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Effect of vacuum frying conditions on physico-chemical properties of banana chips

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ABSTRACT

The feasibility of vacuum frying technology to produce high quality banana chips with lower oil absorption and better flavor and color was investigated. The effects of three frying temperatures (120, 130, and 140°C) and three vacuum pressures (21.3, 31.3, and 41.3 kPa) were studied. The quality of vacuum fried chips was subsequently compared with that of chips fried under atmospheric conditions (101.3 kPa) at 170°C. The rate of moisture loss significantly increased ($p < 0.05$) with the higher temperature and lower vacuum pressure applied in the frying process. In addition, moisture loss was linearly proportionate to the amount of oil content ($R^2 = 0.97$). Frying chips at 140°C and 21.3 kPa resulted in the most volume shrinkage. No significant ($p > 0.05$) difference in color ($L^* = 58.8$, $a^* = 5.1$, $b^* = 23.9$) was found in any of the chips fried under each vacuum condition. Banana chips fried under vacuum pressure conclusively contained ($p < 0.05$) less oil, were lighter in color, had higher volume shrinkage, less crispness, and a harder texture than atmospherically fried chips.

Keywords: Vacuum frying; Moisture loss; Oil uptake; Textural characteristics; Banana chips

1. INTRODUCTION

Atmospheric and vacuum frying processes employ basic knowledge of the simultaneous transfers of heat and mass (Krokida et al., 2000b). In general, heat being transferred from the hot oil towards the moist food results in the evaporation of water within the food and the absorption of oil (Saguy and Pinthus, 1995; Moreira et al., 1997; Krokida et al., 2000b; Mellema, 2003) Several studies have observed that food traditionally fried in the atmosphere at 170-190°C usually has a high oil content (Guillaumin, 1988; Mallikarjunan et al., 1995; Roa and Delaney, 1995) and the sugars in fruit regularly turn dark from caramelization and Maillard reactions. These reactions, particularly, were not observed during vacuum frying.

Fried vegetable and fruit commodities have become more popular in world markets because of the revolutionary development of the vacuum frying technique that is normally applied to fruits (such as banana, jackfruit, and apple) with high starch content. In vacuum frying, food is heated under lower atmospheric pressure in a closed vessel. Water from and within the food surface is rapidly removed when the temperature suddenly reaches the boiling point of the oil (about 60-70°C, considerably lower than in normal conditions-170-190°C) with respect to the vacuum effect and deoxygenation (Garayo and Moreira, 2002; Shyu and Hwang, 2001). Therefore,

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the vacuum fried fruit chips could provide healthier products as they taste better and are crispier and lighter since they contain minimum residual oil and retain important nutrients (Garayo and Moreira, 2002; Guillaumin, 1988; Shyu and Hwang, 2001). At present, a vacuum frying system could be developed for installation in either a conveyor or a robot system (Moreira et al., 1999).

Shyu and Hwang (2001) studied the effects of processing conditions on the quality of vacuum fried apple chips. They used three levels of temperature, 90, 100, and 110°C and a single vacuum pressure condition, 98.66 kPa, to fry each chip treatment. They found the moisture content and breaking force of apple chips decreased with an increase in frying temperature and time while the oil uptake in the product considerably declined. The L* color of fried apple chips visibly decreased with higher temperature. In contrast, both a* and b* colors of apple slices increased rapidly when fried at 100°C for 20 min. Hardness was employed as a physical index to describe the fried product; the optimal range of temperature for vacuum frying was approximately 100-110°C for 20-25 min, and the concentration of immersing fructose solution was about 30-40%. In addition, Garayo and Moreira (2002) investigated the effects of vacuum frying on the characteristics of potato chips at three frying oil temperatures (118, 132, and 144°C) and three vacuum pressures (3.12, 9.89, and 16.66 kPa). They reported that rate of moisture loss during vacuum frying of potato chips was directly related to oil absorption. The chips fried at 144°C and 3.12 kPa retained the highest amount of oil and the fryer's operating conditions did not affect the final oil content of the chips. Furthermore, the final oil content of the product at 144°C and 3.12 kPa decreased up to 32.8% when compared with that in atmospheric frying (165°C). As expected, the potato chips fried under lower pressure exhibited higher volume shrinkage and lighter color and were harder than chips fried under atmospheric conditions. Yamsaengsung et al. (2011) studied the effect of oil temperature and ripeness on dimensional changes of vacuum fried banana chips and they observed that a frying temperature of 110°C on banana on the second day of ripeness yielded the highest expansion in volume. A study of Sothornvit (2011) showed that vacuum fried banana chips coated with an edible coating and produced using the higher speed during the oil centrifuge step maintained good quality and low oil content.

