Kinetics of moisture loss and oil uptake during deep fat frying of Gethi (*Dioscorea kamoonsensis Kunth*) strips

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Abstract Investigation was carried out to study kinetics of moisture loss, oil uptake and tristimulus colour during deep fat frying of Gethi (*Dioscorea kamoonsensis kunth*) strips. Deep fat frying of Gethi strips of size $6 \times 6 \times 40$ mm was carried out in a laboratory scale fryer at different temperatures ranging from 120 to 180 °C. The investigation showed that the moisture loss and oil uptake followed the first order kinetics equation ($r > 0.95$, $p < 0.05$). The kinetic coefficients for moisture loss and oil uptake increased significantly ($p < 0.05$) with temperature from 0.166 to 0.889 min^{-1} and 0.139 to 0.430 min^{-1} respectively. The temperature dependency of rate constants for moisture loss and oil uptake values was described using Arrhenius equation ($r > 0.99$, $p < 0.01$). The activation energies for moisture loss and oil uptake were found to be 41.53 KJ/mol and 27.12 KJ/mol respectively. The hunter colour parameters were significantly affected by frying temperature and frying time. The hunter lightness (L) value increased with respect to frying time initially, followed by decline and same trend was observed at higher temperatures of frying with elevated rate, whereas hunter redness (a) value increased significantly ($p < 0.01$) with time as well as temperature of frying and obeyed zero order rate equation. The temperature dependency kinetic coefficients of Hunter (a) value were described by

Arrhenius equation and the energy of activation for change in hunter redness was found to be 42.41 KJ/mol ($r > 0.99$, $p < 0.01$). The other hunter colour parameters such as chroma, hue angle and total colour difference were markedly affected by frying temperature as well as frying time.

Keywords Deep fat frying · *Dioscorea* · Mass transfer · Kinetics · Activation energy · Hunter colour value

Introduction

Deep fat frying is one of the most important unit operations in catering as well as food processing operations and a traditional cooking method to achieve desirable sensory attributes such as flavour and texture in variety of foods and their products (Blumenthal and Stier 1991; Mohan and Delany 1995). The temperature of the oil for deep fat frying is usually carried in the range of 120–200 °C (Costa and Oliveira 1999; Debnath et al. 2003). These conditions of frying lead to rapid cooking, desirable change in sensory characteristics such as flavour, colour, texture development and high rate of heat and mass transfer. The frying process is more complex due to the coupling of both heat and mass transfer phenomena (Farkas et al. 1996; Yamsaengsung and Moreira 2002). During frying, heat and moisture transfers are coupled as in the drying process. It is a simultaneous heat and moisture transfer process where moisture leaves the food in the form of vapour; while oil is absorbed simultaneously (Liu-Peng et al. 2005). Deep fat frying involves several closely coupled mechanisms, such as convective and diffusive heat and mass transfer, in addition to chemical, physico-chemical reactions and transformations. During the frying process the chemical, physical and sensory characteristics of the food were modified. Chemical changes in the form of gelatinisation of starch, denaturation of protein, inactivation of enzymes and flavour development takes place. The physical

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changes such as softening of tissue, decrease in moisture content, increase in oil content, formation of crust and shrinkage/swelling of the product takes place (Patterson et al. 2004). The driving force for mass transfer is the pressure gradient caused by the conversion of water into steam. The quantitative information describing moisture loss, oil absorption, crust formation, interaction of water and oil, colour formation, are required for process control and optimisation. Deep fat frying combines heat treatment of high moisture foods with dehydration. Dehydration in hot oil at higher temperature is characterised by a very high rate of moisture removal and there is good evidence that this rapid drying is critical for ensuring favourable product quality (Baumann and Escher 1995). During deep fat frying, heat and mass (moisture & fat) transfer, both within and around the food takes place which leads to formation of crust. The fat not only acts as a heat transfer medium but also enters the food product during the frying process.

The mass transfer (moisture loss & oil uptake), colour development and texture are the most important factors for describing the quality of fried food products. The kinetics of mass transfer, colour 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., (Krokida et al. 2001a; Moyano and Berna 2002). The oil content of product is significantly affected by initial moisture content and particle size distribution. Higher initial moisture content and small particle size resulted in higher residual oil content and the ratio of residual oil content to water removed was independent of frying oil temperature (Moreira et al. 1997). The absorption of oil was inversely related to sample thickness (Bouchon and Pyle 2004). The oil temperature and thickness of potato strips had a significant effect on oil uptake, moisture loss and colour whereas the porosity of fries increased with increasing oil temperature and sample thickness (Krokida et al. 2001b). The rate of water loss during frying was much higher than that of oil uptake during deep fat frying of chickpea flour suspensions (Bhat and Bhattacharya 2001). The frying temperature and sample thickness are the most significant process parameters affecting the rate constants and equilibrium moisture and oil content (Krokida et al. 2000c).

