



The effect of fatty acid composition on the oil absorption behavior and surface morphology of fried potato sticks via LF-NMR, MRI, and SEM

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ABSTRACT

The oil absorption behavior of food during deep-frying greatly affects the quality of the final fried food. However, the research on oil absorption lacks comprehensive analysis and understanding. In this paper, the oil content, moisture content, oil distribution, and microstructure changes of fried potato sticks were explored via traditional method as well as advanced instruments, including low field nuclear magnetic resonance, magnetic resonance imaging, and scanning electron microscopy, and the differences and their corresponding relevance were analyzed and discussed. Results showed that the fatty acid composition of oils is highly related to their viscosity and surface tension, influencing the oil uptake of final products. Oil content was positively correlated with the peak height in the range of 20 ms–1000 ms ($r^2 = 0.99348$ at 140 °C, $r^2 = 0.99060$ at 180 °C). Oil distribution and microscopic morphology of the fried strips were affected by oil type and temperature.

1. Introduction

Fried products, such as French fries and fried chicken, are popular especially among young people. They are easy to prepare and bring a unique flavor to a huge and continuously growing market (Honerlaw et al., 2019). However, fried food usually has very high oil content, with some even exceeding the 50% dry basis. A high oil content corresponds to a high amount of energy and calories. An increasing number of studies have shown that the frequency of some diseases associated with high-fat diets, including obesity and diabetes, has been increasing every year (Honerlaw et al., 2019). With the continuous development of societies, people develop a stronger health awareness, and the importance of low-fat and low-calorie diets has grown. Meanwhile, from the perspective of food processing industries, a lower oil content corresponds to a lower production cost (Kalogianni, Karapantsios, & Miller, 2011). Therefore, the mechanism of oil uptake in fried food needs to be explored further with the final goal of reducing their oil content. Recent studies have increasingly focused on the oil absorption behavior of fried food and have classified their oil uptake behavior. These categories include replacement of water (Costa & Oliveira, 1999; Rice & Gamble, 1989), surface-active agents (Blumenthal, 1991), and condensation effect (Gamble & Rice, 1987).

Many studies have also explored measures for reducing the oil content of fried food (Dueik & Bouchon, 2011).

The same food is fried with different frying oils, resulting in different flavors, textures and oil content. While most of the existing literatures have focused on the changes in the physical and chemical properties of oils after prolonged use, only few have examined how the differences among various types of oils affect the oil absorption behavior of food. In addition, few studies have exhaustively explained the development of oil content, oil distribution, and microstructural changes of fried food during deep-fat frying and cooling and the mechanisms behind the impregnation of oil into fried food products. Although a certain amount of studies have been published over the past decade, they are mostly limited to specific types of frying oils or food ingredients (Chen et al., 2019; Kim, Kim, Lee, Yoo, & Lee, 2010).

Naghshineh, Ariffin, Ghazali, Mirhosseini, and Mohammad (2010) examined the effect of fatty acid composition on the physicochemical properties of blending oil. Kalogianni et al. (2011), Li, Wu, Liu, Jin, and Wang (2015), and Sahasrabudhe, Staton, and Farkas (2019) explored the effect of deep-fat frying on oil viscosity, surface tension, and other physical characteristics. However, most studies have only focused on either one or two types of frying oils in exploring the oil absorption mechanism of fried food (Dana & Saguy, 2006; Su, Zhang, Fang, &

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Zhang, 2017), and very few have examined the effects of the physical and chemical properties of different frying oils on the oil absorption behavior of these food. Meanwhile, none of the above studies have thoroughly examined the links between the characteristics of different types of oils and the oil absorption behavior of fried food.

Meanwhile, those factors that influence the oil uptake behavior of food during deep-fat frying and cooling are complex, and the conventional instrumental analytical methods of property evaluation may be insufficient in explaining these factors. One traditional method for determining the oil content of fried food is Soxhlet extraction, which has a simple operation and low cost (Chen et al., 2017). However, this method consumes a large amount of organic reagents, pollutes the environment, dissolves fat-soluble components in food and subsequently leads to test deviations, can only determine the total oil content in the sample, and unable to provide any information about the spatial distribution of oils. Therefore, the use of modern analysis techniques, including imaging and advanced microscopy, to understand the changes in food products at the microscopic level during frying is imperative in exploring their oil absorption mechanism.

In recent years, some non-destructive testing techniques have been developed for the detection of oil content, such as differential scanning calorimetry (Aguilera & Gloria, 1997), near-infrared spectroscopy (Kim, Park, & Choung, 2007), and nuclear magnetic resonance (NMR) (Chen et al., 2017). NMR technology has begun to emerge in the detection of grease quality because of its simple and fast operation, accurate measurement, high repeatability and low sensitivity to the operator's technology and judgment. Zhang, Saleh, and Shen (2013) used low field nuclear magnetic resonance (LF-NMR) to discriminate the adulteration of fresh vegetable oils with used frying oils. Shi et al. (2018, 2019) achieved rapid determination of squalene and sterol in vegetable oils using NMR combined with partial least squares, and achieved rapid detection of adulteration in camellia oils using NMR combined with chemometrics. Zhu et al. (2019) predicted the fatty acid composition in camellia oil via NMR combined with partial least squares regression. In most studies, NMR was mainly used for oil adulteration and trace component detection, and was rarely used for rapid detection of oil content. Chen et al. (2017) used LF-NMR to achieve rapid detection of oil content, but the sample used was a starch simulation system instead of actual food.

In this paper, traditional method has been used in combination with LF-NMR and magnetic resonance imaging (MRI), to study the changes in fried food during their processing, and their corresponding relevance were analyzed and discussed. These tools are proved useful in exploring the oil content and distribution of fried potato sticks and the results obtained from them can be mutually confirmed. Microscopy techniques, scanning electron microscope (SEM), was used to explore the effects of oil type and frying temperature on the surface microstructure changes of these fried products.

Those frying oils with a high oleic acid content usually offer better health benefits and stability (Nieva-Echevarría, Goicoechea, Manzanos, & Guillén, 2016). Compared with animal fats, vegetable oils have a higher amount of unsaturated fatty acids, which are greatly beneficial for the human health (Multari, Marsol-Vall, Heponiemi, Suomela, & Yang, 2019). Therefore, in this paper, high oleic sunflower oil (HOSFO), high oleic rapeseed oil (HORSO), sunflower oil (SFO), rapeseed oil (RSO), peanut oil (PNO), palm oil (PO), rice bran oil (RBO), maize oil (MO), soybean oil (SO) and cottonseed oil (CSO) were selected as frying oils. The relationship between the fatty acid composition, viscosity, and surface tension of these frying oils and the oil content, oil distribution, and surface morphology changes of fried potato sticks was also explored.

