Effect of Frying Process on Nutritional Property, Physicochemical Quality, and *in vitro* Digestibility of Commercial Instant Noodles

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The effects of frying process on the nutritional property, physicochemical quality, and *in vitro* digestibility of instant noodle products are investigated in this study. Scanning electron microscope (SEM) and Fourier transform infrared spectrometer (FT-IR) were also used to explore the changes in the microstructure and protein transformation. Noodles, after the frying process, showed a lower proportion of carbohydrate, protein, fiber, and also total starch and digestible starch, but higher content of fat and resistant starch in the proximate analysis. The frying process was also considered to improve the texture, surface color, and sensory properties of instant noodle products, accompanied by better cooking quality, including shorter cooking time and lower cooking loss during the rehydration. The honeycomb-like, porous, and less uniformed structure, and also the higher levels of β-sheets and β-turns, and the lower proportion of α-helixes of protein structure from fried instant noodle was also observed. The *in vitro* digestibility of starch and protein were downregulated in the fried group (81.96% and 81.31, respectively, on average) compared with the non-fried group (97.58% and 88.78, respectively, on average). Thus, the frying process lowered the glycemic index and regulated protein secondary structure by inhibiting continuous digesting enzyme activity, generating starch-lipid complexes, and changing the levels of protein transformation. In conclusion, our findings will provide an innovative evaluation of the frying process on instant noodles and even other various starch-based prepared food products.

Keywords: frying process, instant noodle, nutritional property, physicochemical quality, *in vitro* digestibility

INTRODUCTION

Noodle has been recognized as the second largest flour product with a slightly lower consumption than bread (1). In particular, instant noodle has become increasingly popular due to its excellent flavor and convenience in preparation, cooking, and delivery (2). Deep frying that involves a series of complex processes including Maillard and caramelization reaction, oxidation, polymerization, and hydrogenation promotes fried noodles to gain more popularity for their unique fried flavor, crispy texture, and golden appearance (3, 4). Recently, with consumers' increasing health concerns, high-oil content of fried food associated with a higher risk of developing chronic diseases, such as

GRAPHICAL ABSTRACT | Construction of experimental methods and quality assessment system.
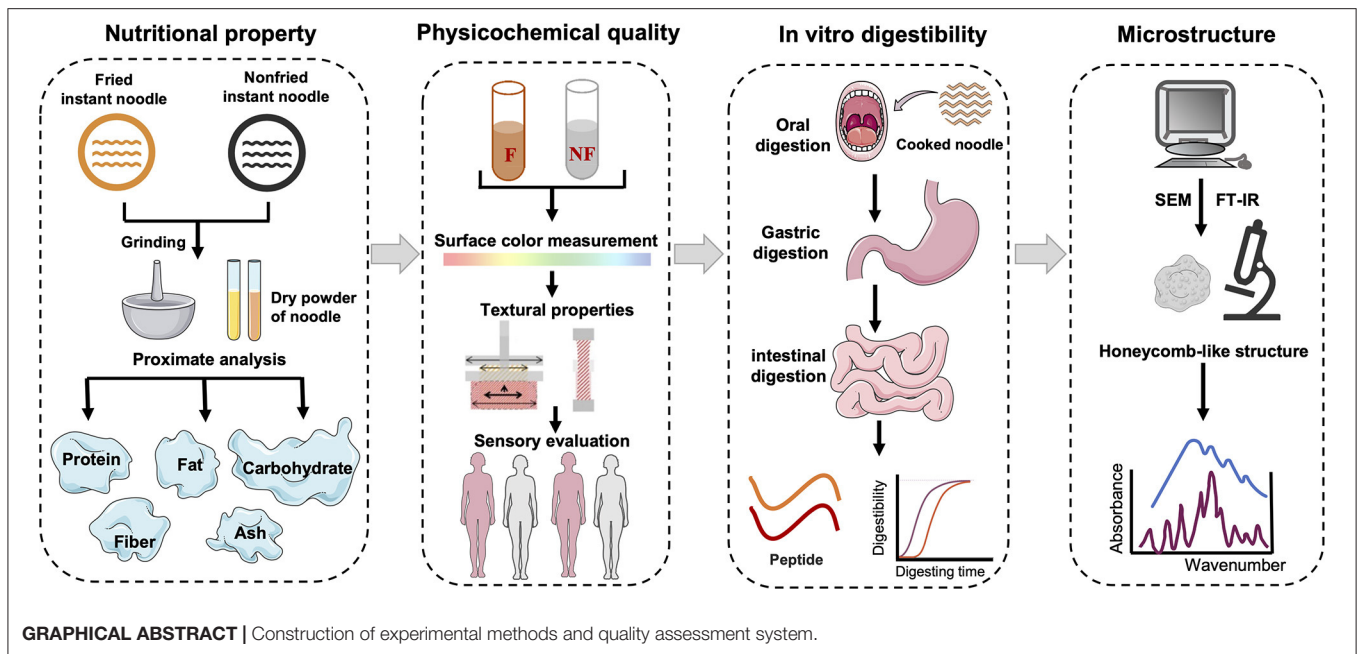
obesity, diabetes, and cardiovascular disorder, could be a potential factor influencing consumers' loyalty (5, 6), which make it necessary to systematically evaluate the effect of frying process on instant noodle and its nutritional attributes in human body.

