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Effect of Whole Wheat Flour on the Deep-frying Kinetics of Chinese Sachima

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Abstract The effects of whole wheat flour (WWF) on the deep-frying kinetics of Chinese Sachima sticks were investigated in this study. Refined wheat flour (RWF) in the Sachima dry mix formula was replaced with WWF at different levels. There was a linear relationship between moisture content and structural oil content for all WWF substitution samples during deep-frying. The kinetic coefficients of moisture and oil transfer decreased significantly by substitution with WWF. WWF increased the spin-spin relaxation time of water molecules by enhancing the water-binding capacity in Sachima dough. The G' (storage modulus) and G" (loss modulus) of Sachima dough reduced and the onset and peak temperatures increased as the substitution levels of WWF increased. Furthermore, WWF can partially substitute RWF to produce lower oil content Sachima, which had a smooth surface with fewer and smaller voids. In conclusion, WWF affect significantly the oil absorption of Sachima.

Keywords: *whole wheat flour, Sachima, mass transfer, thermal properties, oil absorption*

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1. Introduction

Sachima is one of the fastest expanding sectors of the traditional Chinese snacks market and is now gaining popularity throughout the world [1]. The three basic ingredients for preparing Sachima are refined wheat flour, eggs, and syrup. Sachima has a distinctive flavor and texture owing to the deep-frying process, which results in a higher oil content (about 30-40%) [2]. Deep-frying is a food preparation technique that is widely used to produce snacks and instant foods [3]. However, fried foods have relatively high oil content. For example, the average oil content of Sachima is 30-40%, which is higher than that of instant fried noodles [1]. It is well known that consuming foods with high oil content is associated with obesity, cancers, and angiocardiopathy [1,4], which has led to an increasing demand for food with lower oil content. Several studies have examined the production of fried foods with lower oil content [5,6,7]. It has been reported that oil absorption by food during deep-frying is significantly affected by product variables, such as composition, product shape, surface roughness, porosity, and process conditions [8]. Other studies have also reported on modified deep-frying procedures: pre-drying, super-heated steam preparation and other pre-treatments to reduce oil absorption by instant fried noodles and potato strips [9,10]. In addition, cereal dough mixed with certain polysaccharides and oligosaccharides can also produce lower fat fried cereal products, Liang et al. found that both xanthan and β-cyclodextrin reduced the oil content of Sachima [11]. Gamonpilas et al. used cross-linked tapioca starches to reduce the oil content of deep-fried breaded chicken strips [12].

Dietary fiber is one of the most important functional ingredients, can also make a contribution to reducing oil absorption during deep-frying [13]. Kim et al. reported that the oil content was reduced by 24.4% compared with the control, when 5% of a batter was replaced with soybean husk powder [14]. Yadav and Rajan reported that oat bran improved the moisture retention and weakened the oil absorption significantly when deep-frying poori [15]. Furthermore, β-glucan-enriched materials were used as an oil barrier for instant fried noodles [16]. Whole wheat flour (WWF) is one of the most common and important sources of dietary fiber, but studies on its use in deep-fried snacks are limited. Li et al. had evaluated the qualities of Chinese youtiao products containing extra WWF in appropriate different content, which did not affect products' acceptability in terms of texture or volume for consumers [17]. The quality of Sachima incorporating WWF was investigated in [1]. They found that the total oil content of fried Sachima sticks could be reduced by up to 24% compared with the control. However, the mechanisms of how WWF resists oil in

Sachima are still not clearly understood. In this study, RWF in the Sachima dry mix formula was replaced by WWF at different levels so that the effects of WWF on the deep-frying kinetics of Chinese Sachima could be investigated.

2. Materials and Methods

2.1. Materials

RWF and WWF were provided by Jiangnan Flour Co. Ltd. (Danyang, Jiangsu, China) and their basic components were shown in Table 1. Gluten and palm oil were supplied by Lianhai Biological Technology Co. Ltd. (Haimen, Jiangsu, China) and COFCO Eastocean Oils & Grains Industrial Co. Ltd. (Zhangjiagang, Jiangsu, China), respectively. Baking powder and ammonium bicarbonate were purchased from Angel Yeast Co. Ltd. (Yichang, Hubei, China) and Huanle Food Additives Co. Ltd. (Zhengzhou, Henan, China), respectively. Eggs were purchased from a local supermarket.

2.2. Preparation of Sachima Dough Sticks

The Sachima dough sticks were prepared according to [1]. In the modified-formula dry mixes of Sachima dough, the refined wheat flour was replaced by whole wheat flour at levels of 25, 50, 75, and 100%.