Dioscorea species are popular in Africa, West Indies, some parts of Asia and South & Central America. It is cultivated in the tropics and many parts of sub-tropics and temperate zones. They are excellent source of dietary energy for most people in the tropics, but the methods of processing for value addition are as such inadequate. There are about 600 species of *Dioscorea* found in the world and about 50 species of *Dioscorea* are found in India (The wealth of India 1952). Gethi *Dioscorea kamoensis kunth* and also called as kamo yam is an aerial tuber (bulbils) crop grown in central Himalayas, Nepal, Bhutan and south east part of India and is cultivated at 2500–14000 feet altitudes. Tubers are sub

void and it is a perennial climber growing up to 2–5 m height. *Dioscorea* species contained a phyto chemical diosgenin which is widely used in modern medicine for progesterone and other steroid drugs. These are used as contraceptives and in treatment of various disorders of genitary organs and in a host of other diseases such as asthma and arthritis. The plant produces tubercles; the tubers are eaten as vegetable by the women suffering from leucorrhoea (Chouhan 1999). The nutritional composition of wild yam of Nepal was evaluated (Bhandari et al. 2003). There is a need to develop a value added fried product from Gethi. The present investigation was carried out to study the kinetics of moisture loss, oil uptake and hunter colour parameters of Gethi (*Dioscorea kamoensis kunth*) during deep fat frying.

Material and methods

Raw materials

Gethi (*Dioscorea kamoensis kunth*) was collected from Defence Institute of Bio-Energy Research, Pithoragarh, India and the tubers were washed with water, peeled with sharp stainless steel knife & diced in the form of strips of size $6 \times 6 \times 40$ mm using a dicer (Urshell, USA), the dimension was adjusted by adjusting the slicing blade of the dicer and soaked in boiled and cooled water containing potassium meta bisulphite (0.1 %) for 30 min. The soaked strips were drained, blanched in boiling water at 95 °C for 5 min, drained again and cooled to room temperature before subjecting to deep fat frying.

Analytical methods

The proximate composition of Gethi (*Dioscorea kamoensis kunth*) like moisture content was determined by hot air oven method by keeping the sample at 100 °C for 10 h, protein content was determined by micro kjeldahl method, crude fat by Soxhlet extraction method using petroleum ether as solvent for 16 h, ash and crude fibre were estimated as described by Ranganna (1986). Carbohydrates content was calculated by subtracting the sum of moisture, fat, protein, ash and crude fiber from 100. The energy content was estimated by multiplying protein and carbohydrates contents by 4 Kcal and fat content by 9 Kcal and was expressed in Kcal/100 g fresh sample.

Frying

A laboratory scale deep fat fryer (Continental Equipments India Ltd, Bangalore, India) with temperature control and wire mesh basket was used for frying. Sun flower oil (Gold winner brand, Kaleesuwari refinery Pvt Ltd, Tumkur, India) was used as the frying medium and the material to oil ratio

was kept constant at 1:25 w/v. The frying temperature was controlled by adjusting the temperature controller of the mini table-top deep fat fryer and frying temperature of the oil was measured using a digital thermometer (Spectrochem Pvt Ltd, Mumbai, India). The Gethi strips were fried at different time intervals; the fried samples were strained for one min and placed on an adsorbent paper to remove surface oil. After each cycle the oil quantity was checked and quantity was maintained constant.

Colour measurement

Colour measurement was carried out using Hunter colour meter (Mini scan XE plus, Model 45/0-S, Hunter Associates Laboratory Inc, Reston, VA, USA). The colour co-ordinates values obtained were L, a, b in Hunter scale. The illuminating source is a D65 lamp and the measurement was carried out at 10° observations. The instrument was calibrated with standard white and black tiles provided by the manufacturer. The colour co-ordinate 'L' refers to lightness/darkness, 'a' refers to redness/greenness and 'b' refers to yellowness/blueness.

Rate constants for moisture loss and oil uptake

The experimental data of moisture loss and oil uptake with respect to frying time were fitted into a first order exponential kinetics model as reported (Moreira et al. 1995; Krokida et al. 2001a, b; Das Gupta et al. 2006).

$$\frac{(X_t - X_e)}{(X_0 - X_e)} = e^{-k_x t} \quad (1)$$

$$\frac{(Y_t - Y_e)}{(Y_0 - Y_e)} = e^{k_y t}$$

where X_0 , X_t , X_e are the moisture contents (kg/kg db) of initial, at time t and at equilibrium respectively and Y_e , Y_t are the oil contents (kg/kg db) at equilibrium and at time t respectively, k_x & k_y are rate constants for moisture loss and oil uptake (min^{-1}) respectively and t is time of frying in minutes.