Starch is the primary component of wheat flour, and the changes in its amount and structure give rise to the difference in nutrition, functionality, and palatability of instant noodle. Different dehydration treatments have been reported to influence the formation of starch-lipid complexes, thus altering their solubility (7). It is also noted that the formation of starch–lipid complexes during processing could affect the physicochemical qualities of starch, the texture, and digestibility of the final product (8). Besides, protein is another important factor that can contribute to the properties of instant noodles. For instance, some research indicated that instant noodles with higher protein content can exhibit firmer and more elastic texture (9), whereas others found that abnormal digestibility of cereal proteins could potentially reduce the bioavailability by forming the protein–fiber polymer and inhibiting the release of the peptide and amino acids, and thus negatively influencing the potentials of cereal proteins and the peptides derived from the hydrolysis of these premium proteins to lower the risks of obesity, type-2 diabetes, and cardiovascular diseases (10). To date, most of the research focus on optimizing the formula to improve the nutritional and sensory quality of fried instant noodles (11, 12). However, the mechanistic understanding of the effect of frying

process on digestibility and structural characteristics of protein and starch remains limited, and their influence on the quality of final products also needs further investigation.

In this study, the measurement of proximate composition, optical properties, sensory evaluation, cooking qualities, and texture analysis were conducted to compare the nutritional value, physicochemical properties, and consumer acceptance of fried instant noodle (dehydrated by frying in oil) and non-fried instant noodle (removed the moisture by hot air drying). *In vitro* gastrointestinal digestion model was established, and the analysis of glycemic index, kinetic modeling, and proteolysis rate was also performed to explore the digestibility of starch and protein. Scanning electron microscopy (SEM) analysis and Fourier transform infrared spectroscopy (FT-IR) analysis were combined to obtain the microstructure of instant noodles during *in vitro* digestion.

MATERIALS AND METHODS

Materials

Water used in all the experiments was obtained from a reverse osmosis water purification system. Trypsin (1,000–2,000 U/mg) and α-amylase (≥5,000 U/g) from the porcine pancreas were purchased from Sigma-Aldrich, Switzerland. Pepsin (≥250 U/mg) from porcine gastric mucosa, serine, and artificial saliva (pH = 6.8) were obtained from Solarbio, Beijing, CN. Pancreatin (≥4,000 U/g), o-phthalaldehyde, and bovine serum albumin were bought from Yuanye, Shanghai, CN. Ethanol and petroleum ether were purchased from Aladdin, Shanghai, CN. All the chemical reagents used were of analytical grade.

Abbreviations: SEM, scanning electron microscopy; FT-IR, Fourier transform infrared spectroscopy; RDS, rapidly digestible starch; SDS, slowly digestible starch; RS, resistant starch; area under curve (AUC); HI, hydrolysis index; eGI, expected glycemic index; OPA, O-phthalaldehyde; TPA, texture profile analysis; TS, total starch; DS, digestible starch; IVPD, *in vitro* protein digestibility.

Sample Collection and Preparation

All the samples used in this study were purchased from the online shopping channels of T-mall Supermarket. The selected instant noodle products, including fried instant noodle 1 (F1), fried instant noodle 2 (F2), fried instant noodle 3 (F3), non-fried instant noodle 1 (NF1), non-fried instant noodle 2 (NF2), non-fried instant noodle 3 (NF3), occupied the major market in their respective segments in China, and thus these 6 samples are the typical products for exploring the effect of frying process on nutritional property, physicochemical quality, and *in vitro* digestibility of commercial instant noodles. The detailed information and frying methods of instant noodle products can be found in **Supplementary Material Table S1**. After collection, the dry samples were obtained through being freeze-dried, ground, passed through a 100-mesh sieve, and stored at room temperature, whereas the wet samples were obtained after cooking in boiling water for 5 min.

Proximate Composition

Moisture, protein, fat, and ash content of instant noodle samples were evaluated by constant weight method, Kjeldahl method, Soxhlet extraction method, and burning method, respectively, as the standard procedure from AOAC [13]. Carbohydrate was calculated by subtracting the values of moisture, protein, fiber, and ash contents from 100. The fiber was measured with a Fiber Assay Kit (BC4285 Solarbio Co., Beijing, CN) according to the manufacturer's protocols.

Physical Quality Assessments
Optics

The effect of frying on optic property of instant noodle products was determined by Colorimeter (YS6060, Sanen Co, Shenzhen, CN). Every noodle sample (5 g) was placed in the center of the glass plate for color measurement (L*, a*, and b*). The color of the noodle products was recorded with a precalibrated colorimeter at room temperature. The ΔE value was calculated according to the following equation, indicating the total color difference.

$$\Delta E = \sqrt{(L_s^* - L_0^*)^2 + (a_s^* - a_0^*)^2 + (b_s^* - b_0^*)^2}$$

where Ls*, as*, and bs* are L*, a*, and b* of the sample, and L_0^*, a_0^*, and b_0^* are L*, a*, and b* of the blank control.

Thermal Properties

The effect of frying process on the thermal properties of instant noodle products was determined according to Song et al. with differential scanning calorimetry (DSC, Metler Toledo, Schwerzenbach, Switzerland) [14]. The noodles were freeze-dried, ground, and passed through a 100-mesh sieve. The powder (5 mg) and distilled water (15 mg) were mixed in a stainless-steel pan. DSC was performed from 20 to 200°C at a rate of 10 K/min, and then the heat flow and DSC curves were obtained.

Texture

The effect of frying on texture property of instant noodle products was evaluated according to Cao et al. using a TA-XT2i Texture Analyzer (Stable Micro System Ltd, United Kingdom) [11]. A set of three cooked noodle samples was placed on the platform, measured with the HDP/PFS metal blade, and compressed until a compression ratio of 70% was reached with pretest speed, test speeds, posttest speeds of 4.0, 1.0, and 1.0 mm/s, respectively. Three replicates per sample were analyzed.