2. Materials and methods

2.1. Materials

The HOSFO, HORSO (Jinli Co. Ltd., Suzhou, Jiangsu, China), PNO, PO, RBO, MO, SFO, SO (Jiali Co. Ltd., Shanghai, China), and CSO (Changyuan Co. Ltd., Jinan, Shandong, China) used in this study were bought from a local supermarket (Auchan, Wuxi, Jiangsu, China). All the oils used were 100% pure oils without any antioxidants. Meanwhile, the potatoes (*Solanum tuberosum L.*, Helan15 variety, Shandong, China) used in this study were obtained from a local agricultural market (Wuxi, Jiangsu, China) and were stored at 10 °C before use. The initial moisture content of these potatoes was 83.42 ± 0.31 g/100 g determined by method of AOAC (2001).

2.2. Determination of fatty acid composition

2.2.1. Methylation of fatty acids

25 ± 0.1 mg of oil was weighed into a 5 mL centrifuge tube before dissolving 2 mL of *n*-hexane (chromatographically pure, Macklin, Shanghai, China). Afterward, 0.5 mL of the KOH-CH₃OH solution (2 mol/L, KOH: analytical purity, methanol: chromatographically pure, Sinopharm Chemical Reagent Co., Ltd., Shanghai, China) was added. The mixture was shaken for 2 min by using a vortex shaker (UVS-1, Youyi United Technology Co., Ltd., Beijing, China), and the upper organic phase was transferred to a 5 mL centrifuge tube. An appropriate amount (about 2 g) of anhydrous sodium sulfate (Sinopharm Chemical Reagent Co., Ltd., Shanghai, China) was then added for dehydration before shaking and centrifuging (8000 rpm, 5 min) the solution by a centrifuge (Taibang Electromotor Industry Co., Ltd., Zhejiang, China).

2.2.2. Gas chromatographic conditions

Gas chromatography equipped with a flame ionization detector (7820A, Agilent Technologies, California, USA) was employed to determine the fatty acid composition of the ten vegetable oil samples following the procedures described by Multari, Marsol-Vall, Heponiemi, Suomela, and Yang (2019). A PEG-20 M capillary column (30 m × 0.32 mm, 0.25 μm) was used with N₂ as the carrier gas (purity 99.999%) and 3 mL/min of group purge flow. The sample passed through a 0.22 μm organic membrane, and a 1 μL injection was administered. The split ratio was 80:1, and the sample collection time was 30 min. The inlet and detector temperatures were both set at 250 °C. The temperature for the FID detector was initially set at 150 °C, which increased to 190 °C at 5 °C/min for 2 min before increasing to 240 °C at 5 °C/min for 10 min.

2.3. Measurement of oil viscosity and surface tension

The viscosity of the ten vegetable oils was measured following the methods described in Li et al. (2015) with slight modifications. The temperature dependence of the viscosity of these oils was determined by using a DHR-3 rheometer (TA Instrument-Waters LLC, USA, parallel plate diameter: 60 mm).

Determination of viscosity at different shear rates: The shear rate was set between 10 s^{-1} and 1000 s^{-1} , and the temperature was kept constant at 35 °C.

Determination of viscosity at variable temperatures: The shear rate was set at 20 s^{-1} for a temperature range of 30 °C–100 °C, and the heating rate was set at 5 °C/min. All samples were measured after 1 min of initial temperature equilibration.

The surface tension of oil was determined by using a DCAT21-surface tension meter (Dataphysics, Germany) equipped with a Wilhelmy plate. All experiments were conducted in triplicate. The mean and standard deviations were presented.

2.4. Sample preparation and frying process

Fresh raw potatoes were taken out from a cryogenic storage room (10 °C) and kept at room temperature for 24 h before they were washed with running tap water, peeled, and cut into sticks (10 × 10 × 50 mm) with a cutting machine (Baimao Kitchen Appliances, Zhejiang, China). The potato sticks were blanched for 3 min in boiling water (1:8 sample/water ratio, g/g) before they were cooled to room temperature (25 °C). The excess moisture from the surface of these sticks was drained by using an absorbent paper. The moisture content of the blanched potato sticks was $86.32 \pm 0.52\%$.

The blanched potato sticks were fried using HOSFO, HORSO, RSO, PNO, PO, RBO, MO, SFO, SO and CSO in the ten same fryers (EF-3.5L, Guangdong Youtian Household Appliances Co., LTD, Fushan, China). Meanwhile, 100 g of potato sticks were fried in 2.5 L oil at frying temperatures of 140 °C and 180 °C. The fryers were preheated and maintained at frying temperature for 30 min before frying the potato sticks. After frying for 3 min, the frying basket containing the sample was taken out from the frying oil, shaken for 10 s, and removed from the fryer. The frying experiments for each oil at two temperatures (140 °C and 180 °C) were conducted in triplicate, respectively. All frying oils were used once only and changed before each frying to ensure that the oil used for each frying was fresh.

2.5. Determination of oil content

The oil content of fried food was divided by Bouchon, Aguilera, and Pyle (2003) into three fractions, namely, surface oil, surface penetrated oil, and matrix oil. We determined the surface oil content (SOC), matrix oil content (MOC), surface penetrated oil content (SPOC), and total oil content (TOC), which was computed as the sum of SOC, SPOC and MOC.

The sum of surface oil and surface penetrated oil content was measured following the procedures specified in previous research (Pedreschi, Cocio, Moyano, & Troncoso, 2008; Yang, Wu, Li, Zhang, & Qi, 2019). A fried potato stick was quickly removed from the frying oil and dipped in a constant weight aluminum box containing 30 mL petroleum ether for 1 s to 2 s. The oil content dissolved in petroleum ether was computed as the sum of surface oil and surface penetrated oil content, for the potato stick that was quickly removed from the fryer and not cooled, thereby giving the surface oil not enough time to penetrate. The measurement was repeated at least six times.

Another portion of the potato sticks taken out of the fryer was cooled under ambient conditions for 20 min and was placed in an aluminum box containing petroleum ether for 1 s to 2 s. The measurement process was the same as that used for the sum of surface oil and surface penetrated oil content. The measurement was repeated at least six times and result is classified as SOC. The SPOC of sample was recorded by the sum of surface oil and surface penetrated oil content subtracting the average SOC of the sample.

The potato stick samples after removing the sum of surface oil and surface penetrated oil content was freeze dried (LGJ-18C, Sihuan Scientific Instrument Co., Ltd., Beijing, China), and the remaining oil content in the measurement sample was extracted by using the Soxhlet extraction method. This part of the oil was classified as MOC. TOC was computed as the sum of SOC, SPOC and MOC.

2.6. Determination of moisture content

Moisture content was determined following the procedures prescribed in AOAC (2001). The fried potato sticks were finely chopped and weighed at approximately 2 g into an open glass dish (30 mm in diameter). The glass dishes containing the samples were placed in a drying oven (Shanghai Yiheng Scientific Instrument Co., Ltd.) and heated at 105 °C for 24 h until the mass change was ≤ 2 mg. The moisture content of the fried sticks was expressed as the mass of moisture in the

sample to the mass of the wet matter of the sample (wet basis, wb).

