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KINETIC OF THE PHYSICAL QUALITY CHANGES DURING DEEP FAT FRYING OF SWEET POTATO CHIP

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ABSTRACT

Investigation was carried out to study kinetics of moisture loss, oil uptake, lightness and textural changes during deep fat frying of sweet potato *(Ipomoea batatas L.)* chip. Sweet potato slides of 2mm thickness were fried in a laboratory scale fryer at different temperatures ranging from 120 to 150°C. The investigation showed that the moisture loss, oil uptake, lightness followed the first order kinetics equation while the textural change was displayed as two terms equation. The first term of textural change was the softening of tissue and the second one was the crust hardening process. The kinetic coefficients of the changes of all above parameters increased significantly ($p < 0.05$) with the increasing of temperature. The temperature dependency of rate constants for moisture loss, oil uptake, lightness and textural change values were described via Arrhenius equation ($r > 0.98$, $p < 0.05$). The activation energies of moisture loss, oil uptake, lightness and textural changes (softening of the tissue and crust hardening) were 13.54 ± 1.28, 10.47 ± 0.56, 34.01 ± 1.36, 1.11 ± 0.06 and 24.68 ± 1.47 KJ/mol respectively.

KEYWORDS: Sweet potato, kinetic, deep frying, moisture loss, oil uptake, lightness, texture.

INTRODUCTION

Sweet potato *(Ipomoea batatas L.)* is an important food crop around the world [1]. With high in energy, dietary fiber, potassium and vitamin C, low in fat and important sources of the dietary antioxidant β-carotene [2], sweet potato specially is known as a major economical and healthy food crop in developing countries [3]. The carbohydrate composition in sweet potato roots greatly affects the eating quality and processing traits [4]. Sweet potato is becoming increasingly popular as an alternative raw material for the production of sweet potato chips [5], The use of the red fleshed sweet potato for the production of chips would further enhance nutrition of the consumers because of their significant content of phytonutrients, such as β-carotene, phenolic acids, anthocyanin, and dietary fiber [6, 7]. In addition, the frying process results in unique flavor, color and texture attributes which are the main drivers of consumer acceptability of the products [8, 9].

Frying is one of the oldest processes of food preparation. For decades, consumers have desired fried foods because of their unique combination of flavor and texture. The quality of the products from frying depends not only on the frying conditions, but also on the type of oils and the pre-treatment method of material during the process [10].

Blanching, drying and freezing normally are pre-treatment ways to apply for chip product processing. Drying improves the color and texture of product, drying decreases the oil uptake and frying time for the fried product while freezing ensures the availability of the semi-finished products for processing.

Deep-fat frying is a widely used food process. It consists of immersion of food pieces in hot vegetable oil and is a simultaneous heat and mass transfer process which leads to a succession of physical and chemical changes in the product [11]. The physical changes such as softening of tissue, decrease in moisture content, increase in oil content, formation of crust and shrink-age/swelling of the product takes place [12]. Chemical changes in the form of gelatinization of starch, denaturation of protein, inactivation of enzymes and flavor development takes place. This is normally performed with a deep fryer or chip pan. Industrially, a pressure fryer or vacuum fryer may be used [13].

The term "quality" comprises several parameters of the frying material, either in mid-state or after completion of frying process [14]. The properties that determine the overall quality in food frying are moisture content, color, textural properties, structure, oil content and nutritional value.

The quantitative information describing moisture loss, oil absorption, crust formation, interaction of water and oil, color formation, are required for process control and optimization and are the most important factors for describing the quality of fried food products. The kinetics of mass transfer, color and texture change during deep fat frying depend on several factors, such as nature of agricultural raw material, initial moisture content, nature of oil, frying temperature and time, product shape and size, pre treatment etc., [15, 16].

Kinetic studies of quality changes during frying are the great importance because knowledge on kinetic parameters during the process enables prediction of final quality changes and improves the final product value through correct selection of frying conditions [11].

For the many years, kinetic studies of changes in some important physical properties in potatoes during frying has been made by some researchers [17, 14, 13]. The present investigation was carried out to study the kinetics of moisture loss, color and texture changes as well as the relationship between moisture content and oil uptake during frying process of the sweet potato chip products pre-treated by blanching and freezing.