Cooking Quality

The effect of frying on cooking quality of instant noodle products was determined based on cooking time, cooking loss, and water adsorption. The cooking time was obtained when the opacity in the center of instant noodle products disappeared [15]. The water adsorption was expressed as the percentage of increased weight compared with the raw noodle products [16], and the cooking loss was calculated by the amount of solid substance lost to cooking water [17].

Sensory Evaluation

The effect of frying on sensory attributes (firmness, elasticity, slipperiness, chewiness, and overall acceptability) of cooked instant noodle products was analyzed as described by Sajad AhmadSofi with minor modifications [18]. The healthy and taste-sensitive panelists were selected, excluding the patients with color blindness, rhinitis, stomatitis, and gastroenteritis. The sensory training was carried out, composed with basic sensory knowledge including common assessment methods and analysis, and also experimental skills, such as sample evaluation process and rules of scoring table. A total of 20 trained panelists comprising food scientists, research scholars, and students from the department of Tianjin Key Laboratory of Food Science and Health, Nankai University scored F1, F2, F3, NF1, NF2, and NF3 based on liking and disliking using a 9-point hedonic scale.

In vitro Starch Digestibility and Estimated Glycemic Index

The effect of frying on starch digestibility of instant noodle products was determined according to the procedure of our previous study [19], modified from Englyst et al. [20]. The starch digestibility was determined by measuring the content of glucose with the GOPOD kit (K-GLUC, Megazyme Bray, Co. Wicklow, Ireland). The content of rapidly digestible starch (RDS, $\leq$ 20 min), slowly digestible starch (SDS, 20–120 min), and resistant starch (RS, > 120 min) was also calculated. The degree of starch hydrolysis was fitted to the first-order rate equation:

$$C_t = 1 - e^{-kt}$$

where Ct is the amount of starch digested at time t (min), and k (min^{-1}) is the first-order rate coefficient. The value of k can be calculated from the slope of a linear least-squares fit of a plot of ln (1 – Ct) against *t*.

The values were plotted on a graph and the area under the curve (AUC) was determined using GraphPad Prism 5 (GraphPad Software Inc., San Diego, CA, USA). The hydrolysis index (HI) of each sample was calculated by the

TABLE 1 | Constituents of the synthetic juices of the protein digestion model[a].

	Gastric juice	Duodenal juice	Bile juice
Organic and inorganic components	1 g bovine serum albumin	1 g bovine serum albumin	1.8 g bovine serum albumin
		9 mL CaCl2·2H$_2$O[b]	10 mL CaCl2·2H$_2$O
			30 g bile
Enzymes	2.5 g pepsin	9 g pancreatin	
	3 g mucin	1.5 g lipase	
pH	1.30 ± 0.02	8.1 ± 0.2	8.2 ± 0.2

[a]After mixing all the ingredients (inorganic components, organic components, and enzymes), the volume was increased to 500 ml with distilled water.
[b]The concentration of CaCl$_2$·2H$_2$O reagent is 22.2 g/L.

following equation:

$$HI = \frac{AUC\ of\ sample}{AUC\ of\ reference\ food}$$

The expected glycemic index (eGI) was thus estimated using the following model:

$$eGI = 0.549 \times HI + 39.71$$

In vitro Protein Digestibility

The *in vitro* protein digestibility of instant noodle products was determined using a modified version described by Hur et al. (21). The phases of *in vitro* protein digestion model include mouth, stomach, and intestine, accompanied by the addition of artificial saliva (A7990, pH = 6.8, Solarbio Co., Ltd., Beijing, CN), and preprepared stimulated gastric, duodenal, and bile fluids, whose formulas are listed in **Table 1**.
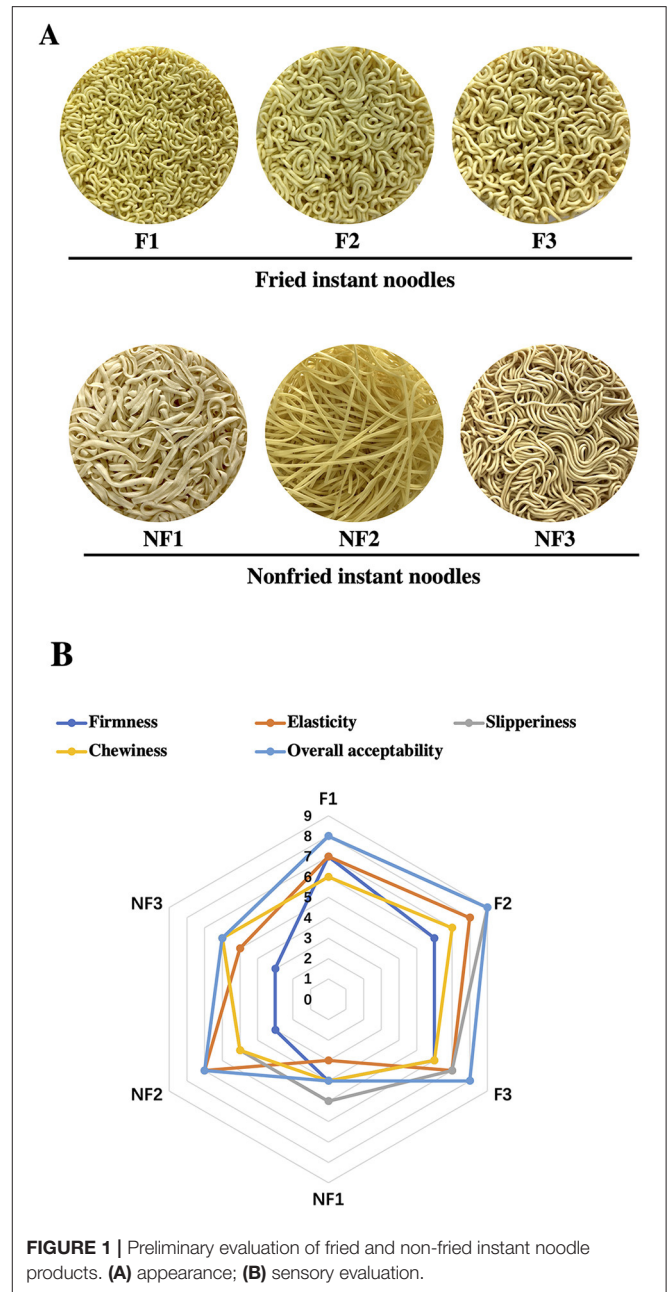
The degree of hydrolysis of the digested sample was analyzed using microplate OPA assay as described by Jadhav et al. (22). Appropriately 25 μL of diluted samples after centrifuging (10,000g, at 4°C for 20min) was mixed with 175 μL OPA reagent in the microtiter plate. The plate was incubated at 37°C for 2 min and the absorbance was measured at 340 nm. Standard was obtained using serine and degree of hydrolysis and was determined as follows:

$$Degree\ of\ hydrolysis\ (\%) = \frac{h_{sample}}{h_{total}} \times 100\%$$

$$h_s = \frac{Serine\ NH_2 - \beta}{h_{total}} \times 100\%$$

$$Serine\ NH_2 = \frac{OD_{sample} - OD_{blank}}{OD_{stand} - OD_{blank}} \times 0.9516 meqv/L$$
$$\times \frac{0.1 \times 100/g}{X \times P}$$

where h$_{sample}$ is the concentration of free amino groups in the samples (mmol), h$_{total}$ is the concentration of free amino

FIGURE 1 | Preliminary evaluation of fried and non-fried instant noodle products. **(A)** appearance; **(B)** sensory evaluation.

groups per gram of completely hydrolyzed protein (8.83 mmol/g protein). X is the weight of the sample tested; P is the protein content of the sample tested; and α and β are expressed by the constants 1.00 and 0.40, respectively.

Fourier Transform Infrared Spectroscopy Microscopy Analysis

Fourier transform infrared spectroscopy microscopy analysis of instant noodle products during *in vitro* digestion was carried out using the method of Wang et al. (23) with a Thermo Scientific Nicolet IS50 spectrometer (Thermo Fisher Scientific, Waltham, MA, U.S.A.). Noodle sheets from stimulated digesting

TABLE 2 | Quality evaluation of fried and non-fried instant noodle (dry basis).

Characteristic	Fried instant noodle			Non-fried instant noodle		
	F1	F2	F3	NF1	NF2	NF3
Proximate composition						
Carbohydrate (%)	72.95 ± 0.11[c]	74.74 ± 0.10[c]	71.85 ± 0.84[c]	84.50 ± 0.19[a]	84.10 ± 0.36[b]	84.36 ± 0.12[a]
Fat (%)	17.49 ± 0.33[a]	12.86 ± 0.01[b]	17.05 ± 0.84[a]	1.95 ± 0.17[c]	2.51 ± 0.33[c]	2.72 ± 0.17[c]
Protein (%)	8.21 ± 0.18[e]	9.85 ± 0.03[b]	9.22 ± 0.04[c]	10.07 ± 0.02[b]	11.38 ± 0.04[a]	8.95 ± 0.01[d]
Ash (%)	1.22 ± 0.02[d]	2.14 ± 0.04[c]	1.33 ± 0.06[d]	2.37 ± 0.03[b]	0.74 ± 0.01[e]	3.12 ± 0.02[a]
Fiber (%)	0.12 ± 0.01[c]	0.41 ± 0.06[b]	0.55 ± 0.03[b]	1.05 ± 0.03[a]	1.14 ± 0.08[a]	0.87 ± 0.04[a]
Texture						
Hardness (N)	1025.53 ± 70.66[d]	1794.15 ± 22.15[b]	1200.57 ± 75.46[c]	2290.06 ± 23.33[a]	1801.65 ± 51.775[b]	2425.04 ± 7.51[a]
Springiness (N)	0.92 ± 0.02[c]	1.19 ± 0.19[b]	0.85 ± 0.01[d]	0.94 ± 0.02[b]	0.70 ± 0.05[e]	3.51 ± 0.19[ac]
Cohesiveness (N)	0.43 ± 0.02[c]	0.54 ± 0.02[b]	0.47 ± 0.01[c]	0.67 ± 0.01[a]	0.42 ± 0.01[c]	0.42 ± 0.01[c]
Chewiness (N)	3817.96 ± 18.53[a]	1269.37 ± 53.37[b]	1172.55 ± 10.59[b]	263.47 ± 33.67[e]	451.18 ± 8.90[d]	975.08 ± 69.53[c]
Gumminess (N)	978.08 ± 31.37[a]	937.25 ± 22.10[a]	530.24 ± 7.40[b]	1054.46 ± 4.95[a]	521.31 ± 68.66[b]	1087.37 ± 60.58[a]
Resilience (N)	0.28 ± 0.01[a]	0.20 ± 0.01[b]	0.18 ± 0.01[b]	0.13 ± 0.01[c]	0.17 ± 0.01[b]	0.17 ± 0.01[b]
Cooking quality						
Cooking time (s)	203 ± 2.0[d]	238 ± 2.5[c]	159 ± 1.0[e]	382 ± 1.5[a]	266 ± 0.5[b]	261 ± 1.0[b]
Cooking loss (%)	9.60 ± 0.37[b]	11.08 ± 0.30[b]	9.90 ± 0.05[b]	14.93 ± 0.62[a]	14.48 ± 0.55[a]	12.40 ± 0.21[b]
Water Absorption (%)	126.34 ± 3.42[e]	139.16 ± 0.13[d]	130.20 ± 0.49[e]	205.02 ± 1.75[a]	195.78 ± 2.10[b]	175.65 ± 0.11[c]
Color						
L*	87.08 ± 0.01[a]	84.92 ± 0.01[c]	84.45 ± 0.02[d]	85.85 ± 0.01[b]	84.15 ± 0.01[f]	84.30 ± 0.01[e]
a*	−0.36 ± 0.01[e]	−0.25 ± 0.02[d]	−0.17 ± 0.01[c]	0.73 ± 0.02[a]	0.64 ± 0.02[b]	0.70 ± 0.01[a]
b*	25.08 ± 0.03[c]	25.16 ± 0.02[b]	25.32 ± 0.01[a]	13.15 ± 0.01[f]	19.38 ± 0.01[d]	16.68 ± 0.01[e]
ΔE	14.15 ± 0.01[a]	13.39 ± 0.02[b]	13.40 ± 0.02[b]	5.41 ± 0.02[e]	7.76 ± 0.01[c]	5.63 ± 0.01[d]