2.7. Low field nuclear magnetic resonance (LF-NMR) measurement

The oil proton signal of the fried samples was determined by using a 23 MHz LF-NMR analyzer (NMI20-015V-I, Newman Technology Co., Ltd., Suzhou, China) following the methods presented in previous research (Chen et al., 2017; Nieva-Echevarría et al., 2016). The fried samples were thoroughly freeze dried by using a freeze dryer (LGJ-18C, Sihuan Scientific Instrument Co., Ltd., Beijing, China) before the measurement to remove interference from hydrogen signals in water molecules. Each potato stick was weighed at 2 ± 0.001 g and placed in a 25 mm diameter nuclear magnetic coil, and the test temperature was kept constant at 32 °C. The Carr–Purcell–Meiboom–Gill sequence was employed. The parameter of TW was set at 2200.000, NS was set at 6, and NECH was set at 8000.

2.8. Magnetic resonance imaging (MRI)

The oil distribution in the fried potato sticks was observed by using the non-destructive analytical technique MRI (MesoMR23-060H-I, Newman Electronic Technology Co., Ltd., Shanghai, China) following the procedures described in previous research (MacMillan, Hickey, Newling, Ramesh, & Balcom, 2008; Yang et al., 2019). A freeze-dried potato strip sample was taken and wrapped with a raw tape wrap to prevent contamination of the instrument and was placed in a 25 mm test glass tube. Coronal were selected as the imaging orientations. Slices number was set to 1, and the slice width was set to 10 mm to ensure that the entire sample can be scanned. The test resonance frequency was set at 23.312 MHz, and the magnet strength was 0.5 T. The temperature was maintained at 32 °C during the test.

2.9. Microstructural observation

The microstructural observation of fried potato sticks was performed by using SEM (S-4800, Hitachi, Ltd., Tokyo, Japan). The dried and de-oiled samples with the outer surface facing up were fixed on the metal sample stage. The stage was then placed in a gold sprayer for 5 min to be coated with gold palladium instead of in the vacuum chamber of SEM. Images of the potato sticks surface microstructure were obtained at an accelerating voltage of 5 kV and $100 \times$ magnification.

2.10. Statistical analysis

All measurements were repeated at least thrice. The data were presented as means and standard deviations. Analysis of variance and correlation was conducted using IBM SPSS 20.0 (SPSS Inc., Chicago, USA) to check for significant differences in the values. Microsoft Excel 2013 and Origin Pro 9.0 were used for the calculations and for plotting the figures, respectively. For image acquisition in 2.8 and 2.9, at least six parallel samples were prepared for each measurement, and one sample was taken as the result. ZEN software (Carl Zeiss, Germany) were used for the measurement of the signal intensity of images from MRI.

3. Results and discussion

3.1. Analysis of fatty acid composition, viscosity, and surface tension of the ten vegetable oils

Triglycerides are the main components of edible oils. Therefore, the difference in the fatty acid composition of triglycerides is important in studying the physical and chemical properties of oils (Kitts & Jones, 1996). Fatty acids in edible vegetable oils mainly include saturated fatty acids, monounsaturated fatty acids (MUSFA), and polyunsaturated

Table 1
The main fatty acid composition of ten vegetable oils (n = 3).

Oil type	Palmitic(C16:0)	Stearic(C18:0)	Oleic(C18:1)	Linoleic(C18:2)	Linolenic(C18:3)	ECN	ESFAC
HOSFO	4.82 ± 0.03 ^c	2.96 ± 0.02 ^c	81.57 ± 0.04 ⁱ	9.42 ± 0.06 ^a	1.23 ± 0.01 ^e	16.86 ± 0.03 ^f	7.78 ± 0.01 ^c
HORSO	4.01 ± 0.01 ^a	2.20 ± 0.01 ^c	74.04 ± 0.39 ^h	14.27 ± 0.06 ^c	3.88 ± 0.02 ^g	16.75 ± 0.01 ^e	6.21 ± 0.01 ^b
RSO	4.14 ± 0.03 ^b	1.88 ± 0.07 ^b	63.38 ± 1.04 ^g	20.15 ± 0.30 ^d	8.74 ± 0.06 ⁱ	16.58 ± 0.01 ^d	6.02 ± 0.05 ^a
PNO	10.97 ± 0.17 ^e	2.81 ± 0.44 ^c	46.82 ± 1.05 ^f	35.81 ± 2.38 ^e	0.00 ± 0.00 ^a	16.55 ± 0.02 ^d	14.37 ± 0.31 ^e
PO	40.38 ± 0.03 ^j	4.30 ± 0.04 ^g	44.08 ± 0.05 ^e	11.05 ± 0.10 ^b	0.17 ± 0.01 ^b	16.52 ± 0.02 ^d	44.68 ± 0.02 ⁱ
RBO	17.68 ± 0.09 ^h	1.62 ± 0.08 ^a	40.33 ± 0.14 ^d	38.36 ± 0.16 ^c	1.44 ± 0.01 ^f	16.42 ± 0.03 ^c	19.30 ± 0.09 ^g
MO	12.41 ± 0.01 ^g	1.70 ± 0.01 ^a	27.98 ± 0.00 ^c	56.79 ± 0.05 ^g	1.11 ± 0.05 ^d	16.30 ± 0.03 ^b	14.11 ± 0.06 ^e
SFO	6.80 ± 0.01 ^d	3.72 ± 0.01 ^f	23.62 ± 0.28 ^b	65.23 ± 0.50 ⁱ	0.15 ± 0.02 ^b	16.23 ± 0.03 ^a	10.52 ± 0.03 ^d
SO	11.27 ± 0.01 ^f	4.34 ± 0.03 ^g	24.36 ± 0.04 ^b	52.64 ± 0.08 ^f	6.01 ± 0.03 ^h	16.27 ± 0.03 ^b	15.61 ± 0.02 ^f
CSO	22.24 ± 0.06 ⁱ	2.30 ± 0.02 ^d	16.02 ± 0.07 ^a	57.60 ± 0.02 ^h	0.24 ± 0.01 ^c	16.20 ± 0.03 ^a	24.54 ± 0.04 ^h

Values expressed are means of 3 standard deviations.

Means in the row with different superscripts are significantly different at $p \leq 0.05$.

fatty acids (PUSFA) (Kitts et al., 1996).