Colour kinetics

The Hunter colour 'a' value (redness) with respect to frying time at different frying temperatures was fitted into a zero order kinetic model,

$$C_t = C_0 + k_b t \quad (2)$$

where, C_t is Hunter redness (a) value at time t min, C_0 is the initial Hunter redness (a) value, t is time in min and k_b is the rate constant min^{-1} .

Temperature dependency of rate constants

The temperature dependence of rate constants was evaluated using Arrhenius equation. Several authors used Arrhenius

equation to describe the temperature dependency of rate constant of moisture loss and oil uptake in deep fat frying process (Ateba and Mittal 1994; Indra et al. 1999; Debnath et al. 2003; Math et al. 2004; Budzaki and Seruga 2005; Yildiz et al. 2007; Moreira et al. 2009; Bravo et al. 2009), as

$$k = k_0 e^{-E_a/RT} \quad (3)$$

where, k is rate constant at temperature T , k_0 is the frequency factor/pre-exponential coefficient, E_a is the activation energy J/mol, R is the universal gas constant = 8.314 J/K mol and T is temperature in Kelvin.

Modelling

The frying temperature significantly affects the equilibrium moisture/oil content during deep fat frying. The following models were tested for establishing the relation between ratios of equilibrium oil content to equilibrium moisture content with temperature of frying. The model equations were linear; second order polynomial, exponential and power law type equation as

$$\begin{aligned} O_{eq}/M_{eq} &= a + b T \\ O_{eq}/M_{eq} &= a + b T + c T^2 \\ O_{eq}/M_{eq} &= a^* \exp(b T) \\ O_{eq}/M_{eq} &= a^* (T)^b \end{aligned} \quad (4)$$

where M_{eq} and O_{eq} are equilibrium moisture and oil contents in kg/kg db, T is the temperature in Kelvin and a , b , c are empirical constants.

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 (Statistica 7.0, Stat soft, Tulsa, USA). The model fitting was evaluated by determining the correlation coefficient (r) and the 5 % significance level ($p < 0.05$).

Results and discussion

Proximate composition

The Table 1 shows the proximate composition of Gethi (*Dioscorea kamoonsensis kunth*). The moisture content of Gethi was 73.85 % (wet basis) and it is within the range of other *Dioscorea* species reported in literature. The protein was about 1.34 %, which is low as compared to that of other species; the protein content was markedly higher in case of *D. dumentorum* by 10.3 % and it was comparable to *D. deltoidea* & *D. versicolour* vis-à-vis Gethi and the protein

Table 1 Proximate composition of fresh Gethi (*Dioscorea kamoonsensis kunth*)

Parameter	Quantity (%)
Moisture	73.8±0.20
Protein	1.34 ±0.06
Ash	1.03 ±0.03
Crude Fat	0.35 ±0.01
Crude Fibre	1.08 ±0.03
Carbohydrates (By difference)	22.3 ±0.89
Energy Kcal/100 g	98.0±4.32

Mean ± SD (n=3)

content was higher in case of *D dumetorum* yellow variety compared to Gethi. The ash content of Gethi at 1.03 % is within the range of other species, the maximum and minimum ash contents were reported in *D dumetorum* (3.79 %) and *D versicolour* (0.5 %). Fat and crude fibre contents were found to be 0.35 % and 1.08 % respectively. The fat content is comparable with other species which ranges from 0.2 to 0.54 % in other *Dioscorea* species. The maximum fat content was in the *D alata* as reported. A crude fibre content of 1.08 % in *Dioscorea kamoonsensis kunth* is comparable with other species. A fibre content of 2.44 % fresh weight basis was in *D dumetorum* white variety and the yellow variety was found to have 2.24 %. The carbohydrate content of Gethi (*Dioscorea kamoonsensis Kunth*) was about 22.35 % (by difference) and was within range of other species; on the other hand, *D rotundata* species had higher carbohydrate content. The energy value of Gethi was 98 Kcal/100 g and is akin to those of other *Dioscorea* species (Gopalan et al. 2000; Afoakwa and Sefa-Dedeh 2001; Bhandari et al. 2003; Onwuka and Ihuma 2007). These variations in proximate composition might be due to their geographical source, genetic origin, soil fertility, climatic conditions and harvesting periods.