2.3. Deep-frying of Sachima Sticks

Deep-frying was carried out in a fryer (Yuda Household Electrical Appliances Co. Ltd., Guangdong, China) filled with 2 L palm oil. The material-to-oil ratio was kept at 1:80 g/mL. The Sachima sticks were removed from the frying basket after 10, 20, 40, 60, 80, 120, 160, and 200 s of deep-frying at 170 °C and the excess oil was drained by tapping the strainer sharply five times (about 5 s), followed by immersion in anhydrous ether for 20 s. The moisture content (MC) was determined by drying the samples at 105 °C to a constant mass and SOC estimated by Soxhlet extraction with anhydrous ether [18]. MC and SOC were based on the dry weight of Sachima dough before deep-frying. Each sample was measured in triplicate.

2.4. NMR spin-spin relaxation (T_2) measurements of Sachima dough

The effect of WWF on NMR relaxation in Sachima dough was measured by a Niumag Benchtop Pulsed low field NMR Analyzer PQ001 (Niumag Electric Corporation, Shanghai, China) according to the methods described by Chen et al. [19]. The resonance frequency for protons was 22.101 MHz, and the temperature of the magnet was maintained at between 31.99-32.01 °C. Approximately, 4 g of the Sachima dough samples was placed in a 15 mm glass tube and inserted in the NMR probe. The spin-spin relaxation time (T_2) was determined using Carr-Purcell-Meiboom-Gill sequences. The measurements were performed in triplicate for each sample.

2.5. DSC Analysis of Sachima Dough and Fried Sticks

A differential scanning calorimeter (DSC-Q200; TA Instruments, New Castle, DE, USA) was used to analyze the gelatinization properties of Sachima dough. The aluminum pan containing 5 mg of the dough sample was hermetically sealed and heated from 20 to 100 °C at a rate of 5 °C/min. An empty pan was used as a reference. The thermograms were recorded, along with the onset (T_o), peak (T_p), and conclusion (T_c) temperatures and the enthalpy of gelatinization (ΔH_g).

The crystallization properties of fried Sachima sticks were also investigated using DSC. A slice of crust (5 mg), cut from each fried Sachima stick, was encapsulated in an aluminum pan, then cooled from 25 °C (room temperature) to -60 °C at a rate of 5 °C/min. An empty pan was used as a reference. The enthalpy (ΔH_c) of oil crystallization was obtained to investigate the differences in oil absorption between the different samples. The tests were made in triplicate for each sample.

2.6. Estimation of Mass Transfer Coefficients of Moisture and Oil in Sachima Sticks during Deep-frying

A first-order mass transfer kinetics model has been reported to fit the data for moisture loss and oil absorption during deep-frying [9,20]:

$$\frac{dm}{dt} = -k_m(m_t - m_\infty) \tag{1}$$

$$\frac{do}{dt} = +k_o(o_t - o_\infty) \tag{2}$$

With an appropriate transformation, equations (1) and (2) can be described by the following equations [9]:

$$\ln\left(\frac{m_t - m_\infty}{m_0 - m_\infty}\right) = \ln(m_r) = -k_m t \tag{3}$$

$$\ln\left(\frac{o_t - o_\infty}{o_0 - o_\infty}\right) = \ln(o_r) = +k_o t \tag{4}$$

where m and o represent MC and SOC; subscripts 0 and t represent the relevant content at time, t = 0 and t, respectively; m_∞ and o_∞ are the equilibrium MC (dm/dt = 0) and SOC (do/dt = 0) values, respectively, which do not exist in reality but are used as pseudo-coefficients for the convenience of calculation. The pseudo-coefficients, m_∞ and o_∞ were determined when three successive MC and SOC measurements differed from the average value by less than ± 1.2% [21]; m_r and o_r are the diffused moisture and oil ratios; k_m and k_o are the kinetic coefficients for mass transfer of moisture and oil; – and + represent moisture loss and oil absorption, respectively, during deep-frying.

Table 1. The basic components of whole wheat flour and refined wheat flour (dry basis, %)

Type of flour	Protein	Starch	Dietary fiber	Fat	Ash	Wet gluten
Whole wheat flour	13.15±0.20[b]	70.61±1.36[a]	12.40±0.44[b]	2.10±0.04[b]	1.72±0.03[b]	21.79±1.03[a]
Refined wheat flour	12.59±0.05[a]	81.75±0.33[b]	3.15±0.12[a]	1.08±0.03[a]	0.54±0.01[a]	31.03±0.78[b]

Data are expressed as mean ± SD (n = 3). Values in the same column with different superscript letters are significantly different (p< 0.05).

