Kinetic, rheological and thermal studies of flaxseed (*Linum usitatissimum* L.) oil and its utilization

Sneh Punia¹ · Kawaljit Singh Sandhu^{1,2} · Sanju Bala Dhull¹ · Maninder Kaur³ · Anil Kumar Siroha¹

Revised: 19 March 2020 / Accepted: 8 April 2020 / Published online: 20 April 2020
© Association of Food Scientists & Technologists (India) 2020

Abstract In present study kinetic, thermal and rheological characteristics of oil isolated from flaxseed were studied and because of high content of α -linolenic acid (essential omega-3 fatty acid), flaxseed oil was incorporated in muffins by replacing fat/shortening at different levels (10%, 20%, 30% and 40%). To evaluate rheological behaviour, the experimental data of flow behaviour for flaxseed oil was fitted to Power law model, consistency index (K) and flow behaviour index (n) and Arrhenius parameters (activation energy and frequency factor) were evaluated. The n value of the oil treated at 10, 15, 20, 25 and 30 °C were found between 0.8 to 0.9, which suggested the non-Newtonian fluid behaviour of flaxseed oil. Thermal properties of flaxseed oil was evaluated using DSC (differential scanning calorimetry). The flaxseed oil possessed three endothermic and one shoulder peak. Gas chromatography revealed the fatty acids composition qualitatively and quantitatively and flaxseed oil is dominated by unsaturated fatty acids. Saturated oil was replaced with flaxseed unsaturated fat and results showed that substituting oil with flaxseed fat at level upto 20% produced muffins possessed the better texture, colour, aroma, mouth feel and overall quality score. **Practical application:** Modern diet lifestyle demands of healthy natu-

ral foods represent a challenge for food manufacturers to lead towards the healthy new trends. Fats imparts lubrication, texture, flavour and acceptability therefore used as major ingredients in bakery goods. Fats contains saturated fatty and dietary intake of saturated fatty acids in excess amount leads to many health disorders. Therefore, substitution of saturated fatty acid with PUFAs (omega-3 and omega-6) for the protection against diseases and metabolic disorders may be a solution for healthy and nutritious product development.

Keywords Flaxseed oil · GC–MS · DSC · Rheology · Muffins

Introduction

Flax (*Linum usitatissimum*), a small flowering annual herb commonly known as linseed, belongs to family *Lineaceae* and used as food, for medicinal purposes and as nutritional product. On the report of FAO (2017), the global production of flaxseed was 2,794,344 tonnes whereas it was 184,000 tonnes in India. Flaxseed has come out as one of the functional ingredient in food and is the richest source of lipids (40%), proteins (25%), dietary fiber (28%), vitamins and minerals (de Moura et al. 2016). These components in flaxseed that are associated with health benefits are include α -linolenic acid (essential amino acid), and dietary fiber (Hall et al. 2006) and phenolic acids, flavonoids, phenylpropanoids and tannins (Kasote 2013). Flax oil is rich in polyunsaturated fatty acid (73%) followed by monounsaturated fat (18%) and saturated fat (9%) (Cunnane et al. 1993; Dubois et al. 2007). Among PUFAs, flaxseed oil is a dietary source of essential fatty acid, omega-3 (n-3, alpha-linolenic acid) and it plays an important role in the

✉ Sneh Punia
snehpunia69@gmail.com; dimplepoonina@gmail.com

¹ Department of FST, Chaudhary Devi Lal University, Sirsa, India

² Department of FST, Maharaja Ranjit Singh Punjab Technical University, Bathinda, India

³ Department of FST, Guru Nanak Dev University, Amritsar, India

preventing and treating of many cardio-vascular (Larsson et al. 2004).

Modern diet lifestyle demands of healthy natural foods represent a challenge for food manufacturers to lead towards the healthy new trends. Fats imparts lubrication, texture, flavour and acceptability therefore used as major ingredients in bakery goods. Fats contains saturated fatty and dietary intake of saturated fatty acids in excess amount leads to many health disorders. Therefore, substitution of saturated fatty acid with PUFAs (omega-3 and omega-6) for the protection against diseases and metabolic disorders may be a solution for healthy and nutritious product development. An effective avenue to increase the consumption of essential fatty acids is through the incorporation of flaxseed oil in food products (Oomah 2001). Many researches have been conducted to reduce/replace fat content of bakery goods (Punia et al. 2019; Rodriguez-Sandoval et al. 2017; Rangrej et al. 2015; Lim et al. 2010). The flaxseed meal or oil can easily be incorporated into common food products such as breads, rolls, cereals, muffins, margarines, and salad dressings (Fitzpatrick, 2006). Flaxseed oil is a source of essential fatty acids, such as linoleic acid and linolenic acid, required in the diet for normal health (Lee and Lip 2003). Therefore, in the present investigation attempts were made to characterize the flaxseed oil and to formulate muffins with replacement of saturated fat with flaxseed oil.