Moisture loss and oil uptake

The Fig. 1a shows the moisture loss of Gethi (*Dioscorea kamoonsensis kunth*) strips during deep fat frying at different temperatures ranging from 120 to 180 °C at different time intervals up to 15 min frying. The initial moisture content was 2.825 kg/kg db (73.85 % fresh weight basis). 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. Moisture content reduced from 2.825 kg/kg db to 0.492, 0.151, 0.026 and 0.002 kg/kg db at 120, 140, 160 and 180 °C of frying temperatures respectively up to 15 min of frying. The frying oil temperature showed significant negative effect on moisture content during deep fat frying of Gethi (*Dioscorea kamoonsensis kunth*) strips. The moisture content of Gethi decreased exponentially with frying time at different

Fig. 1 Effect of frying time on **a**) moisture content (kg/kg db) and **b**) oil uptake (kg/kg db) during deep fat frying of Gethi at frying 120 °C (♦), 140 °C (■), 160 °C (▲) and 180 °C (■) temperatures (n=3, Mean ± SE)

frying temperatures and the data was fitted into first order kinetic model equation (Eq. 1) reported in literature (Krokida et al. 2001a, b; Das Gupta et al. 2006). The rate constant for moisture loss (k_x) was calculated using first order rate equation ($r > 0.97$, $p < 0.01$). The rate constant for moisture loss increased significantly ($p < 0.01$) from 0.166 to 0.889 min^{-1} with increase in frying temperature and reported in Table 2. At the initial stages of frying the moisture loss was not significant upto 15 s of frying at different frying temperatures. The deep fat frying process involves four stages such as initial heating, surface boiling, falling rate and bubble end point. The extent of time for each stage depends upon the initial conditions, process parameters, and product composition, size, shape etc. The initial heating is the period of time during which the

Table 2 Kinetic rate constants for moisture loss, oil uptake, hunter redness value and equilibrium moisture and oil contents during deep fat frying of Gethi (*Dioscorea kamoonsensis kunth*) at different frying temperatures

Parameter	Temperature (°C)			
	120	140	160	180
Moisture loss rate constant k_x (min^{-1})	0.166 ^a ±0.002	0.338 ^b ±0.001	0.476 ^c ±0.001	0.889 ^d ±0.001
Oil uptake rate constant k_y (min^{-1})	0.139 ^a ±0.006	0.219 ^b ±0.014	0.315 ^c ±0.033	0.430 ^d ±0.021
Hunter a value rate constant k_b (min^{-1})	0.205 ^a ±0.004	0.319 ^b ±0.001	0.684 ^c ±0.003	1.070 ^d ±0.004
Equilibrium moisture content (kg/kg db)	0.492 ^d ±0.005	0.151 ^c ±0.006	0.026 ^b ±0.003	0.0020 ^a ±0.0003
Equilibrium oil content (kg/kg db)	0.146 ^a ±0.004	0.162 ^b ±0.004	0.210 ^c ±0.004	0.289 ^d ±0.009

Mean ± SD ($n=3$). The values showing different superscripts within a row are significantly different at $p<0.05$

surface of the material heats from initial temperature to the boiling point of the surface water, where heat was transferred to the food material from the oil by convection at the surface and conduction through the uncooked solid phase. This phase is of very short duration and the amount of water loss was negligible. In the second stage, also called as surface boiling stage where there is sudden loss of moisture at the surface, increase in surface transfer and initiation of crust formation takes place. The surface boiling changes the surface conditions from free convection to boiling conditions, which lead to increase in surface turbulence and vapour generation. It results in explosions of bubbles in the frying process. In the third stage, also known as falling rate stage where the bulk amount of moisture is lost, the core region attains the boiling temperature of water and thickening of the crust layer. This stage constitutes the longest time duration in deep fat frying. The final bubble end point stage, described as the apparent cessation of moisture loss from the food material involves several factors such as complete removal of water, reduction of heat transfer and larger size of crust formation (Farkas et al. 1996; Moreira and Barrufet. 1998).

The residual oil content of Gethi strips during deep fat frying at different temperatures up to 15 min is shown in Fig. 1b. The oil uptake increased with respect to frying temperature as well as time of frying, and oil content reached a maximum equilibrium value at specific temperature. The amount of oil uptake was higher at higher temperature of frying at same time of frying. The oil uptake data showed exponential increase with respect to frying time and was fitted in first order kinetic model ($r>0.94$, $p<0.05$) Eq. (1). The oil uptake rate constant (k_y) increased significantly ($p<0.05$) from 0.139 to 0.430 min^{-1} with increase in frying temperature and reported in Table 2. Mass transfer phenomena i.e., moisture loss and oil absorption gets more intense at higher frying temperatures. The rate of moisture loss is high compared to that of oil uptake at all the frying temperatures. Similar results were reported in deep fat frying of chick pea flour suspensions traditionally called as *Boondi* (Bhat and Bhattacharya 2001). Bouchon et al. (2003) reported that only a small amount of oil penetrates during frying,