The ten major vegetable oils have different major fatty acid contents as can be seen in Table 1. HOSFO has the highest oleic acid content of up to $81.57 \pm 0.04\%$, followed by HORSO, RSO, PNO, and RBO were $74.04 \pm 0.39\%$, $63.38 \pm 1.04\%$, $46.82 \pm 1.05\%$ and $40.33 \pm 0.14\%$, respectively. Oleic and palmitic acids have the highest percentages of PO (44.08% and 40.38% , respectively). The main fatty acids of MO, SFO, SO and CSO are linoleic acid (56.79% , 65.23% , 52.64% , and 57.60% , respectively). The effective carbon atoms number (ECN) was calculated as follows based on the procedures of Geller and Goodrum (2000):

$ECN = \sum P_i (C_i - Db_i)$, where P, C, and Db denote fatty acid percentage, number of carbon atoms, and number of double bonds, respectively. The ECN of HOSFO, HORSO, RSO, PNO, PO, RBO, MO, SFO, SO and CSO are 16.86 ± 0.03 , 16.75 ± 0.01 , 16.58 ± 0.01 , 16.55 ± 0.02 , 16.52 ± 0.02 , 16.42 ± 0.03 , 16.30 ± 0.03 , 16.23 ± 0.03 , 16.27 ± 0.03 and 16.20 ± 0.03 , respectively, as presented in Table 1.

Fig. 1A illustrates the evolution of apparent viscosity as a function of shear rate for the ten vegetable oils at 35 °C. These ten vegetable oils are Newtonian fluids given that their viscosity hardly changes along with an increasing shear rate. The viscosity values of these ten

vegetable oils are $(50.16 \pm 0.12) \times 10^{-3}$ Pa·s for HOSFO, $(49.83 \pm 0.03) \times 10^{-3}$ Pa·s for HORSO, $(47.19 \pm 0.07) \times 10^{-3}$ Pa·s for RSO, $(46.53 \pm 0.03) \times 10^{-3}$ Pa·s for PNO, $(44.15 \pm 0.01) \times 10^{-3}$ Pa·s for RBO, $(44.00 \pm 0.03) \times 10^{-3}$ Pa·s for PO, $(40.26 \pm 0.07) \times 10^{-3}$ Pa·s for MO, $(39.93 \pm 0.02) \times 10^{-3}$ Pa·s for SO, $(38.28 \pm 0.01) \times 10^{-3}$ Pa·s for SFO, and $(37.95 \pm 0.09) \times 10^{-3}$ Pa·s for CSO. Fig. 1a and b show that viscosity is positively correlated with ECN ($r^2 = 0.97817$) and oleic acid content ($r^2 = 0.97384$), which is consistent with the findings of previous studies (Kim et al., 2010; Li et al., 2015).

Many studies have reported that the viscosity of various oils is related to their fatty acid composition (Kim et al., 2010). An increase in the content can increase the viscosity of vegetable oils, but the opposite effect is observed for PUSFA because an increase in the number of π bonds tightens these bonds, thereby reducing the rotation of the C–C bond, decreasing the activation energy, facilitating the flow, and lowering viscosity (Kim et al., 2010). In addition, a larger ECN corresponds to the greater activation energy and higher viscosity of oil (Li et al., 2015). Previous studies have shown that the correlation between viscosity and PUSFA is stronger than that between viscosity and MUSFC and is highly correlated with the content of oleic and linoleic acids. A larger number of double bonds in vegetable oil corresponds to a faster

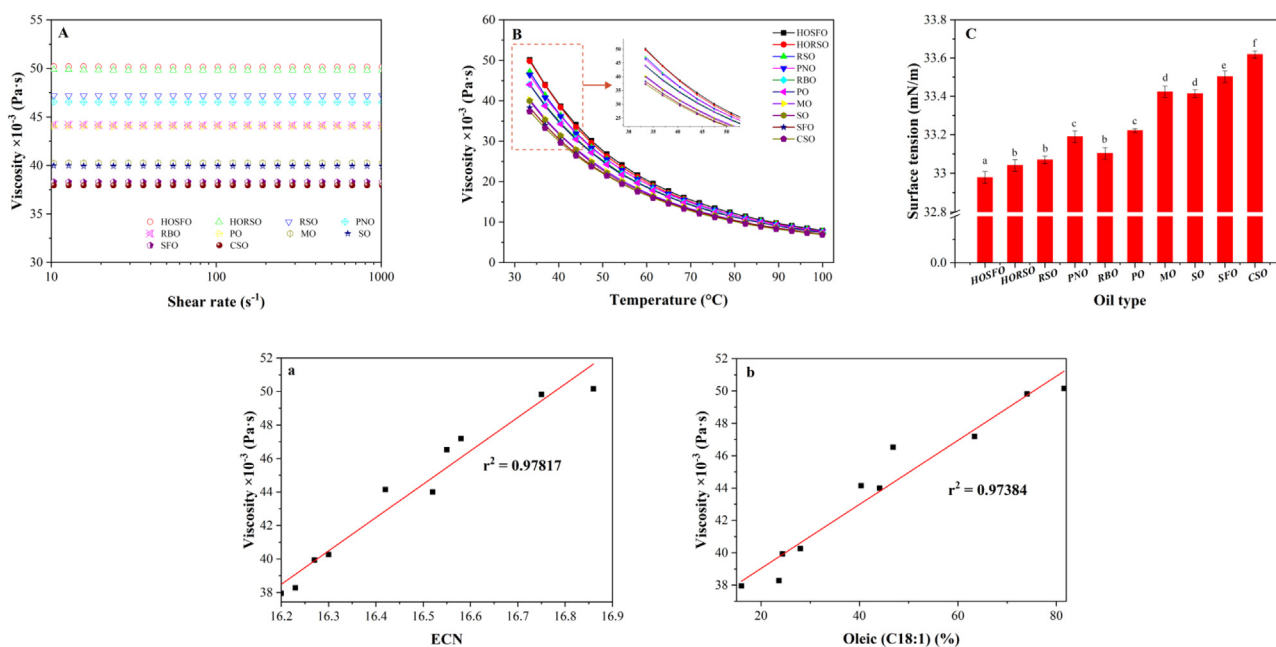


Fig. 1. Viscosity profiles, surface tension profiles and correlation analysis of the ten vegetable oils; (A) viscosity profiles of the ten vegetable oils with an increasing shear rate (10^{-1} to 1000 s^{-1}); (B) viscosity profiles of the ten vegetable oils during heating ($30 \text{ }^\circ\text{C}$ to $100 \text{ }^\circ\text{C}$); (C) surface tension profiles of ten vegetable oils; (a) correlation between the viscosity and the ECN of the ten vegetable oils; and (b) correlation between the viscosity and the oleic acid content of the ten vegetable oils.

change in viscosity along with temperature (Kim et al., 2010; Naghshineh et al., 2010). These conclusions are further confirmed in this paper.

Viscosity is a physical property of frying oils that is not only related to the fatty acid composition of these oils but also to their temperature (Kim et al., 2010). Table 1B shows the change in the viscosity of the ten vegetable oils as the test temperature changes from 30 °C to 100 °C. As the temperature increases, the viscosity of these ten vegetable oils exponentially decreases, which is consistent with the findings of previous research (Kalogianni, Karastogiannidou, & Karapantsios, 2009; Sahasrabudhe, Rodriguez-Martinez, O'Meara, & Farkas, 2017). This finding can be attributed to the fact that the elevated temperature facilitates the movement of molecules and reduces the forces among them, thereby allowing the liquid layers to pass by one another and subsequently reducing the viscosity (Sahasrabudhe, Rodriguez-Martinez, O'Meara, & Farkas, 2017).