Many researchers primarily had examined the effects of atmospheric frying parameters, but some focused-on pressure frying (Mallikarjunan et al., 1995; Roa and Delaney, 1995) and others on vacuum frying (Garayo and Moreira, 2002; Shyu and Hwang, 2001). However, a great variety of vacuum fried fruits are still available in the food markets, but technological information has been adversely protected by confidential documents and patents. Thus, various parameters for optimization of the process have not been made available throughout the fried food industry. Therefore, the objective of this study was to investigate the effect of vacuum pressure and temperature on the physico-chemical characteristics of banana chips.

2. MATERIALS AND METHODS

2.1 Sample preparation

Green and firm Musa Banana (*Musa sapientum* Linn. Musaceae) were bought from the same local market (Nakorn Pathom Province, Thailand). The banana was peeled, cleaned, and cut into slices 2 mm thick. All the slices were reshaped to circles of 26.5 mm in diameter; each slice weighed approximate 1 g. After being air-dried for 10 min, the slices were randomly selected for chemical compositions to be analyzed in triplicate. In this experiment, the banana slices with consistent initial moisture content (62.0 ± 1.5%), fat (0.25 ± 0.05%), soluble solids content (2.0 ± 0.5°Brix), pH (6.0 ± 0.2), L* (76.5 ± 1.5), a* (3.5 ± 0.3), b* (16.5 ± 0.5), and firmness (72.5 ± 1.2 N) were selected. Banana slices were kept in plastic bags until further frying experiments.

2.2. Frying experiments

For atmospheric frying, the samples were fried at 170°C and used as the control. The frying experiments were conducted using an electric vacuum fryer (Owner Foods Machinery Thailand), size 30 × 30 × 45 cm and a capacity of 9 L of oil. A 25 g sample of banana slices was randomly fried in 3.6 L of commercial soybean oil (Argkun, Cheer Co, Ltd., Thailand) with three different vacuum pressures (21.3, 31.3, and 41.3 kPa) and oil temperatures (120, 130, and 140°C). As soon as the oil reached the temperature required, the prepared slices were placed in the aluminum basket, then the fryer lid was closed, and the pressure inside the fryer vessel was evacuated. The basket was immersed in the heated oil at a depth of 5 cm from the surface oil for 2 min. At the end of frying, the vessel was depressurized, and the basket was lifted out of the hot oil. The fryer lid was opened, and the banana chips were removed from the basket then air cooled for 5 min until they reached room temperature. Subsequently, all samples were placed in freezer bags and frozen at -20°C until further physico-chemical analysis, except samples for moisture content analysis. Each treatment was performed in triplicate.

2.3. Finished products' analyses

Before physico-chemical analysis of fried banana chips, the samples were taken from the freezer and left at room temperature for 30 min. These samples were tested for total oil content, degree of shrinkage, color, and texture.