Materials and methods

Flaxseed cultivar LC-2023 was procured from PAU, Ludhiana, Punjab. All chemicals and reagents used in the study were of analytical grade. Chemicals ethyl alcohol, hexane, phenolphthalein, potassium hydroxide, acetic acid, chloroform, potassium iodide, sodium thiosulphate, potassium dichromate, hydrochloric acid, and potassium iodide were used.

Extraction of flaxseed oil

The oil from flaxseed was extracted by using the method of Zhang et al. (2011). The ground flaxseeds (100 g) were mixed with 600 ml hexane in a flask. The mixture was agitated by a mechanical stirrer for 3 h at room temperature. The supernatant was then filtered through the filter paper under a vacuum. The extraction procedure was repeated three times. The solutions were then collected and concentrated with a rotary evaporator to acquire the flaxseed oil. After centrifugation, the flaxseed oil obtained was further dried in a vacuum drying oven to remove the residual hexane. Finally, the flaxseed oils were stored in a

freezer (-20°C) for subsequent physico-chemical analyses.

Quality analysis of flaxseed oil

Peroxide and acid value of flaxseed oil was measured by using the method of AOAC (1999). The results were expressed in mill equivalent/Kg and mg/gram. Free fatty acids and iodine value was determined according to AOCS (1998). The percentage of free fatty acids was expressed as oleic acid equivalents. Abbe refractometer and densimeter was used to determine refractive index and density.

Fatty acid composition of flaxseed oil

Gas chromatography–Mass spectrometry (GC–MS) was used to examine the fatty acids composition of flaxseed oil. To run the sample, fatty acid methyl esters were prepared by following the standard method of ISO (2000). Separation and purification was carried out on chromatograph which is equipped with a detector and capillary column. 1.0 μL sample and nitrogen as a carrier gas is used. The temperature of column was programmed from 100 to 180 $^{\circ}\text{C}$ at 20 $^{\circ}\text{C}/\text{min}$, and then to 230 $^{\circ}\text{C}$ at 10 $^{\circ}\text{C}/\text{min}$ with a holding time of 5 min at 230 $^{\circ}\text{C}$. Fatty acid methyl esters were quantified as % of the total peak areas.

Thermal properties

Thermal behaviour of the flaxseed oil was evaluated using a DSC. The flaxseed oil (5 ± 0.3 mg) was weighed in a pan and experiment was performed within the temperature range of -80 to 100°C at a heating rate of 5 $^{\circ}\text{C}/\text{min}$.

Rheological properties

Rheological behaviour of the flaxseed oil was measured using a rheometer (Anton Paar, Austria) according to the method reported by Sathivel et al. (2008a) with some modifications. A small amplitude oscillatory rheological measurement was made for different oils with a Modular Compact Rheometer (Anton Paar, Austria) equipped with parallel plate system (4 cm diameter). The gap size was set at 1000 μm . The strain and frequency were set at 0.5% and 5 Hz, respectively, for all determinations. Flaxseed oil's apparent viscosity was measured at 10, 15, 20, 25, and 35 $^{\circ}\text{C}$ at shear rates with values ranging from 1 to 800 s^{-1} . The power law (Eq. 1) model was fitted to analyze the flow behavior of oil.

$$\eta = K(T) \dot{\gamma}^{n-1} \quad (1)$$

where, σ , γ , K and n are the shear stress (Pa), shear rate (s^{-1}), consistency index ($Pa \cdot s^n$), and average value of flow behaviour index.

For frequency sweep measurement, the oil loaded on the rheometer ram. Frequency sweep test was performed at 25 °C and values of G' , G'' , and $\tan \delta$ were derived at 25 °C.

Muffin preparation

Muffins were prepared from full fat and substitution of fat by flaxseed oil at different levels (10, 20, 30 and 40%) by following the method of Nicol (1995). Wheat flour, fat, sugar, eggs, milk, baking powder, and oil ingredients were used. Sugar, eggs, fat and milk were grinded properly using a mixer. Wheat flour, salt and baking powder were then added and mixed thoroughly. The batter was filled into a muffin cup and baked at 200–220 °C for 25–30 min in an oven (pre-heated).

