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Research Article

Batter Characteristics and Oil Penetration of Deep-Fried Breaded Fish Nuggets: Effect of Wheat Starch—Gluten Interaction

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To understand the effect of the interaction between wheat starch (WS) and wheat gluten (WG) on batter characteristics and oil penetration of deep-fried breaded fish nuggets, batters were prepared using a WS and WG blend at the ratios of 15 : 1, 13 : 1, 11 : 1, 9 : 1, and 7 : 1 w/w, respectively, and batter-breaded fish nuggets (BBFNs) were fried at 170°C for 40 s followed by 190°C for 30 s. Moisture adsorption isotherms of WS and WG, viscosity, rheological behavior, and calorimetric properties of the batters were measured, and pick-up of BBFNs, thermogravimetric properties of the crust, and oil transport were investigated. The moisture absorption capacity of WG was higher than WS at a low water activity (0.04–0.65), while the opposite trend was observed at a highwater activity (0.65–0.88). As the proportion of WS decreased, the viscosity, G" and tan δ of batter, pick-up of BBFNs, temperature and enthalpy change (ΔH) of protein denaturation and WS gelatinization, and oil penetration of BBFNs during deep-fat frying, which are decreased until reaching a minimum value at the ratio of 11 : 1 w/w, then increased ($p < 0.05$). However, G' of batter and thermogravimetry temperatures of crust exhibited the opposite trend. These results proved that the WS–WG interaction significantly affected the batter characteristics and oil penetration of BBFNs during deep-fat frying, which can be used to guide the manufacturing of low-fat fried BBFNs.

1. Introduction

Fried batter-breaded foods, with tender and crispy textures, are popular food items all over the world [1–3]. However, the golden protective layer (crust), formed during deep-fat frying, contains excess fat while over-intake of these fried foods may cause obesity and negatively impact human health, leading to potential risks of cardiovascular disease and hypertension [4, 5]. Therefore, there has been an increasing interest to reduce the fat content of fried foods by changing the formulation of batter in recent years [6].

A batter, typically consisting of flour, water, seasonings, and other ingredients, is a highly-complex system employed for fried foods, and it is affected by the interactions among components [7]. During deep-fat frying, the crust is formed due to the gelatinization of starch and denaturation of protein, which inhibits the evaporation of moisture and changes the surface structure, resulting in the low-fat content of fried foods [3, 8]. The mechanism of fat-absorption reduction may result from the interaction between wheat starch (WS) and wheat protein, which affects the viscosity, rheological properties, and thermal properties of batter and pick-up of batter-breaded foods [9, 10]. It was reported that a starch-protein complex was formed when gelatinized starch penetrated into the denatured protein network during deep-fat frying, which made the gel network tighter and more compact [11, 12]. The formulation becomes the key factor that affects the characteristics of the batter.

However, the effect of the interaction between WS and wheat protein on the batter characteristics, resulting in a reduction of fat absorption, has not been clearly explained.

We had reported that WS-WG interaction in the batter significantly affected the quality attributes of fried batter-breaded fish nuggets (BBFNs) and also inhibited oil penetration, when fried BBFNs were prepared by treating fish with batters composed of WS and wheat gluten (WG) blends at five ratios [13]. However, there is scarce information on the effect of WS-WG interaction on the batter characteristics, leading to a difficult understanding of the relationship between quality attributes of fried BBFNs and formulations of batter. Therefore, the main objectives of this present work were to determine the rheological behavior and calorimetric properties of batters prepared with WS and WG at various ratios, pick-up of BBFNs, thermogravimetric properties of the crust, and oil transport during deep-fat frying, and to analyze the effect of WS–WG interaction on the batter characteristics and oil penetration.

2. Material and Methods

2.1. Materials

2.1.1. Organic/Biological Materials. Frozen silver carp surimi with 3.0% sodium tripolyphosphate was provided by Honghu Jinli Aquatic Food Co., Ltd. (Honghu, China). WS (starch content 87.2%, moisture content 10.9%, and damaged starch content 10.8%) and WG (protein content 83.1%, moisture content 7.6%) were purchased from Beijing Ruimaijiahe Food Co., Ltd. (Beijing, China). Breadcrumbs of < 2 mm particle size were provided by Wuxi Jinhuanghua Food Co., Ltd. (Wuxi, China).

2.1.2. Chemicals. Sudan Red B was purchased from Shanghai Hengdailao Biological Co., Ltd. (Shanghai, China). Sulfuric acid was purchased from Sinopharm Chemical Reagent Co., Ltd. (Beijing, China).

2.2. Determination of Moisture Adsorption Isotherm. Two groups of WS and WG (1.5 g, five samples for each group) were individually aliquoted into aluminum cups, then these cups were placed in a desiccator with a controlled water activity (a_w) of 0.88, 0.75, 0.56, 0.34, and 0.04 at 20 ± 0.5°C, respectively, via different concentrations of sulfuric acid solutions [14]. The weight of aluminum cups was measured every 12 h until they reached a constant weight. The moisture content at equilibrium was determined through a mass balance according to the AOAC [15]. Adsorption isotherms (curves of equilibrium moisture content vs. a_w) were analyzed according to the Guggenheim-Anderson-de Boer (GAB) classical model, which assumes a multilayer adsorption [16–18].

$$X = X_0 \frac{CKa_w}{(1 - Ka_w)(1 - Ka_w + CKa_w)}, \quad (1)$$

where X and X_0 refer to the moisture content and the saturated adsorption capacity of water, respectively; K represents the equilibrium constant for adsorption; C is a constant that represents the difference in free enthalpy of the water molecules in the pure liquid and adsorbed states.

Table 1: Formula of the batter (WS and WG represent wheat starch and wheat gluten, respectively).

WS : WG, w/w	WS (g)	WG (g)	Water (g)
15 : 1	93.7	6.3	98.0
13 : 1	92.9	7.1	98.0
11 : 1	91.7	8.3	98.0
9 : 1	90.0	10.0	98.0
7 : 1	87.5	12.5	98.0

2.3. Preparation and Characterization of Batters

2.3.1. Batter Preparation. Batters were prepared according to the method given in a published report [13] with slight modifications. The mixture of WS and WG (100 g) at five ratios (15 : 1, 13 : 1, 11 : 1, 9 : 1, and 7 : 1, w/w) and deionized water (98 g) were mixed according to Table 1, and the resultant batter was prepared by stirring at 1000 rpm for 10 min using an electric mixer (R-30, Yuhua Instrument Co., Ltd., Shanghai, China) to form homogeneous batters.

2.3.2. Measurement of Batter Viscosity. The batter viscosity was measured based on the method developed by [19]. The batter was poured into No. II thermostat cup to ensure the rotor is covered over 1 mm. The NDJ-7 viscometer (Shanghai Jingke Tianmei Trading Co., Ltd., Shanghai, China) was employed for the measurement and the operating temperature was set at 25°C. Once the reading was stable, the data was recorded. The thermostat cup was thoroughly cleaned and dried after each use. The batter viscosity (η; MPa·s) was calculated according to the following equation:

$$\eta = kA, \quad (2)$$

where k and A represent the coefficient of the rotor and the reading of the viscometer, respectively.

