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Comparative assessment of algal oil with other vegetable oils for deep frying

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ABSTRACT

Algae is an emerging source of vegetable oil. In this study, a comparative assessment of algal oil for deep frying with sunflower and palm oil was performed. Potato sticks were fried for four consecutive days in each of the individual oils under study. These oils were analyzed for density, refractive index, viscosity, oil uptake, acid value, percentage free fatty acid, acidity, peroxide value, total polar compounds, color, radical scavenging activity and fatty acid profile. Fried potato sticks were evaluated for texture and sensorial properties, the latter was performed using a fuzzy logic method. Principle component analysis was done for a variety of physicochemical parameters. This study revealed that the algal oil had the highest physical and chemical stability during the frying process compared to sunflower and palm oils. Potato sticks fried in algal oil had a superior texture and improved sensorial properties. Based on these results it can be concluded that algal oil has a great potential to be used for deep frying foods.

1. Introduction

Over the last 25 years, the global vegetable oil production has been booming due to exponential population growth and depletion of fossil fuels [1]. Palm oil is a major contributor in vegetable oil; but, unfortunately, increased palm plantation has resulted in deforestation which is one of the main environmental issues linked to global warming [2]. Microalgae are reported to have seized the focus of research as a valuable biomass for food, feed and fuel in recent years [3]. Microalgae oil, which has similar chemical composition as vegetable oil with rich monounsaturated fatty acids content, could be a suitable alternative to palm oil. Many recent studies have revealed the health potentials associated with the monounsaturated fatty acids from microalgae [4]. In this regard, San Francisco-based TerraVia Holdings, Inc., US (Formally, Solazyme) is using heterotrophic microalgae fermentation for specially tailored oils containing 87% of monounsaturated fatty acids. These microalgae utilizes sugar and directly produce oil [5]. Vegetable oils are prone to undergo oxidation under various process conditions. To overcome this problem; many strategies have been put in place such as genetic modification of plants (83% oleic acid containing soybean seeds produced by DuPont Technology), chemical modification or use of various additives [6].

Deep frying, that involves immersing food in oil at high temperatures that range from 150 to 190 °C, is one of the most popular methods of cooking to achieve desirable product attributes [7,8]. During the frying process, oil undergoes a series of reactions which can produce toxic or carcinogenic compounds. Initially, due to primary oxidation free fatty acids, conjugated diene or conjugated triene and peroxides are produced. Afterwards alcohol, aldehydes, ketones and cyclic compounds are generated as secondary oxidation products [9]. These generated products can deteriorate the functional, sensory and nutritional quality of oils [10]. Amongst all frying oils, those with high oleic acid content such as sunflower and palm oils have better health profiles and stability [11].

In the global context, it is important to possess comparative data of the performance of a completely new source of deep frying oil with prevailing vegetable oils. Therefore, the present research was carried out for comparative assessment of algal oil with the most commonly used vegetable oils (from sunflower and palm) during deep-frying processes. Effect of deep-frying on the characteristics of algal, sunflower and palm oils such as density, refractive index, viscosity, oil uptake, acid value, percentage free fatty acid, acidity, peroxide value, total polar compounds, color, radical scavenging activity and fatty acid profile was assessed. Potato sticks were used as food matrix for the textural and sensorial evaluation of deep frying oil based on previous studies [8,12].

2. Material and methods

2.1. Material

Refined sunflower oil (Liberty oil mills limited, Thane, Maharashtra, India) and refined palm oil (Yog oil traders, Mumbai, India) were

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purchased from local market of Mumbai, India. Algal oil (AlgaWise™ High stability High oleic oil, RBD) was gifted by TerraVia Holdings, Inc., USA. McCain® potato sticks were purchased from D-mart® Mumbai, India. All chemical used were analytical grade and purchased from SD fine Ltd., Mumbai, India.

2.2. Experimental design and frying of potato sticks

The frying experiment was carried out in an electrically heated sand bath in which 3 frying baths were kept simultaneously. Each frying bath was filled with 800 ml of oils. Each day, the oil was heated at 160 ± 5 °C and allowed to equilibrate for 30 min. The time required for attaining 160 °C was approximately 60 min. Each batch of 40 g of potatoes were fried for 5 min, four times a day at an interval of 45 min. The frying process was repeated with each oil sample for four consecutive days. A total of 16 frying batches were processed and the alternative batches were used for sensorial and texture analysis. The frying baths were kept open during frying. The frying heater was turned off at the end of each day and oils were allowed to cool. After approximately 90 min, the oils were cooled to 60 °C and filtered to remove any debris using a stainless steel strainer. Each day 40 ml of each oil was withdrawn and stored at −20 °C until analyzed.