Textural properties of muffins

Muffins prepared with full fat and fat replaced with flaxseed oil were evaluated for their textural properties using TA/XT2 texture analyzer. Hardness, chewiness, springiness and cohesiveness of muffins were measured.

Sensory evaluation of muffins

For acceptability, muffins samples were examined on a nine-point hedonic scale for their colour, flavour, texture, aroma, and overall acceptability (ABNT 1993). The scale of values ranged from a 9 (high score), “like extremely”, to 1 (low score), “dislike extremely”. All muffins were analysed in the same session.

The intent of purchase was assessed using a five-point hedonic scale anchored from 5 = “certainly would buy” and 1 = “certainly wouldn’t buy”. The index of acceptability (IA) was estimated using the following equation

$$IA = \frac{\text{Score} * 100}{9}.$$

For sensorial evaluation of the muffins, most of the panellists were female between 25 and 35 years old who like muffins frequently and staff of the department of FST, CDLU, Sirsa, India.

Statistical analysis

The data reported in the tables were an average of triplicate observations and were subjected to one-way ANOVA

using Minitab Statistical Software version 15 (Minitab, USA).

Results and discussion

Quality analysis of flaxseed oil

Peroxide value (PV) of 0.4 meq/kg oil, acid value of 0.48 mg/g and free fatty acid of 0.14% in oleic acid was estimated for flaxseed oil. The lower peroxide values indicated superior quality and longer shelf life of flaxseed oil. The effect of temperature (30, 40, 50, 60, 70, 80 and 90 °C) upto 7 h. The stored oil at 30 °C for 6 h exhibited minimal peroxide value, whereas at 70–90 °C, higher PV were observed. So it may be suggested that, flaxseed oil should be stored at low temperature. As reported by Rudan-Tasic and Klofutar (1999), PV should be less than 5 for the acceptability of food product. Therefore, flaxseed oil was found satisfactory quality characteristics and may be used in the present study as fat replacer. Refractive index and density was 1.4873 and 0.9176 g/cm³.

Rheological properties

Steady shear

Figure 1a shows the apparent viscosity of oil as a function of shear rate ranging from about 1 to 800 s^{-1} . The influences of shear rate and temperature on the apparent viscosity may be combined into a single expression i.e. power law model.

$$\eta_{(app)} = K(T) \gamma^{n-1} \quad (2)$$

where γ is the shear rate (s^{-1}), and n is the average value of flow behaviour index and K is the consistency index ($Pa \cdot s^n$). The dependency of $K(T)$ on temperature was well explained through Arrhenius equation:

$$K(T) = A e^{(-E_a/RT)} \quad (3)$$

where, A , E_a , R and T are the frequency factor, activation energy (KJ/mol), absolute temperature (K) and gas constant (8.314 J/mol K) n and $K(T)$ were interpreted through intercept and slope of $\ln$ of apparent viscosity versus $\ln$ of shear rate plots at the temperature of 10, 15, 20, 25 and 30 °C. At different temperatures (10, 15, 20, 25 and 30 °C), the calculated value of n ranged between 0.8 to 0.9 for flaxseed oil (Table 1). This n value is near to unity indicating its almost newtonian behaviour. As shown in figure of natural logarithm of K against $1/T$ for flaxseed oil, showed a linear relationship ($R^2 = 0.99$) and suggested that

Fig. 1 **a** The apparent viscosities of the flaxseed oil at various temperatures (A-10 °C, B-15 °C, C-20 °C, D-25 °C, E-30 °C). **b** Arrhenius plots for flaxseed oil. **c** Angular frequency dependence of G' and G'' at 25 °C for flaxseed oil

Table 1 Flow behavior index, consistency index, apparent viscosity, and Arrhenius parameters of flaxseed oil

Temperature (°C)	n	K(Pa s) ⁿ	Apparent viscosity	R ²
10	0.8 ± 0.01 ^a	0.08 ± 0.002 ^c	0.071 ± 0.001 ^c	0.948
15	0.9 ± 0.01 ^a	0.063 ± 0.001 ^d	0.056 ± 0.002 ^d	0.968
20	0.9 ± 0.02 ^a	0.056 ± 0.001 ^c	0.043 ± 0.001 ^c	0.972
25	0.8 ± 0.01 ^a	0.045 ± 0.002 ^b	0.024 ± 0.002 ^b	0.969
30	0.9 ± 0.03 ^a	0.038 ± 0.001 ^a	0.020 ± 0.001 ^a	0.979
LSD (p < 0.05)	0.02	0.01	0.01	
E _a	27.8 kJ/mol			
A	2.3 × 10 ⁻⁵			