2.3.3. Determination of Rheological Moduli. The rheological behavior of the batter was evaluated with temperature sweep in the oscillation mode using a DHR-2 dynamic rheometer (TA Instruments, New Castle, DE, USA) according to the method described in the previous study [20]. An aliquot of 2 g batter in an aluminum plate was placed on the test platform of the rheometer with a 60 mm diameter and 2° gap angle of cone-plate geometry. To avoid moisture evaporation, the batter samples were enclosed within an air escape cover. The determination of the dynamic rheological behavior of the batters was conducted by ramping the temperature from 0°C to 90°C at a heating rate of 2°C/min with a stress amplitude of 0.01 and frequency of 1 Hz. The storage modulus (G'), the loss modulus (G''), and the loss tangent ($\tan \delta = G''/G'$) were recorded.

2.3.4. Differential Scanning Calorimetric (DSC) Analysis. The determination of the calorimetric properties of the batters was performed using a Q-2000 differential scanning calorimeter (TA Instruments, New Castle, DE, USA). An aliquot of 5 mg batter was added to a stainless-steel pan and hermetically sealed. An empty pan was served as the reference. The pans were equilibrated at 25 ± 1°C for 5 min and then heated to 130°C within 9 min. The onset temperature ($T_{0,i}$), peak temperature ($T_{p,i}$), and enthalpy change (ΔH_i) of starch gelatinization or protein denaturation for component i (i represents WS or WG) were analyzed with the TA Universal Analysis 2000 software.

2.4. BBFN Preparation and Pick-Up. Frozen silver carp surimi was cut into small pieces followed by thawing at room temperature (25 ± 1°C). An aliquot of 300 g thawed silver carp surimi was added to a Model HR 7633 chopper mixer (Philips Household Appliances Co., Ltd., Zhuhai, China), and finely chopped at 1200 rpm for 5 min. Subsequently, an aliquot of 3 g salt with NaCl (food grade) was added, and the mixture was chopped for another 7 min at 2000 rpm. The minced surimi was processed into fish nuggets (5.8 ± 1 g, 6 cm × 1.5 cm × 1.5 cm). The fish nuggets were immediately immersed into the batter for 10 s and then allowed to drain for 15 s. The process was repeated until the liquid drainage disappeared. Finally, the fish nuggets were rolled with breadcrumbs to obtain uniform coverage.

The pick-up (the weight ratio of batter to BBFNs) was calculated according to the following equation reported by Salvador et al. [21]:

$$\text{Pick} - \text{up}/\% = \frac{A_1 - A_2}{A_1} \times 100, \quad (3)$$

where A_1 and A_2 represent the total weight of BBFNs (g) and the weight of fish nuggets (g), respectively.

2.5. Process and Analyses of Fried BBFNs

2.5.1. Frying Process. A blast drying oven (101-BS, Shanghai Yuejin Medical Equipment Co., Ltd, Shanghai, China) was employed for the frying process. BBFNs were first fried at 170°C for 40 s and then fried at an increased temperature (190°C) for 30 s. Before the analysis of the thermodynamic properties of the crust, the fried BBFNs were drained to remove excess oil and cooled at room temperature (25 ± 1°C) for 1 h in a stainless-steel strainer.

2.5.2. Thermogravimetric Analysis (TGA) of Crust. The crust of fried BBFNs was peeled off and crushed with a FW80 high-speed pulverizer (Zhengzhou Kefeng Instrument Co., Ltd., Zhengzhou, China), then sieved with a 100-mesh sieve. An aliquot of 5 g crushed crust was added to aluminum oxide pans equipped with the TGA/DSC1 thermogravimetric analyzer (Mettler-Toledo International Co., Ltd., Shanghai, China), and the temperature was increased from 20°C to 700°C at a rate of 10°C/min, then cooled from 700°C to 500°C at a rate of 20°C/min under a nitrogen flow rate of 60 mL/min. An empty aluminum oxide pan was used as the reference. The differential thermogram (DTG) curve of the crust was obtained by converting the thermal weight (TG) spectrum to derivative weight percent using the STARe evaluation software [22].

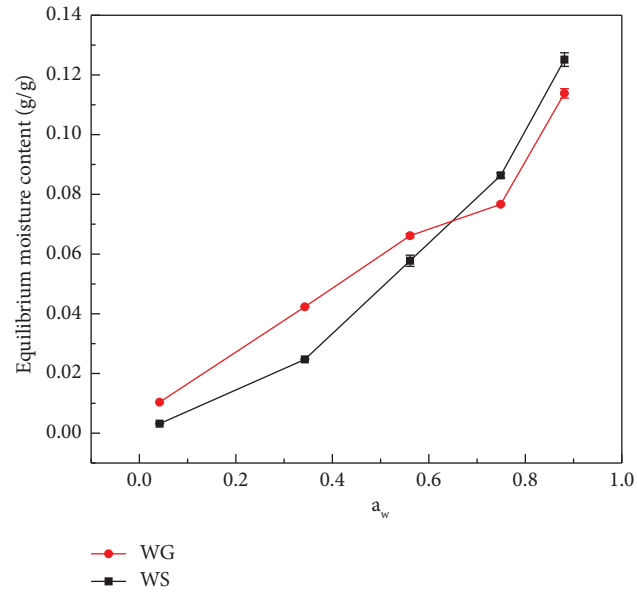

Figure 1: Moisture adsorption isotherms for WS and WG. WS and WG represent wheat starch and wheat gluten, respectively.

2.5.3. Oil Transport Examined by Optical Microscopy. Sudan red B (0.75 g) was dissolved in the soybean oil (1.5 L) and heated at 60°C for 4 h to make a uniform dyed oil [23]. BBFNs were fried according to the aforementioned frying procedure. After being cooled to room temperature (25 ± 1°C), fried BBFNs were cut into thin slices (5 mm × 3 mm × 3 mm) from the junction between the crust and core. An optical microscope (Shanghai BM optical instrument manufacturing Co., LTD, Shanghai, China) was used to observe the oil transport phenomenon across the cross-section at 4x magnifications in the reflective mode.

2.6. Statistical Analysis. Analyses were performed in triplicate. The results were expressed as a mean ± standard deviation. The data obtained were subjected to statistical analysis using the SPSS software (Version 17.0; SPSS Inc., Chicago, IL, USA). The comparison of means was performed by Duncan's multiple range tests, and the statistically significant difference was defined at a level of $p < 0.05$.