From the curves trend of the viscosity of these ten vegetable oils with temperature (Fig. 1B), no significant difference can be inferred in the viscosity of these oils at frying temperature (140 °C–180 °C). However, their viscosity at lower temperatures may affect the rate of oil drainage during post-fry cooling, which is very important for oil uptake.

The surface tension of the ten vegetable oils is inversely proportional to their viscosity as can be seen from Fig. 1C. The surface tension are 32.978 ± 0.03 mN/m, 33.04 ± 0.03 mN/m, 33.069 ± 0.02 mN/m, 33.189 ± 0.03 mN/m, 33.103 ± 0.03 mN/m, 33.221 ± 0.01 mN/m, 33.423 ± 0.03 mN/m, 33.413 ± 0.02 mN/m, 33.50 ± 0.03 mN/m, 33.618 ± 0.02 mN/m, respectively, as the arrangement of HOSFO, HORSO, RSO, PNO, RBO, PO, MO, SO, SFO, and CSO. The surface tension of frying oil plays a key role in oil uptake behavior (Sahasrabudhe et al., 2017). The surfactant substance formed during frying is responsible for the changes in the rates of heat and mass transfer and may affect the penetration of oil into the food for different wettability according to surfactant theory of deep frying (Blumenthal & Stier, 1991; Kalogianni et al., 2009).

3.2. Analysis of changes in oil and moisture contents by traditional method

Fig. 2A and B show the MOC, SOC, SPOC and TOC of potato sticks

fried by these ten frying oils at two frying temperature. The average TOC of these fried sticks are 38.74 ± 0.21%, 38.29 ± 0.23%, 36.79 ± 0.12%, 36.42 ± 0.16%, 37.79 ± 0.06%, 36.11 ± 0.26%, 33.08 ± 0.66%, 33.11 ± 0.06%, 31.92 ± 0.17%, 32.74 ± 0.09%, respectively, at a 140 °C frying temperature, and 40.11 ± 0.03%, 40.09 ± 0.13%, 39.91 ± 0.13%, 38.17 ± 0.47%, 39.37 ± 0.10%, 36.59 ± 0.13%, 34.32 ± 0.43%, 34.07 ± 0.03%, 34.48 ± 0.03%, 34.51 ± 0.22%, respectively, at a 180 °C frying temperature. A significant difference can be observed among these TOC ($p < 0.05$). Oil distribution of fried potato sticks also can be seen from Figure A and B, which shows that SPOC has the highest proportion, followed by SOC and MOC.

From the correlation analysis of viscosity and total oil content in Fig. 3c and d, it can be seen that the viscosity is positively correlated with TOC, and the correlation is relatively high ($r^2 = 0.92796$ at 140 °C, $r^2 = 0.93530$ at 180 °C), which means a higher oil viscosity may correspond to a higher oil content of the potato sticks. SOC and SPOC follow the same trend, which is also related to oil viscosity. Meanwhile, the MO contents of the fried potato sticks are 4.01 ± 0.32%, 4.01 ± 0.11%, 4.27 ± 0.51%, 5.02 ± 0.38%, 3.38 ± 0.33%, 4.01 ± 0.03%, 4.77 ± 0.13%, 4.09 ± 0.07%, 3.97 ± 0.03%, 4.01 ± 0.03%, respectively, at a 140 °C frying temperature, and no significant differences are observed among these contents ($p > 0.05$). Therefore, MOC is less affected by the viscosity of oil than the other oil contents.

Oil absorption behavior is an important parameter that affects the quality of fried food, and many studies have attempted to explore the oil uptake of food during deep frying (Blumenthal, 1991; Bouchon et al., 2003; Chen et al., 2019; Dana et al., 2006; Su et al., 2017). The viscosity and surface tension of the frying oil affect the wettability of the oil and food during the frying process, the heat transfer and mass transfer rate, the draining of oil during the post-frying and cooling stages, and therefore the oil content.

Frying temperature is another important factor that influences oil content. Fig. 2B presents the oil content of the fried potato strips at a frying temperature of 180 °C. The four-part oil content of TOC, SOC, MOC, and SPOC at this temperature follow the same trend as that recorded at a frying temperature of 140 °C, but TOC was higher than that

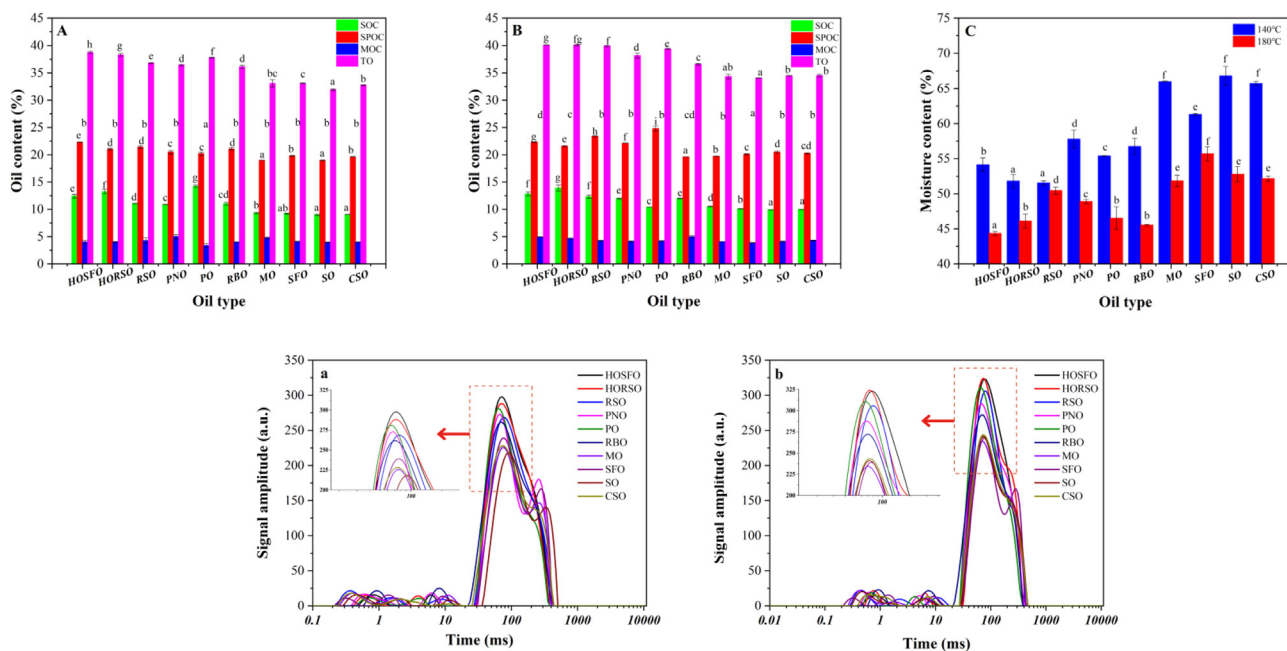


Fig. 2. Oil content (SOC, SPO, MOC, and TOC), moisture content and LF-NMR spectra of potato sticks fried using the ten vegetable oils; (A) oil content of potato sticks fried at 140 °C; (B) oil content of potato sticks fried at 180 °C; (C) moisture content of potato sticks fried using the ten vegetable oils; (a) LF-NMR spectra of potato sticks fried at 140 °C; and (b) LF-NMR spectra of potato sticks fried at 180 °C.

