	B	
16	69,3		B	
20	65,2			C

Frying time	Pretreatments	Mean	Grouping	
4	Untreated	76,0	A	
8	Untreated	75,5	A	
12	Untreated	74,4	A	
4	Pre-coated	73,7	A	B
8	Pre-coated	73,2	A	B
16	Untreated	72,6	A	B

Table A.1 (continued)

12	Pre-coated	72,4	A	B			
16	Pre-coated	71,4	A	B	C		
20	Untreated	68,7		B	C	D	
4	Pre-dried	68,4		B	C	D	
8	Pre-dried	66,3			C	D	E
20	Pre-coated	65,3				D	E
12	Pre-dried	64,6				D	E
16	Pre-dried	64,0				D	E
20	Pre-dried	61,7					E

Table A.2 Two way ANOVA and Tukey’ s comparison test results for moisture content of crust and core region of the deep-fat fried untreated potatoes at 4, 8, 12, 16 and 20 min frying time.

Factor	Levels	Values
Frying Time	5	4; 8; 12; 16; 20
Region	2	Core; Crust

Table A.2 (continued)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Frying Time	4	61,74	61,74	15,44	0,68	0,623
Region	1	4013,37	4013,37	4013,37	176,25	0,000
Frying Time*Region	4	55,13	55,13	13,78	0,61	0,668
Error	10	227,71	227,71	22,77		
Total	19	4357,95				

Grouping information was made by using Tukey method and 95.0 % confidence

Region	Mean	Grouping	
Core	82	A	
Crust	53,7		B

Frying time	Mean	Grouping
4	69,5	A
8	69,2	A
12	68,9	A
16	66,7	A
20	64,9	A

Table A.2 (continued)

Frying time	Region	Mean	Grouping	
16	Core	83,0	A	
12	Core	82,6	A	
8	Core	82,3	A	
4	Core	81,4	A	
20	Core	80,8	A	
4	Crust	57,5		B
8	Crust	56,1		B
12	Crust	55,3		B
16	Crust	50,5		B
20	Crust	49,1		B

Table A.3 Two way ANOVA and Tukey' s comparison test results for oil content of deep-fat fried untreated, pre-dried and pre-coated potatoes at 4, 8, 12, 16 and 20 min frying time.

Factor	Levels	Values
Frying time	5	4; 8; 12; 16; 20
Pretreatments	3	Pre-coated; Pre-dried; Untreated

Table A.3 (continued)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Frying Time	4	4,16554	4,16554	1,04138	62,93	0,000
Pretreatment	2	0,54792	0,54792	0,27396	16,55	0,000
Frying time*Pretreatment	8	0,43051	0,43051	0,05381	3,25	0,023
Error	15	0,24823	0,24823	0,01655		
Total	29	5,39220				

Grouping information was made by using Tukey method and 95.0 % confidence

Pretreatment	Mean	Grouping		
Untreated	2,7	A		
Pre-dried	2,5		B	
Pre-coated	2,4			C

Frying time	Mean	Grouping			
20	3,1	A			
16	2,8		B		
12	2,5			C	
8	2,2				D
4	2,1				D

Table A.3 (continued)

Frying time	Pretreatment	Mean	Grouping					
20	Untreated	3,3	A					
20	Pre-dried	3,2	A	B				
16	Untreated	2,9	A	B	C			
20	Pre-coated	2,9	A	B	C			
16	Pre-dried	2,9	A	B	C			
12	Untreated	2,7		B	C	D		
12	Pre-dried	2,7		B	C	D		
16	Pre-coated	2,5			C	D	E	
8	Untreated	2,4			C	D	E	
4	Untreated	2,2				D	E	F
12	Pre-coated	2,2				D	E	F
4	Pre-coated	2,2				D	E	F
8	Pre-coated	2,1					E	F
8	Pre-dried	2,1					E	F
4	Pre-dried	1,9						F

Table A.4 Two way ANOVA and Tukey' s comparison test results for oil content of crust and core region of the deep-fat fried untreated potatoes at 4, 8, 12, 16 and 20 min frying time.