3. Results and Discussion

3.1. Moisture Adsorption Isotherms for WS *and* WG. The moisture adsorption isotherm represents the relationship between a_w and moisture content (the weight of water per unit weight of dry matter) at a constant temperature, reflects the ability of WS and WG to bind water [24]. As depicted in Figure 1, the equilibrium moisture content of WS increased steadily with an increase of a_w for a_w <0.74, and to an even

Table 2: Effect of the WS : WG ratios on the viscosity of batter and the pick-up of BBFNs (WS and WG represent wheat starch and wheat gluten, respectively; data are presented as mean value ± standard deviations from triplicate experiments ($n = 3$); mean values listed in columns with different letters indicate statistically significant differences ($p < 0.05$)).

WS : WG (w/w)	Viscosity (MPa.s)	Pick-up (%)
15 : 1	397 ± 6^{b}	36.0 ± 0.6^{a}
13 : 1	373 ± 6^{c}	29.6 ± 0.5^{c}
11 : 1	340 ± 10^{d}	27.1 ± 0.7^{d}
9 : 1	387 ± 6^{b}	30.1 ± 0.4^{c}
7 : 1	443 ± 6^{a}	33.8 ± 0.7^{b}

greater extent for a_w >0.74, which represents a type III isotherm [25]. For the moisture adsorption isotherm of WG, the equilibrium moisture content of WG increased rapidly when the a_w was between 0.04 and 0.56. However, the equilibrium moisture content experienced a slower increase when a_w ranged from 0.56 to 0.75. Finally, it rose sharply again after 0.75 with the fastest rate. This indicated that the WG adsorption isotherm had a type II characteristic, and the shape was an anti-"S" type. Both equilibrium adsorption isotherms of WG and WS fit well into the GAB model. The equation with the relationship between moisture content (X) and a_w for WG ($X = 0.2483a_w/(1 - 7.4521a_w)(1+ 44876a_w)$) and WS ($X = 0.0625a_w/(1 - 0.6468a_w)(1+ 0031a_w)$) were fitted, and the R^2 was 0.9577 and 0.9972, respectively. The results were similar to those of Roman–Gutierrez et al. [25] and Moreira et al. [26].

Before the WS adsorption curve exceeded WG (i.e., a_w with 0.04–0.65), the equilibrium moisture content of WS was lower than WG. However, the equilibrium moisture content of WS rose faster than that of WG after the intersection. The initial moisture content (total content of bound water and free water) of WS and WG was 0.11 g/g and 0.08 g/g, respectively (Figure 1). According to the equation of the GAB model, the initial water activity ($a_w = 0.83$) of WS was slightly higher than WG ($a_w = 0.74$). This observation suggested that WG had a stronger water-binding ability than WS. In addition, the water in isothermal interval II (a_w of 0.15–0.7) is multilayer bound water, which can bind to the acylamino and sulfhydryl groups in protein and hydroxyl groups in starch by hydrogen bonds, the equilibrium moisture content of the WS and WG in the isothermal interval II at a certain temperature and a_w reflects its water absorption capacity [27]. Figure 1 indicates that WG had a stronger water absorption capacity than WS.

3.2. Characteristics of Batters

3.2.1. Viscosity and Pick-Up. The viscosity of batter and the pick-up of BBFNs at five WS : WG ratios are shown in Table 2. It is apparent that the lowest viscosity (340 MPa.s) and pick-up (27.1%) were obtained for a WS : WG ratio of 11 : 1 w/w. For WS : WG ratios below 11 : 1 w/w, the viscosity and pick-up decreased with the increasing ratio of WS : WG, while the opposite trend occurred for the ratios above 11 : 1 w/w. Other studies also suggested the importance of starch/protein concentration on viscosity [21, 28, 29]. The surface of high-purity WS granules often suffered mechanical damage during an extraction process [30]. Since the swelling power of starch granules in cold and hot water increased with the degree of damage (except when the damage was excessively severe) [31], exposed starch granules were expected to be more soluble in water, thereby increasing the batter viscosity [32, 33]. When starch was added to the batter at a high ratio (WS : WG ratio of 15 : 1 w/w), the damaged WS granules underwent full-swelling during the stirring process, which increased the batter viscosity (397 MPa.s), resulting in a high pick-up (36.0%). A similar pick-up (36.1%) was obtained by adding low cross-linking tapioca starch into the batter of fried chicken [34]. As the WS : WG ratio decreased from 15 : 1 w/w to 11 : 1 w/w, a decrease in viscosity and pick-up was observed, resulting from the greater diffusion of swollen and deformed WS granules into the WG gel network during the stirring process [35], with the enhancement of WS–WG interaction (through intermolecular hydrogen bonds formed by the high levels of glutamic acid and hydroxylated amino acids in WG), which led to enhanced fluidity of the batter, thereby resulting in the decrease of batter viscosity [27]. Besides, the interaction between WS and WG could alter the behavior of moisture absorption, perhaps through an exterior layer formed by WG that would hinder the diffusion and absorption of water [36, 37]. The high viscosity observed for the lowest WS : WG ratio could be ascribed to a stronger WG gel network, which led to a larger retention of moisture.

3.2.2. Rheological Moduli. Dynamic rheology was used to determine the viscoelastic moduli for the batter prepared using five WS : WG ratios, to judge whether the batter is mainly viscous or elastic. The G' reflects changes in the conformational entropy of curled polymeric chains and is expressed as the elasticity of batter, while G'' refers to the viscosity deformation caused by the relative movement of segments, molecular chains, and the energy loss caused by internal friction, which is expressed as the viscosity of batter [38]. The tan δ was used to express the relative viscoelastic characteristics. When the tan δ is less than 1, it represents a dominant elastic feature; if the value is larger than 1, it is characterized by viscosity [39].

The rheological behaviors of batters are depicted in Figure 2. The trend of the G' and G'' vs. temperature profiles at five WS : WG ratios were similar (Figures 2(a) and 2(b)). The profiles can be divided into three stages. G' and G'' of five batters increased slowly with an increasing temperature at the first stage (<40°C). As the temperature rose, the gel network formed by denatured WG would be filled with the swollen and deformed WS granules, which might promote cross-linking between WG and WS molecules into a three-dimensional gel, leading to increasing viscoelasticity [28, 38, 40].