2.7. Measurements of Rheological Properties of Sachima Dough

Rheological properties (G': storage modulus and G": loss modulus) of Sachima dough were measured according to Huang et al. [22] by a DHR3 rheometer (TA Instruments, West Sussex, UK).

2.8. Analysis of Scanning Electron Micrographs of Fried Sachima Sticks

The surface and inner section microstructure of fried Sachima sticks were investigated using a scanning electron microscope (SEM, S-4800; Hitachi, Tokyo, Japan). Before SEM examination, the fried Sachima sticks were defatted using anhydrous ether for 12 h and dried to obtain clear SEM images [16]. The defatted samples were mounted on the top of an aluminum stud with double-faced adhesive tape and coated with platinum in an ion sputter coater (E-1030; Hitachi, Tokyo, Japan).

2.9. Statistical Analysis

The resulting data were analyzed using the Duncan's multiple range test in the SPSS version 17.0. Statistical significance was set at the 5% level and the data were expressed as mean ± SD.

3. Results and Discussion

3.1. Effect of Whole Wheat flour on Mass Transfer of Moisture and Oil Coefficient of Sachima Sticks during Deep-frying

The changes in MC and SOC of fried Sachima sticks during deep-frying at 170 °C are shown in Figure 1 (a, b). At the beginning of the process, the materials heated rapidly when the temperature of the surface water had not reached boiling point. This phase was very short and the amount of water loss was negligible [20]. After 20 s, the moisture content of the Sachima sticks decreased sharply (Figure 1 (a)), which indicated the heating process had reached the boiling stage. During this stage, the materials greatly expanded and produced a large number of bubbles owing to water vapor generation. As a result, the MC of Sachima sticks decreased rapidly until 150 s by when most of the moisture had been lost and the thickness of the crust layer of the Sachima sticks was increasing. After 150 s, the MC content of sticks was relatively stable. The opposite trend for SOC can be observed in Figure 1(b). There was a linear relationship between MC and SOC content for all samples in Figure 1(c), which had correlation coefficients between -0.98 and -0.99 ($p< 0.05$). Similar phenomena have been reported by Debnath et al. [9], who pointed out that a decreasing moisture content led to an increasing oil content during deep-frying, with values of correlation coefficients very similar to the present study.

The initial and equilibrium contents of moisture and oil in fried Sachima sticks at different levels of WWF are shown in Table 2. The results indicated that the equilibrium MC and SOC were significantly affected by the level of WWF substitution ($p < 0.05$). An increase in WWF substitution led to an increase in equilibrium MC from 8.20 to 12.40%, but a decrease in equilibrium SOC from 47.06% to 32.10%. The kinetic coefficients of moisture and oil mass transfer were calculated by using Equations (3) and (4), respectively. According to Figure 1 (d), an increase in WWF substitution level in the fried Sachima sticks resulted in lower values of k_m (0.0267-0.0221 s^{-1}) and k_o (0.0249-0.0189 s^{-1}). A significant linear relationship was found between both k_m and k_0 and the level of WWF substitution, with correlation coefficients of 0.99 ($p< 0.05$). It could be argued that the substitution of WWF in Sachima sticks had a significant influence on restraining the mass transfer of moisture and oil during deep-frying. The same effect was reported by Debnath et al. [9], who found that the kinetic coefficients of mass transfer in a chickpea flour-based snack food decreased during deep-frying. This reduction attributed to the increased density of the material matrix caused by pre-drying.

3.2. Effect of Whole Wheat Flour on the Water State in Sachima Dough

The differences in the water state of a food system reflect the different interactions between water molecules and hydrotropic components [19]. To demonstrate the effect of WWF on the water state in Sachima dough, the spin-spin relaxation time (T_2) of water molecules was determined by NMR with no destruction. A shorter T_2 indicates a lower degree of water freedom. The typical T_2 curves are presented in Figure 2, in which three main peaks were identified: T_{21} (0-1 ms) for tightly bound water, T_{22} (1-5 ms) for less tightly bound water and T_{23} (5-100 ms) for weakly bound water. For Figure 2, the three peaks shifted to the left to lower values of T_2 with the increasing level of WWF substitution, indicating that the water-binding capacity of Sachima dough was enhanced by the addition of WWF. As shown in Table 3, there was a positive correlation ($R = 0.99$, $p < 0.05$) between the substitution level of WWF and the peak area ratio of T_{21}. The portion of water in this region was perceived as absorbed by starch and other polysaccharides. Li *et al.* attributed the increasing peak area ratio of T_{21} to the matrix of arabinoxylans, which mainly exist in wheat bran and have a strong water binding capacity owing to their polysaccharide structure [23]. The peak area ratio of T_{22} had a range of 18.51-19.13% with a significant change only between the 0 and 25% levels and the 100% substitution level. The peak area of T_{23} was the largest proportion of the T_2 relaxation time and was found to have a negative correlation (R= −0.96; $p < 0.05$) with an increasing WWF substitution level. It is possible that a hydrophilic component, gluten with a high water absorption capacity caused by its porous framework, worked in this region. It has been reported that the dietary fiber in WWF would dilute the gluten protein and affect the formation of the gluten matrix in the dough [24]. Then, more water migrated from the gluten into the dietary fiber with an increasing WWF content, leading to the decreasing peak area ratio of T_{23}. Therefore, the addition of WWF to Sachima dough could inhibit water migration from the dough system during deep-frying, resulting in lower oil absorption. These findings agreed with the study proposed that oat dietary fiber had a significant effect on reducing oil absorption in batters because of its high water-holding capacity [25].