Factor	Levels	Values
Frying Time	5	4; 8; 12; 16; 20
Region	2	Core; Crust

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Frying Time	4	5.502	5.502	1.375	112.43	0.000
Region	1	813.434	813.434	813.434	66493.63	0.000
Frying Time*Region	4	6.442	6.442	1.611	131.65	0.000
Error	10	0.122	0.122	0.012		
Total	19	825.500				

Grouping information was made by using Tukey method and 95.0 % confidence

Region	Mean	Grouping	
Crust	13,0	A	
Core	0,2		B

Table A.4 (continued)

Frying time	Mean	Grouping
4	7,4	A
8	6,9	B
20	6,3	C
16	6,1	C
12	6,1	C

Frying time	Region	Mean	Grouping
4	Crust	14,8	A
8	Crust	13,7	B
20	Crust	12,3	C
12	Crust	12,0	C
16	Crust	12,0	C
20	Core	0,3	D
16	Core	0,3	D
12	Core	0,2	D
8	Core	0,2	D
4	Core	0,1	D

Table A.5 Two way ANOVA and Tukey' s comparison test results for volumetric shrinkage of the deep-fat fried untreated, pre-dried and pre-coated potatoes at 4, 8, 12, 16 and 20 min frying time.

Factor	Levels	Values
Frying time	5	4; 8; 12; 16; 20
Pretreatments	3	Pre-coated; Pre-dried; Untreated

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Frying time	4	0,209255	0,209255	0,052314	70,31	0,000
Pretreatment	2	0,011150	0,011150	0,005575	7,49	0,006
Frying time*Pretreatment	8	0,011827	0,011827	0,001478	1,99	0,120
Error	15	0,011160	0,011160	0,000744		
Total	29	0,243392				

Grouping information was made by using Tukey method and 95.0 % confidence

Pretreatment	Mean	Grouping	
Pre-coated	0,3	A	
Untreated	0,2		B
Pre-dried	0,2		B

Table A.5 (continued)

Frying time	Mean	Grouping
16	0,4	A
12	0,3	B
20	0,3	B
8	0,2	C
4	0,1	D

Frying time	Pretreatment	Mean	Grouping					
16	Pre-coated	0,4	A					
16	Pre-dried	0,4	A	B				
20	Pre-coated	0,3	A	B	C			
12	Pre-coated	0,3	A	B	C	D		
16	Untreated	0,3	A	B	C	D		
12	Pre-dried	0,3	A	B	C	D	E	
20	Untreated	0,3	A	B	C	D	E	
20	Pre-dried	0,3	A	B	C	D	E	
12	Untreated	0,3		B	C	D	E	
8	Pre-coated	0,2			C	D	E	F
8	Untreated	0,2				D	E	F
8	Pre-dried	0,2					E	F

Table A.5 (continued)

4	Untreated	0,1	F	G
4	Pre-coated	0,1	F	G
4	Pre-dried	0,1		G

Table A. 6 Two way ANOVA and Tukey' s comparison test results for porosity of the deep-fat fried, pre-dried and pre-coated potatoes for 4, 8, 12, 16 and 20 min frying time.

Factor	Levels	Values
Frying time	5	4; 8; 12; 16; 20
Pretreatments	2	Pre-coated; Pre-dried

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Frying time	4	930,480	930,48	232,62	6,21	0,009
Pretreatments	1	33,360	33,36	33,36	0,89	0,368
Frying time*Pretreatment	4	319,040	319,04	79,76	2,13	0,152
Error	10	374,650	374,65	37,47		
Total	19	1657,530				

Table A.6 (continued)

Grouping information was made by using Tukey method and 95.0 % confidence

Pretreatments	Mean	Grouping
Pre-coated	66,1	A
Pre-dried	63,5	A

Frying time	Mean	Grouping
4	70,9	A
8	70,2	A
12	68,1	A
16	61,8	A B
20	52,7	B

Frying time	Pretreatment	Mean	Grouping
4	Pre-coated	74,2	A
12	Pre-dried	72,6	A
8	Pre-coated	72,1	A
8	Pre-dried	68,3	A B
4	Pre-dried	67,7	A B
12	Pre-coated	63,7	A B
16	Pre-dried	63,3	A B