Among five WS : WG ratios, the lowest G' of batter was observed for a WS : WG ratio of 7 : 1 w/w at the first stage of heating (<40°C), while G' for the 15 : 1 w/w ratio was the

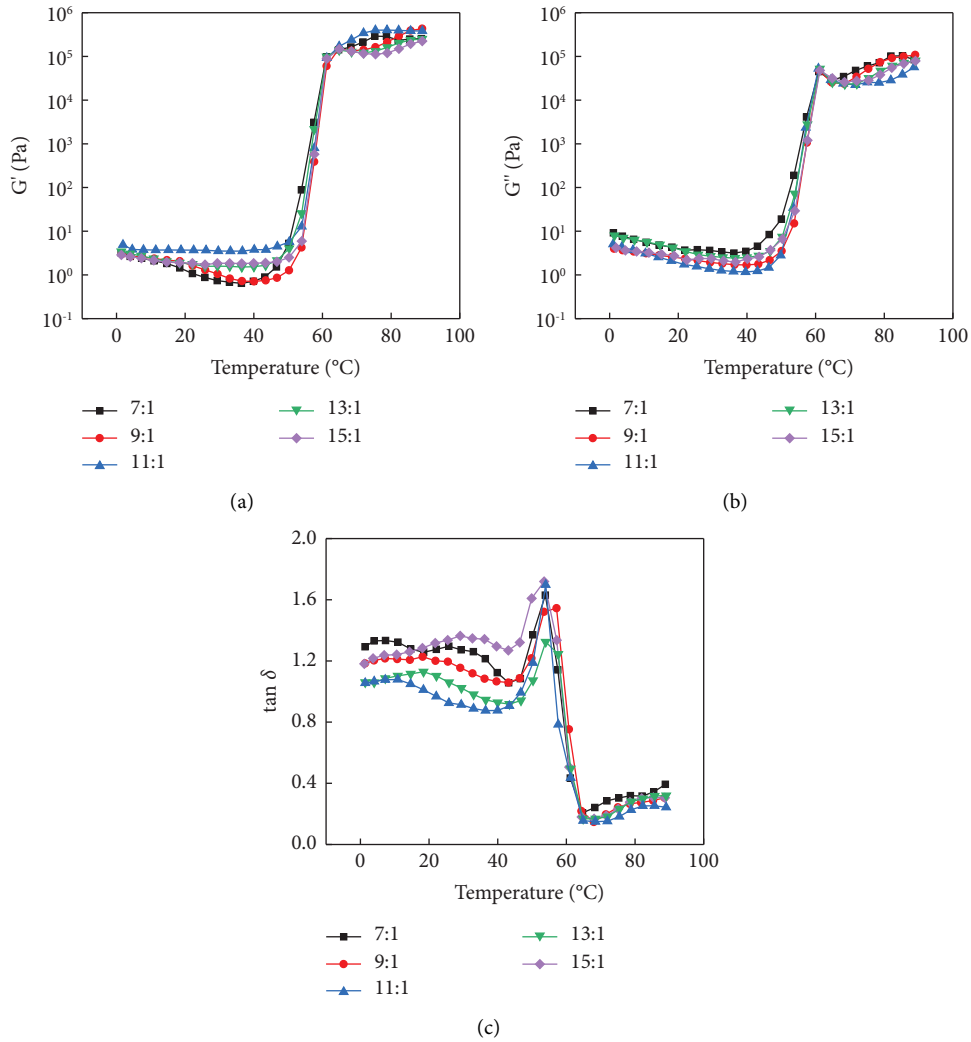

FIGURE 2: Effect of the WS : WG ratios on the rheological behavior of the batter. (a), (b), and (c) represent the storage modulus (G'), the loss modulus (G''), and the loss tangent (tan δ), respectively. Values of the WS : WG ratio (w/w) are given in the legend.

lowest at the third stage (>60°C). At a WS : WG ratio of 11 : 1 w/w, G' was the highest in the first and the third stages, suggesting the highest gel elasticity of batter; in contrast, G'' of batter was the highest for the lowest WS : WG ratio (7 : 1 w/w) throughout the entire temperature range, reflecting a high viscosity occurred at the highest WG content. The lowest G'' (i.e. the lowest viscosity) was observed for an 11 : 1 w/wWS : WG ratio at all temperatures, allowing the batter to more readily undergo polymerization [38]. Among the composite gels formed, the lowest gel elasticity and the weakest gel were obtained for a WS : WG ratio of 15 : 1 w/w, while an 11 : 1 w/w ratio provided the strongest elastic gels because the gel had the best moisture-holding capacity and the lowest fat absorption [13]. A similar result was also reported by Xue and Ngadi [29].

As depicted in Figure 2(c), tan δ vs. temperature profiles at five WS : WG ratios were similar and can be divided into four stages. At the initial stage of heating (0–45°C), tan δ was mostly above 1.0 but fluctuated with time, and the batter presented a viscous sol. When the heating temperature was higher than 45°C (the second stage), tan δ increased sharply as a result of the batter viscosity increased due to the water-swellable starch particles, which strengthen the degree of hydrogen bonding between starch and gluten [40]. The parameter tan δ was maximized at 54°C except for the 9 : 1 w/wWS : WG ratio, coincident with the maximum viscosity of the batter. At the third stage (54–65°C), tan δ decreased sharply with an increase in temperature. It can be seen that as the temperature approached 60°C, tan δ decreased below 1.0, suggesting that gel began to form because of denatured WG and gelatinized WS [38]. At 65°C, the tan δ declined to its lowest value (<0.2), under which conditions the batter was the most elastic. Then, tan δ slightly rose again at the fourth stage of heating (65–90°C), indicating that stable WS-WG composite gels were formed [41].

When tan δ approached 1.0, the ratio of 11 : 1 w/w produced the lowest (gel point) temperature, which meant the gel formation time was the shortest, and the elasticity was the highest among all five batters [38]. With a protective layer, the formation of a mixed WS/WG gel could inhibit

Table 3: Effect of the WS : WG ratios on the calorimetric parameters of batter (WS and WG represent wheat starch and wheat gluten, respectively; $T_{0,i}$ and $T_{p,i}$ refer to the temperatures of starch gelatinization or protein denaturation required for the initial and maximum peak values, respectively, and ΔH_i represents the amount of crystal melting during gelatinization for component i; data are presented as mean value ± standard deviations from triplicate experiments ($n = 3$); mean values listed in columns with different letters indicate statistically significant differences ($p < 0.05$)).

WS : WG (w/w)	$T_{0,\ WS}$ (°C)	$T_{p,\ WS}$ (°C)	ΔH_{WS} (J/g)	$T_{0,\ WG}$ (°C)	$T_{p,\ WG}$ (°C)	ΔH_{WG} (J/g)
WS	47.0 ± 0.1	59.3 ± 0.4	28.3 ± 0.3			
WG				86.4 ± 0.52	91.0 ± 0.3	33.6 ± 0.2
15 : 1	55.4 ± 0.1[a]	60.6 ± 0.5[a]	2.1 ± 0.1[a]	101.3 ± 0.0[a]	105.9 ± 0.0[a]	0.64 ± 0.0[a]
13 : 1	54.7 ± 1.0[a]	60.0 ± 1.2[a]	2.2 ± 0.0[a]	97.3 ± 0.1[a]	98.9 ± 0.2[c]	0.49 ± 0.1[a]
11 : 1	55.5 ± 0.3[a]	60.3 ± 0.5[a]	2.6 ± 0.3[a]	93.5 ± 0.1[a]	94.3 ± 0.0[e]	0.32 ± 0.0[a]
9 : 1	55.5 ± 1.6[a]	60.6 ± 0.4[a]	2.1 ± 0.1[a]	94.8 ± 0.2[a]	96.0 ± 0.3[d]	0.39 ± 0.0[a]
7 : 1	57.9 ± 1.7[a]	60.0 ± 0.9[a]	2.5 ± 0.4[a]	98.3 ± 0.3[a]	100.3 ± 0.5[b]	0.58 ± 0.1[a]

moisture evaporation and alleviate oil penetration during deep-fat frying. The oil transport experiment supported this premise (described later).