suggesting that oil uptake and moisture loss are not synchronous phenomena. Sahin et al. (2000) reported that oil uptake was negatively correlated with moisture content and changed quadratically with frying time. It was reported that moisture loss obeys the first order kinetic model, whereas fat uptake obeys second order polynomial equation during deep fat frying of catla fish, whereas oil absorption obeyed non-linear effect during deep fat frying of *papad* (Math et al. 2004; Pandey et al. 2008). Oil absorption during deep fat frying has been classified as surface related phenomena. The oil absorption strongly linked with the amount of moisture removal from the food. The absorption of oil depends on change in microstructure caused by deep fat frying, which results in change in surface roughness, porosity and pore size distribution etc. It has been well established that oil absorption occurs mainly during cooling process after frying as a result of adhesion and capillary action. This was due to condensation of steam and interfacial tension between the oil and gas within the pores structure (Moreira and Barrufet 1998). Higher frying temperature leads to faster moisture loss from the food material and higher the initial moisture content of the material, higher is the oil absorption. The cooling temperature has the largest effect on oil absorption; higher cooling temperature leads to lower oil absorption because of lower capillary pressure difference (Yamsaengsung and Moreira 2002). Similar type of results was reported for different products (Baumann and Escher 1995; Baardseth et al. 1996; Suleaman et al. 2001; Garayo and Moreira 2002; Liu-Peng et al. 2005; Sobukola et al. 2008a).

Colour

Colour of fried product is an important parameter and to be controlled during processing together with texture, moisture and oil contents. Colour of the fried product is a result of moisture loss, oil migration and Maillard reaction that depends on the amount of reducing sugar and amino acids of proteins at the surface, temperature and time of frying (Krokida et al. 2001c). Experimental data of hunter colour parameters were shown in Fig. 2. The change in hunter

lightness (L) value, hunter redness (a) value, chroma, hue angle and change in total colour difference are significant with respect to frying time and frying temperature.

Hunter Lightness (L) value

Hunter 'L' values (Lightness) with respect to frying time at different frying temperatures are shown in Fig. 2a. The Hunter L value increased initially followed by a decrease

at all the temperatures of frying. The trend was more pronounced at higher temperatures of frying. The initial Hunter lightness (L) was about 53.1 and the maximum L value was obtained at 9 min of frying at 120 °C frying temperature, whereas the maximum 'L' values were obtained at 7, 3 and 1 min corresponding to frying temperatures 140, 160 & 180 °C. The initial increase in hunter Lightness (L) value was due to loss of moisture, which leads to the product becoming whitish, and then decrease due to oil impingement

Fig. 2 Effect of frying time on **a)** Hunter L values, **b)** Hunter a values, **c)** Hunter b values, **d)** Chroma, **e)** Hue angle and **f)** Total colour difference during deep fat frying of Gethi at frying 120 °C (♦), 140 °C (■), 160 °C (▲) and 180 °C (■) temperatures ($n=3$, Mean $\pm$ SE)

and formation of Maillard reaction products between reducing sugars and proteins. This phenomenon was high at higher temperatures of frying. The colour development of the product during deep fat frying depends on drying rate (moisture loss), oil uptake and heat transfer coefficient during the different stages of frying. The rate of change of colour was found as such highly temperature dependent. The hunter lightness value is a critical parameter in frying process and is considered as a primary quality factor evaluated by the consumer when considering the product quality. Low Lightness values results a dark colour and is formed due to non-enzymatic browning reactions. The lightness values above 60 were referred to as excellent; 56–60 as acceptable and below 50–55 as marginally acceptable (Pangloli et al. 2002). The lightness values were in the range 48–60 during deep fat frying of Gethi. The lightness value of tofu decreased exponentially with frying time and obeyed first order kinetic equation and the activation energy was 76.0 KJ/mol during deep fat frying (Baik and Mittal 2003). This change in lightness values may be attributed to the loss of moisture content and browning that took place during frying as a result of acrylamide formation and non enzymatic browning reaction (Pedreschi et al. 2005, 2007).