2.3. Physical properties

Various physical properties were studied to assess the influence of frying process on oil quality. The density of oil samples were measured using specific gravity bottles with 10 ml capacity [13]. Refractive index (RI) of oil samples were studied using Abbe refractometer (Guru Nanak Instruments, New Delhi) [14]. Measurement of viscosity was carried out with a Brookfield programmable rheometer (model DV-III, Brookfield Engineering Labs, USA) [15]. Oil absorption of fried samples were determined gravimetrically [16]. From the last batch of each frying day, oil was extracted from 1 g of fried potato sticks using petroleum ether (B. P. 60–80 °C) by the Soxhlet method (Instant Soxhlet apparatus-Socs plus, Pelican Equipment's, Chennai, India). Results were expressed as g of oil absorbed on g of fried potato sticks. All experiments were conducted in triplicate. Mean and standard deviations were reported.

2.4. Chemical properties

Acid value of oil samples were determined as described by Cho et al. and expressed as mg KOH/g of sample [17]. The percentage free fatty acid was calculated from the function below [18]: Percentage free fatty acid as oleic acid = 0.503 × acid value. Acidity of oil samples were analyzed as per the protocol of Chammem et al. [19]. Peroxide value (PV) was determined as described by Chammem et al., [19]. Total polar compounds (TPC) in oil samples were determined based on the methods of AOCS [20]. Weight of non-polar and polar fraction was recorded for each sample in duplicate. TPC was expressed as g of TPC per g of oil sample. For fatty acid profile of control and after frying processed oil samples were analyzed using gas chromatography equipped with flame ionization detector (GC-FID) (Agilent Technologies 7820A). Fatty acid methyl esters (FAME's) were prepared from oil using H_2SO_4 as described by Tarmizi et al. and Mishra et al. [21,22]. A DB-23 capillary column (30 m × 0.250 mm id., film thickness 0.25 μm was used. The oven temperature was held for 10 min at 100 °C and subsequently increased to 240 °C at 4 °C/min. Each FAME peak was identified and quantified by referring a 37 component FAME standard mix (Supelco®, Bellefonte, USA).

2.5. Color

The color of the oil samples were measured using μQuant Elisa plate reader (Biotek® Instrument Inc., Winooski). 200 μl of oil was placed in 96 well plates. The absorbance of oil samples were taken at 425 nm [23]. Three separate samples from collected oils were analyzed in triplicate.

2.6. Radical scavenging activity

Radical scavenging activity of oil was determined and compared to that of trolox, using DPPH radical scavenging methods. Ability to scavenge free radical of oil sample was tested based on the method of Sahreen et al. [24]. A standard curve was plotted using standard trolox (0–300 μM) and was linear within the given range. Radical scavenging activity was expressed as μM trolox equivalent per ml of oil.

2.7. Texture analysis

A texture analyzer (TA-XT2i, Stable Micro System Co. Ltd., Surrey, UK) was used to evaluate the texture of the fried potato sticks. An even number of batches of potato sticks fried in different oil were taken for texture analysis. The fried potato sticks were placed over the heavy duty platform and was compressed by a moving probe (P/2). Test conditions used were: pre-test speed- 10 mm/s, test-speed- 10 mm/s, and post-test speed- 10 mm/s. The deformation distance was maintained at 2 mm. The force used was 50 kg. The force-time curve was recorded, analyzed and was expressed in grams using software Texture expert exceed version 2.64 (Stable Micro Systems, Ltd). The parameters obtained were: hardness (g) and fracturability (mm). Three fried potato sticks were tested and values were reported as mean.

2.8. Sensory analysis

Sensory analysis was performed for potato sticks fried in sunflower, palm and algal oil. Odd number batches were taken for sensory analysis after they reached room temperature. Sensory analysis of fried potato sticks were performed by 10 trained panelists from Food Engineering and Technology Department, Institute of Chemical Technology, India. Panelists were educated by giving instructions about positive and negative control [25]. Sensory evaluation was conducted using fuzzy logic method as described by Sinija and Mishra [26].

2.9. Statistical analysis

All samples were analyzed in triplicate and expressed in the form of average. The significant differences between mean values were assessed by one-way analysis of variance (ANOVA). Tukey test was carried out using SPSS 16.0 software to determine whether there was any significant difference at the level of $p < 0.05$. Figures were plotted in OriginPro 9.1 software. All calculations were performed in Microsoft excel 2013. Principal component analysis (PCA) was performed using STATISTICA 7.0 software.

3. Result and discussion

3.1. Effect of deep frying on physical properties of oils

Density of oils can affect the frying of potato sticks as it is responsible for change in heat transfer and buoyant moment of gas bubbles in any oil during frying. Preferably, frying oil should not change its density even after several frying cycles [27]. Slight change in density was observed in the case of sunflower oil and palm oil; whereas algal oil density remained unchanged even after the fourth day of frying (Table 1).

RI, the physical method of characterization of materials including oils, is the ratio of speed of light in a vacuum to the speed of light through a given material. There is a relationship between fatty acid chemistry and RI of oils which includes chain length and degree of unsaturation. The RI of sunflower oil, as control, was 1.470. After frying

Table 1
Effect of frying cycle on physical properties, chemical properties and radical scavenging activity of deep frying oils.