3.2.3. Calorimetric Properties. The effect of the WS : WG ratio on the calorimetric parameters is shown in Table 3. $T_{0,i}$ and $T_{p,i}$ refer to the temperatures of starch gelatinization or protein denaturation required for the initial and maximum peak values, respectively, and ΔH_i represents the amount of crystal melting during gelatinization for component i. ΔH for starch reflects the breaking of hydrogen bonds, which turns starch from a semicrystalline state into a soluble state; ΔH for protein represents the net caloric change, which was involved in the unfolding of the native structure and the formation of new bonds among protein molecules [42, 43].

The gelation temperatures for WS and WG, 59.3°C ($T_{p,WS}$) and 91.0°C ($T_{p,WG}$), respectively, were consistent with the results of Yu et al. [39]. The formation of a WS-WG mixture did not change $T_{p,WS}$ appreciably. However, it led to a significant decrease of enthalpy for WS and WG and an increase of $T_{0,WG}$, $T_{p,WG}$, and $T_{0,WS}$, the latter trend is indicative of an increase in thermal stability [43]. Compared to individual WS or WG, all mixtures of WS-WG reduced the free water of batter and inhibited the gelatinization of starch by limiting the swelling of WS due to WG strong absorption of water. Ribotta et al. found that the denatured polypeptides would also form a gel network to envelop some starch granules and inhibit the swelling and gelatinization of WS, leading to an increase in $T_{0,WS}$ and a decrease in ΔH for starch gelatinization [44]. In the case of protein denaturation, the increased $T_{0,WG}$ and $T_{p,WG}$ might result from hydrophilic interaction with water, which reduced the free water content, leading to less efficient heat transfer to the unfolding of initiate protein [45]. The WS–WG interaction decreased ΔH or energy requirement for starch gelatinization or protein denaturation and promoted batter gelation during deep-fat frying [44, 45].

There were no significant differences in values of $T_{0,WS}$, $T_{p,WS}$, and ΔH_{WS} among the five WS : WG ratios ($p > 0.05$). When the ratio of WS : WG was 11 : 1 w/w, the $T_{0,WG}$, $T_{p,WG}$, and ΔH_{WG} were the lowest, which indicated that the gel point temperature was the lowest among the five batters, and the thermal stability of gel was the highest [46]. This result is consistent with the rheological behavior of the batter (Figure 2).

3.3. Analyses of Fried BBFNs

3.3.1. TGA of Crust. TG and DTG curves represent the relationship between weight change and temperature, and between the rate of weight change and temperature, respectively. The temperature corresponding to the peak for a given heating stage of the DTG is used to analyze thermal stability [47]. The effect of the WS : WG ratio on TG and DTG curves for the crust of fried BBFNs is depicted in Figure 3. It could be seen from the curves that the weight loss of the crust was divided into two stages. The weight loss of the first stage might be determined by the evaporation of moisture and decomposition of fat, while the weight loss of the second stage resulted from the depolymerization of WS -WG gel. Meanwhile, a small peak appeared in the DTG curve at approximately 220°C in all five crusts, indicating that the crusts started to lose moisture, after which the rate of weight loss increased rapidly. At the initial stage of heating, the DTG curve did not vary significantly with the WS : WG ratio (285–287°C). With continued heating, depolymerization and decomposition of high-molecular weight WS and WG would occur, resulting in the loss of WS-WG gel weight [48, 49]. As the WS : WG ratio decreased from 15 : 1 w/w to 11 : 1 w/w, the maximum temperature increased. However, a further ratio decrease led to a slight decrease in the temperature. The 11 : 1 w/wWS : WG ratio showed a maximum decomposition rate at 393°C, indicating the highest thermal stability, a thermostable gel was formed during deep-fat frying that was not easy to decompose, which hindered the moisture evaporation in the crust and further reduced the fat content of fried BBFNs [13, 50].

3.3.2. Oil Transport Examined by Optical Microscopy. Sudan red B, a thermostable and fat-soluble dye, possesses similar penetration behavior as a frying oil, which can be used as a marker to locate oil present within fried batter-breaded foods [23, 51]. The penetration of frying oil into fried BBFNs was observed by frying the BBFNs in oil dyed with Sudan red B (Figure 4). The oil penetration mainly occurred within the crust and with the interface between the crust and core, and the oil did not reach up to the core region, except for the 15 : 1 w/w and 7 : 1 w/wWS : WG ratios. The WS : WG ratio significantly influenced the oil