Values are an average of triplicate observations (Mean ± SD); Values followed by a similar superscript in a row do not differ significantly (P < 0.05). n = Flow behavior index, K = consistency index (Pa s)ⁿ, E_a = activation energy (KJ/mol), A = the frequency factor

dependency of K on temperature may be described well by Arrhenius expression (Fig. 1b). The values of E_a and A was 27.8 KJ mol⁻¹ and 2.3 × 10⁻⁵ was calculated through slope of Arrhenius plots for flaxseed oil. After putting the Eqs. (3) into Eq. (2), the apparent viscosity of oil may be predicted as a function of shear rate and temperature using the Eq. (4) with the calculated parameters.

$$\eta = K(T) = Ae^{(-E_a/RT)}\dot{\gamma}^{n-1} \quad (4)$$

In Fig. 1b, the solid line is representing apparent viscosity (predicted) for flaxseed oil. As seen from figure, Eq. (4) is appropriate for describing apparent viscosity as a function of temperature as well as shear rate.

Frequency sweep test

The changes in G' and G'' for flax seed oil is shown in Fig. 1c. During frequency sweep test it was observed that flaxseed oil was stable during the observed frequency range (0.1 to 100 rad/s). G' is a measure of the energy stored in the material and recovered from it per cycle while G'' is a measure of the energy dissipated or lost per cycle of sinusoidal deformation (Ferry 1980). G' , G'' and $\tan \delta$ value was found 3.54 Pa, 6.53 Pa and 1.84, respectively. It was observed that G'' value found higher than G' value, showed that oil is more viscous than elastic. No crossover was found between G' and G'' in the frequency range (0.1–100 rad/s), indicating stability of oil at this frequency range. G' and G'' value was slightly increase with increase in the frequency. For measuring the viscoelastic behaviour, $\tan \delta$ is evaluated. A $\tan \delta > 1$ and $\tan \delta < 1$ indicates viscous and elastic behaviour. Frequency sweeps have been used to provide further insight into the structure of biomaterials (Mendez-Montealvo et al. 2008). The frequency dependency of G' and G'' provide significantly valuable information about the flow behaviour of oil.

Fatty acid composition

Flaxseed oil is known as a rich source of essential fatty acids and composition of fatty acids are depicted in Table 2. The saturated and unsaturated fatty acid content for flaxseed was 17.38 and 80.18%, respectively. Epidemiological studies have reported that polyunsaturated fatty acids (PUFA), especially omega-3 in flaxseed oil is associated with many health benefits. As by several enzymes α -linolenic acid (ALA) metabolized to eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which are positively associated with treatment of many cancers, cardio vascular diseases, etc. As reported by

Bayrak et al. (2010), flaxseed contains 75–90% unsaturated and 9–11% saturated fatty acids. The fatty acid composition of flaxseed oil is dominated by linolenic acid (49.43), followed by linoleic acid (16.32), oleic acid (14.43), palmitic acid (9.95), stearic acid (7.43%), respectively. Simopoulos (2002) reported linolenic acid (53%), linoleic acid (17%), oleic acid (19%), palmitic acid (5%) and stearic acid (3%) in flaxseed oil. He reported that flaxseed oil provides an excellent n-3/n-6 ratio.

Thermal properties

Differential scanning calorimetry (DSC), a thermoanalytical technique is used to investigate the exothermic and endothermic changes with the increasing temperature. On account of its sensitivity and precision, DSC has been extensively used to study the transitions in phase (Manek et al. 2005). For edible oil, a particular DSC curve is observed, related to fatty acid composition and polar compounds of oils (Zhang et al. 2014). For flaxseed oil, DSC thermo-grams are shown in Fig. 2. Results showed that flaxseed possessed three endothermic and one shoulder peak. For first peak onset temperature is -74.56°C and melting peak temperature is -71.31°C . The first peak melts at low temperature which may be attributed to the presence of polyunsaturated fatty acids (Sathivel et al. 2008b). Oils with high degree of unsaturated fatty acids melt at low temperature whereas reverse is observed for saturated fatty acids. For second and the third peaks, the onset temperature of -42.93°C and -33.88°C and melting peak temperature of 38.48°C and -30.12°C was observed. These endothermic peak with maxima at -38 and -31°C , may be attributed to the melting of unstable crystals of unsaturated triacylglycerols and more stable crystals of unsaturated triacylglycerols, respectively