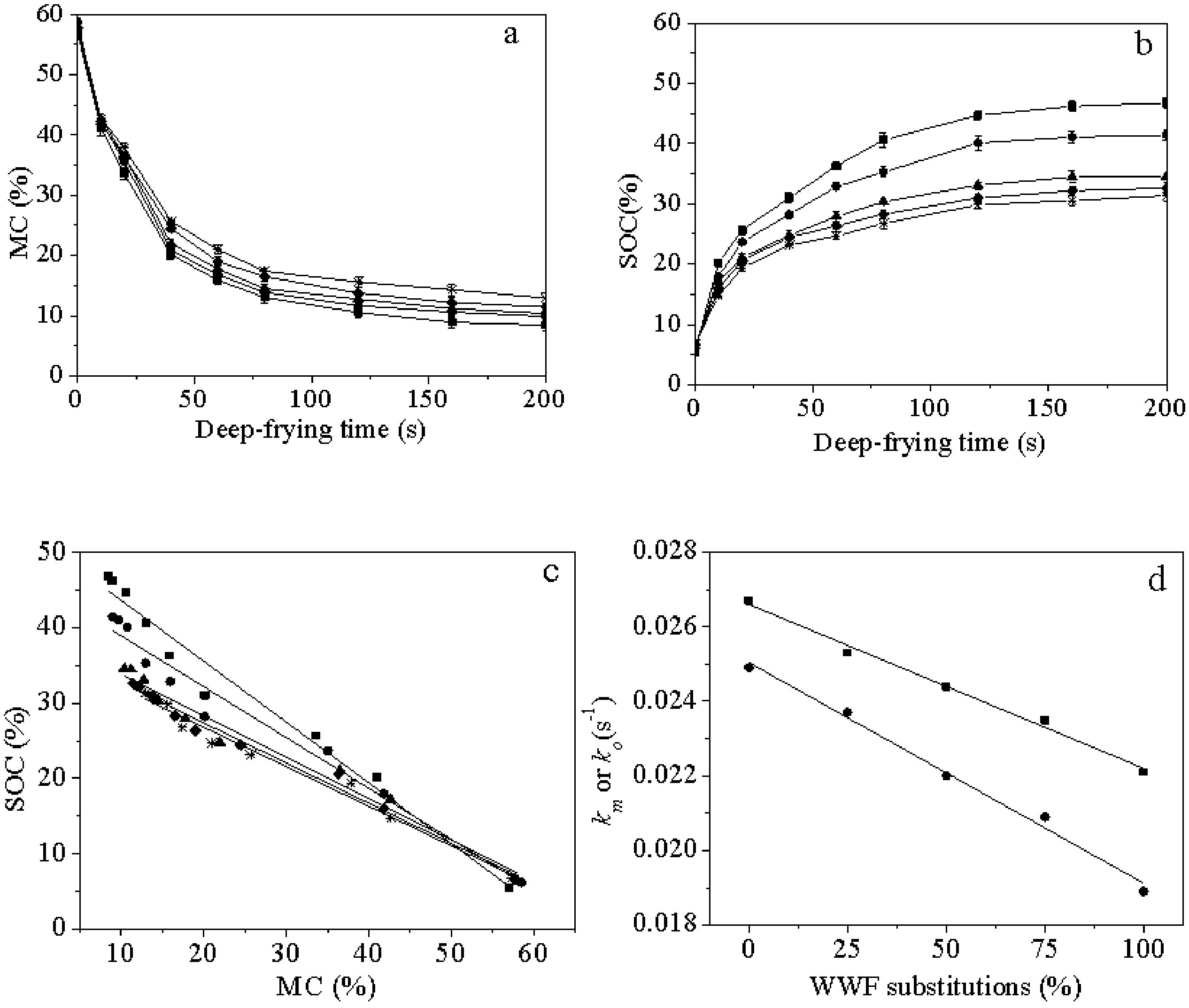

Figure 1. (a) Effect of whole wheat flour on the changes in MC in fried Sachima sticks during deep-frying (WWF substitution level: ■ 0% (control), ● 25%, ▲ 50%, ◆ 75%, * 100%); (b) Effect of whole wheat flour on the changes in SOC in fried Sachima sticks during deep-frying (WWF substitution level: ■ 0% (control), ● 25%, ▲ 50%, ◆ 75%, * 100%); (c) Linear relationship between MC and SOC of fried Sachima sticks with different whole wheat flour substitutions during deep-frying (WWF substitution level: ■ 0% (control), ● 25%, ▲ 50%, ◆ 75%, * 100%); (d) Linear relationship between kinetic coefficients k_m (■)/ k_o (●) and WWF substitution of fried Sachima sticks during deep-frying.

Table 2. Effect of whole wheat flour on the MC and SOC of fried Sachima sticks

Level of WWF substitution	Moisture Content (MC)		Structural Oil Content (SOC)	
	Initial MC (%)	Equilibrium MC (%)	Initial SOC (%)	Equilibrium SOC (%)
0% (control)	57.98±0.67 [NS]	8.20±0.57 [a]	5.52±0.31[a]	47.06±0.79 [a]
25% [A]	58.62±0.48	9.50±0.84 [b]	6.19±0.61 [b]	41.80±0.89 [b]
50%	58.05±1.01	9.98±0.39 [c]	6.46±1.01[b]	35.10±0.39 [c]
75%	56.87±0.65	10.96±0.41 [d]	6.61±0.68 [bc]	33.12±0.41[d]