MATERIALS AND METHODS
Preparation of samples
Sweet potatoes *(Ipomoea batatas L.,* Japanese variety*)* were supplied from Metro Super Market, Cantho, Vietnam. The cleaned sweet potatoes were peeled, cut into 2mm thickness slides by potato cutting machine made from Ohmichi Sangyo Co. LTD. Slides of potato were blanched in solution of natri bisulfite 0.1% at 90°C for 3 minutes. After 15 min under air flow they were packed and frozen at -25°C for 2 days.

Frying process was carried out in vacuum frying equipment with the pressure of 720mmHg. Shortening was used for frying sweet potato. The frying temperatures were set up 120, 130, 140 and 150°C and the time for each frying temperature were 0, 1, 2, 4, 6, 8 and 10 minutes. The frying products were determined the contents of moisture and oil, hardness (maximum force to break the sample) and lightness (L value).

Determination of the moisture and oil content
The moisture content of sweet potato chip was measured by drying the samples in a convection oven until constant mass at 105°C, fat content was analyzed by Soxhlet extraction method using petroleum ether as solvent. The moisture and fat contents was calculated on a dry weight basis.

Color measurement
Color measurement was carried out using Hunter color meter (Minolta Chroma Meter CR 300). The color coordinates values obtained were L, a, b in Hunter scale. The instrument was calibrated with standard white and black tiles provided by the manufacturer. The color coordinate "L" refers to lightness/darkness.

Texture measurement
Hardness of samples were measured by using Rheo tex with the punch diameter being 12mm. The cross-head run again after stopping when hit the sample surface. Hardness was determined as the maximum force (MF, g force) required to break the surface of the sections.

Rate constants for moisture loss and oil uptake
The experimental data of moisture loss and oil uptake with respect to frying time was fitted into a first order exponential kinetics model as equations of (1) and (2) [18, 14, 19, 13].

$$\frac{(W_t - W_e)}{(W_i - W_e)} = e^{-k_w t} \tag{1}$$

$$\frac{(O_e - O_t)}{(O_e - O_i)} = e^{-k_0 t} \tag{2}$$

Where W_i, W_t, W_e are the moisture contents (%, db) of initial, at time t and at equilibrium respectively and O_e, O_t and O_i are the oil contents (%, db) at equilibrium at time t and at initial respectively; k_w, k_o are rate constants for moisture loss and oil uptake (min^{-1}) and t is time of frying in minutes.

Color kinetics
The Hunter color "L" value (lightness) with respect to frying time at different frying temperatures was fitted into a first order kinetic model as equation (3) [20, 21].

$$\frac{(L_t - L_e)}{(L_i - L_e)} = e^{-k_l t} \qquad (3)$$

Where, L_t, L_i and L_e are Hunter lightness value at time t, at initial and at equilibrium respectively; k_l is the rate constant of lightness change (min^{-1}) and t is time in min.

Texture kinetics
Pedreschi and Moyano (2005) [22] modeled textural changes in potato slices during frying using the parameter normalized maximum force, MF* (value of MF at any time divided by the value of MF at time zero). MF* allowed softening of the tissue and crust development processes to be followed during frying because it represents the force required to penetrate the sample. The equation (4) was used to describe the variation of MF* with frying time:

$$MF^* = \exp(-k_s t) + k_h t^2 \qquad (4)$$

Where, MF*: normalized maximum force; k_s: kinetic constant for softening of the potato tissue during frying (s^{-1}); k_h: kinetic constant for the crust hardening process during frying (s^{-2}) and t is frying time (s).

Temperature dependency of rate constants
The temperature dependence of rate constants of moisture loss and lightness changes in deep fat frying process were evaluated using Arrhenius equation as equation (5) [23-25].

$$k = k_{co} \exp(Ea/RT) \qquad (5)$$

Where, k is rate constant at temperature T, k_{co} is the frequency factor/pre-exponential coefficient, Ea is the activation energy J/mol, R is the universal gas constant (8.314 J/mol) and T is temperature in Kelvin.

Statistical analysis
Experimental data were subjected to analysis of variance at 5 % significance level ($p<0.05$). The model equations were fitted by method of least squares at 95 % confidence level using statistical software (Portable Statgraphics Centurion 15.2.11.0 and Microsoft Excel 2007). The model fitting was evaluated by determining the correlation coefficient (r) and the 5% significance level ($p<0.05$).