The moisture content of the raw banana and banana chips were determined using an infrared moisture analyzer (model SMO01, Scaltec Instruments, Heiligenstadt, Germany) operating at 105°C. Samples, each weighing 2 g, were dried to obtain constant weight. Moisture content was calculated by the weight difference between the fresh (W_1) and dried (W_2) samples and expressed as a percentage of the fresh sample as moisture content (%) = $((W_1-W_2)/W_1) \times 100$. The measurement was performed in triplicate.

Total oil content of banana chips was determined using Soxhlet extraction with hexane (AOAC, 1995). The measurement was performed in triplicate.

Degree of shrinkage in volume (S_V) was evaluated by:

$$S_V = \frac{V_o - V_t}{V_o} \times 100$$

Where V_o is the original volume of the sample (m^3) and V_t is the volume (m^3) of the sample at time t. The volume of the sample at any given time could be calculated by $V = (\pi Dd / 4)L$ where D is the larger diameter of the sample (m), d is the smaller diameter (m) of the sample, and L is the sample's thickness (m). Ten samples were randomly taken to evaluate the degree of shrinkage for each frying condition at the equilibrium time.

The color of banana chips was measured using a Color-view™ spectrophotometer (model 9000, Gardner, USA). Before the test, the colorimeter was calibrated on a white plate (CIE $L^* = 98.76$, $a^* = -0.19$, $b^* = -0.06$). The L^*, a^*, and b^* values were recorded to present the color development of fried products. The measurement was performed in triplicate.

A Texture Analyzer (model TA-XT2i, Stable Micro Systems, UK) was applied to describe the changes in physical characteristics of fried chips and measure the maximum shear force (N/kg). The speed of the blade set with a Warner Bratzer probe was set up as follows: for pre-test at 5 mm/s, test at 5 mm/s, and post-test speed at 10 mm/s. The maximum force value was considered an indicator of the overall hardness of the fried chips. The curve slope was considered as an indicator of index of firmness and the distance from the original point to the maximum force point as an indicator of displacement. Each treatment was tested in five replications.

2.4. Data analysis

Statistical analyses were performed using the General Linear Model Program (GLM) to test the effects of frying temperature and pressure on the physico-chemical properties of fried banana chips. Least Significant Difference (LSD) was used to estimate the significant differences among the means of each treatment at 5% probability level using SAS program (Ver. 8.1, SAS Inst., Cary, NC, USA).

3. RESULTS AND DISCUSSION

3.1. Influence of temperature and pressure on moisture content

An increase in the oil temperature resulted in a significant reduction ($p < 0.05$) of moisture retention of the fried banana chips with the same pressure. For example, at a vacuum pressure 41.3 kPa, the moisture content of fried chips decreased up to 67.6% at 130°C and by 76.9% at 140°C when compared with the content at 120°C. As expected, more moisture was removed from the chips fried at the same temperature ($p < 0.05$) when lower vacuum pressure was applied because frying at lower pressure proportionately reduced the boiling point of water to less than 100°C, for example 76.5°C for 41.3 kPa, 70.1°C for 31.3 kPa, and 61.3°C for 21.3 kPa. Toledo (1991) explained the phenomenon of moisture reduction during frying to a capillary action. In vacuum frying, food is heated under reduced pressure in a closed system, therefore leading to a lower boiling point of water and frying oil. Consequently, the unbound water in the vacuum fried chips could be rapidly removed when the oil temperature reached the boiling point of water (Shyu and Hwang, 2001; Garayo and Moreira, 2002).

A comparison of the moisture retention in both vacuum and atmospheric fried banana chips is presented in Table 1. All chips fried at 130-140°C and 21.3-31.3 kPa had very much lower moisture retention than those fried under traditional atmospheric conditions. However, the moisture content of atmospheric fried chips was not significantly different from chips fried at 120°C, 21.3 kPa and 130°C, 41.3 kPa. During atmospheric frying, the product temperature was raised from room temperature (24-25°C) to the boiling point of water (100°C). The inner moisture was converted to water vapor causing a pressure gradient and the vapor escaped at weak points in the fried food surface. This process occurred at an extremely fast pace because liquid water had a high specific heat.