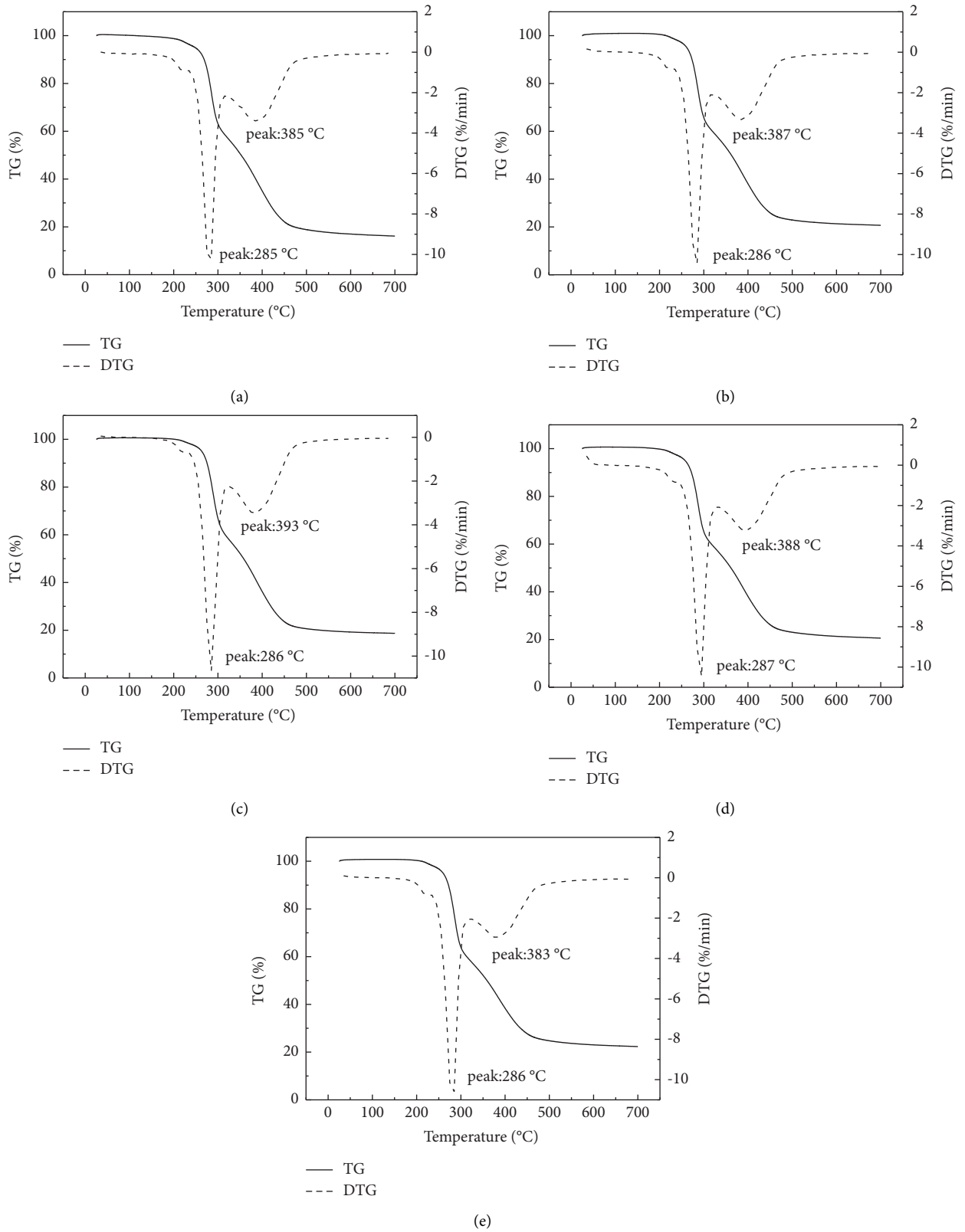

Figure 3: Effect of the WS : WG ratios on the thermal parameters of the crust. (a–e) refer to the WS : WG ratios of 15 : 1, 13 : 1, 11 : 1, 9 : 1, and 7 : 1 w/w, respectively.

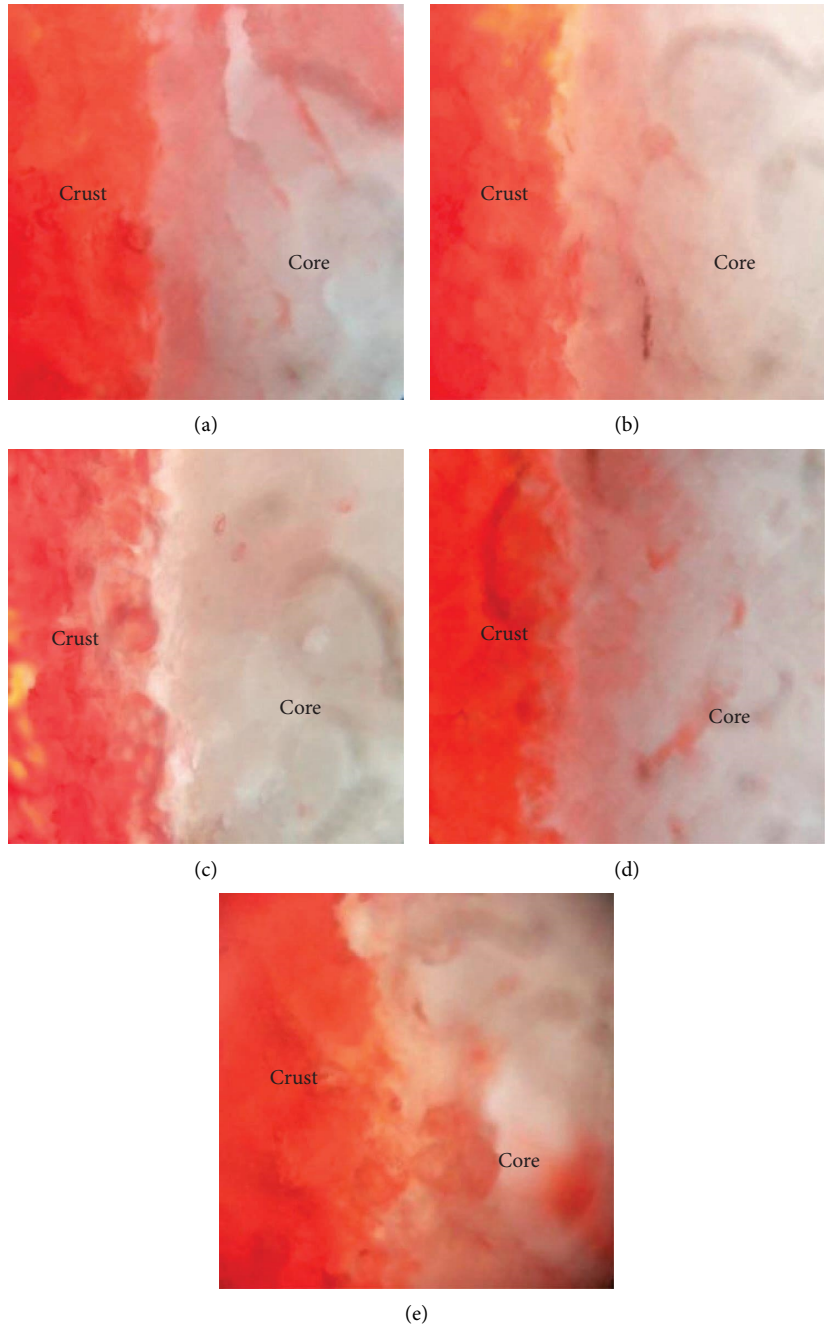

Figure 4: Effect of the WS : WG ratios on oil penetration of fried BBFNs. All the images were taken at 4x magnification in reflective mode. (a–e) refer to the WS : WG ratios of 15 : 1, 13 : 1, 11 : 1, 9 : 1, and 7 : 1 w/w, respectively.

penetration into fried BBFNs. The depth of oil penetration was first decreased and then increased as the WS : WG ratio was decreased, and the 11 : 1 w/wWS : WG ratio produced the lowest oil penetration within the crust and at the interface between the crust and the core. Furthermore, the red illumination was observed in the core region with the 15 : 1 w/w and 7 : 1 w/wWS : WG ratio. Results from the oil transport analysis were in accordance with the rheological behavior, calorimetric properties of the batters, and thermogravimetric properties of the crust, confirming that the WS-WG interaction significantly affected the batter characteristics, leading to the change in oil penetration of BBFNs with five WS : WG ratios during deep-fat frying [13].