Table 2 Fatty acid composition of flaxseed oil

Fatty acids	Percentage
Linolenic acid	49.43 ± 0.11
Linoleic acid	16.32 ± 0.09
Oleic acid	14.43 ± 0.21
Palmitic acid	9.95 ± 0.15
Stearic acid	7.43 ± 0.19
Saturated fatty acids	17.38 ± 0.31
Unsaturated fatty acids	80.18 ± 0.12
Other fatty acids	2.44 ± 0.09
n-3/n-6 ratio	4.61 ± 0.13

Values are an average of triplicate observations (Mean $\pm$ SD)

Fig. 2 DSC thermogram of flaxseed oil

(Zhang et al. 2014). Enthalpy of 17.818 J/g, 3.1447 J/g and 32.804 J/g was observed for first, second and third peak. Thermogram of flaxseed showed a shoulder peak at around -5.5°C , which may be attributed to the conversion of the metastable phase to the more stable form (Sathivel 2005). Zhang et al. (2011) compared the thermal characteristics of flaxseed oil from two different varieties, namely fibre-flax seed and oil-flax seed and thermogravimetric curves showed that the oil-flax seed oil was more stable than the fibre-flax seed oil. Thermal profiles indicated that the fibre-flax seed oil had higher melting peak temperature and larger enthalpy.

Physical and textural parameters

The physical and textural characteristics of muffins prepared from full fat and fat replaced with flaxseed oil at different level are shown in Table 3. Porous structure, spongy texture and high volume are characteristics of muffins which is attributed by a stable batter is required (Martinez-Cervera et al. 2012). An enhancement in weight of muffins was observed as the fat replaced with flaxseed oil. The increase in weight of muffins when fat is replaced with flaxseed oil is due to the fact that hydrogenated fat does not support aeration due to formation of beta crystals (Knightly 1981). As reported by Baltsavias et al. (1997), the dough which is less aerated is denser in nature resulting in greater weight. As the flaxseed oil content increased, significant ($p < 0.05$) decrease in muffins height were observed. The reduction in the height of the muffins may be due to reduction in air cells and poor gas retention ability of the batter (Khalil 1998). The results reported that the full fat containing muffins possessed the highest volume and specific volume and with progressive increased addition of flaxseed oil at different levels, both the volume and specific volume were decreased. The textural

properties for muffins prepared from full fat and substitution of fat with flaxseed oil at different levels (10, 20, 30 and 40%) are shown in Table 4. The results demonstrated that flaxseed oil incorporation in muffin significantly ($P < 0.05$) affected the texture of crumb. The muffins prepared with full fat had the hardness of 47.9 N and with increasing concentration of flaxseed oil in muffins, the hardness increased from 49.3 to 69.4 N. Martinez-Cervera et al. (2013) reported that hardness of muffins is inversely associated with volume, smaller the volume harder will be the muffin. Tess et al. (2015) defined chewiness, the energy required to masticate the food which is easy to swallow and springiness is related to freshness in a bakery product and greater springiness values defines high quality of any product.

The muffin prepared from full fat was significantly ($P < 0.05$) more springier (1.36) and chewer (25.24) than flaxseed oil incorporated muffins. With increasing flaxseed oil level in muffins, the springiness and chewiness of the muffins significantly ($P < 0.05$) were decreased. Cohesiveness of 0.354 was observed for full fat muffin and it decreased significantly ($P < 0.05$) as the concentration of flaxseed oil was increased. Higher the cohesiveness, more will be the volume and gas retention ability (Tess et al. 2015).

Sensory evaluation

The descriptive sensorial score of muffins that were prepared with full fat and fat substitution by the flaxseed oil upto 40% are presented in Table 4. Pictorial representation of muffins with different levels (0, 10, 20, 30, 40%) of flaxseed oil as fat replacer. Miskelly and Moss (1985) concluded that sensory evaluation methods do not require trained panellist, require small size samples and less time. The sensory panellists rated full fat muffins with the

Table 3 Physical and textural properties of muffins prepared from full fat and flax seed oil at different levels (10, 20, 30, 40%)