Table 1 Chemical composition and physical attributes of banana chips from frying process under different vacuum pressures and oil temperatures

Temperature (°C)	Pressure (kPa)	Moisture (%)	Oil Content (%)	Color		
				L*	a*	b*
120	21.3	4.0 ^{c} (0.8)	23.0 ^{c} (0.2)	59.0 ^{a} (0.8)	5.2 ^{b} (0.6)	24.9 ^{ab} (0.5)
	31.3	7.7 ^{b} (0.2)	18.6 ^{e} (1.4)	58.9 ^{a} (2.2)	5.2 ^{b} (0.5)	23.6 ^{b} (0.5)
	41.3	10.8 ^{a} (0.8)	13.2 ^{g} (1.1)	58.6 ^{a} (0.4)	5.0 ^{b} (0.5)	23.3 ^{b} (0.8)
130	21.3	1.6 ^{e} (0.1)	23.1 ^{c} (0.5)	59.2 ^{a} (2.4)	5.2 ^{b} (0.1)	24.4 ^{b} (0.5)
	31.3	2.4 ^{d} (0.1)	20.9 ^{d} (0.4)	60.5 ^{a} (1.2)	4.9 ^{b} (0.4)	23.2 ^{b} (1.4)
	41.3	3.5 ^{c} (0.2)	15.1 ^{f} (0.7)	59.4 ^{a} (0.8)	5.1 ^{b} (0.4)	23.8 ^{b} (0.7)
140	21.3	0.7 ^{f} (0.1)	24.9 ^{b} (0.7)	58.3 ^{a} (1.4)	5.4 ^{b} (0.5)	23.8 ^{b} (0.3)
	31.3	1.8 ^{de} (0.2)	23.9 ^{bc} (0.9)	58.7 ^{a} (0.2)	5.6 ^{b} (0.4)	24.2 ^{b} (1.9)
	41.3	2.5 ^{d} (0.8)	21.7 ^{d} (0.5)	60.8 ^{a} (2.8)	4.9 ^{b} (0.5)	23.7 ^{b} (1.8)
170	101.3	3.8 ^{c} (0.6)	28.9 ^{a} (0.8)	54.5 ^{b} (0.7)	8.5 ^{a} (0.4)	27.2 ^{a} (0.8)

Numerical number in the table presented $\overline{x}$ (SD)

$^{a\text{-}g}$ means within a column with unlike superscript letters are significantly different ($p < 0.05$).

3.2. Influence of temperature and pressure on oil content

Oil uptake was a complex phenomenon that happened mostly when the products were removed from the fryer during the cooling stage (Tseng et al., 1994; Moreira et al., 1995; Ufheil and Escher, 1996). The fresh banana employed in this investigation contained 0.25% of the initial oil content. Thus, the residual oil inside the chips, approximately 95%, was acquired from the frying oil. Both temperature and pressure applied in the fryer contributed to the remarkably lower ($p < 0.05$) oil absorption. The higher the pressure applied in the fryer, the more the reduction of oil uptake. As expected, the oil content of the chips fried at 120°C incrementally increased by approximately 40.2% at 31.3 kPa and 74.2% at 21.3 kPa compared to the oil content at 41.3 kPa. The banana chips fried at 120°C and 41.3 kPa absorbed less oil (about 13.2%) and contained about two times less than the traditional atmospheric fried chips (Table 1). Garayo and Moreira (2002) also reported the same results indicating that probably more oil adhered to the chip's surface with higher temperature and lower vacuum pressure.

Several studies attempted to investigate the relationship between moisture loss and oil uptake in vacuum fried products (Garayo and Moreira, 2002). Pinthus et al. (1993) and Pinthus and Saguy (1994) previously proposed a linear relationship between oil uptake and water removal and reported that the initial and final moisture content of fried products had a direct impact on the oil uptake via the simple mechanism of water replacement.