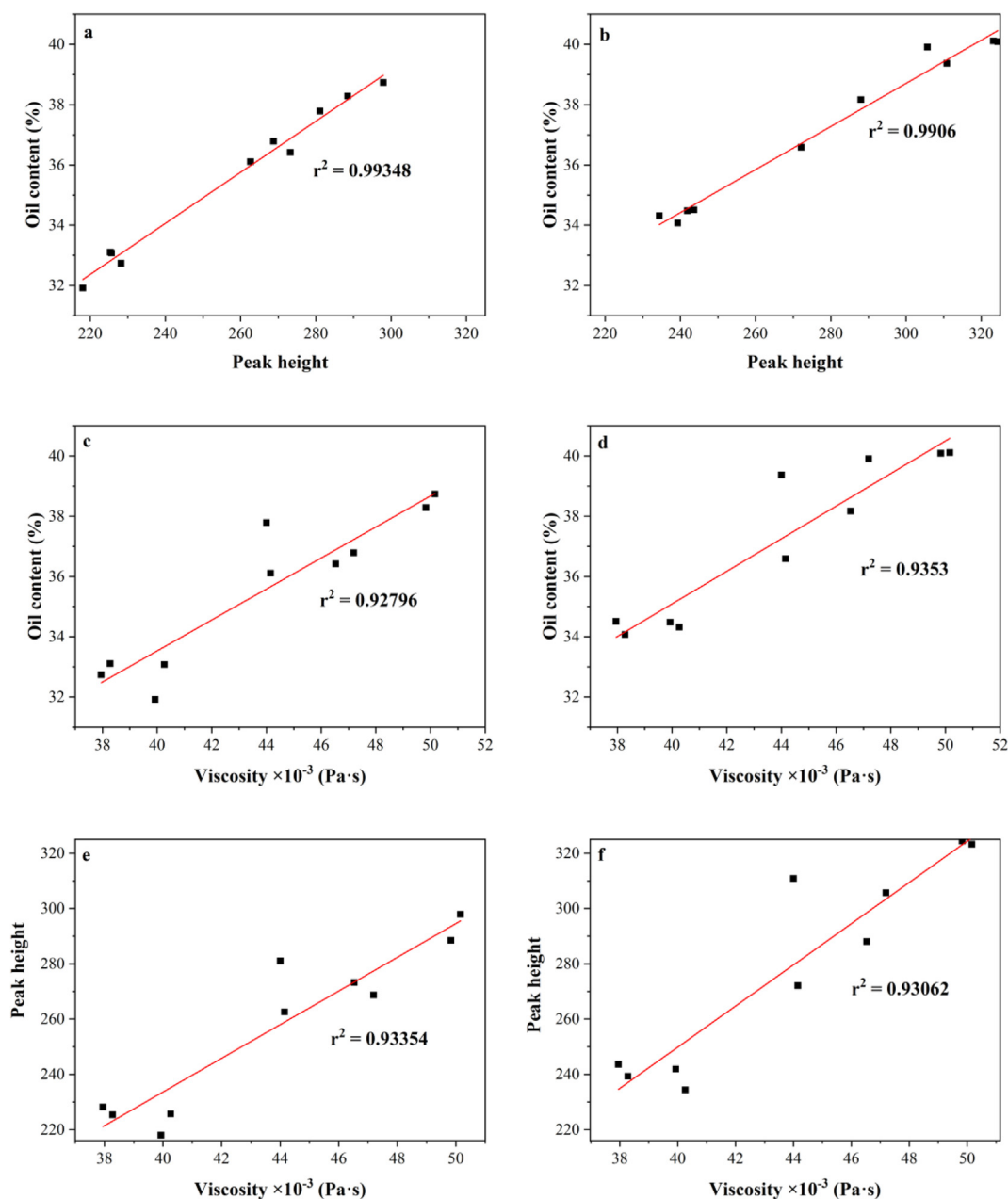


Fig. 3. Correlation between the (a) oil content and peak height of potato sticks fried at 140 °C; (b) oil content and peak height of potato sticks fried at 180 °C; (c) viscosity of the ten vegetable oils and oil content of potato sticks fried at 140 °C; (d) viscosity of the ten vegetable oils and oil content of potato sticks fried at 180 °C; (e) viscosity of the ten vegetable oils and peak height fried at 140 °C; and (f) viscosity of the ten vegetable oils and peak height fried at 180 °C.

at frying temperature of 140 °C. In other words, higher frying temperatures may result in a higher oil content. The conclusions of some studies contradict our findings that higher frying temperatures can lead to a lower oil content. This finding can be attributed to the fact that a high temperature rapidly forms an outer shell around the food surface, thereby preventing the oil from entering. However, the effect of frying temperature may also be related to the shape and size of the food, and a higher temperature may destroy the structure of the food and subsequently increase its oil content.

The moisture content of the fried potato sticks is presented in Fig. 2C. Before frying, the moisture content of the blanched potato sticks was $86.32 \pm 0.52\%$. After frying, the moisture content of potato sticks fried by ten vegetable oils decreased. The effect of the initial moisture content of food on oil uptake cannot be ignored given that a high moisture content increases moisture loss during frying, thereby increasing the number of pores and subsequently increasing the oil

uptake (Barutcu, Sahin, & Sumnu, 2009). Ngadi, Wang, Adedeji, and Raghavan (2009) reduced the oil content of chicken nuggets by reducing their initial moisture content. However, the effect of the initial moisture content of food on their oil absorption behavior is not absolute, which means that a higher water loss does not necessarily correspond to a higher oil content (Zhang, Li, Ding, & Fan, 2016).