	Weight (g)	Height (cm)	Volume (ml)	Specific volume (ml/g)	Hardness (N)	Chewiness (N)	Springiness	Cohesiveness
Full fat	46.99 $\pm$ 0.56 ^a	4.54 $\pm$ 0.06 ^c	148.7 $\pm$ 1.33 ^d	3.16 $\pm$ 0.14 ^c	47.9 $\pm$ 0.34 ^a	25.24 $\pm$ 0.01 ^d	1.36 $\pm$ 0.05 ^e	0.354 $\pm$ 0.003 ^e
FF-10%	47.55 $\pm$ 0.64 ^b	4.44 $\pm$ 0.05 ^d	144.2 $\pm$ 1.03 ^d	3.03 $\pm$ 0.18 ^d	49.3 $\pm$ 0.26 ^b	25.01 $\pm$ 0.03 ^d	1.25 $\pm$ 0.02 ^d	0.346 $\pm$ 0.003 ^d
FF-20%	48.32 $\pm$ 0.33 ^c	4.21 $\pm$ 0.05 ^c	135.7 $\pm$ 0.89 ^c	2.80 $\pm$ 0.11 ^c	56.6 $\pm$ 0.46 ^c	24.21 $\pm$ 0.02 ^c	1.22 $\pm$ 0.02 ^c	0.338 $\pm$ 0.005 ^c
FF-30%	49.78 $\pm$ 0.26 ^d	4.09 $\pm$ 0.05 ^b	128.6 $\pm$ 1.23 ^b	2.58 $\pm$ 0.21 ^b	61.7 $\pm$ 0.21 ^d	23.99 $\pm$ 0.03 ^b	1.18 $\pm$ 0.03 ^b	0.329 $\pm$ 0.002 ^b
FF-40%	50.56 $\pm$ 0.36 ^e	3.99 $\pm$ 0.04 ^a	121.9 $\pm$ 1.12 ^a	2.41 $\pm$ 0.13 ^a	69.4 $\pm$ 0.36 ^e	22.06 $\pm$ 0.02 ^a	1.13 $\pm$ 0.06 ^a	0.318 $\pm$ 0.002 ^a

Values followed by a similar superscript in a column do not differ significantly ($P < 0.05$)

Table 4 Sensory evaluation scores of muffins with different levels (0, 10, 20, 30, 40%) of flaxseed oil as fat replacer

Parameters	Full fat	FF-10%	FF-20%	FF-30%	FF-40%	LSD (p < 0.05)
Crust shape	9.3 ± 0.12 ^d	8.8 ± 0.11 ^c	8.1 ± 0.13 ^c	8.0 ± 0.09 ^b	7.3 ± 0.12 ^a	0.10
Crumb color	9.1 ± 0.16 ^b	9.0 ± 0.09 ^b	8.8 ± 0.08 ^{ab}	8.6 ± 0.19 ^a	8.5 ± 0.11 ^a	0.12
Crumb grain size	8.9 ± 0.17 ^c	8.1 ± 0.12 ^d	7.3 ± 0.12 ^c	6.5 ± 0.08 ^b	5.1 ± 0.23 ^a	0.14
Flavour	9.3 ± 0.09 ^c	9.0 ± 0.22 ^d	8.5 ± 0.16 ^c	7.7 ± 0.15 ^b	6.3 ± 0.12 ^a	0.16
Texture	8.2 ± 0.09 ^c	7.9 ± 0.08 ^d	7.5 ± 0.09 ^c	6.1 ± 0.07 ^b	4.7 ± 0.34 ^a	0.10
Aroma	8.9 ± 0.12 ^c	7.9 ± 0.09 ^d	7.1 ± 0.23 ^c	6.3 ± 0.09 ^b	4.3 ± 0.08 ^a	0.15
Overall acceptability (IA%)	93 ^e	88 ^d	81 ^c	71 ^b	51 ^a	
Certainly would buy (%)	–	79.2 ± 1.02 ^d	71.5 ± 1.23 ^c	67.4 ± 1.35 ^b	55.3 ± 0.99 ^a	1.03
Probably would buy (%)	–	35.5 ± 0.35 ^d	31.7 ± 0.46 ^c	30.8 ± 0.33 ^b	28.7 ± 0.28 ^a	0.33
Maybe buy/maybe wouldn't buy (%)	–	11.4 ± 0.09 ^a	12.3 ± 0.11 ^b	13.6 ± 0.13 ^c	18.3 ± 0.23 ^d	0.16
Probably wouldn't buy (%)	–	1.7 ± 0.02 ^a	2.5 ± 0.23 ^b	3.4 ± 0.07 ^c	7.3 ± 0.09 ^d	0.11