The chips were removed from the frying oil and kept under vacuum and temperature conditions. At this stage, as the vessel was vented, the pore pressure within the banana chips instantly increased to atmospheric levels. Consequently, air and surface oil were simultaneously carried through the empty pore spaces until atmospheric pressure was finally reached. As usual, gas was substantially diffused faster into the pore spaces if low pressure was applied. Thus, it sufficiently obstructed the oil from entering the product's pores. In addition, most of the oil began to be absorbed during the cooling period after the chips were first removed from the vacuum fryer, and then the adhered oil gradually continued to penetrate the pore spaces (Bouchon et al., 2003; Garayo and Moreira, 2002;).

As expected, frying under atmospheric conditions could increase ($p < 0.05$) the final oil content of the chips more significantly than vacuum conditions. Garayo and Moreira (2002) also reported that the moisture of atmospheric fried products evaporated at a fast rate and resulted in the formation of large capillary pores. The pores were filled with gas. At this period, the capillary pressure was negligible so there was no force driving oil to flow into the chip's pores. In contrast, as the chips cooled down, the pressure inside the pores suddenly changed because of the increase in capillary pressure. This difference in pressure between the surface and the pores of the chips directly caused interfacial tension between oil and gas vapor. The surface oil started to diffuse very rapidly in the porous chips through the damaged areas and increased the internal oil content (Garayo and Moreira, 2002; Moreira et al., 1995; Pinthus and Saguy, 1994; Saguy and Pinthus, 1995; Ufheil and Escher, 1996). Furthermore, the higher oil temperatures led to faster development of a solid crust and consequently surface properties were favorable for oil uptake (Pinthus and Saguy, 1994; Baumann and Escher, 1995; Pinthus et al., 1995b; Saguy and Pinthus, 1995; Pinthus et al., 1997; Krokida et al., 2000a).

3.3. Influence of temperature and pressure on color

The effects of oil temperature and vacuum pressure on the color of banana chips were demonstrated in Table 1. There were no significant differences ($p > 0.05$) in lightness (L^*), green-red (a^*), and blue-yellow (b*) values for all chips fried in the vacuum conditions.

In contrast, chips fried in normal atmospheric conditions, 170°C, exhibited significantly ($p < 0.05$) darker appearance, with more red and yellow color than chips fried under vacuum, as confirmed by an increment in a* and b* values and reduction in L*. The changes in color during frying were the results of starch gelatinization and non-enzymatic browning reactions (Richardson and Hyslop, 1985; Shyu and Hwang, 2001; Garayo and Moreira, 2002).

3.4 Influence of temperature and pressure on shrinkage

The volume shrinkage of all banana chips at various levels of pressure and oil temperature was reported in Table 2. Volume shrinkage of about 40.7% was found in all vacuum fried banana chips in this experiment. A significant difference ($p < 0.05$) was observed in volume shrinkage when a pressure of 41.3 kPa was applied at a frying temperature of 130 and 140°C. The use of lower vacuum pressure tended to receive more volume shrinkage due probably to higher mass diffusivity and more moisture loss. The rapid evaporation rate of surface water during vacuum frying caused major surface shrinkage of fried products. When the oil temperature reached the boiling point of water, the free and/or loosely bound water remaining inside the chips suddenly vaporized, then quickly left fruit cells, and created large pores all over the whole chip texture (Shyu and Hwang, 2001; Garayo and Moreira, 2002). Shyu and Hwang (2001) also found that the rates of heat transfer among cells were due to surface shrinkage and contributed to the distribution of uneven sized pores.