	Physical properties			Chemical properties					RSA	Color
Oil and frying cycle	Density (g/ml)	Refractive index	Viscosity (mPas)	AV (mg KOH/g)	Acidity (%)	% FFA (g/g)	PV (meq/kg)	TPC (g/g)	DPPH (μM/ml)	OD at 425 nm
Control sunflower oil	0.912^{a}	1.470^{a}	29.00^{a}	0.17^{a}	0.75^{a}	0.08^{a}	1.47^{a}	8.30^{a}	198.57^{c}	0.105^{a}
Sunflower oil-1	0.912^{a}	1.471^{a}	35.67^{b}	0.32^{b}	0.95^{b}	0.16^{a}	2.73^{b}	10.35^{b}	179.29^{b}	0.173^{b}
Sunflower oil-2	0.913^{a}	1.471^{a}	44.00^{c}	0.52^{c}	1.00^{b}	0.26^{b}	3.80^{c}	14.99^{c}	168.28^{b}	0.185^{c}
Sunflower oil-3	0.914^{a}	1.472^{a}	63.67^{d}	0.65^{d}	1.12^{c}	0.33^{b}	4.80^{d}	22.30^{d}	152.62^{a}	0.204^{d}
Sunflower oil-4	0.915^{a}	1.473^{a}	83.33^{e}	0.67^{d}	1.19^{d}	0.34^{b}	6.53^{e}	29.99^{e}	147.41^{a}	0.214^{e}
Control palm oil	0.890^{a}	1.464^{a}	44.33^{a}	0.15^{a}	1.07^{a}	0.08^{a}	1.53^{a}	14.75^{a}	307.70^{d}	0.408^{a}
Palm oil-1	0.893^{a}	1.464^{a}	47.33^{a}	0.43^{b}	1.07^{a}	0.22^{b}	2.87^{b}	15.99^{b}	120.16^{c}	0.425^{b}
Palm oil-2	0.898^{a}	1.464^{a}	59.67^{b}	0.58^{c}	1.19^{b}	0.29^{c}	3.93^{c}	18.37^{c}	78.13^{b}	0.437^{c}
Palm oil-3	0.905^{a}	1.465^{a}	75.67^{c}	0.71^{d}	1.53^{c}	0.36^{d}	5.13^{d}	20.46^{d}	47.99^{a}	0.460^{d}
Palm oil-4	0.914^{a}	1.465^{a}	89.00^{d}	0.88^{e}	1.91^{d}	0.44^{e}	5.93^{e}	26.75^{e}	43.64^{a}	0.468^{e}
Control algal oil	0.915^{a}	1.467^{a}	40.67^{a}	0.06^{a}	0.65^{a}	0.03^{a}	0.73^{a}	5.92^{a}	127.41^{d}	0.165^{a}
Algal oil-1	0.915^{a}	1.467^{a}	41.00^{a}	0.19^{b}	0.66^{a}	0.09^{b}	1.40^{b}	7.10^{b}	106.25^{c}	0.216^{b}
Algal oil-2	0.915^{a}	1.467^{a}	40.67^{a}	0.30^{c}	0.70^{b}	0.15^{c}	2.47^{c}	8.84^{c}	83.49^{b}	0.223^{c}
Algal oil-3	0.915^{a}	1.467^{a}	41.00^{a}	0.39^{d}	0.74^{c}	0.19^{d}	3.07$_{d}$	12.75^{d}	63.49^{a}	0.232^{d}
Algal oil-4	0.915^{a}	1.467^{a}	42.00^{a}	0.47^{e}	0.79^{d}	0.23^{e}	3.53^{e}	18.04^{e}	59.87^{a}	0.243^{c}

Note: AV-Acid value, FFA- Free fatty acids, PV- Peroxide value, TPC- Total polar compounds, DPPH- 1,1-Diphenyl-2-picrylhydrazyl, RSA- Radical scavenging activity. All values are averages of three determinations.
Means within a column for each type of oil marked with the different letters differ significantly at $P < 0.05$.

on fourth day; slight increase in the RI value was observed (1.473), however, it was statistically insignificant (Table 1). These findings are in accordance with Manral et al., who observed no significant change in RI of sunflower oil even after frying for 14 h [28]. Similarly, non-significant changes were observed in the case of palm oil. Moreover, algal oil refractive index (1.467) remained unchanged during and after frying process (Table 1).

Palm oil had higher initial viscosity values compared to sunflower and algal oil (Table 1). The viscosity of sunflower and palm oils were affected during the frying process; however, no change in algal oil viscosity was noted even after repetitive frying. Oleic acid was the main fatty acid present in algal oil which was more resistant to oxidative modification (Table 2) [29]. Similar findings for palm oil were reported by Kalogianni et al. [15]. Change in viscosity due to a generation of polymeric compounds has been reported by many authors [29]. Viscosity of natural oil depends on the degree of saturation. Frying process is very well known for increasing the oil saturation. Saturation reaction due to frying can also change the viscosity of oils. However, polymerization reaction is mainly responsible for changes in viscosity compared to that of saturation induced reactions [29].