3.3. Analysis of oil content and distribution by LF-NMR and MRI

LF-NMR and MRI were used to evaluate oil content and distribution. The relaxation signal curve of the fried potato sticks samples is shown in Fig. 2a and b. A single peak in the range of $20 \text{ ms} < T_2 < 1000 \text{ ms}$ corresponds to the oil molecular signal, and the intensity of this peak is proportional to the oil content seen from Fig. 3a and b ($r^2 = 0.99348$ at 140 °C, $r^2 = 0.99060$ at 180 °C), which is consistent with previous research results (Chen et al., 2017). As can be seen from Fig. 2a and b,

the average peak intensities of the ten samples at a frying temperature of 140 °C are 297.95, 288.47, 268.74, 273.22, 281.07, 262.63, 225.68, 225.36, 218.01, and 228.20, whereas those at a frying temperature of 180 °C are 323.22, 324.41, 305.68, 288.00, 310.86, 272.10, 234.40, 239.31, 241.89, and 243.60, respectively. The oil content estimated from the peak intensity of the oil molecule is consistent with the TOC measured by traditional method, and peak height is also proportional to the viscosity of the frying oils seen from Fig. 3e and f ($r^2 = 0.93354$ at 140 °C, $r^2 = 0.93062$ at 180 °C).

LF-NMR has been used in many studies to analyze moisture distribution and oil quality (Cunhaa, Netoa, & Colnago, 2019; Su et al., 2017). As its working principle, the relaxation signal of LF-NMR changes when the hydrogen protons in the micro-molecular structure of the sample being tested are in a constant magnetic field and when the external world resonates with the radio frequency pulse (Cunhaa, Netoa, & Colnagob, 2019). Chen et al. (2017) used the signal peak intensity of soybean oil as the ordinate and the quality of soybean oil as the abscissa to generate the standard working curve of oil content and then quantitatively analyzed the oil content of fried starch simulation system by using LF-NMR. LF-NMR shows several advantages over conventional method. For instance, LF-NMR does not require sample preparation, is non-destructive, and can be analyzed quickly, thereby making the entire test process last for approximately 1 min.

Fig. 4A and B were the pseudo color images of oil distribution in the longitudinal sections of fried potato sticks obtained by MRI. The different colors in the picture denote the concentration of oil in the area. The oil content is from high to low, and the corresponding colors are red, yellow, green, and blue. Through the color distribution of these pictures, the oil content and distribution can be qualitatively described. Fig. 4C shows the oil signal intensity value calculated from the gray scale image of the fried potato sticks by ZEN software. A strong correlation can also be seen from figure B and C between the oil content obtained from MRI imaging and the oil content obtained by the

conventional soxhlet extraction method, $r^2 = 0.93397$ at frying temperature of 140°C and $r^2 = 0.88012$ at frying temperature of 180°C, thereby indicating a reasonable potential to predict one from the other. The results obtained from MRI are also consistent with those obtained from the above measurement. In our previous studies (Yang et al., 2019), MRI was used to analyze the oil distribution of the sample, and the oil was mainly concentrated on the outer surface of the sample, wrapping the sample like an eggshell. Meanwhile, in this study, the samples fried at a 140 °C frying temperature showed a similar oil distribution (Fig. 4A). Fig. 4B shows that the entire potato stick fried at 180 °C was almost entirely covered with oil, including its appearance and interior. This phenomenon may be ascribed to the fact that the structure of the sample was broken at a high frying temperature (180 °C) and, accompanied by intense heat and mass transfer, the sample was almost completely dehydrated and a large amount of oil entered its insides. The whole sample subsequently became a crust.

3.4. Observing the microscopic morphology of fried potato sticks surface by SEM

Microscopy uses a magnification tool to produce a visible image of a structure or detail that is too small to be seen by the human eye. In this paper, SEM was used to observe the surface micro-morphological changes of fried potato stick samples. Fig. 5A shows that many regular polygonal holes, which was the cellular structure of the potatoes, have appeared on the surface of the lyophilized un-fried sample, which was left after the evaporation of water. The surface of the fried samples was rugged for the gelation of the starch, cell structure disappeared, and both the intense heat and mass transfer influenced their surface morphology.

The surface morphology of food may affect its oil absorption behavior. Rugged product surfaces make it easier for oil to remain on the surface, thereby leading to a higher oil absorption (Rahimi & Ngadi,

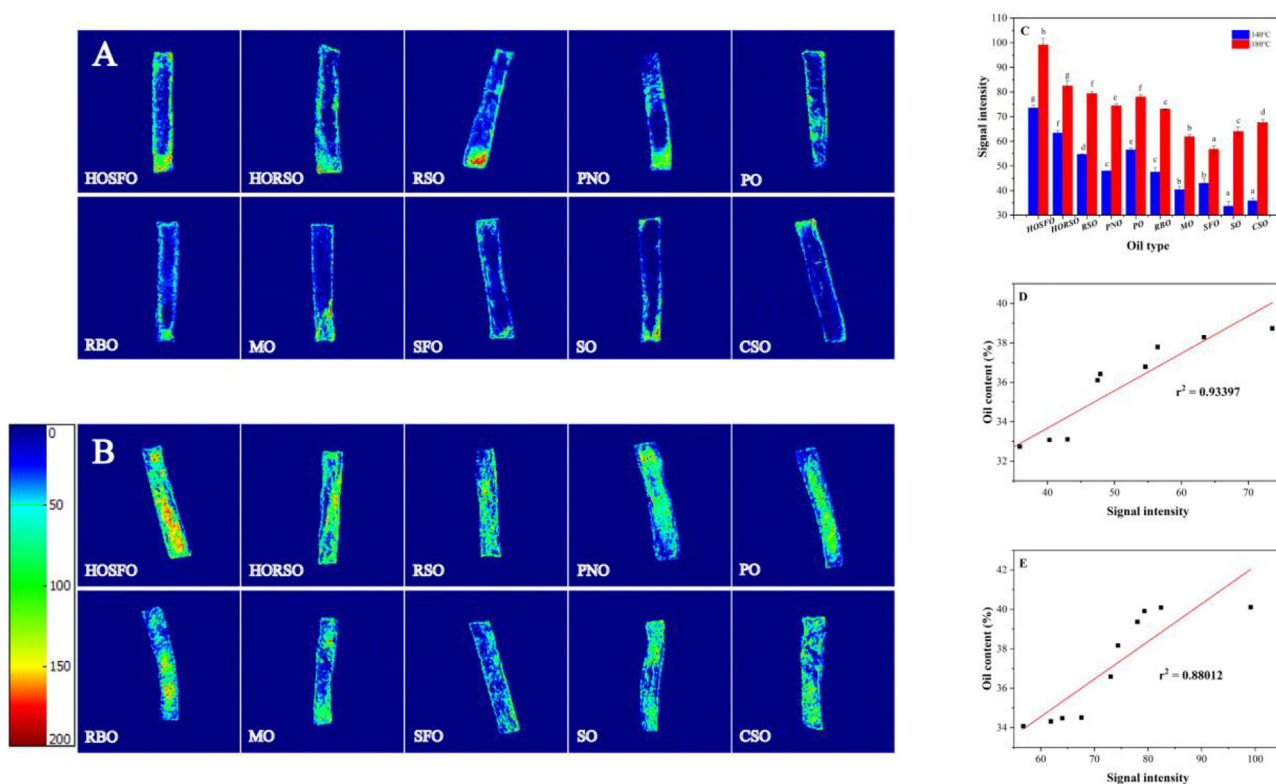


Fig. 4. Images of oil distribution obtained by a low field nuclear magnetic resonance imager (MRI) and correlation analysis; (A) MRI images of potato sticks fried at 140 °C; (B) MRI images of potato sticks fried at 180 °C; (C) oil signal intensity values of MRI images; (D) correlation between the oil content and oil signal intensity of potato sticks fried at 140 °C; and (E) correlation between the oil content and oil signal intensity of potato sticks fried at 180 °C.