RESULTS AND DISCUSSION
Moisture loss and oil uptake

The moisture content of sweet potato chip during deep fat frying at different temperatures ranging from 120 to 150°C at different time intervals up to 10 min frying was shown in Figure 1A. The moisture content decreased markedly with respect to increased frying time and temperature. The rate of moisture loss was higher at elevated frying temperatures corresponding to same time of frying. The moisture content of sweet potato chip decreased exponentially with frying time at different frying temperatures and the data was fitted into first order kinetic model equation (Equation 1) mentioned in above. The rate constant for moisture loss (k_w) was calculated using first order rate equation (r > 0.98, p < 0.01). The rate constant for moisture loss increased significantly (p < 0.05) from 0.905 ± 0.018 to 1.202 ± 0.031 min^{-1} with increase in frying temperature and reported in Table 1.

A

B
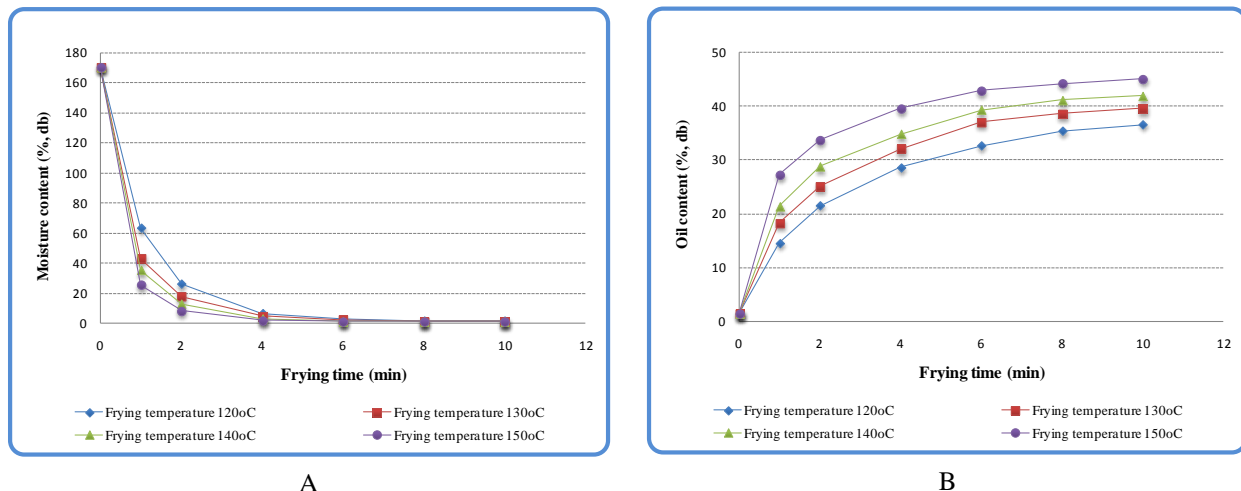
Figure 1. Effect of frying time on moisture content (A) and oil uptake (%, db) (B) during deep fat frying of sweet potatoes

Beside, the oil content of sweet potato chip during deep fat frying at different temperatures up to 10 min is shown in Figure.1B. The oil uptake increased with respect to frying temperature as well as time of frying. The amount of oil uptake was higher at higher temperature of frying at same time of frying. Similar to the moisture loss, the oil uptake data showed exponential increase with respect to frying time and was fitted in first order kinetic model as equation (2), ($r > 0.99$, $p < 0.01$). The oil uptake rate constant (k_o) increased significantly ($p < 0.05$) from 0.399 ± 0.002 to 0.504 ± 0.003 min^{-1} with increase in frying temperature and was reported in Table 2. Similar results were reported in deep fat frying of Gethi (*Dioscorea kamoonensis kunth*) strips [26] at different temperatures ranging from 120 to 180°C at different time intervals up to 15min.

Table 1. Kinetic rate constants for moisture loss, oil uptake, hunter lightness value and texture during deep fat frying of sweet potatoes at different frying temperatures

Parameters	Frying temperature (°C)			
	120	130	140	150
Moisture loss rate constant k_w (min^{-1})	$0.905^a \pm 0.018$	$0.981^b \pm 0.028$	$1.117^c \pm 0.010$	$1.202^d \pm 0.031$
Oil uptake rate constant k_o (min^{-1})	$0.399^a \pm 0.002$	$0.446^b \pm 0.001$	$0.471^c \pm 0.005$	$0.504^d \pm 0.003$
Hunter L value rate constant k_l (min^{-1})	$0.021^a \pm 0.003$	$0.029^b \pm 0.002$	$0.039^c \pm 0.004$	$0.043^d \pm 0.004$
Softening of the tissue rate constant k_s (s^{-1})	$0.980^a \pm 0.009$	$0.989^{ab} \pm 0.011$	$0.994^b \pm 0.006$	$1.005^c \pm 0.005$
Crust hardening rate constant k_h (s^{-2})	$0.0043^a \pm 0.0004$	$0.0053^b \pm 0.0007$	$0.0064^c \pm 0.0008$	$0.0074^d \pm 0.001$