Table 2 Textural characteristics of banana chips after frying under different vacuum pressures and oil temperatures

Temperature (°C)	Pressure (kPa)	Shrinkage (%)	Hardness (N)	Index of firmness	Displacement at peak force (mm)
120	21.3	39.9 ^{b} (1.3)	17.3 ^{b} (.05)	3.5 ^{c} (0.8)	4.7 ^{d} (.05)
	31.3	39.7 ^{b} (1.8)	17.0 ^{b} (9.0)	3.3 ^{d} (1.5)	4.5 ^{e} (9.0)
	41.3	39.3 ^{b} (0.6)	16.5 ^{c} (6.0)	3.2 ^{e} (0.3)	4.2 ^{f} (6.0)
130	21.3	42.2 ^{a} (1.3)	18.4 ^{ab} (1.5)	3.6 ^{b} (0.9)	5.0 ^{b} (1.5)
	31.3	41.6 ^{a} (1.3)	18.0 ^{ab} (1.4)	3.6 ^{b} (1.6)	4.9 ^{c} (1.4)
	41.3	39.9 ^{b} (1.3)	17.5 ^{b} (1.9)	3.5 ^{c} (0.5)	4.5 ^{e} (1.9)
140	21.3	42.3 ^{a} (1.2)	19.9 ^{a} (1.1)	3.7 ^{b} (0.9)	5.3 ^{a} (1.1)
	31.3	42.0 ^{a} (1.8)	19.5 ^{a} (1.1)	3.6 ^{b} (1.2)	5.1 ^{b} (1.1)
	41.3	39.5 ^{b} (0.7)	18.2 ^{ab} (1.5)	3.6 ^{b} (0.3)	5.0 ^{b} (1.5)
170	101.3	4.3 ^{c} (0.4)	12.5 ^{d} (0.5)	3.9 ^{a} (0.2)	3.2 ^{g} (0.5)

Numerical number in the table presented $\bar{x}$ (SD)

$^{a-g}$ means within a column with unlike superscript letters are significantly different ($p < 0.05$).

One major difference between the chips fried under two different production regimes was the surface porosity generated during the frying process. As expected, the chips fried under vacuum pressure retained a substantially higher degree of volume shrinkage when compared to atmospheric conditions in which the oil temperature was normally above the boiling point of water. The outer cells were then dehydrated as water was released from the intercellular spaces in the form of steam bubbles (Aguilera et al., 2001). The bubble formation at the product's surface created great gas expansion inside the pores. Thus, the chips would undergo both less shrinkage in width and more expansion in thickness with respect to the build-up of gas pressure inside the samples and the formation of gas pockets (Pinthus et al., 1995a; Kawas and Moreira, 2001; Yamsaengsung and Moreira, 2002a, 2002b; Mellema, 2003).

From visual inspection, the surface of the vacuum fried chips contained less expansion in thickness and generated numerous small bubbles as opposed to the chips fried under atmospheric pressure, which exhibited more expansion and larger bubbles (Garayo and Moreira, 2002). Several studies also reported a linear relation between oil content and porosity during frying (Pinthus et al., 1995a; Saguy and Pinthus, 1995; Vasanti Nair et al., 1996). They supported the theory that the greater the oil uptake in fried products, the more porous they would be.

3.5. Influence of temperature and pressure on texture

An important quality of fried fruit chips is the retention of crispness throughout shelf life. In general, there exists a great variety of textural measurements since each technique depends on the meaningfully textural parameter of interest (Segnini et al., 1999). Bourne et al. (1966) measured the initial slope and the maximum force required to break potato chips and recorded the change in the force-distance curves. They recommended the initial slope was capable of representing a potential method to measure crispness of products due to its having less variability than the maximum force to break. However, Salvador et al. (2002) indicated the texture profile of fried, battered squid ring corresponded to a crispy product which suffered multiple cracks before being pierced by the plunger (the curve had more than 1 peak), and its maximum penetration force value was lower. Baixauli et al. (2003) reported the crispness of batters containing dextrin decreased slightly with time after frying. This was indicated by the less steep curve and more displacement at peak force at longer times after frying. During the frying process, the textural characteristics of products continuously changed since the internal moisture moved outward from the banana chips via the oil transfer. Conclusively, the textural attributes of vacuum fried banana chips at higher oil temperature and lower vacuum pressure provided intensively greater hardness, index of firmness (curve slope), and longer displacement at peak force. In contrast, the atmospheric fried chips exhibited less hardness, shorter displacement at peak force, and a higher index of firmness. As the oil temperature increased and the vacuum pressure decreased, the rate of heat transfer also was excessively augmented and subsequently the surface of fried chips hardened because of thicker crust formation, greater volume shrinkage, and more starch gelatinization (Aguilera et al., 2001; Mellema, 2003).