Oil uptake is an important parameter for the consumer as well as processing industries point of views [30] where both prefer food products with low oil uptake. In the case of processing industry, lower the oil uptakes mean lower production costs [15]. From Fig. 1, it can be seen that with an increase in frying time an increased oil uptake was observed for all type of oil samples under study. Highest oil uptake was recorded for potato sticks fried in sunflower oil at fourth day of frying cycle. Oil uptake for potato sticks fried in algal oil was lower compared to that of sunflower and palm oil. Thus, it can be concluded that algal oil could be the healthier choice of oil for consumers and an economic alternative for food industries.

Table 2
Fatty acids composition of oil before and after frying process.

Fatty acids	Frying cycle (days)	Sunflower oil (%)	Palm oil (%)	Algal oil (%)
Palmitic acid (C16:0)	0	10.13 ± 0.01	41.28 ± 0.55	6.03 ± 0.01
	4	12.27 ± 0.06	45.03 ± 0.34	7.60 ± 0.54
Stearic acid (C18:0)	0	4.84 ± 0.21	5.58 ± 0.27	4.97 ± 0.14
	4	5.18 ± 0.11	5.09 ± 0.09	3.82 ± 0.30
Oleic acid (C18:1)	0	26.35 ± 0.04	38.51 ± 0.12	86.60 ± 0.42
	4	28.78 ± 0.13	40.08 ± 0.35	85.84 ± 1.17
Linoleic acid (C18:2)	0	58.67 ± 0.25	14.64 ± 0.15	2.40 ± 0.26
	4	53.77 ± 0.04	9.81 ± 0.10	3.10 ± 0.34

All values are averages of two determinations with ± standard deviation.

3.2. Effect of deep frying process on chemical properties of oils

During the frying process, various chemical reactions takes place which includes oxidation, hydrolysis, polymerization and fission. Free radicals initiate oxidation during frying process. The main factors that influence oxidation are: frying temperature, type of food material, moisture content, enzymatic reaction, and exposure to light and the presence of catalyst. Triglycerides undergo oxidation in one of its unsaturated fatty acyl groups. Increase in the concentration of alkyl radical is observed with respect to alkyl peroxyl radical at the frying temperature. As a result; polymeric compounds are predominantly formed through reaction mainly involving alkyl and alkoxyl radicals [31]. The acid value is an important parameter to evaluate the quality of oil which is an indicator of free fatty acid content in oil. Ideally, cooking oil should have an acid value in the range of 0.00–3.00 mg KOH/g of oil. Lower acid value is credential of good quality oil. Generally, for any edible oil an acid value above 3.00 mg KOH/g may lead to human gastrointestinal discomfort, diarrhea and liver damage [32]. All oil used in the present study were refined and showed an acid value < 3.0 mg KOH/g for all the samples under study (Table 1). Effect of the deep frying process was observed in the case of all oils with respect to frying time. In case of sunflower oil control sample acid value was 0.17 mg KOH/g of oil and after the fourth day of frying process, it was noted as 0.67 mg KOH/g of oil. Palm oil showed the highest increase in acid value as compared to other oils. The acid value of control palm oil was 0.15 mg KOH/g; however, it was increased to 0.88 mg KOH/g after the fourth day of frying. A comparatively minor increase in acid value of algal oil was observed from 0.06 mg KOH/g to 0.47 mg KOH/g after the fourth days of frying. Generation of free fatty acids (FFA) was observed in the case of all oil samples under study. The highest percentage of FFA was generated in case of palm oil (0.44%) and lowest were observed in algal oil (0.23%) after the fourth day of the frying process. The constant increase in the formation of FFA can be attributed partly due to the hydrolysis and partly due to the carboxylic groups, which then accelerate the decomposition of hydroperoxides during frying [33].