Results are reported in means ± standard deviations (n = 3). Results were analyzed using the Newman–Keuls test. Means with different letters in the same row are significantly different at $p < 0.05$.

TABLE 3 | Thermal properties of fried and non-fried instant noodle.

Characteristic	Fried instant noodle			Non-fried instant noodle		
	F1	F2	F3	NF1	NF2	NF3
Temperature (°C)						
T_{o1}	60.16 ± 0.57[a]	59.22 ± 1.07[a]	59.30 ± 0.29[a]	58.10 ± 0.29[a]	57.62 ± 0.39[a]	58.69 ± 0.31[a]
T_{p1}	96.42 ± 1.44[a]	95.31 ± 0.33[a]	94.99 ± 0.58[a]	89.48 ± 1.44[b]	90.55 ± 0.21[b]	90.19 ± 0.42[b]
T_{o2}	131.76 ± 0.29[a]	131.44 ± 0.60[a]	129.12 ± 0.58[a]	122.18 ± 0.58[c]	122.18 ± 1.15[c]	126.54 ± 0.28[b]
T_{p2}	158.02 ± 0.58[a]	154.81 ± 0.94[a]	154.13 ± 1.04[a]	150.84 ± 0.31[b]	149.98 ± 2.33[b]	149.38 ± 0.57[b]
Δ H (J/g)						
ΔH_1	32.24 ± 0.39[a]	33.36 ± 1.21[a]	32.53 ± 2.01[a]	29.60 ± 1.05[a]	31.99 ± 0.49[a]	30.12 ± 0.47[a]
ΔH_2	23.08 ± 1.93[a]	21.36 ± 0.93[a]	22.09 ± 0.55[a]	18.95 ± 1.29[a]	20.96 ± 1.51[a]	19.28 ± 0.63[a]
ΔH_{total}	55.32 ± 2.32[a]	54.72 ± 2.14[a]	54.62 ± 2.56[a]	48.55 ± 2.34[a]	52.95 ± 2.00[a]	49.40 ± 1.10[a]

T_o, onset temperature; T_p, peak temperature; ΔH: enthalpy change of thermal transition. Results are reported in means ± standard deviations (n = 2). Results were analyzed using the Newman–Keuls test. Means with different letters in the same row are significantly different at $p < 0.05$.

phases of mouth, stomach, and intestine were freeze-dried, and a flat surface was obtained after treatment. Spectrums were collected 4 times with a resolution of 4 cm^{-1} in the wavenumber region between 4,000 and 400 cm^{-1}. The spectral analysis referred to the methods described by Mehtap Fevzioglu with minor modifications (24). The secondary structure was processed by introducing second derivative techniques and Fourier-self deconvolution of the amide I region of the protein (1,600–1,700 cm^{-1}) using OMNIC software (Thermo Electron Corp.).

Scanning Electron Microscopy Analysis

The microstructure of the instant noodle products during *in vitro* digestion was determined by scanning electron microscope (SEM, S-3400N, Hitachi, Japan) with magnifications of ×500 and ×3,000 referred from Anju et al. (25). The instant noodle products were installed on the black ribbon, and the vacuum evaporator was used for sputtering gold plating. The ribbon with the sample was then placed in the SEM unit, and the images were captured at a different magnification at 15 kV accelerating voltage.

Statistical Analysis

All the results are reported as the mean values and standard deviations (SDs). One-way analysis of variance (ANOVA) followed by Newman–Keul's multiple comparison test ($p < 0.05$) was conducted to determine the significant differences between mean values using GraphPad Prism 5 (GraphPad Software Inc., San Diego, CA, USA).

RESULTS

Proximate Composition, Color, Thermal, Cooking Quality, and Texture Analysis

The proximate composition of instant noodle samples is shown in **Table 2**. The frying process increased the levels of fat content of F1, F2, and F3, but not in non-fried groups, whose fat was mainly derived from raw wheat flour. The carbohydrate content of F1, F2, and F3 was lower than NF1, NF2, and NF3. Compared with fried samples, non-fried instant noodle products contain higher protein and fiber content, especially NF2 has the highest protein ($11.38 \pm 0.04a$) and fiber ($1.14 \pm 0.08a$). The frying treatment did not have a significant effect on the ash content of these two types of instant noodle products, which might be related to different product formulations.

Fried and non-fried noodles showed significant ($p < 0.05$) differences in color values, which are presented in **Table 2** and **Figure 1**. Compared with non-fried noodle, F1, F2, and F3 showed a lower similarity to standard flour, with a significantly decreased yellowness (a*), an increased redness (b*), and an insignificant change in lightness (L*). In addition, the effect of the frying process on cooking qualities of instant noodle products can be seen in **Table 2**. The levels of cooking time, cooking loss, and water absorption capacity of NF1, NF2, and NF3 were significantly higher than those of F1, F2, and F3 ($p < 0.01$), probably due to the poor network development of non-fried instant noodle.