Table A.6 (continued)

16	Pre-coated	60,4	A	B
20	Pre-coated	59,9	A	B
20	Pre-dried	45,5		B

Table A.7 Two way ANOVA and Tukey' s comparison test results for porosity of the crust and core region of deep-fat fried untreated potatoes for 4, 8, 12, 16 and 20 min frying time.

Factor	Levels	Values
Frying Time	5	4; 8; 12; 16; 20
Region	2	Core; Crust

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Region	1	1702,75	1702,75	1702,75	99,50	0,000
Frying time	4	1217,12	1217,12	304,28	17,78	0,000
Region*Frying time	4	219,94	219,94	54,98	3,21	0,061
Error	10	171,13	171,13	17,11		
Total	19	3310,94				

Table A.7 (continued)

Grouping information was made by using Tukey method and 95.0 % confidence

Region	Mean	Grouping	
Core	77,3	A	
Crust	58,8		B

Frying time	Mean	Grouping	
4	81,9	A	
20	69,1		B
8	67,8		B
12	61,7		B
16	59,6		B

Region	Frying time	Mean	Grouping		
Core	4	84,8	A		
Core	8	79,7	A		
Crust	4	79	A		
Core	20	78,3	A		
Core	12	71,8	A	B	
Core	16	71,5	A	B	
Crust	20	59,9		B	C

Table A.7 (continued)

Crust	8	55,9	B	C
Crust	12	51,6		C
Crust	16	47,7		C

Table A.8 Two way ANOVA and Tukey' s comparison test results for signal intensity of T_1 weighted coronal MR images of the deep-fat fried untreated, pre-dried and pre-coated potatoes for 4 and 16 min frying time.

Factor	Levels	Values
Pretreatment	3	Pre-coated; Pre-dried; Untreated
Frying time	2	4; 16

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Pretreatment	2	2240,1	2240,1	1120	4,98	0,053
Frying time	1	8266,7	8266,7	8266,7	36,79	0,001
Pretreatment*Frying time	2	2470,9	2470,9	1235,4	5,50	0,044
Error	6	1348,3	1348,3	224,7		
Total	11	14325,9				

Table A.8 (continued)

Grouping information was made by using Tukey method and 95.0 % confidence

Pretreatment	Mean	Grouping
Pre-dried	387,3	A
Pre-coated	363,1	A
Untreated	355,2	A

Frying time	Mean	Grouping	
16	394,8	A	
4	342,3		B

Pretreatment	Frying time	Mean	Grouping		
Pre-coated	16	396,8	A		
Untreated	16	394,1	A		
Pre-dried	16	393,5	A		
Pre-dried	4	381,1	A	B	
Pre-coated	4	329,4		B	C
Untreated	4	316,3			C

Table A.9 Two way ANOVA and Tukey' s comparison test results for signal intensity of water suppression MR images of the deep-fat fried untreated, pre-dried and pre-coated potatoes for 4 and 16 min frying time.

Factor	Levels	Values
Pretreatment	3	Pre-coated; Pre-dried; Untreated
Frying time	2	4; 16

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Frying time	1	580,60	580,60	580,60	10,20	0,019
Pretreatment	2	168,90	168,90	84,45	1,48	0,300
Frying time*Pretreatment	2	98,57	98,57	49,29	0,87	0,467
Error	6	341,51	341,51	56,92		
Total	11	1189,59				

Grouping information was made by using Tukey method and 95.0 % confidence

Pretreatment	Mean	Grouping
Untreated	51,6	A
Pre-coated	46	A
Pre-dried	42,5	A

Table A.9 (continued)

Frying time	Mean	Grouping
16	53,6	A
4	39,7	B

Frying time	Pretreatment	Mean	Grouping
16	Untreated	56	A
16	Pre-dried	53,4	A
16	Pre-coated	51,5	A
4	Untreated	47,2	A
4	Pre-coated	40,5	A
4	Pre-dried	31,5	A

Table A.10 Two way ANOVA and Tukey' s comparison test results for spin-spin relaxation times (T_2) of the deep-fat fried untreated, pre-dried and pre-coated potatoes for 4 and 16 min frying time.