100%	57.29±0.92	12.40±0.43 [e]	6.81±0.92 [d]	32.10±0.43 [e]

Data are expressed as mean ± SD (n = 3). Values in the same column with different superscript letters are significantly different ($p < 0.05$). The letter 'a' denotes the lowest value. NS: no significant difference.

[A]: the levels of RWF replaced by WWF.

Table 3. Effect of whole wheat flour on T_2 distribution of Sachima dough

Level of WWF substitution	Peak area ratio (%) ^{B}		
	T_{21}	T_{22}	T_{23}
0% (control)	5.22±0.14 ^{a}	19.13±0.23 ^{c}	76.65±0.12 ^{e}
25% ^{A}	6.62±0.16 ^{b}	19.12±0.41 ^{c}	74.26±0.25 ^{d}
50%	7.34±0.25 ^{c}	18.71±0.39 ^{abc}	73.95±0.32 ^{c}
75%	8.27±0.28 ^{d}	18.87±0.38 ^{bc}	72.86±0.38 ^{b}
100%	9.11±0.31 ^{e}	18.51±0.31 ^{ab}	72.38±0.27 ^{a}

Data are expressed as mean ± SD (n = 3). Values in the same column with different superscript letters are significantly different (p< 0.05). The letter 'a' denotes the lowest value.
^{A}: the levels of RWF replaced by WWF.
^{B}: percentage of each peak area in total areas (T_{21}, T_{22}, and T_{23}).

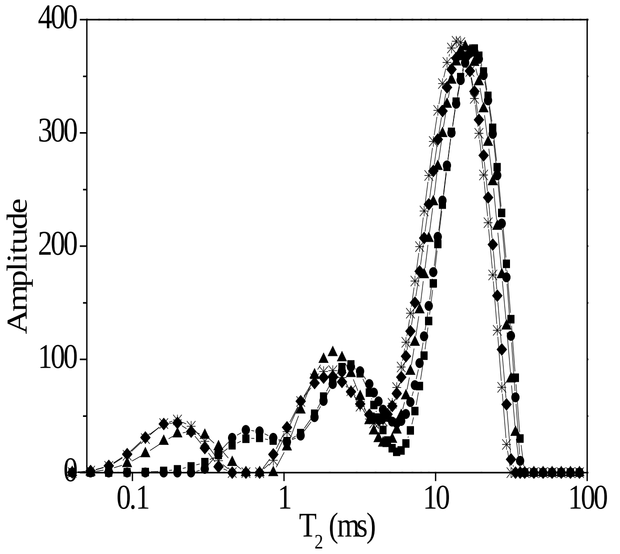

Figure 2. Effect of whole wheat flour on the T_2 relaxation time distribution of Sachima dough (WWF substitution level: ■ 0% (control), ● 25%, ▲ 50%, ◆ 75%, * 100%)