Values are an average of triplicate observations (Mean ± SD). Number of panellists = 20 (Mean ± SD). Values followed by a similar superscript in a row do not differ significantly (P < 0.05)

highest score. The muffins (full fat) had a desirable crumb colour, fine crumb grain size, a pleasant mouth feel and soft texture. Highest overall acceptability scores (81%) was observed till fat was replaced with 20% flaxseed oil and further substitution with oil, a decrease in acceptability scores was reported. Spehar and Santos (2002) reported that the index of acceptability greater than 81% confirms the acceptability of products by the panellists. Muffins prepared from FF-40% possessed the lowest scores in terms of overall acceptability because of densely packed crumb grain, hard texture and glossy mouth feel. Through evaluation it may be suggested that in all evaluated sensory parameters, no significant (p < 0.05) difference was found till 20% replacement of fat with flaxseed oil which showed that utilization of flaxseed oil as fat replacer did not affect sensory parameters. The result acquired for the purchase intent was found to be satisfactory, as 71.5% of response was found to be “would certainly buy” for muffins with fat replacement of 20%.

Principal component analysis

The sensory evaluation score of muffins were subjected to principal component analysis (PCA). The score plot muffins prepared from fat replaced flaxseed oil at 30 and 40% were located at the left of score plot while muffins from full fat and fat replaced at 10 and 20% were located at the right of the score plot with the positive score in first principal component. The muffins prepared from 10% substitution of fat with flaxseed oil were found to the closest to the full fat muffins in terms of sensorial score.

Conclusion

The present study provided the information regarding thermal characteristics and rheological behaviour of flaxseed oil which found to be useful for analysis of evaluation of quality and production cost. Low acid and peroxide values suggested that flaxseed oil may be suitable as edible/cooking oil. Keeping this view in mind, flaxseed oil was incorporated as fat replacer in formulating muffins. Up to 20% incorporation of flaxseed oil in muffins, possessed the better texture, colour, mouth feel and acceptability. Further, substitution of saturated fat with oil in muffins decreased the acceptance in terms of flavour, aroma, mouth feel, texture and overall acceptability.

References

- AOAC (1999) Official methods of analysis, 16th edn. Association of Official Analytical Chemists, Arlington, VA
- AOCS (1998) Official methods and recommended practices of the American Oil Chemist's Society, 4th edn. AOCS, Champaign
- Baltsavias A, Jurgens A, Van Vliet T (1997) Rheological properties of short doughs at small deformation. *J Cereal Sci* 26(3):289–300
- Bayrak A, Kiralan M, Ipek A, Arslan N, Cosge B, Khawar KM (2010) Fatty acid compositions of linseed (*Linum usitatissimum* L.) genotypes of different origin cultivated in Turkey. *Biotechnol Bioequip* 24(2):1836–1842
- Cunnane SC, Ganguli S, Menard C, Liede AC, Hamadeh MJ, Chen ZY, Jenkins DJ (1993) High α -linolenic acid flaxseed (*Linum usitatissimum*): some nutritional properties in humans. *Br J Nutr* 69(2):443–453
- de Moura CMA, Junior MSS, Fiorda FA, Caliar M, Vera R, Grossman MVE (2016) Cooking and texture properties of glutenfree fettuccine processed from defatted flaxseed flour and rice flour. *Int J Food Sci Technol* 51(6):1495–1501