The acidity of oil is defined as the amount of fatty acids no longer

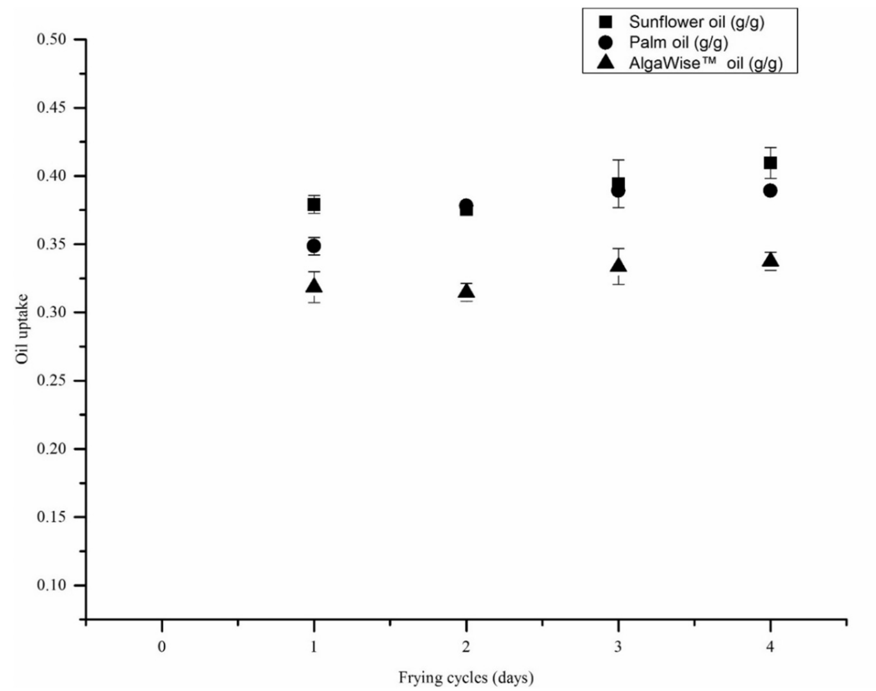

Fig. 1. Effect of frying cycle on oil uptake of oils. (All values are averages of three determination with ± standard deviation).

linked to their parent triglyceride molecules. It is measured as a percentage of oleic acid in 100 g of oil [34]. Acidity of oil samples was increased with increased frying time (Table 1). The acidity values for control samples of sunflower, palm, and algal oil were 0.75, 1.07 and 0.65% respectively. After the fourth day of frying; acidity of oil samples were increased to 1.19, 1.91 and 0.79% for sunflower oil, palm oil, and algal oil respectively. Lesser change in acidity was observed in the case of algal oil compared to that of all other oils under study.

Peroxide value is the most regularly used method for evaluating primary oxidation of oils. Hydroperoxides are primary products of lipid oxidation which are generally referred to as peroxides. Peroxides are organic compounds formed from triglycerides. Hydroperoxides react with iodide ions to form iodine which in turn is measured by titration with thiosulphate. Peroxide value of over 10 meq/kg, is considered to be rancid and the oil bearing such value should not be used for food purpose. Peroxide value of fresh oils below 2 meq/kg, is considered to be good [35]. Peroxide value of control oil samples were < 2 meq/kg (Table 1). A comparison of data showed that peroxide value of algal oil (control) was lower than other oils under study. It was also found that peroxide value increased with respect to the frying cycle of oils. Highest change in peroxide value was observed for sunflower oil which was 6.5 meq/kg of oil.

TPC quantification is a method of choice for evaluation of oil quality because most of the decomposition products (e.g. free fatty acids, polymer components, aldehydes, and ketones) generated during the process of deep frying are polar in nature. Therefore measurement of TPC is an important parameter for evaluation of the quality of deep frying oils. Many European countries such as Spain, Portugal, France, Germany, Belgium, Switzerland, Italy and the Netherlands have established a regulatory limit of 25% TPC in frying oils [36]. Out of the three oils, the highest TPC (14.74%) was observed for control palm oil, followed by control sunflower oil (8.29%) and algal oil. The TPC value of control algal oil was observed as 5.92% (Table 1). During frying process, TPC of all oil samples were increased with frying time. Sunflower oil showed a highest change in TPC from 8.29 to 29.98% after the fourth day of frying. Whereas lowest change in TPC was observed in case of algal oil from initial 5.92 to 18.04% TPC after fourth day of frying.

The fatty acid composition was determined by GC-FID of the methyl esters of fatty acids. Calculations were done by the integrator of the gas chromatograph on the basis of the fractional peak areas. There was an apparent increase in saturated fatty acid content and a decrease in unsaturated fatty acid content was observed (Table 2). Palmitic acid (C16:0) concentration was found to be increased after frying processes in all oil samples. The highest percentage of palmitic acid was present in palm oil i.e. 41.28% which was increased to 45.03% after fourth day of frying. The stearic acid content was decreased after frying process in all oil samples under study. It was found that algal oil contained highest oleic acid content (86.60%), a monounsaturated fatty acid (MUFA). The presence of high oleic acid content is a significant parameter for having highest stability as well as health benefits. Previous reports state the adverse effect associated with consumption of saturated oil compared to monounsaturated or polyunsaturated oils especially for cardiovascular disease [37]. Looking at the fatty acid profile of sunflower oil, it can be seen that the principal fatty acid present was linoleic acid (C18:2), one of the healthiest FA but is more prone to deterioration during deep frying conditions. In the case of palm oil, the principal fatty acid was palmitic acid (C16:0) which is known for an increase in low-density lipoprotein-cholesterol [23]. Hence, the most favorable lipid profile observed for frying oil was observed for algal oil which contained less saturated fatty acids and more monounsaturated fatty acids.

3.3. Effect of deep frying on color of oils

From absorbance reading it can be seen that control sunflower oil showed lighter color (0.105) as compared to palm (0.408) and algal oil (0.165). This might be due to the lower carotenoid pigment content [35]. Significant changes in absorbance at 425 nm were recorded in all oil samples (Table 1). This is due to the brown pigments from potato sticks dissolved in oil and also due to degrading effect of frying process on oils. Brown pigments might have generated from potato sticks due to Mallard's reaction which is most favorable at higher frying temperature [23]. Color readings were in agreement with Sebastian et al. and Li et al., who observed an increased absorbance readings with increased frying time. The reason for this increase was due to the accumulation of highly conjugated oxidation products [23,38].