The DSC results of fried and non-fried noodle products showed typical gelatinization endotherms, and the thermal transition parameters including To (onset temperature), Tp (peak temperature), and ΔH (enthalpy change) can be found in **Table 3** and **Supplementary Figure S1**. The onset temperature and peak temperature of F1, F2, and F3 were higher than that of NF1, NF2, and NF3, indicating that it is not easy to denature at lower temperatures for fried instant noodle products. The frying process also induced an increase in ΔH from 30.57 to 32.70 J/g and from 19.73 to 22.18 J/g, on average, inhibiting the degree of gelatinization due to the higher thermal stability of the fried instant noodle products.

Furthermore, texture analysis has been widely used in the evaluation of food quality due to its high sensitivity and objectivity. According to the results in **Table 2**, the frying process had no significant intervention effect on the springiness, cohesiveness, and gumminess of the instant noodle, but could significantly downregulate the hardness and increase chewiness and resilience.

Sensory Evaluation

The consumer acceptance of instant noodle products was evaluated based on sensory attributes, such as firmness, elasticity, slipperiness, chewiness, and overall acceptability appearance, using a 9-point hedonic scale (**Figure 1B**). Fried instant noodle products were more accepted, especially F2 had the highest sensory score for firmness (6), elasticity (8), slipperiness (9), chewiness (7), and overall acceptability (9), but all the non-fried samples showed a decline in all the sensory attributes and thus reduced overall acceptance.

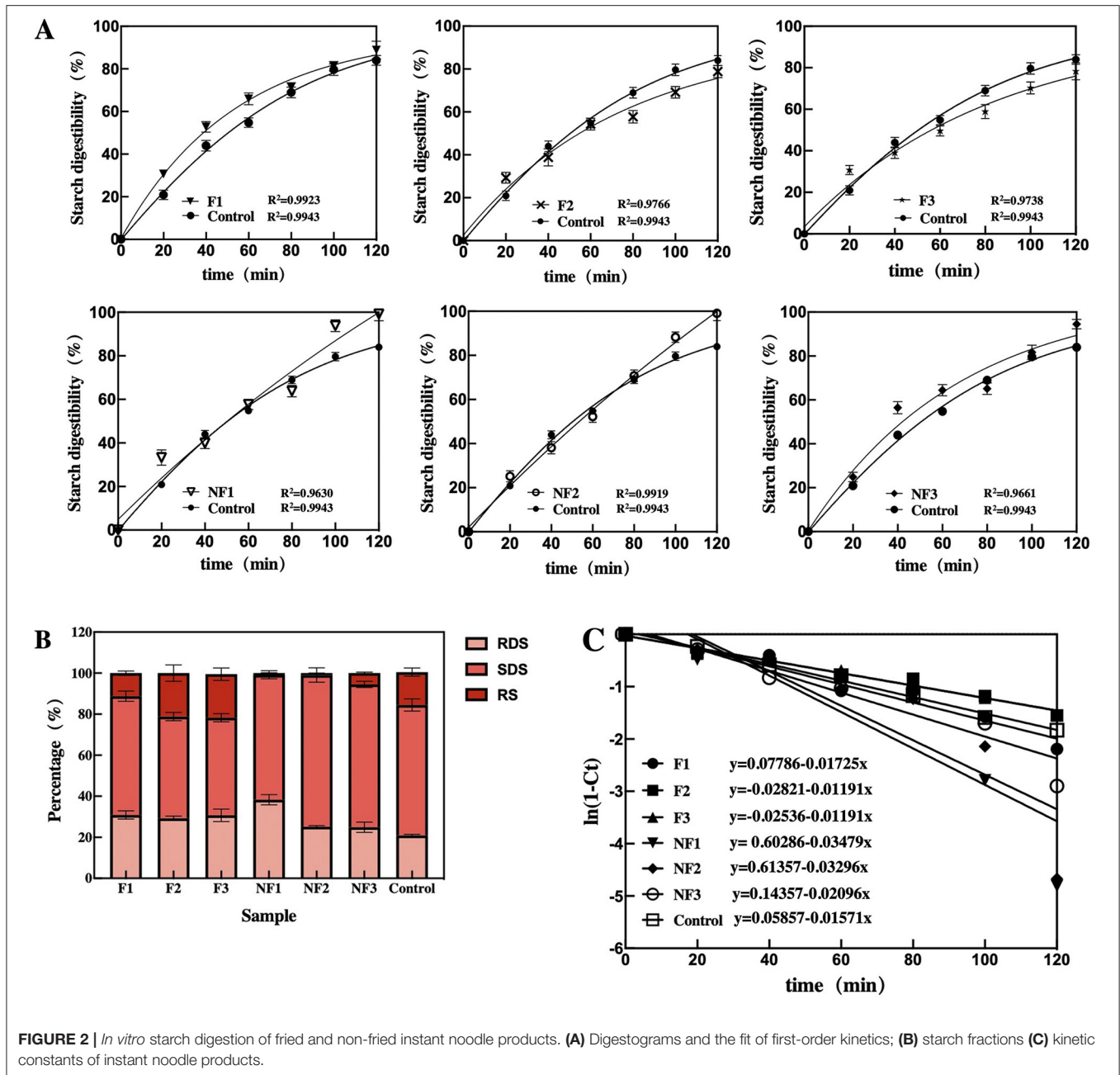## Starch Digestibility and Expected Glycemic Index

The results of *in vitro* starch digestion are shown in **Figure 2**. All these starch digestograms of instant noodle products were characterized by a rapid digestion phase during the initial 40 min, followed by a slower digestion phase afterward (**Figure 2A**). There were no significant differences in the hydrolysis rate at an early stage, while the frying process lowered the degree of starch hydrolysis at a slower hydrolysis rate of instant noodle products afterward. The final digestion percentages at 2 h were 88.78%, 78.82, and 78.29% for fried instant noodle products (F1, F2, and F3 respectively), commonly lower than 99.18%, 99.06%, and 94.50% for NF1, NF2, and NF3 respective products without the frying process.