Hunter redness (a) value

Hunter redness (a) values with respect to frying time at different frying temperatures are as shown in Fig. 2b. The Hunter redness (a) values increased significantly ($p < 0.05$) with increase in frying time and frying temperature. The initial Hunter redness value was 2.48 and after 15 min of frying increased to 5.77, 7.52, 12.71 and 18.53 at 120, 140, 160 and 180 °C of frying temperatures respectively. The hunter redness increased linearly with respect to frying time and the rate of colour formation was high at higher temperatures of frying. Since the change in hunter redness (a) values was linear with respect to frying time this reveals that the colour formation (redness) followed zero order kinetics. The Hunter redness (a) value was modelled using zero order kinetic model (equation 2) and the rate constants were 0.205, 0.319, 0.684 and 1.070 min⁻¹ ($R^2 > 0.98$) at frying temperatures 120, 140, 160 and 180 °C respectively. The increase in Hunter redness (a) value may be due to moisture loss, impingement of oil and formation of Maillard reaction products during frying of Gethi strips. Similar results were reported in case of deep fat frying of potato discs (sahin 2000). The redness (a) values were found significantly higher for potato chips fried at atmospheric pressure than the potato chips fried at vacuum condition due to marked increase in Maillard reaction products (Garayo and Moreira 2002). The redness of tofu increased exponentially with frying conditions and obeyed the first order kinetic equation during deep fat frying of tofu (Baik and Mittal 2003). All the processing variables such as pre frying hot air drying temperature, drying time and frying time significantly affected the redness of yam

slices during deep fat frying (Sobukola et al. 2010). The redness value increased with blanching temperature and frying time whereas it decreased with blanching time due to leaching out of reducing sugars which was responsible for formation of Maillard reaction products (Sobukola et al. 2008b). However, the redness of the yam slices increased with increase in temperature and time of frying and it decreased with increase in initial dry matter content of the tubers (Sobukola et al. 2008a). The redness colour parameter of potato followed a first order kinetics to determine the rate of change of colour during deep fat frying and with appreciable correlation between the acrylamide content of the chips and their colour (Pedreschi et al. 2005). In the present investigation Gethi strips obeyed the zero order kinetic equation. The deviation may be due to nature of raw material, time and temperature of frying, nature of the frying medium, initial colour of the raw material and their physico-chemical characteristics. The increase in redness values could be attributed to the high temperature and low moisture content, which initiated the nonenzymatic browning such as Maillard reaction and caramelisation of sugars.

Hunter yellowness (b) value

The hunter yellowness (b) values changed from 19.08 to 27.17. No specific trend of change in Hunter yellowness with respect to frying time and frying temperature during deep fat frying of Gethi strips was observed (Fig. 2c). The yellowness of tofu increased initially with frying time and followed by decline, the trend was more pronounced at higher temperature of frying and it obeyed the first order kinetic equation for colour development as well as colour degradation (Baik and Mittal 2003). The change in yellowness of potato strips followed a first order rate equation during deep fat frying (Krokida et al. 2001b). The yellowness of yam slices increased with blanching time and frying time, whereas, it decreased with increase in blanching temperature during deep fat frying and, frying time had a significant effect on yellowness of yam slices (Sobukola et al. 2008b). The yellowness of yam slices was not affected by frying temperature, frying time and initial dry matter content during deep fat frying (Sobukola et al. 2008a), whereas yellowness values were markedly higher for potato chips fried at atmospheric pressure than the potato chips fried at vacuum condition (Garayo and Moreira 2002).

Chroma

The variation in magnitude of chroma values with respect to frying time at different temperatures of Gethi during frying was shown in Fig. 2d. The magnitude of chroma values increased marginally with frying time initially and reached a maximum value and then declined at final stages of frying. The same trend was observed at higher temperatures of frying with elevated rates. This result can be attributed that

the hunter redness (a) values increased markedly with frying time as well as frying temperature, whereas there was no significant change in hunter yellowness (b) values during deep frying and at final stage of frying the yellowness was observed markedly decreasing. Similar trend was observed at higher temperatures of frying with elevated rate. The change in chroma values was attributed to increase in hunter redness (a) values and change in hunter yellowness (b) values. This phenomenon was due to loss of moisture, impingement of oil and non enzymatic browning such as Maillard reaction and caramelisation of sugar of Gethi during frying. The chroma values decreased significantly with increasing during hot air drying of kiwi fruit slices and obeyed the first order rate equation (Mohammadi et al. 2008).

Hue angle

The variation in magnitude of hue angle with respect to frying time at different temperatures during deep fat frying of Gethi was shown in Fig. 2e. The hue decreased to 76.2°, 71.4°, and 60.3°, 51.7° from 82.8° at 120, 140, 160 and 180 °C frying temperatures respectively. The hue angle decreased linearly with increase in frying time and same trend was observed in elevated rate at higher temperatures of frying. This was due to increase in hunter redness (a) value which was markedly affected by frying temperature and frying time, where as the hunter yellowness (b) values were not affected by frying time. The hue angle directed towards red axis during deep fat frying of Gethi, which was due to change in the ratio of hunter yellowness (b) to hunter redness (a) values. This phenomenon was due to loss of moisture, impingement of oil and non enzymatic browning such as Maillard reaction and caramelisation of sugar of Gethi during frying. Similar type of result was reported for kiwi fruit slices during hot air drying (Mohammadi et al. 2008).