4. Conclusions

The WS : WG ratio strongly impacted the viscosity, rheological behavior, and calorimetric properties of a wheat starch-based batter, the pick-up of BBFNs, the thermogravimetric characteristics of crust, with an 11 : 1 w/wWS : WG ratio producing the minimum value ($p < 0.05$) of them, leading to the lowest oil penetration. WG acted as a water absorbent, inhibited the

swelling of WS, and increased the gelatinization temperature due to competitively binding-free water in the batter. In addition, the WS-WG interaction promoted the gelatinization of starch and the formation of a protein gel network, further reinforcing the thermal stability of the batter, and resulting in the ridged crust. For these two reasons, more moisture in BBFNs was retained during deep-fat frying, which hindered oil penetration. These results could provide theoretical support to reduce the fat content of fried BBFNs.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Ethical Approval

Ethical approval was not required for this research.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Jiaqi Feng interpreted the results and drafted the first manuscript. Jiwang Chen generated the research concept, designed the original study, interpreted the results, and edited the manuscript. Zijun Yuan performed the experimental research. Chaofan Chen, Wenshui Xia, and E Liao provided technical support. Douglas G. Hayes advised the experimental design and edited the manuscript.

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References

[1] R. G. Brannan, E. Mah, M. Schott et al., "Influence of ingredients that reduce oil absorption during immersion frying of battered and breaded foods," *European Journal of Lipid Science and Technology*, vol. 116, no. 3, pp. 240–254, 2014.

[2] E. K. Oke, M. A. Idowu, O. P. Sobukola, S. A. O. Adeyeye, and A. O. Akinsola, "Frying of food: a critical review," *Journal of Culinary Science & Technology*, vol. 16, no. 2, pp. 107–127, 2018.

[3] A. O. Oladejo, H. Ma, W. J. Qu et al., "Application of pretreatment methods on agricultural products prior to frying: a review," *Journal of the Science of Food and Agriculture*, vol. 98, no. 2, pp. 456–466, 2018.

[4] C. Dourado, C. Pinto, F. J. Barba, J. M. Lorenzo, I. Delgadillo, and J. A. Saraiva, "Innovative non-thermal technologies affecting potato tuber and fried potato quality," *Trends in Food Science & Technology*, vol. 88, pp. 274–289, 2019.

[5] T. V. Gadiraju, Y. Patel, J. M. Gaziano, and L. Djoussé, "Fried food consumption and cardiovascular health: a review of current evidence," *Nutrients*, vol. 7, no. 10, pp. 8424–8430, 2015.

[6] J. T. Liberty, J. Dehghannya, and M. O. Ngadi, "Effective strategies for reduction of oil content in deep-fat fried foods: a review," *Trends in Food Science & Technology*, vol. 92, pp. 172–183, 2019.

[7] P. Varela and S. M. Fiszman, "Hydrocolloids in fried foods. A review," *Food Hydrocolloids*, vol. 25, no. 8, pp. 1801–1812, 2011.

[8] R. Pongsawatmanit, S. Ketjarut, P. Choosuk, and P. Hanucharoenkul, "Effect of carboxy methyl cellulose on properties of wheat flour-tapioca starch-based batter and fried, battered chicken product," *Agriculture and Natural Resources*, vol. 52, no. 6, pp. 565–572, 2018.

[9] S. Ketjarut and R. Pongsawatmanit, "Influence of tapioca starch on thermal properties of wheat flour-based batter and quality of fried battered chicken wingsticks," *International Journal of Food Engineering*, vol. 11, no. 5, pp. 641–650, 2015.

[10] A. Santillán-Moreno, F. Martínez-Bustos, E. Castaño-Tostado, and S. L. Amaya-Llano, "Physicochemical characterization of extruded blends of corn starch–whey protein concentrate- agave tequilana fiber," *Food and Bioprocess Technology*, vol. 4, no. 5, pp. 797–808, 2011.

[11] E. Llorca, I. Hernando, I. Pérez-Munuera, S. M. Fiszman, and Á. M. Lluch, "Effect of frying on the microstructure of frozen battered squid rings," *European Food Research and Technology*, vol. 213, no. 6, pp. 448–455, 2001.

[12] S. Naruenartwongsakul, M. S. Chinnan, S. Bhumiratana, and T. Yoovidhya, "Effect of cellulose ethers on the microstructure of fried wheat flour-based batters," *LWT--Food Science and Technology*, vol. 41, no. 1, pp. 109–118, 2008.

[13] C. F. Chen, J. W. Chen, Z. J. Yuan et al., "Effect of the wheat starch/wheat protein ratio in a batter on fat absorption and quality attributes of fried battered and breaded fish nuggets," *Journal of Food Science*, vol. 85, no. 7, pp. 2098–2104, 2020.

[14] M. Włodarczyk-Stasiak, A. Mazurek, J. Jamroz, S. Pikus, and R. Kowalski, "Physico chemical properties and structure of hydrothermally modified starches," *Food Hydrocolloids*, vol. 95, pp. 88–97, 2019.

[15] AOAC, *Official Methods of Analysis of AOAC International*, Association of Official Analytical Chemists, Rockville, Maryland, 2005.

[16] P. J. Lunde and F. L. Kester, "Chemical and physical gas adsorption in finite multimolecular layers," *Chemical Engineering Science*, vol. 30, no. 12, pp. 1497–1505, 1975.

[17] K. Skog and G. Viklund, "Processing contaminants: acrylamide," *Encyclopedia of Food Safety*, vol. 5, pp. 363–370, 2014.

[18] R. K. Vishwakarma, U. S. Shivhare, and S. K. Nanda, "Moisture adsorption isotherms of guar (Cyamposis tetragonoloba) grain and guar gum splits," *LWT--Food Science and Technology*, vol. 44, no. 4, pp. 969–975, 2011.

[19] Y. N. Sun, M. Zhang, and D. C. Fan, "Effect of ultrasonic on deterioration of oil in microwave vacuum frying and prediction of frying oil quality based on low field nuclear magnetic resonance (LF-NMR)," *Ultrasonics Sonochemistry*, vol. 51, pp. 77–89, 2019.

[20] S. D. Chen, H. H. Chen, Y. C. Chao, and R. S. Lin, "Effect of batter formula on qualities of deep-fat and microwave fried fish nuggets," *Journal of Food Engineering*, vol. 95, no. 2, pp. 359–364, 2009.

[21] A. Salvador, T. Sanz, and S. Fiszman, "Effect of the addition of different ingredients on the characteristics of a batter coating for fried seafood prepared without a pre-frying step," *Food Hydrocolloids*, vol. 19, no. 4, pp. 703–708, 2005.

[22] S. Garg and A. K. Jana, "Characterization and evaluation of acylated starch with different acyl groups and degrees of

substitution," *Carbohydrate Polymers*, vol. 83, no. 4, pp. 1623–1630, 2011.

[23] J. H. Shan, J. W. Chen, D. Xie, W. S. Xia, W. Xu, and Y. L. Xiong, "Effect of xanthan gum/soybean fiber ratio in the batter on oil absorption and quality attributes of fried breaded fish nuggets," *Journal of Food Science*, vol. 83, no. 7, pp. 1832–1838, 2018.

[24] A. Palaniappan and E. Jakobsson, "Fourier analysis of conservation patterns in protein secondary structure," *Computational and Structural Biotechnology Journal*, vol. 15, pp. 265–270, 2017.