3.4. Effect of deep frying on radical scavenging activity of oils

Free radicals generated during frying process leads to free radical chain reaction of oil degradation. This free radical chain reaction is a widely accepted mechanism of lipid peroxidation. Radical scavenging activity of oils may directly react with and quench peroxide radicals to terminate the peroxidation chain reaction and improve the quality and stability of oils during frying. The most common used assay for determination of radical scavenging activity is DPPH radical assay. In this method, DPPH is scavenged by oil through the donation of hydrogen that stabilizes the DPPH molecule. The DPPH radical molecule has an absorbance at 517 nm which disappears after acceptance of hydrogen radical from oil. The radical scavenging activity of all oil samples were decreased as frying process progressed (Table 1). A similar trend of decrease in radical scavenging activity due to the frying process was reported by Chammem et al. [19]. Significant change in radical scavenging activity of oils were observed in all oils under study. Drastic change in radical scavenging activity of palm oil was observed from 307.70 to 43.64 μM/ml after the fourth day of frying.

3.5. Effect of deep frying on textural quality of fried potato sticks

Texture, in terms of hardness and fracturability/crispness, is a crucial factor while considering the characteristics of the fries. Sample hardness was determined using a probe and applying force on the surface of the sample. As the sample shattered and moved away from its path; hardness was recorded as the maximum peak force. The distance at which this peak force occurred; was recorded as fracturability i.e. the shorter the distance at the peak the greater was the fracturability characteristic recorded [39]. Table 3 depicts the textural quality of fried potato sticks in terms of hardness and fracturability. The textural quality of potato sticks deteriorated as the frying process progressed. Amongst all the potato sticks fried in three oil samples; potato sticks fried in algal oil retained the maximum hardness during all the frying cycles (represented by the lower rate of decrease of hardness values than that observed in the other oils). This may be attributed due to the lower degradation of fatty acid during algal oil frying process as compared to that of sunflower and palm oil. The fried potato sticks in algal oil also retained the best texture (least reduction in crispness/fracturability). This indicated that the frying oil had significant impact on maintaining the chemical structure and property of food material fried which ultimately helped in retaining final fried product texture and quality.

3.6. Effect of deep frying on sensory properties of fried potato sticks

Evaluation of sensory attribute of the fried potato sticks were carried out for color, aroma, crispness, taste, oiliness and aftertaste. Color attribute score was decreased in sunflower oil with frying batches whereas palm and algal oil color attribute scores were found to increase as supported by their rankings (See supplementary file Table 1). Yellow color of potato sticks was most preferred therefore received the highest score; whereas brown color was least preferred therefore received low scores. The decrease in color scores was found to be closely related to the darkening of fried oil caused by the deterioration of the oil quality during the frying. Aroma of fried potato sticks was not significantly affected by algal oil whereas significant changes were observed in the sticks fried in sunflower and palm oil (see supplementary file Table 1). Crispiness is an important attribute in case of potato sticks. A sensory score of crispiness was highest in fresh algal oil followed by sunflower and palm oil. Crispiness of potato sticks deep-fried in sunflower oil decreased with frying. The most preferred fries were samples fried in algal oil since the potato sticks fried in this oil received the highest taste scores by the trained panelist. This might be due to the neutral flavor of the oil that does not mask the natural flavor of fried potato sticks. The oiliness of product depends on the ability of oil uptake. Here, high scoring was received for deep-fried potato sticks with less oil uptake. The panelist had given consistent preference to algal oil fried potatoes (see supplementary file Table 1), whereas decrease in score value was observed in the case of fried potato sticks fried in sunflower and palm oil as frying time progressed. Fried potato sticks having aftertaste was considered as a negative control and no aftertaste was a positive control. Aftertaste was a non-desirable attribute of this product. From control oil samples, highest aftertaste score values were obtained for algal oil fries followed by sunflower and palm oil. The result suggested algal oil retained most of its sensory attributes even after the fourth day of frying compared to other oils.

Table 4 shows the similarity values of overall ranking of fried potato samples on the fuzzy logic scale. For Sample SO1, similarity values under "Not satisfactory," "Fair," "Medium," "Good" and "Excellent" were 0.00, 0.12, 0.54, 0.96, 0.68 and 0.13 respectively. The highest similarity value, 0.96 was under the 'Good' category; this implied that the overall quality of Sample SO1 was 'Good'. In similar fashion, the overall quality of sample SO3, SO5, SO7, and SO9 was 'Good', whereas the overall quality of sample SO11 and SO13 was "Satisfactory". Sample SO15 showed overall quality to be "Fair". From this similarity values of potato sticks fried in sunflower oil, it is shown that with an increase in frying time, the quality of deep fried potato sticks was degraded. Potato sticks fried in palm oil at first frying batch (sample PO1) showed highest similarity value at scale factor 'Good'. In the case of palm oil highest similarity value of all frying batch samples was following at scale factor of 'Good'. This indicated that the overall sensory value of fried potato sticks did not decrease with frying cycles. When fried in algal oil, the first batch of frying (Sample AO1) showed an overall quality of "Very good". With further proceeding with frying batches, the overall quality of fries remained consistent with the scale factor 'Very good'. Comparing similarity values, potato sticks fried in three different oils at the fifteenth frying cycle, the overall ranking of those samples was:

Sample AO15 (Very good) > Sample PO15 (Good) > Sample SO15 (Fair).