Total colour difference

The Fig. 2f showed the effect of frying time on total colour difference at different frying temperatures. The change in total colour difference increased gradually at lower temperature of frying, whereas at higher temperature it increased initially then followed by decline. This was due to decrease in hunter lightness values and trend was more pronounced at higher temperature of frying. The change in total colour difference was significantly affected by frying conditions and there was a significant change observed in total colour difference during deep fat frying of potato chips at atmospheric and vacuumised conditions (Garayo and Moreira 2002). Total colour difference was significantly affected by frying temperature but unaffected by frying time during deep fat frying of onion rings (Du-Ling et al. 1998). The total colour change of tofu during frying at different temperatures

increased exponentially and followed first order kinetic equation. The increase in magnitude of total colour difference values could be attributed to the high temperature and low moisture content, which initiated the nonenzymatic browning such as Maillard reaction and caramelisation of sugars (Baik and Mittal 2003).

Equilibrium moisture and oil contents

The equilibrium moisture and oil contents during deep fat frying of Gethi strips at different frying temperatures are shown in Table 2. The equilibrium moisture content decreased significantly ($p < 0.05$) whereas equilibrium oil content increased significantly ($p < 0.05$) with increase in frying temperature. The food material was exposed to frying at higher temperature, moisture initially evaporates, the concentration of moisture decreased rapidly. The outer surface became dry, creating a crust that acts as a diffusion barrier. The internal moisture was converted into steam, caused a pressure gradient and steam escaped through capillaries and channels in the cellular structures. As the process progressed, oil adhering to the food, enters the voids left by water during cooling process. The residual oil content was markedly affected by frying temperature, initial moisture content and particle size distribution (Moreira et al. 1997). Similar type of result was reported in case of chickpea flour based snack food during deep fat frying and equilibrium oil content and residual moisture content are strongly related to each other, the equilibrium moisture and oil content are decreased with increase in pre-drying time of banana chips during deep fat frying, which could be attributed to reduced initial moisture content (Debnath et al. 2003; Das Gupta et al. 2006). The equilibrium moisture content decreased with increase in oil temperature whereas equilibrium oil content increased. The effect of oil temperature on equilibrium moisture content of potato strips was more intense at higher values of sample thickness whereas equilibrium oil content was more intense at lower sample thickness (Krokida et al. 2000).

The quantity of oil uptake was directly proportional to the moisture loss. This phenomenon leads to increase in the ratio of equilibrium oil content to moisture content with respect to frying temperature. The equilibrium moisture and oil contents are significantly ($p < 0.05$) affected by frying temperature during deep fat frying of Gethi and these values were highly temperature dependent. The ratio of equilibrium oil content to equilibrium moisture content significantly ($p < 0.05$) increased from 0.297 to 145.8 with increase in frying temperature and indicated that the ratio of equilibrium oil content to moisture content was highly temperature dependent. Several model equations relating to ratio of equilibrium oil content to moisture content was tested and the parameters of the models and correlation coefficient (r) was reported in Table 3. The relation between

Table 3 Parameters of different models relating to ratio of equilibrium oil content to equilibrium moisture content with temperature of frying during deep fat frying of Gethi (*Dioscorea kamoensis kunth*) strips

Model	a (-)	b (K ⁻¹)	c (K ⁻²)	r
$O_{eq}/M_{eq}=a+b T$	-879.843 ^{ns} ±92.913	2.220 ^{ns} ±0.226	-	0.8028
$O_{eq}/M_{eq}=a+b T+c T^2$	14365.05 ^{ns} ±1809.97	-70.157 ^{ns} ±8.79	0.0833 ^{ns} ±0.0115	0.9746
$O_{eq}/M_{eq}=a \cdot \exp(b T)$	1.5688 × 10 ⁻¹¹ *** ±4.119 × 10 ⁻¹²	0.0651*** ±0.0006	-	0.9672
$O_{eq}/M_{eq}=a \cdot (T)^b$	2.088 × 10 ⁻²¹ *** ±1.154×10 ⁻²¹	8.5291*** ±0.0920	-	0.6819

Mean ± SD (n=3), *** $p<0.001$, ** $p<0.01$, * $p<0.05$, ^{ns} non significant $p>0.05$

ratios of equilibrium oil content to moisture content was increased exponentially ($r>0.96$, $p<0.001$) with frying temperature and suggested model equation which was reported as

$$O_{eq}/M_{eq} = 1.5688 \times 10^{-11} \exp(0.0651 T), (r > 0.96, p < 0.001)$$

where O_{eq} and M_{eq} are the equilibrium oil content and equilibrium moisture content in kg/kg db, T is frying temperature in Kelvin.