3.3. Effect of Whole Wheat Flour on the Rheological Properties of Sachima Dough

The increased level of WWF had a destructive effect on the formation of gluten network, which was a critical factor of affecting the Sachima quality during dough mixing and sheeting [26]. As shown in Figure 3a, the G' (storage modulus) values were larger than the G" (loss modulus) values, indicating that the dough was more elastic than viscous. In the frequency sweep test, the G' of Sachima dough reduced with the addition level of WWF, which indicated that the elasticity of dough was restrained. The water absorbent-capacity of WWF highly competes for water with the gluten network and starch granule in dough system, which inhibited sufficient water absorption and formation of gluten network [27]. Kaur et al. reported that the presence of large starch granules in wheat flour is likely responsible for high G' and G" values [28]. However, the starch content and its granular size were diluted and sheared by the increased level of wheat bran in WWF. Therefore, the result of G" of Sachima dough reduced with the increasing WWF content (Figure 3b) might be caused by the smaller granular size and shape of the native starches in the system.

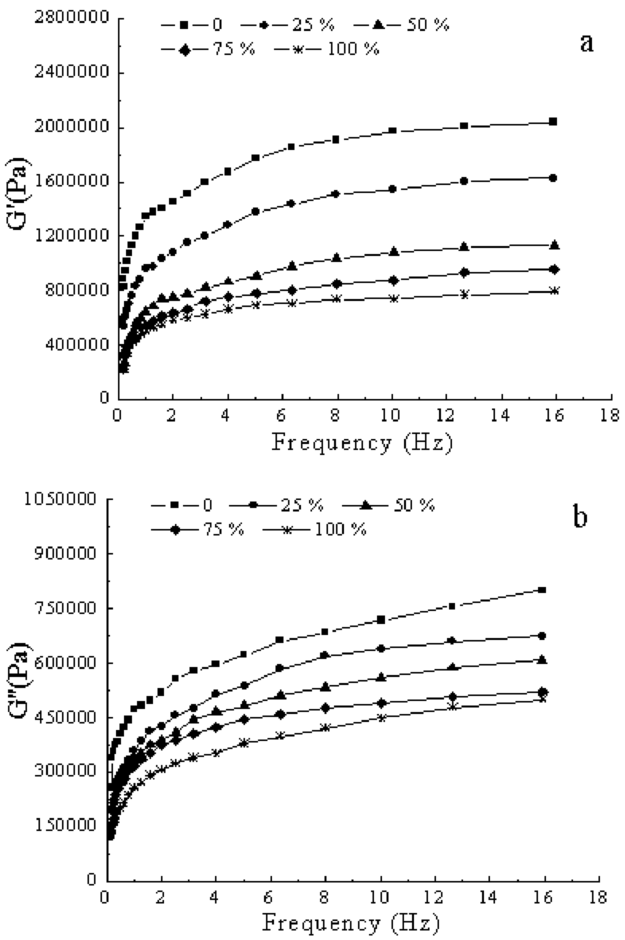

Figure 3. Effect of whole wheat flour on the rheological properties of Sachima dough. (a). G': storage modulus; (b). G'': loss modulus. (WWF substitution level: ■ 0% control, ● 25%, ▲ 50%, ◆ 75%, * 100%)

3.4. Effect of Whole Wheat Flour on the Thermal Properties of Sachima Dough and Fried Sachima Sticks

The effect of WWF on the gelatinization properties of Sachima dough can be observed by DSC. The onset (T_o), peak (T_p) and conclusion (T_c) temperatures are shown in Table 4, as well as the enthalpy for gelatinization (ΔH_g) calculated from the depth and area of the endothermic peak. T_o increased from 60.02 to 63.18 °C, and T_p increased from 65.60 to 67.88 °C. Both of these changes were significantly affected by increasing the substitution levels of WWF from 25 to 100% in the dry mix ($p < 0.05$). As described earlier, dough incorporating WWF had a shorter relaxation time (T_2) compared with the control sample because of the competition for water between the arabinoxylans matrix in WWF and the starch. Conversely, increasing levels of WWF showed the reverse effect on T_c and ΔH_g. T_c decreased significantly ($p < 0.05$) from 86.26 to 83.58 °C as WWF substitution levels increased from 0 to 50%. However, it decreased slightly when WWF substitution increased from 50 to 100%. ΔH_g decreased significantly ($p < 0.05$) when WWF substitution levels increased from 25 to 100%. This observation indicated that adding WWF led to fewer energy for starch gelatinization in Sachima dough, which might be because of fewer amylose content in WWF [29].