Ranking of quality attributes of fried potato sticks, in general, is shown in supplementary file Table 2. The order of the quality attributes observed was:

Mouthfeel (Highly important) > Color (Highly important) > Taste (Highly important) > Crispiness (Highly important) > Aftertaste (Important) > Aroma (Necessary).

Table 3
Textural quality of fried potato sticks in terms of hardness and fracturability with frying batches.

Attribute	Type of oil	Batch 2	Batch 4	Batch 6	Batch 8	Batch 10	Batch 12	Batch 14	Batch 16
Hardness (g)	Sunflower oil	320.03[c]	292.00[c]	251.93[b]	238.97[b]	144.10[a]	143.16[a]	133.60[a]	113.12[a]
	Palm oil	259.00[a]	235.67[a]	225.93[a]	211.45[bc]	171.56[a]	161.53[a]	150.20[ab]	140.10[a]
	Algal oil	222.21[e]	213.87[de]	204.56[cd]	193.87[bcd]	180.46[a]	161.50[abc]	150.60[ab]	139.00[a]
Fracturability (mm)	Sunflower oil	4.53[f]	4.42[e]	4.39e	4.21[de]	4.06[d]	3.71[c]	2.81[b]	2.54[a]
	Palm oil	5.56[f]	5.44[e]	4.81[d]	4.28[c]	3.69[b]	3.58[b]	2.81[a]	2.71[a]
	Algal oil	4.72[h]	4.40[g]	4.27[f]	4.09[e]	3.76[d]	3.29[c]	2.84[b]	2.16[a]

All values are averages of three determinations.
Means within a row for each type of oil marked with the different letters differ significantly at $P < 0.05$.

Table 4
Similarity values of samples for the overall ranking.

	Samples (fried in sunflower oil with batch number)							
Scale factor	SO1	SO3	SO5	SO7	SO9	SO11	SO13	SO15
Not satisfactory, F1	0.00	0.00	0.00	0.02	0.01	0.03	0.14	0.22
Fair, F2	0.12	0.16	0.18	0.27	0.25	0.34	0.66	**0.81**
Satisfactory, F3	0.54	0.62	0.66	0.78	0.76	**0.85**	**0.90**	0.68
Good, F4	**0.96**	**0.96**	**0.95**	**0.92**	**0.94**	0.81	0.37	0.13
Very good, F5	0.68	0.57	0.53	0.37	0.42	0.23	0.02	0.00
Excellent, F6	0.13	0.08	0.06	0.03	0.04	0.00	0.00	0.00
	Samples (fried in palm oil with batch number)							
Scale factor	PO1	PO3	PO5	PO7	PO9	PO11	PO13	PO15
Not satisfactory, F1	0.00	0.01	0.02	0.01	0.01	0.02	0.01	0.01
Fair, F2	0.16	0.18	0.26	0.25	0.25	0.26	0.20	0.23
Satisfactory, F3	0.62	0.66	0.79	0.77	0.77	0.77	0.70	0.73
Good, F4	**0.95**	**0.94**	**0.91**	**0.92**	**0.93**	**0.94**	**0.93**	**0.92**
Very good, F5	0.54	0.50	0.35	0.39	0.38	0.41	0.44	0.39
Excellent, F6	0.06	0.05	0.02	0.03	0.03	0.04	0.04	0.03
	Samples (fried in algal oil with batch number)							
Scale factor	AO1	AO2	AO5	AO7	AO9	AO11	A13	A15
Not satisfactory, F1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fair, F2	0.05	0.04	0.07	0.05	0.08	0.07	0.06	0.05
Satisfactory, F3	0.37	0.36	0.43	0.37	0.44	0.42	0.41	0.37
Good, F4	0.84	0.83	0.85	0.84	0.80	0.85	0.86	0.85
Very good, F5	**0.92**	**0.92**	**0.88**	**1.09**	**0.89**	**0.88**	**0.87**	**0.87**
Excellent, F6	0.31	0.30	0.25	0.47	0.20	0.26	0.26	0.25

Bold-faced texts highlight highest similarity values.
Note: SO-Sunflower oil, PO-Palm oil, AO-Algal oil.