A significant reduction in the hardness and displacement at peak force of the fried chips under atmospheric conditions ($p < 0.05$) indicated more crispness than the chips fried under vacuum pressure. At visual consideration of the shear curve profiles of each treatment, the atmospheric fried chips contained a better crispy texture than the vacuum fried chips as indicated by the presence of numerous and heterogeneous peak patterns, steeper slopes (greater index of firmness), and shorter displacement at peak force compared to the vacuum fried chips (Figure 1). In contrast, shear curve profiles of vacuum fried chips represented less crispness than atmospheric fried chips probably due to the fact that higher oil temperature during frying produced a more open starch network and crust porosity (Yamsaengsung and Moreira, 2002a). Thus, the atmospheric fried products were brittle and puffy in texture.

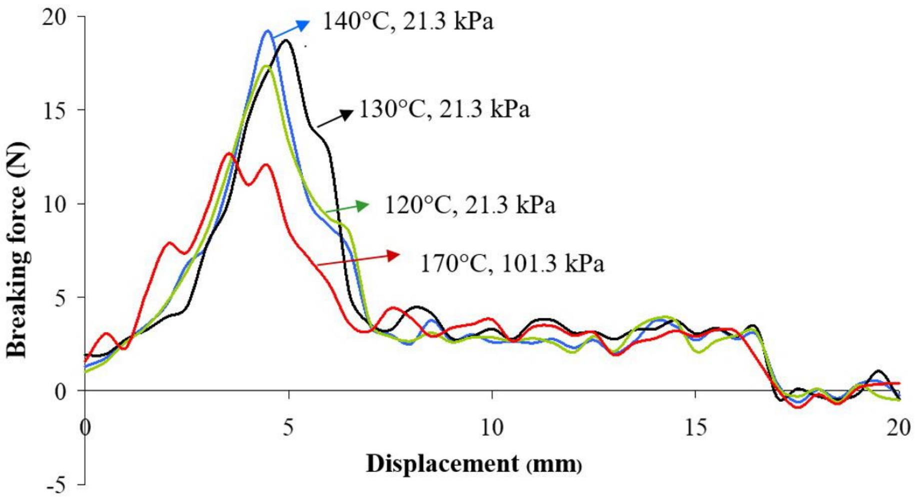

Figure 1 Texture profiles of the fried banana chips from various frying conditions.

4. CONCLUSIONS

The main purpose of using vacuum frying in this experiment was to evaluate its practicability to produce high quality banana chips with lower oil absorption and better color and texture characteristics. The overall quality of vacuum fried chips was then compared with the atmospheric fried chips at 170°C. Frying temperature and vacuum pressure directly affected fried food quality. The highest rate of drying loss rate was obtained from the frying condition at 140°C and 21.3 kPa. The moisture loss of chips was linearly related to amount of oil content. However, the chips fried at 140°C and 21.3 kPa resulted in more volume shrinkage. The overall color of all fried chips in each vacuum treatment was not significantly different but a better natural color than those that were fried under atmospheric conditions. These results support the applicability of vacuum frying technology to provide better quality in terms of oil uptake and color characteristics when compared to atmospheric fried chips. To produce good quality vacuum fried banana chips, a frying condition of 130°C and 41.3 kPa is recommended.

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