In addition, to gain a better mechanistic understanding of the enzymic digestion of starch from instant noodle products with frying methods, the digestion curves were fitted to the first-order kinetic equation (**Table 4**). R^2 for fried and non-fried samples was above 0.9, ensuring that the enzymic digestion of the starches fitted well to first-order kinetics. Furthermore, the content of total starch (TS), digestible starch (DS), and RS can be seen in **Table 4**. The frying process lowered the levels of TS content and raised the proportions of RS. Based on the phases of *in vitro* hydrolysis, starch can be divided into RDS, SDS, and RS (**Figure 2B**). The RDS content of all these instant noodle products fluctuates between 24.91 and 38.30%, which was higher than the standard starch (20.94%).

The influence of the drying method on starch hydrolysis kinetics and the glycemic index of the instant noodle is shown in **Table 4**. Nonlinear parameters of the starch hydrolysis kinetics including kinetics constant (k), HI, and eGI can be found in **Figure 1C** and **Table 4**. The *k* value, representing the enzymatic hydrolysis rate or the susceptibility of starchy foods toward amylolysis (26), showed a significant difference in instant noodle products with and without the frying process. In this study, the values of k obtained from the slopes of the linear plots for F1, F2, and F3, ranged from 1.191 to 1.725×10^{-2} min^{-1}, whereas it fluctuated from 2.096 to 3.479×10^{-2} min^{-1} for NF1, NF2, and NF3. Lower values of k indicated that the frying process probably can increase resistance to enzymatic starch hydrolysis, and obtain lower final starch digestibility (27). Besides, the frying process also reduced the eGI value (on average from 98.92 to 92.52).

In vitro Protein Digestibility

The effect of frying on *in vitro* protein digestibility (IVPD) of instant noodle in oral, stomach, intestine digesting periods is

FIGURE 2 | *In vitro* starch digestion of fried and non-fried instant noodle products. **(A)** Digestograms and the fit of first-order kinetics; **(B)** starch fractions **(C)** kinetic constants of instant noodle products.

shown in **Figure 3A**. During the *in vitro* gastric digestion, the frying process reduced the protein digestibility of F1, F2, and F3, but extended the digestive period probably due to the consistently higher activity of pepsin. In this case, non-fried instant noodle products almost reached the digestion peak at 80 min of digestion period, whereas the digestibility of fried instant noodles showed an upward trend throughout the digestion stage. Besides, during intestinal simulated digestion, the frying process also reduced the level of protein digestibility but did not significantly affect the tendency of protein hydrolysis. Although, IVPD of both these products reached a high level (over 80%) after gastrointestinal digestion, the lower level of protein digestibility

of fried instant noodle products was observed at the end of digestion.

FT-IR Spectroscopy and Protein Secondary Structure

Furthermore, FT-IR spectroscopy is a molecular vibrational spectroscopy that can monitor fine structural information about protein [28]. The results for FT-IR of instant noodle products subjected to the frying treatment during the gastrointestinal digestion are shown in **Figure 3B**. There is a significant difference between the protein structure of fried and non-fried instant noodle. After the frying process, the spectrum peaks of
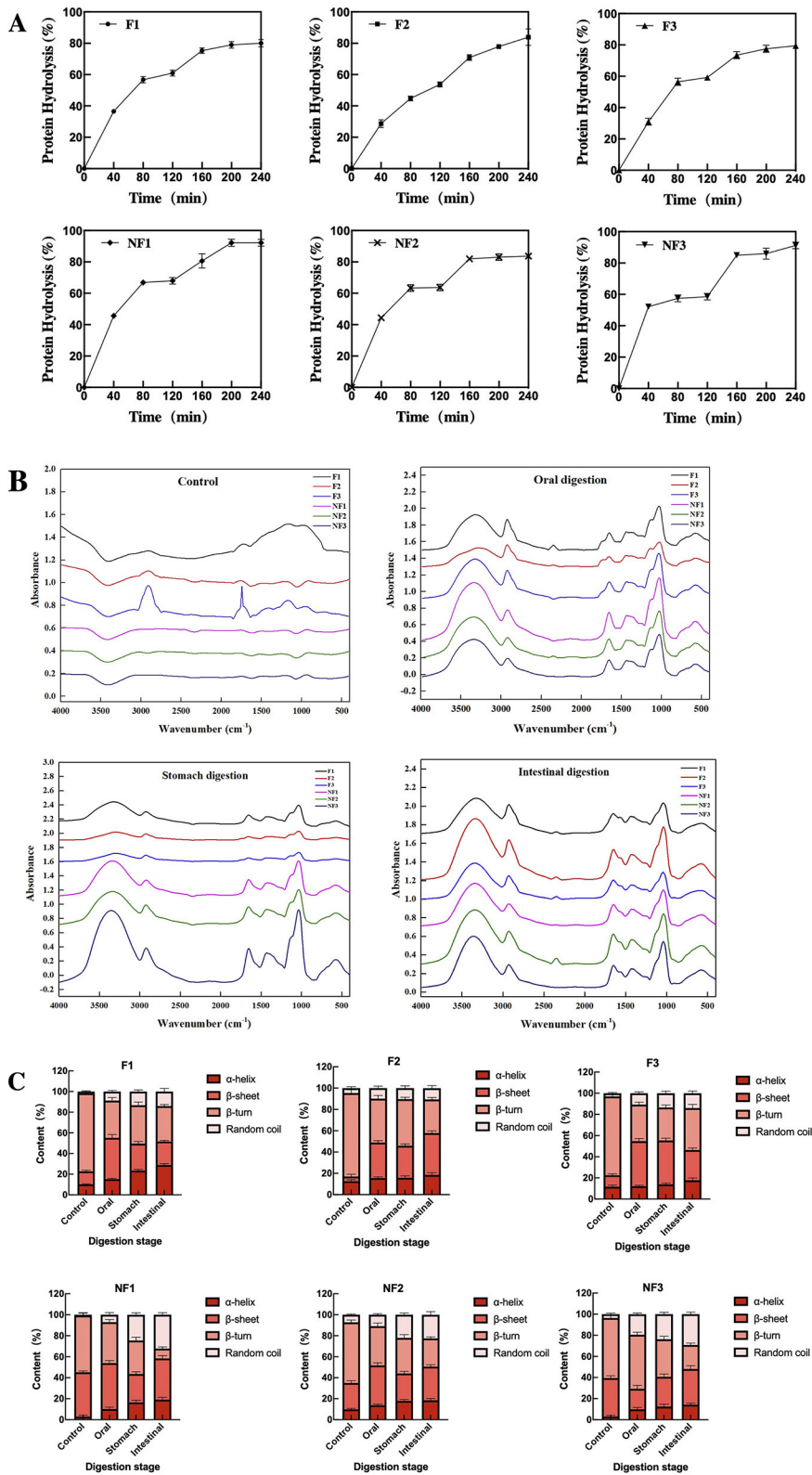
FIGURE 3 | *In vitro* protein digestibility of fried and non-fried instant noodle products. **(A)** Protein hydrolysis rate of F1, F2, F3, NF1, NF2, and NF3, respectively; **(B)** FT-IR spectra during the phases of the untreated, oral, stomach, and intestine; **(C)** protein secondary structure changes during *in vitro* protein digestion.