The DSC method has also been regarded as a reliable technique for the determination of oil content, being faster and easier to perform compared with the conventional solvent extraction method [12]. The values of crystallization temperatures and enthalpies (ΔH_c) of fried Sachima sticks are shown in Table 4. Both T_o and T_p decreased with increasing WWF substitution in the two narrow ranges of 6.07-6.48 and 1.45-2.08 °C. As proposed by Gamonpilas et al. [12], higher values of ΔH_c meant higher oil content, based on the crust sample showing a similar crystallization temperature to the deep-frying oil. As can be seen in Table 4, the values of ΔH_c from fried Sachima sticks showed a substantial decline as WWF substitution levels increased. When all the RWF was replaced by WWF, the ΔH_c value decreased to 19.33 J/g, a 39.1% reduction from the control value.

Table 4. Effect of whole wheat flour on the DSC parameters of Sachima dough and fried Sachima sticks

Level of WWF substitution	Sachima dough				Fried Sachima sticks			
	T_o (°C)	T_p (°C)	T_c (°C)	ΔH_g (J/g)	T_o (°C)	T_p (°C)	T_c (°C)	ΔH_c (J/g)
0% (Control)	60.02 ±0.30 ^{a}	65.60 ±0.29 ^{a}	86.26 ±0.20 ^{d}	2.689 ±0.20 ^{c}	6.48 ±0.17 ^{c}	2.08 ±0.08 ^{d}	-44.82 ±0.54 ^{c}	31.74 ±0.62 ^{e}
25% ^{A}	61.01 ±0.23 ^{b}	66.27 ±0.27 ^{b}	85.38 ±0.32 ^{c}	2.642 ±0.19 ^{bc}	6.39 ±0.22 ^{c}	1.94 ±0.07 ^{cd}	-43.27 ±0.85 ^{ab}	28.58 ±0.71 ^{d}
50%	61.76 ±0.26 ^{c}	66.70 ±0.24 ^{c}	83.58 ±0.28 ^{b}	2.44 ±0.15 ^{bc}	6.22 ±0.09 ^{bc}	1.82 ±0.09 ^{b}	-42.26 ±0.50 ^{a}	24.32 ±0.81 ^{c}
75%	62.73 ±0.19 ^{d}	67.44 ±0.30 ^{d}	83.28 ±0.23 ^{ab}	2.32 ±0.17 ^{ab}	6.10 ±0.08 ^{a}	1.60 ±0.09 ^{b}	-44.19 ±0.78 ^{bc}	20.72 ±0.40 ^{b}
100%	63.18 ±0.17 ^{e}	67.88 ±0.32 ^{e}	83.00 ±0.29 ^{a}	2.05 ±0.14 ^{a}	6.07 ±0.16 ^{a}	1.45 ±0.09 ^{a}	-43.80 ±0.84 ^{bc}	19.33 ±0.63 ^{a}

Data are expressed as mean ± SD (n = 3). Values in the same column with different superscript letters are significantly different (p< 0.05). The letter 'a' denotes the lowest value.
^{A}: the levels of RWF replaced by WWF.