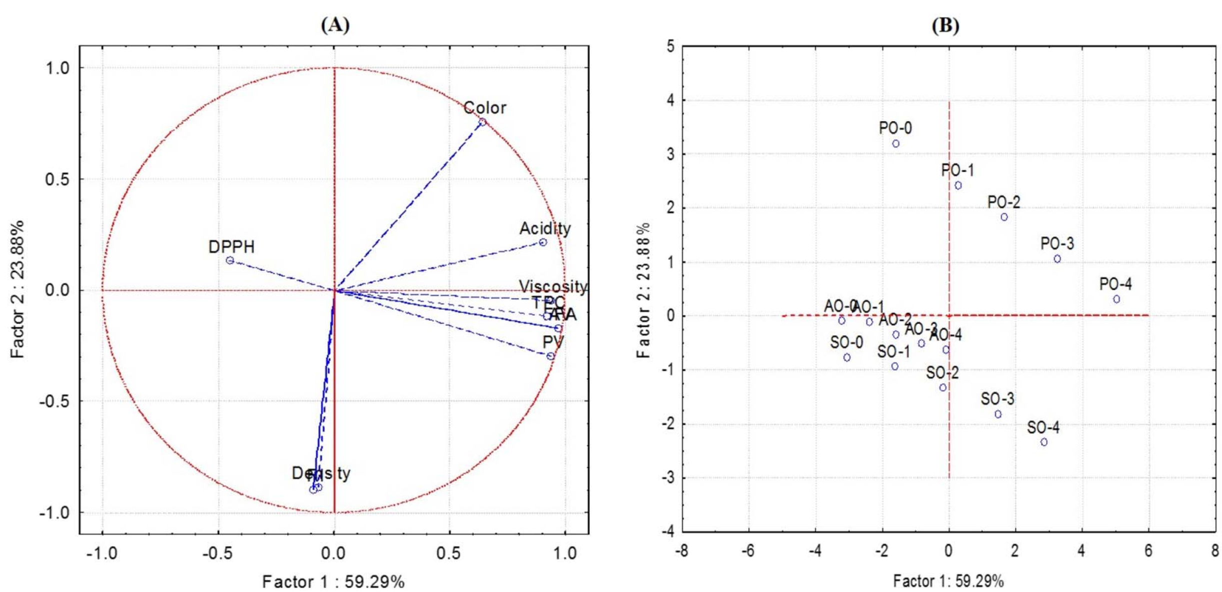

Fig. 2. Principal component analysis was used to study the variation amongst the oil samples and their characteristics for the first two factors: (A) Loading plot (B) Score plot

3.7. Principal component analysis (PCA)

Principle component analysis (PCA), a statistical method was used for analyzing data to understand the similarities and differences between the behavior of oil samples at various frying cycles and of the interrelationships between the measured properties. The first and the second principle components (PCs) described 59.29 and 23.88% of the variance, respectively. Together, the first two PCs represented (83.17%) of the total variability. The loading plot (Fig. 2A) of the two PCs provided the information about correlations between the measured properties. The properties whose curves lie close to each other on the plot were positively correlated while those whose curves run in opposite directions were negatively correlated. PC1 was well characterized by acidity, viscosity, TPC, FFA, PV, AV in the positive quadrant and radical scavenging activity (DPPH) in the negative quadrant. This negative correlation of antioxidant activities from the others on the PCA plot was supported by negative values of correlation coefficient as shown in supplementary file, Table 3. PC2 was influenced by a color value and was correlated negatively with RI and density. RI and density being the closer loadings on the PCA plot exhibited higher values of correlation coefficient (0.61) value. Looking at the Fig. 2A, a visible cluster was observed consisting of viscosity, TPC, FFA, PV, and AV. Their maximum correlation was assured by higher values of correlation coefficient as shown in supplementary file, Table 3. As shown in Fig. 2B, Algal oil samples at all the frying cycles were much similar to the control sunflower oil. The distance between the locations of any two oil samples on the score plot was directly proportional to the degree of differences or similarity between them. The second PC clearly distinguished palm oil from other two oils and confirmed the higher probability of similarities between algal oil with control sunflower oil.

4. Conclusions

The purpose of the present work was to have a realistic portrait of the completely new source (algae) of frying oil to that of existing oils. Physical and chemical characteristics were studied to determine the effect of the frying process on oil properties. Algal oil used in present study is recommended over palm and sunflower oil on the basis of performance as deep frying oil in these studies. It can be concluded that algae oil can be a good alternative source of deep frying oil. Algal oil tested in this study could also be considered a healthier alternative over conventional vegetable oils since it mainly contains monounsaturated fatty acids (MUFAs).

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Authors' contributions to manuscript

AGW and SSA have designed the experiment protocol. AGW and SPP conducted experiments, analyzed results and prepared the manuscript. SKS conducted the radical scavenging activity assay. JGL aided in the analysis and interpretation of data, revised the article critically for important intellectual content. SSA supervised and guided the experimental work as well as assisted in drafting and writing of manuscript. All authors approved the submitted manuscript.

Conflicts of interest

No conflicts, informed consent, human or animal rights applicable.

All guidelines followed in the preparation of food for testing and the use of human subjects were accordance with American Society for Testing and Materials (ASTM) standard guide for sensory evaluation of foods and beverages.

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