(Mean ± SD, The values showing different superscripts within a row are significantly different at $p < 0.05$)

Hunter Lightness (L) value changes

The hunter lightness value (L) is a critical parameter in frying process and is considered as a primary quality factor evaluated by the consumer when considering the product quality [26]. Changes in Hunter "L" values with respect to frying time at different frying temperatures are shown in Figure 2. The Hunter L value decreased during frying at all the temperatures due to moisture loss and the formation of Maillard reaction products between reducing sugars and proteins [27, 26]. The rate of color change seems to be highly temperature dependent, it tends to be faster at higher frying temperatures. The lightness value of sweet potato chip decreased exponentially with frying time and obeyed first order kinetic equation as equation (3) ($r > 0.97$, $p < 0.01$), the rate constants k_l of lightness change increased significantly ($p < 0.05$) from 0.021 ± 0.003 to 0.043 ± 0.004 min^{-1} with increase in frying temperature and was displayed in Table 1. This rule in lightness change during frying process is similar to the result from study of Sahin (2000) which showed the increasing in the constants k_l of lightness change from 0.011 to 0.052 min^{-1} with the increasing in frying temperature from 150 to 180°C [28]. The Hunter lightness L value of sweet potato chip fitted

with Arrhenius equation and the activation energy for lightness change during frying process of it was shown in Table 2.

According to Pangloli *et al.* (2002) [29], the lightness values of potato chip above 60 were referred to as excellent; 56–60 as acceptable and 50–55 as marginally acceptable. So, similarly to potato chip, to maintain the sensory quality of sweet potato chip, the frying time should not exceed 8, 6 and 4 min corresponding to the frying temperature at 130, 140 and 150ºC.
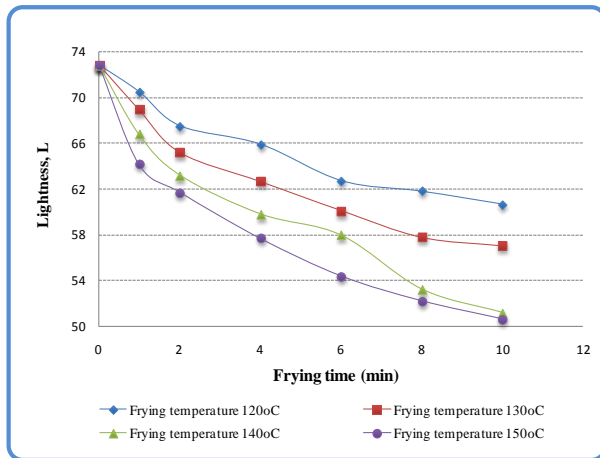

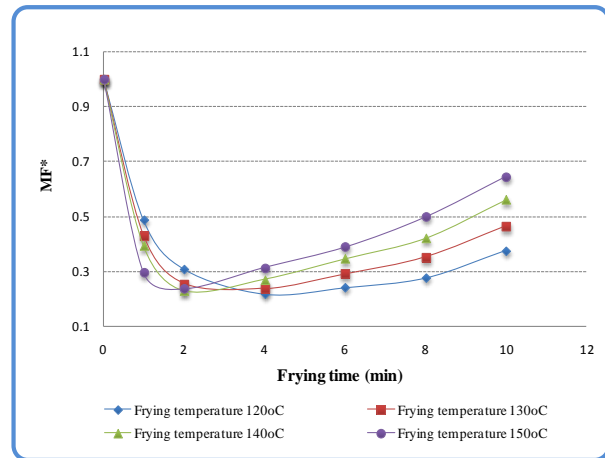*Figure 2. Effect of frying time on lightness during deep fat frying of sweet potatoes*

Figure 2. Effect of frying time on texture during deep fat frying of sweet potatoes