Factor	Levels	Values
Pretreatment	3	Pre-coated; Pre-dried; Untreated
Frying time	2	4; 16

Table A.10 (continued)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Frying time	1	639,48	639,48	639,48	18,47	0,005
Pretreatment	2	58,24	58,24	29,12	0,84	0,477
Frying time*Pretreatment	2	30,35	30,35	15,17	0,44	0,664
Error	6	207,78	207,78	34,63		
Total	11	935,84				

Grouping information was made by using Tukey method and 95.0 % confidence

Pretreatment	Mean	Grouping
Untreated	96,9	A
Pre-dried	96,5	A
Pre-coated	92,1	A

Frying time	Mean	Grouping	
4	102,5	A	
16	87,9		B

Table A.10 (continued)

Frying time	Pretreatment	Mean	Grouping
4	Untreated	106,5	A
4	Pre-dried	102,8	A
4	Pre-coated	98,1	A
16	Pre-dried	90,1	A
16	Untreated	87,4	A
16	Pre-coated	86	A

APPENDIX B

EXPERIMENTAL DATA

Table B.1 Experimental results of the moisture content and oil content of the untreated, pre-dried and pre-coated potatoes deep-fat fried at 180 °C.

Frying time (min)	Pretreatment	Moisture Content (g water/100 g w.b)	Oil Content (g oil/100 g w.b)
4	Untreated	75.99 ± 0.10	2.23 ± 0.08
8	Untreated	75.55 ± 0.09	2.45 ± 0.03
12	Untreated	74.42 ± 0.15	2.69 ± 0.20
16	Untreated	72.61 ± 0.13	2.93 ± 0.19
20	Untreated	68.67 ± 0.29	3.29 ± 0.04
4	Pre-dried	68.42 ± 0.65	1.92 ± 0.08
8	Pre-dried	66.29 ± 1.96	2.09 ± 0.12
12	Pre-dried	64.58 ± 2.12	2.69 ± 0.01
16	Pre-dried	64.01 ± 1.80	2.89 ± 0.14
20	Pre-dried	61.72 ± 2.31	3.19 ± 0.01
4	Pre-coated	73.74 ± 2.00	2.19 ± 0.20
8	Pre-coated	73.21 ± 1.55	2.12 ± 0.01
12	Pre-coated	72.38 ± 2.14	2.19 ± 0.11

Table B.1 (continued)

16	Pre-coated	71.40 ± 0.02	2.53 ± 0.10
20	Pre-coated	65.31 ± 1.46	2.90 ± 0.19

Table B.2 Experimental results of volumetric shrinkage and porosity of the untreated, pre-dried and pre-coated potatoes deep-fat fried at 180 °C.

Frying time (min)	Pretreatment	Shrinkage % $(V_i - V_t / V_i)$	Porosity
4	Untreated	0.14 ± 0.01	
8	Untreated	0.23 ± 0.02	
12	Untreated	0.27 ± 0.00	
16	Untreated	0.32 ± 0.01	
20	Untreated	0.28 ± 0.03	
4	Pre-dried	0.07 ± 0.01	67.58 ± 0.41
8	Pre-dried	0.19 ± 0.04	68.32 ± 4.64
12	Pre-dried	0.30 ± 0.04	72.62 ± 2.57
16	Pre-dried	0.37 ± 0.02	63.25 ± 7.42
20	Pre-dried	0.27 ± 0.00	45.51 ± 7.54

Table B.2 (continued)

4	Pre-coated	0.13 ± 0.04	74.20 ± 2.98
8	Pre-coated	0.24 ± 0.00	72.07 ± 8.82
12	Pre-coated	0.33 ± 0.01	63.67 ± 2.10
16	Pre-coated	0.38 ± 0.05	60.43 ± 8.18
20	Pre-coated	0.34 ± 0.05	59.93 ± 0.24

Table B.3 Experimental results of the moisture content, oil content and porosity for crust and core region of untreated potatoes deep-fat fried in sunflower oil at 180°C.