3.5. Effect of Whole Wheat Flour on the Microstructure of Fried Sachima Sticks

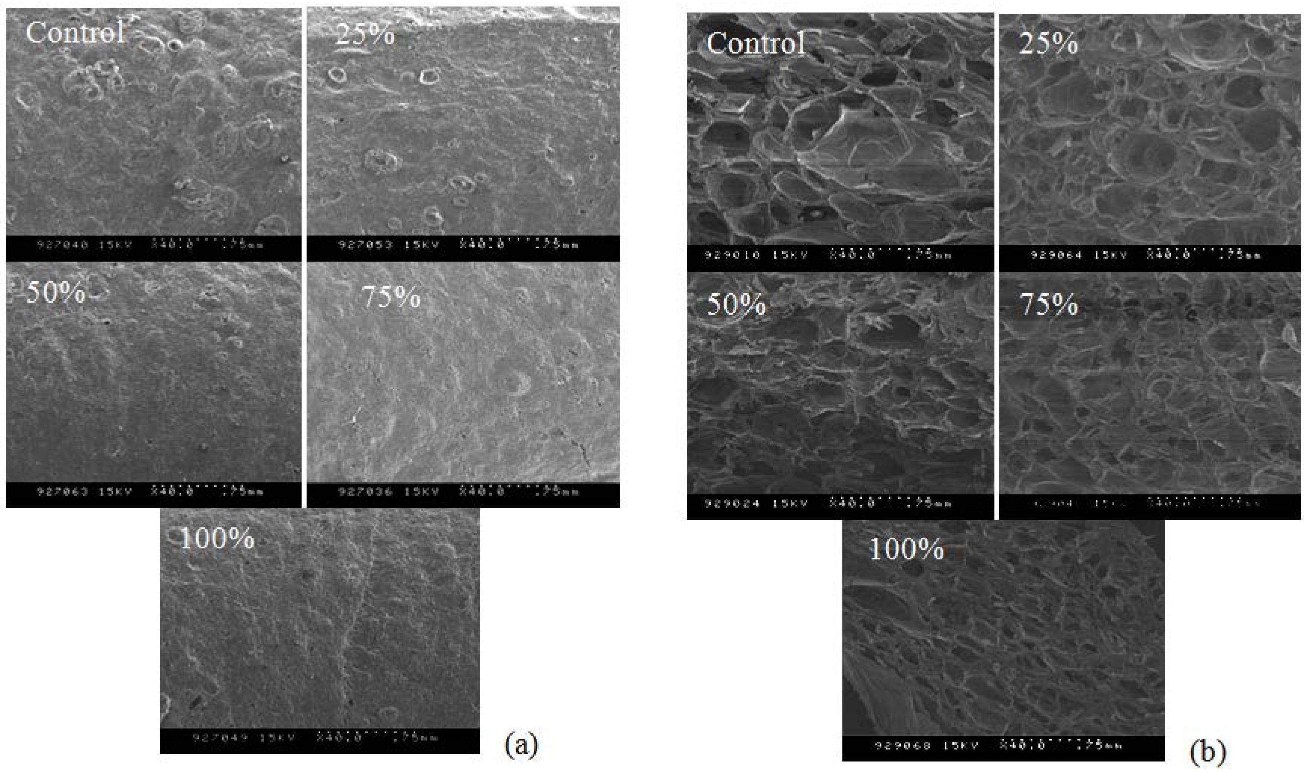

Figure 4. Effect of whole wheat flour on the surface (a) and inner section (b) scanning electron micrographs of fried Sachima sticks Control, 25%, 50%, 75%, and 100% meant the WWF substitution level was 0, 25%, 50%, 75%, and 100%, respectively.

It is recognized that oil absorption should be essentially a surface-related phenomenon: Moreno et al. reported that the surface characteristics of fried foods, particularly the geometrical irregularities or roughness, were highly important in oil absorption kinetics [30]. Figure 4(a) shows scanning electron micrographs of the outer surface of fried Sachima sticks with different WWF substitution levels. The control group had the most collapsed voids, which were widely distributed over the surface as a result of a great deal of moisture evaporation during deep-frying. However, the replacement of RWF with WWF distinctly reduced the number of voids and higher WWF substitution caused a smoother surface structure with fewer and smaller voids. The analogous effect was confirmed by Heo et al. [16], who compared instant fried noodles with or without β-glucan enriched materials (obtained from *lentinus edodes* mushrooms). They suggested that the dense crust would act as a barrier for resisting oil absorption, resulting in lower oil content.

As shown in Figure 4(b), the pores in the inner structure of fried Sachima sticks were smaller and less homogeneous when the WWF substitution levels increased, while the control group had an ideal expanded structure with uniform and large pores. Besides the diluting effect by adding WWF to dry mix, the arabinoxylan matrix in WWF could compete with the gluten for the water [23], thus inhibiting the formation of the gluten network and leading to a poorly expanded porous texture in fried Sachima sticks. Consequently, the substitution of WWF in formula dry mixes of Sachima could affect the surface and inner structure to reduce oil absorption, as expected from the mass transfer results presented in Figure 1 and Table 2.

4. Conclusions

The MC and SOC of fried Sachima sticks during deep-frying were linearly correlated for all levels of WWF substitution ($R > 0.98$). The kinetic coefficients for the transfer of moisture and oil decreased significantly with increasing levels of WWF. Water-binding capacity in Sachima dough was enhanced by WWF with an decreased level of spin-spin relaxation time (T_2) of water molecules. The G' and G" of Sachima dough reduced as the substitution levels of WWF increased. The temperature of starch gelatinization of Sachima dough was increased by WWF, while the gelatinization enthalpy (ΔH_g) of Sachima dough and crystallization enthalpies (ΔH_c) of fried Sachima sticks decreased. These results indicated that WWF has a significant effect on resisting water evaporation and oil absorption by affecting the water state and thermal properties of Sachima dough.

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Conflicts of Interest

The authors state that they have no conflicts of interest.

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