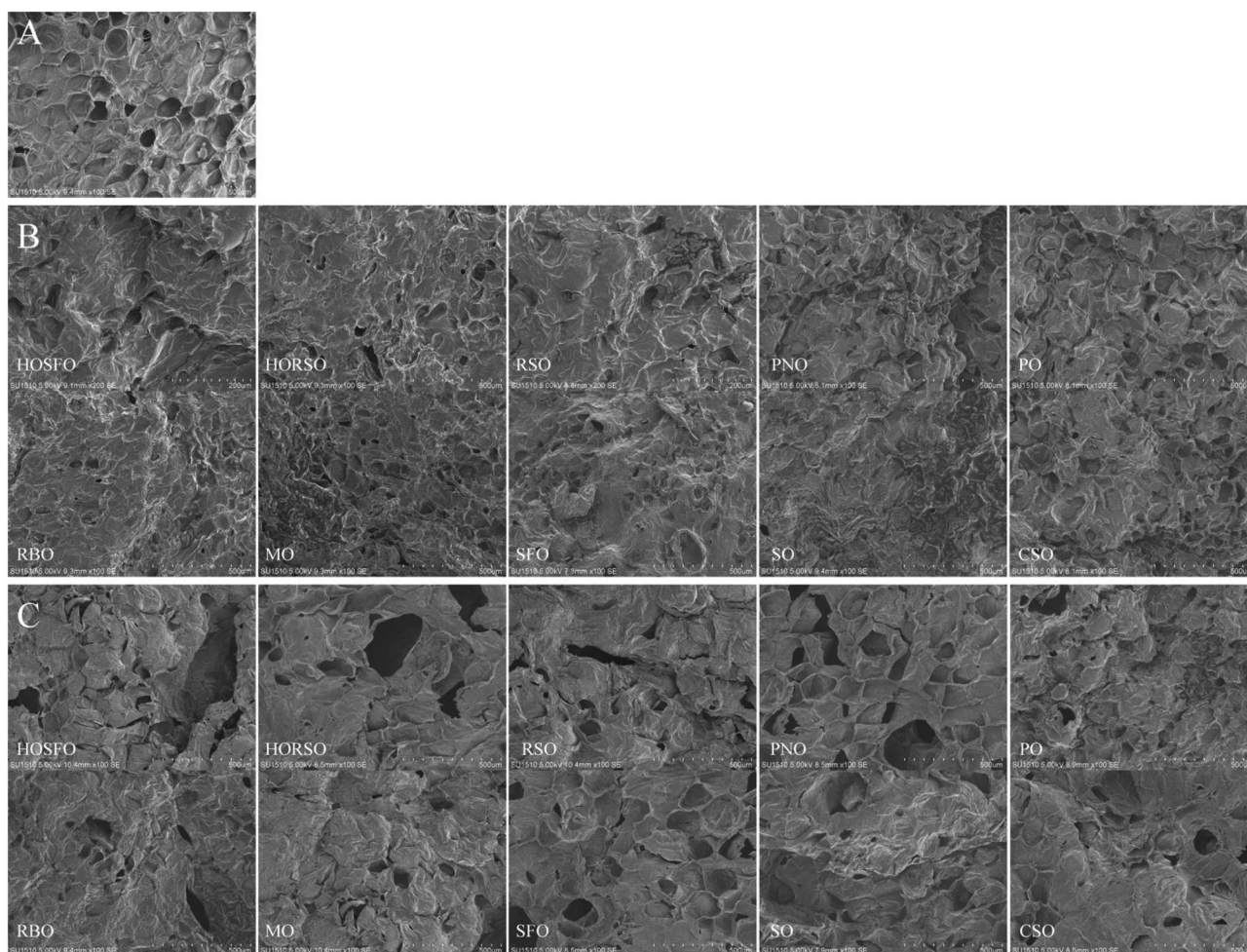


Fig. 5. Change in the surface morphology of the potato sticks as observed via scanning electron microscopy (SEM). All images were taken at 100 magnification; (A) changes in the surface morphology of un-fried potato sticks; (B) changes in the surface morphology of potato sticks fried at 140 °C; and (C) changes in the surface morphology of potato sticks fried at 180 °C.

2016). Fig. 5C shows that the surface morphology of the samples fried at 180 °C is highly uneven, which may explain their high oil content. No obvious differences can be found in the surface morphologies of samples fried by different types of oils.

In porous food materials such as fried potato sticks, having a clear knowledge of the food microstructure is crucial for process optimization and developing relevant equations. Fried product microstructures, such as porosity, also have a significant impact on the physical properties of food, including their mass diffusion coefficient, thermal conductivity, and thermal diffusivity, and may lead to differences in their oil absorption behavior (Millin et al., 2016). The unique surface microstructure formed during frying not only controls fat intake but also contributes to the crispness of coated fried food (Bouchon et al., 2003).

4. Conclusion

In this paper, traditional methods were used along with some advanced instruments, including LF-NMR, MRI, and SEM, to qualitatively and quantitatively analyze the oil content, oil distribution, microstructure, and other changes in the properties of potato sticks fried by ten types of vegetable oils at two frying temperatures. The effects of the fatty acid composition, viscosity, and surface tension of these oils on the oil absorption behavior of potato sticks as well as the link between these parameters were analyzed. The oil content, especially TOC increased along with ECN, viscosity, and frying temperature. The oil content of the samples can be quickly detected based on the peak intensity of the

oil signal captured by LF-NMR. MRI intuitively generated images of the oil distribution in the samples, and oil distribution was strongly influenced by frying temperature. The surface morphology of the fried samples was greatly affected by frying temperature, whereas the different types of oil only had a slight influence. The microstructure of the samples influenced their oil absorption behavior. In sum, those factors influencing the oil absorption mechanism are diverse and complex, and this study may help provide ideas for identifying a more suitable frying oil in the future.

CRediT authorship contribution statement

Dan Yang: Conceptualization, Data curation, Methodology, Investigation, Validation, Formal analysis, Writing - original draft. **Gangcheng Wu:** Validation, Investigation, Writing - review & editing. **Peiyan Li:** Visualization, Investigation. **Xiguang Qi:** Validation. **Hui Zhang:** Supervision. **Xingguo Wang:** Writing - review & editing. **Qingzhe Jin:** Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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