Frying time (min)	Region of potato	Moisture Content (g water/100 g w.b)	Oil Content (g oil/100 g w.b)	Porosity
4	Crust	57.55 ± 0.20	14.75 ± 0.20	78.98 ± 0.78
8	Crust	56.10 ± 2.42	13.71 ± 0.35	55.85 ± 0.74
12	Crust	55.27 ± 4.33	12.01 ± 0.39	51.56 ± 0.51
16	Crust	50.47 ± 3.38	12.01 ± 0.34	47.74 ± 2.85
20	Crust	49.05 ± 4.80	12.35 ± 0.47	59.86 ± 4.11
4	Core	81.39 ± 0.99	0.14 ± 0.00	84.83 ± 2.26
8	Core	82.27 ± 0.27	0.16 ± 0.04	79.75 ± 6.33

Table B.3 (continued)

12	Core	82.63 ± 0.61	0.17 ± 0.00	71.85 ± 5.27
16	Core	83.02 ± 1.18	0.25 ± 0.02	71.50 ± 0.71
20	Core	80.78 ± 1.89	0.32 ± 0.06	78.33 ± 6.47

Table B.4 Experimental results of the Magnetic Resonance imaging analyses for untreated, pre-dried and pre-coated potatoes for 4 min and 16 min frying times.

Frying Time (min)	Pretreatment	Signal intensity of T1 weighted images	Signal intensity of water suppression images	Spin-spin relaxation (T2) times (ms)
4	Untreated	316.32 ± 15.33	47.19 ± 7.78	106.49 ± 1.36
16	Untreated	394.05 ± 17.95	55.99 ± 1.07	87.40 ± 5.33
4	Pre-dried	381.13 ± 19.92	31.52 ± 1.82	102.79 ± 9.97
16	Pre-dried	393.48 ± 11.59	53.44 ± 5.74	90.14 ± 1.46
4	Pre-coated	329.39 ± 14.44	40.49 ± 15.57	98.08 ± 1.43
16	Pre-coated	396.79 ± 7.18	51.52 ± 0.98	86.02 ± 7.28

APPENDIX C

FIGURES OF DEEP-FAT FRIED POTATOES

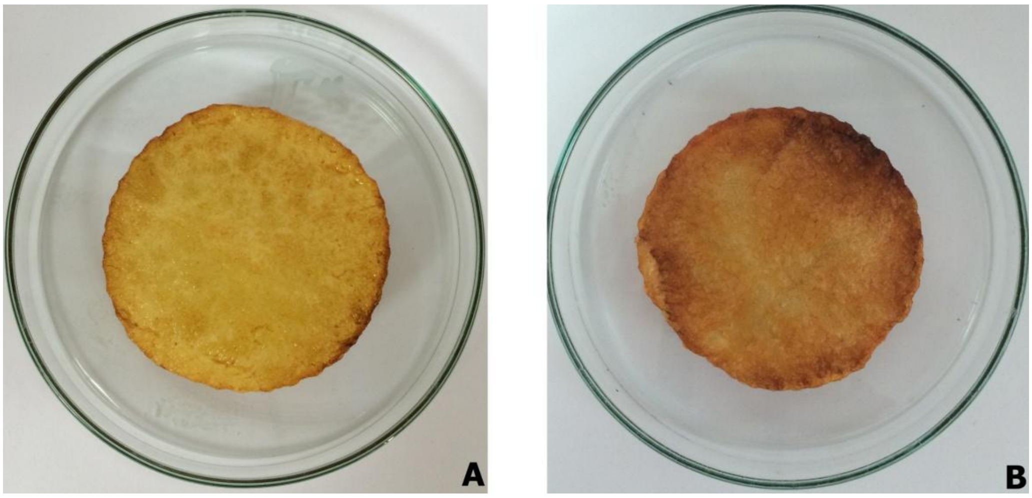

Figure C.1 Untreated potatoes deep-fat fried for 4 min (A) and 20 min (B) at 180°C.