Texture

Frying of raw vegetables induces major changes in their micro-structure that results in their final physical and sensory properties . The most important textural property which denotes freshness and high quality for chip products is crispness [30]. During frying, vegetable tissues show an initial softening that is followed by hardening due to the progressive development of a dehydrated crust [31]. The textural changes during frying process expressed by normalized maximum force (MF*) was modeled into two terms as equation (4). In case of sweet potato chip from this study, the MF* values during frying also fitted into two terms equation above and the softening of the tissue rate constant k_s, crust hardening rate constant k_h were shown in Table 1. Both k_s and k_h increased significantly with the increasing of frying temperature ($p < 0.05$). In addition, the softening of the tissue rate constant k_s is higher than the crust hardening rate constant k_h meaning the softening process was faster than the hardening during frying. The obtained results were similar to the report of Dueik *et al.* (2010) when modeling the textural changes (MF*) of fried carrot crisps [31]. The rate constants k_s and k_h were found to obeyed Arrhenius equation as equation (5) and the activation energy for softening of the tissue and crust hardening during frying process of sweet potato chip was shown in Table 2.

Temperature dependency of rate constants

The frying temperature significantly effects on moisture loss, oil uptake, hunter color values as well as texture of sweet potato chip. The kinetic coefficient for all changes increased significantly with frying temperature. The temperature dependence of kinetic coefficients for all parameters were modeled by Arrhenius equation as equation (5). The activation energy was calculated by the method of least square approximation. The activation energies of moisture loss, oil uptake, hunter lightness (L) color value and normalized maximum force (MF*) were reported in Table 2.

Table 2. Activation energies of mass transfer, hunter lightness value and textural changes of sweet potato chip during deep fat frying

Parameter	Activation energy (kJ/mol)	r
Moisture loss	13.54 ± 1.28	0.984
Oil uptake	10.47 ± 0.56	0.991
Hunter lightness (L) value	34.01 ± 1.36	0.983
Softening of the tissue	01.11 ± 0.06	0.981
Crust hardening	24.68 ± 1.47	0.996

(Mean ± SD)

The results from Table 2 showed that the activation energy for moisture loss was high compared to that of oil uptake, meaning moisture loss was highly temperature sensitive when comparing with oil uptake. This result was in conformity with the established fact of Bhat and Bhattacharya (2001) [32] that the rate of moisture loss was much higher than that of oil uptake at same temperature of frying. Similar type of result was reported by Manjunatha *et al*. (2014) [26] when study deep fat frying of Gethi. Some authors found the activation energy for moisture diffusivity during deep fat frying was 27.6 KJ/mol and 25.4 KJ/mol for potato slices and apple slices respectively [23, 24].

The kinetic rate constants for Hunter lightness L value followed an Arrhenius relationship with temperature and the activation energy for its change was 34.01 ± 1.36 KJ/mol (Table 2). The Hunter lightness L value of fried potatoes was found fitting with Arrhenius equation in the study of Sahin (2000) when using sunflower oil for frying potato disk 25mm in diameter and 5mm thick at the frying temperature of 150, 160, 170 and 180ºC. The author also concluded that the activation energies for the lightness change was 22.67 KJ/mol [28].

Both stages of change in texture of sweet potato were found to obeyed the Arrhenius equation and the activation energies for their changes were respectively 01.11 ± 0.06 and 24.68 ± 1.47KJ/mol (Table 2).

The variation in the activation energies for moisture loss, oil uptake, lightness and textural changes were mainly due to the nature of raw material, its physico – chemical characteristics, size and shape, range of frying temperature and time, type of oil, etc [26]. The results of kinetics study of sweet potato chip during deep frying process could be used for optimization process conditions and quality as such for products.

CONCLUSION

During deep frying of sweet potato chip the kinetics of mass transfers, lightness and textural changes obeyed first order rate equation with the increasing in rate constants when the frying temperature increased. For the kinetic of mass transfers, the rate of moisture loss is higher than the rate of oil uptake at the same temperatures. In case of the kinetic of textural changes, the softening of the tissue rate is higher than the crust hardening rate. The rate of lightness change was relatively low results in the acceptable fried products when the frying time not exceeding 8, 6 and 4 min corresponding to the frying temperature at 130, 140 and 150ºC.

The temperature dependency of their rate constants obeyed the Arrhenius equation. The activation energies of moisture loss, oil uptake, lightness and textural changes (softening of the tissue and crust hardening) were 13.54 ± 1.28, 10.47 ± 0.56, 34.01 ± 1.36, 1.11 ± 0.06 and 24.68 ± 1.47 KJ/mol respectively.

The kinetics study of sweet potato chip during deep frying process can be applied for optimization process conditions for products

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