[25] A. D. Roman-Gutierrez, S. Guilbert, and B. Cuq, "Distribution of water between wheat flour components: a dynamic water vapour adsorption study," *Journal of Cereal Science*, vol. 36, no. 3, pp. 347–355, 2002.

[26] R. Moreira, F. Chenlo, M. D. Torres, and D. M. Prieto, "Water adsorption and desorption isotherms of chestnut and wheat flours," *Industrial Crops and Products*, vol. 32, no. 3, pp. 252–257, 2010.

[27] S. Damodaran, K. L. Parkin, and O. R. Fennema, *Fennema's Food Chemistry*, CRC Press, Boca Raton, FL, USA, 4nd edition, 2008.

[28] H. H. Chen, H. Y. Kang, and S. D. Chen, "The effects of ingredients and water content on the rheological properties of batters and physical properties of crusts in fried foods," *Journal of Food Engineering*, vol. 88, no. 1, pp. 45–54, 2008.

[29] J. Xue and M. Ngadi, "Rheological properties of batter systems formulated using different flour combinations," *Journal of Food Engineering*, vol. 77, no. 2, pp. 334–341, 2006.

[30] C. Primo-Martín, N. van Nieuwenhuijzen, R. J. Hamer, and T. van Vliet, "Crystallinity changes in wheat starch during the bread-making process: starch crystallinity in the bread crust," *Journal of Cereal Science*, vol. 45, no. 2, pp. 219–226, 2007.

[31] R. Tester, "Properties of damaged starch granules: composition and swelling properties of maize, rice, pea and potato starch fractions in water at various temperatures," *Food Hydrocolloids*, vol. 11, no. 3, pp. 293–301, 1997.

[32] J. Blazek and L. Copeland, "Pasting and swelling properties of wheat flour and starch in relation to amylose content," *Carbohydrate Polymers*, vol. 71, no. 3, pp. 380–387, 2008.

[33] J. Hasjim, E. P. Li, and S. Dhital, "Milling of rice grains: the roles of starch structures in the solubility and swelling properties of rice flour," *Starch Staerke*, vol. 64, no. 8, pp. 631–645, 2012.

[34] C. Gamonpilas, W. Pongjaruvat, P. Methacanon, N. Seetapan, A. Fuongfuchat, and A. Klaikherd, "Effects of cross-linked tapioca starches on batter viscosity and oil absorption in deep-fried breaded chicken strips," *Journal of Food Engineering*, vol. 114, no. 2, pp. 262–268, 2013.

[35] S. Y. Shiau and A. I. Yeh, "Effects of alkali and acid on dough rheological properties and characteristics of extruded noodles," *Journal of Cereal Science*, vol. 33, no. 1, pp. 27–37, 2001.

[36] M. Beck, M. Jekle, and T. Becker, "Starch re-crystallization kinetics as a function of various cations," *Starch Staerke*, vol. 63, no. 12, pp. 792–800, 2011.

[37] M. Jekle, K. Mühlberger, and T. Becker, "Starch-gluten interactions during gelatinization and its functionality in dough like model systems," *Food Hydrocolloids*, vol. 54, pp. 196–201, 2016.

[38] K. Q. Wang, S. Z. Luo, X. Y. Zhong, J. Cai, S. T. Jiang, and Z. Zheng, "Changes in chemical interactions and protein conformation during heat-induced wheat gluten gel formation," *Food Chemistry*, vol. 214, pp. 393–399, 2017.

[39] Z. Yu, Y. S. Wang, H. H. Chen, Q. Q. Li, and Q. Wang, "The gelatinization and retrogradation properties of wheat starch with the addition of stearic acid and sodium alginate," *Food Hydrocolloids*, vol. 81, pp. 77–86, 2018.

[40] F. Ortolan, G. P. Corrêa, R. L. da Cunha, and C. J. Steel, "Rheological properties of vital wheat glutens with water or sodium chloride," *LWT--Food Science and Technology*, vol. 79, pp. 647–654, 2017.

[41] J. Y. Li, A. I. Yeh, and K. L. Fan, "Gelation characteristics and morphology of corn starch/soy protein concentrate composites during heating," *Journal of Food Engineering*, vol. 78, no. 4, pp. 1240–1247, 2007.

[42] O. Parniakov, O. Bals, F. J. Barba, V. Mykhailyk, N. Lebovka, and E. Vorobiev, "Application of differential scanning calorimetry to estimate quality and nutritional properties of food products," *Critical Reviews in Food Science and Nutrition*, vol. 58, no. 3, pp. 362–385, 2018.

[43] F. F. Wu, J. Li, N. Yang, Y. S. Chen, Y. M. Jin, and X. M. Xu, "The roles of starch structures in the pasting properties of wheat starch with different degrees of damage," *Starch- Stärke*, vol. 70, no. 5-6, Article ID 1700190, 2018.

[44] P. D. Ribotta, A. Colombo, A. E. León, and M. C. Añón, "Effects of soy protein on physical and rheological properties of wheat starch," *Starch Staerke*, vol. 59, no. 12, pp. 614–623, 2007.

[45] E. Ibanoglu, "Effect of hydrocolloids on the thermal denaturation of proteins," *Food Chemistry*, vol. 90, no. 4, pp. 621–626, 2005.

[46] L. Chen, F. Ren, Z. P. Zhang, Q. Y. Tong, and M. M. A. Rashed, "Effect of pullulan on the short-term and long-term retrogradation of rice starch," *Carbohydrate Polymers*, vol. 115, pp. 415–421, 2015.

[47] I. Gliko-Kabir, A. Penhasi, and A. Rubinstein, "Characterization of crosslinked guar by thermal analysis," *Carbohydrate Research*, vol. 316, no. 1-4, pp. 6–13, 1999.

[48] A. Nawrocka, M. Szymańska-Chargot, A. Miś, A. Z. Wilczewska, and K. H. Markiewicz, "Effect of dietary fibre polysaccharides on structure and thermal properties of gluten proteins: a study on gluten dough with application of FT-Raman spectroscopy, TGA and DSC," *Food Hydrocolloids*, vol. 69, pp. 410–421, 2017.

[49] P. Wang, L. Xu, M. Nikoo et al., "Effect of frozen storage on the conformational, thermal and microscopic properties of gluten: comparative studies on gluten-glutenin-and gliadin-rich fractions," *Food Hydrocolloids*, vol. 35, pp. 238–246, 2014.

[50] L. L. Cui, J. W. Chen, Y. H. Wang, and Y. L. Xiong, "The effect of batter characteristics on protein-aided control of fat absorption in deep-fried breaded fish nuggets," *Foods*, vol. 11, no. 2, p. 147, 2022.

[51] H. Zeng, J. W. Chen, J. L. Zhai, H. B. Wang, W. S. Xia, and Y. L. Xiong, "Reduction of the fat content of battered and breaded fish balls during deep-fat frying using fermented bamboo shoot dietary fiber," *LWT--Food Science and Technology*, vol. 73, pp. 425–431, 2016.