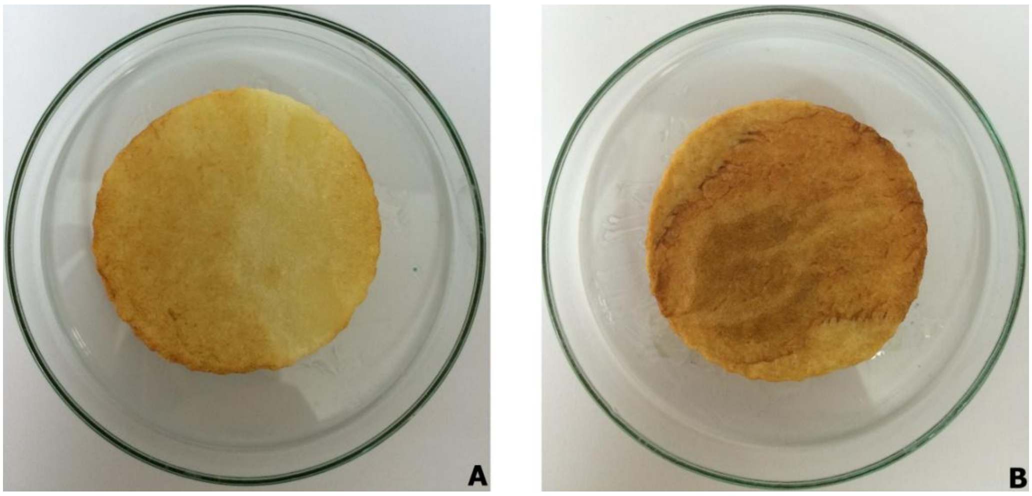

Figure C.2 Pre-dried potatoes deep-fat fried for for 4 min (A) and 20 min (B) at 180°C.

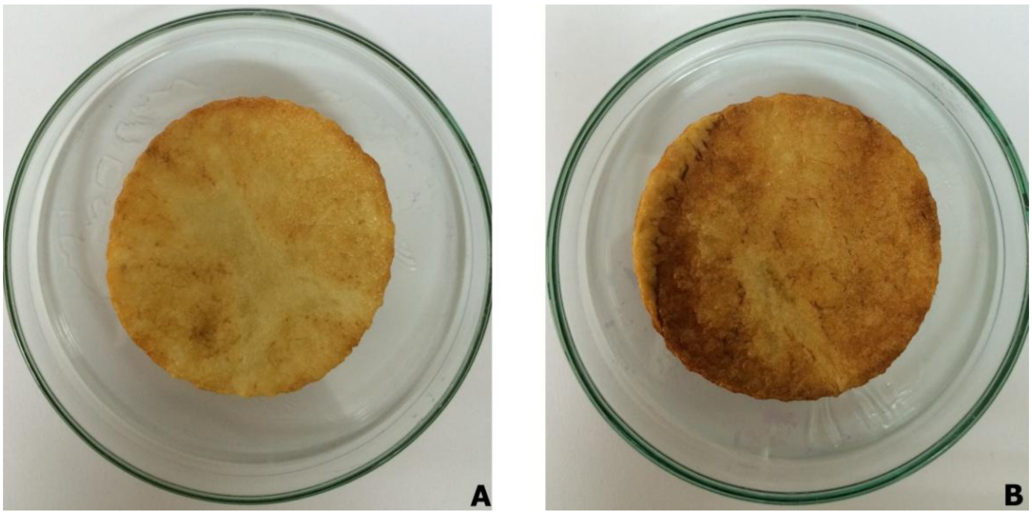

Figure C.3 Pre-coated potatoes deep-fat fried for 4 min (A) and 20 min (B) at 180°C.