- Dubois V, Breton S, Linder M, Fanni J, Parmentier M (2007) Fatty acid profiles of 80 vegetable oils with regard to their nutritional potential. *Eur J Lipid Sci Tech* 109(7):710–732
- FAO—Food and Agriculture Organization of the United Nations (2017) Available from FAOSTAT Statistics database-agriculture. Italy, Rome
- Ferry JD (1980) Viscoelastic properties of polymers, 3rd edn. Wiley, New York (**Chapter 11**)
- Fitzpatrick K (2006) Plant based omega-3: chemistry, applications and potential health benefits. In: Proceedings of the 97th AOCS Annual Meeting and Expo. April 30–May 3, 2006. St. Louis, MO
- Hall III C, Tulbek MC, Xu Y (2006) Flaxseed. In: Taylor S (ed), *Advances in Food and Nutrition Research*, 51, 1–97.
- ISO (2000) ISO Paper 5509: animal and vegetable fats and oils—preparation of methyl esters of fatty acids, 2nd edn. Geneva, ISO
- Kasote DM (2013) Flaxseed phenolics as natural antioxidants. *Int Food Res J* 20:27–34
- Khalil AH (1998) The influence of carbohydrate-based fat replacers with and without emulsifiers on the quality characteristics of low fat cake. *Plant Foods Hum Nutr* 52:299–313
- Knightly WH (1981) Shortening systems: fat, oils and surface-active agents—present and future. *Cereal Chem* 58:171–174
- Larsson SC, Kumlin M, Ingelman-Sundberg M, Wolk A (2004) Dietary long-chain n-3 fatty acids for the prevention of cancer: a review of potential mechanisms. *Am J Clin Nutr* 79:935–945
- Lim CW, Norziah MH, Lu HFS (2010) Effect of flaxseed oil towards physicochemical and sensory characteristic of reduced fat ice creams and its stability in ice creams upon storage. *Int Food Res J* 17:393–403
- Lee KW, Lip GYH (2003) The role of omega-3 fatty acids in the secondary prevention of cardiovascular disease. *Int Med Pub* 96:465–480
- Manek RV, Kunle OO, Emeje MO, Builders PF, Rama Roa GV, Lopez GP, Kolling WM (2005) Physical, thermal and sorption profile of starch obtained from *Tacca leontopetaloides*. *Starch/Starke* 57:1–7
- Martinez-Cervera S, Hera E, Sanz T, Gomez M, Salvador A (2013) Effect of nutriose on rheological, textural and characteristics of Spanish muffins. *Food Bioprocess Technol* 6:1990–1999
- Méndez-Montealvo G, García-Suárez FJ, LA Paredes-López O B-P (2008) Effect of nixtamalization on morphological and rheological characteristics of maize starch. *J Cereal Sci* 48(2):420–425
- Martínez-Cervera S, Sanz T, Salvador A, Fisman SM (2012) Rheological, textural and sensorial properties of low-sucrose muffins reformulated with sucralose/polydextrose. *LWT Food Sci Technol* 45:213–220
- Miskelly DM, Moss HJ (1985) Flour quality requirements for Chinese noodle manufacturer. *J Cereal Sci* 3(4):379–387
- Nicol A (1995) Breakfast muffins. In: McDowall A (ed) *In the bread cookbook*. Smithmark Publisher, New York, pp 94–95
- Oomah BD (2001) Flaxseed as a functional food source. *J Sci Food Agric* 81:889–894
- Punia S, Siroha AK, Sandhu KS, Kaur M (2019) Rheological and pasting behavior of OSA modified mungbean starches and its utilization in cake formulation as fat replacer. *Int J Biol Macromol* 128:230–236
- Rudan-Tasic D, Klofutar C (1999) Characteristics of vegetable oils of some Slovene manufacturers. *Acta Chim Slov* 46(4):511–521
- Rangrej V, Shah V, Patel J, Ganorkar PM (2015) Effect of shortening replacement with flaxseed oil on physical, sensory, fatty acid and storage characteristics of cookies. *J Food Sci Technol* 52(6):3694–3700
- Rodriguez-Sandoval E, Prasca-Sierra I, Hernandez V (2017) Effect of modified cassava starch as a fat replacer on the texture and quality characteristics of muffins. *J Food Meas Charact* 11(4):1630–1639
- Sathivel S (2005) Thermal and flow properties of oils from salmon heads. *J Am Oil Chem Soc* 82(2):147–152
- Sathivel S, Huang J, Prinyawiwatkul W (2008a) Thermal properties and applications of the Arrhenius equation for evaluating viscosity and oxidation rates of unrefined pollock oil. *J Food Eng* 84(2):187–193
- Sathivel S, Prinyawiwatkul W, Negulescu II, King JM (2008b) Determination of melting points, specific heat capacity and enthalpy of catfish oil during different purification steps. *J Am Oil Chem Soc* 85(3):291–296
- Simopoulos AP (2002) The importance of the ratio of omega-6/omega-3 essential fatty acids. *Biomed Pharmacother* 56(8):365–379
- Spehar CR, Santos RLB (2002) Quinoa BRS Piabiru: alternativa-paradiversificacrossistemas de produção de grãos. *Pesquisa Agropecuária Brasileira* 37(6):889–893
- Tess M, Bhaduri S, Ghatak R, Navder KP (2015) Physical, textural and sensory characteristics of gluten free muffins prepared with teff flour (*Eragrostis tef* (ZUCC)Trotter). *J Food Process Technol* 6(9):1–5
- Zhang ZS, Wang LJ, Li D, Li SJ, Özkan N (2011) Characteristics of flaxseed oil from two different flax plants. *Int J Food Prop* 14(6):1286–1296
- Zhang ZS, Li D, Zhang LX, Liu YL (2014) Heating effect on the DSC melting curve of flaxseed oil. *J Therm Anal Calorim* 115(3):2129–2135

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.