Temperature dependency of rate constants

The frying temperature had a significant effect on moisture loss, oil uptake, hunter colour values as well as equilibrium moisture and oil contents. The kinetic coefficient for moisture loss, oil uptake increased significantly with frying temperature. The temperature dependence of kinetic coefficients for moisture loss, oil uptake and hunter redness were modelled by Arrhenius equation (Eq. 3). The activation energy was calculated by the method of least square approximation. The activation energies of moisture loss, oil uptake and hunter redness (a) colour value were reported in Table 4 and were found to be 41.53, 27.12 and 42.41 respectively. The activation energy for moisture loss was high compared to that of oil uptake, which indicated that moisture loss was highly temperature sensitive than that of oil uptake. This was a well established fact that the rate of moisture loss was much higher than that of oil uptake at same temperature of frying (Bhat and Bhattacharya 2001). Similar type of result was reported in deep fat frying of chick pea flour based snack food frying (Debnath et al. 2003). The activation

energy for moisture removal was 14.34 KJ/mol in case deep fat frying of composite product *samosa* – an Indian traditional filled pastry snack food, whereas, in case of vacuum frying of potato chips it was almost equal to that of Gethi (Indra et al. 1999; Moreira et al. 2009). The activation energy for moisture diffusion was 2.70 KJ/mol for beef meat ball frying and 97.69 KJ/mol in case of deep fat frying of *catla catla* fish (Ateba and Mittal 1994; Pandey et al. 2008). The activation energy for moisture diffusivity was 30 KJ/mol whereas for fat diffusivity it was 5.5 KJ/mol in case of deep fat frying of korostula dough (Budzaki and Seruga 2005). The activation energy for moisture diffusivity during deep fat frying was 27.6 KJ/mol, 25.4 KJ/mol 44.89 KJ/mol for potato slices, apple slices and *papad* respectively (Math et al. 2004; Yildiz et al. 2007; Bravo et al. 2009). The activation energy for change in Hunter redness (a) value was 42.41 KJ/mol ($r>0.99$) in case of Gethi. Sahin (2000) reported that the activation energy for Hunter 'a' value was 71.60 KJ/mol in case of deep fat frying of potatoes. The activation energies for lightness and redness values were 76.0 KJ/mol and 165.0 KJ/mol respectively for deep fat frying of tofu, whereas for greenness-yellowness colour values for colour development and colour degradation were equal and found to be 117.0 KJ/mol (Baik and Mittal 2003). The deviation in the activation energies for moisture loss, oil uptake and colour changes were due to nature of raw material, its physico-chemical characteristics, size and shape, range of frying temperature and time, nature of oil etc. As such, the activation energy levels highlighted the relatively higher temperature dependence of moisture loss and Hunter values compared with the oil uptake during deep fat frying of Gethi strips. The data on kinetics of deep fat frying of Gethi could be used for facilitating manufacture of deep fat fried snacks with optimal process conditions and quality as such.

Table 4 Activation energies of mass transfer and hunter redness (a) value of Gethi (*Dioscorea kamoensis kunth*) during deep fat frying

Parameter	Activation energy (kJ/mol)	r
Moisture loss	41.53±0.18	0.9929
Oil uptake	27.12±2.76	0.9944
Hunter redness (a) value	42.41±0.24	0.9958

Mean ± SD (n=3)

Conclusions

1. Frying kinetics of mass transfers obeyed first order rate equation with rate constants for moisture loss 0.166 to 0.889 min⁻¹ and for oil uptake 0.139 to 0.430 min⁻¹ of

Gethi (*Dioscorea kamoonsensis Kunth*) strips during deep fat frying.

2. The hunter lightness (L) value increased initially, followed by decline with increase in frying time and the trend was more pronounced at higher temperatures of frying.
3. Hunter redness (a) value increased significantly with frying temperature and frying time and followed the zero order kinetic equation having rate constant ranging from 0.205 to 1.070 min⁻¹.
4. The colour parameters such as chroma, hue angle and total colour difference were strongly influenced by frying conditions.
5. The temperature dependency of rate constants obeyed the Arrhenius equation. The activation energies of moisture loss, oil uptake and hunter redness (a) value were 41.53, 27.12 and 42.41 KJ/mol respectively.
6. The temperature dependency of moisture loss was higher compared to that of oil uptake during deep fat frying of Gethi (*Dioscorea kamoonsensis Kunth*).
7. The equilibrium moisture content was decreased significantly ($p < 0.05$) whereas, equilibrium oil content increased significantly ($p < 0.05$) with increase in frying temperature and the mathematical model between ratio of equilibrium oil to moisture content with frying temperature was established.

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