TABLE 4 | *In vitro* starch digestion and estimated glycemic index of fried and non-fried instant noodle.

Characteristic	Fried instant noodle			Non-fried instant noodle		
	F1	F2	F3	NF1	NF2	NF3
Starch composition						
TS (g/100g)	62.41 ± 0.26[d]	69.93 ± 0.70[c]	63.26 ± 0.11[d]	74.70 ± 0.14[a]	70.06 ± 0.10[c]	72.97 ± 0.04[b]
RS (g/100g)	11.22 ± 1.42[b]	21.18 ± 1.98[a]	21.71 ± 1.38[a]	0.82 ± 0.66[c]	0.94 ± 0.83[c]	5.50 ± 0.04[c]
DS (g/100 g)	51.19 ± 1.69[b]	48.74 ± 1.69[b]	41.56 ± 1.49[c]	73.89 ± 0.52[a]	69.11 ± 0.94[a]	67.47 ± 0.08[a]
Nonlinear parameters						
$K \times 10^{-2} (\text{min}^{-1})$	1.725 ± 0.183[e]	1.191 ± 0.086[d]	1.191 ± 0.075[d]	3.479 ± 0.901[a]	3.296 ± 0.844[b]	2.096 ± 0.353[c]
R^2	0.952	0.978	0.983	0.915	0.926	0.938
AUC Sample	6393 ± 22.84[b]	5766 ± 40.60[c]	5752 ± 29.61[c]	6804 ± 25.48[a]	6481 ± 19.26[b]	6794 ± 19.52[a]
HI	103.01 ± 0.73[b]	92.91 ± 1.28[c]	92.68 ± 0.93[c]	109.64 ± 0.81[a]	104.43 ± 0.60[b]	109.47 ± 0.61[a]
eGI	96.26 ± 0.40[b]	90.72 ± 0.70[c]	90.59 ± 0.51[c]	99.90 ± 0.44[a]	97.04 ± 0.33[b]	99.81 ± 0.34[a]

TS, Total Starch; RS, Resistant Starch; DS, Digestible Starch; Values were expressed as the average of triplicates ± standard deviations. Results were analyzed using the Newman–Keuls test. Different letters within the same row are significantly different (p < 0.05).

undigested instant noodle products showed an irregular trend and remarkably increased the spectrum peak of instant noodle during gastric digestion at the wave number of 3,000–3,500 cm^{-1}. The absorption peaks in the wavelength of 1,150 cm^{-1} and 850 cm^{-1} were also influenced by the frying process. The analysis of amide-I bands (1,600–1,700 cm^{-1}) by second-derivative, Fourier self-deconvolution, and curve-fitting was also conducted to quantify the protein secondary structure of instant noodle (**Figure 3C**). Different special bands were observed in protein, including β-sheets (1,615–1,637 cm^{-1} and 1,682–1,700 cm^{-1}), β-turns (1,664–1,681 cm^{-1}), α-helixes (1,646–1,664 cm^{-1}), and random coils (1,637–1,645 cm^{-1}) (29). During the entire digestion process, the content of β-turns in fried instant noodle decreased significantly, but NF1, NF2, and NF3 did not show a similar trend without being fried. Furthermore, compared with non-fried instant noodle products, the frying process raised the levels of β-sheets, β-turns, and random coil, and lowered the percentage of α-helixes.

Scanning Electron Microscope

The effect of frying process on the internal microstructures of the instant noodle during *in vitro* digestion is shown in **Figure 4A**. It was observed that the native gluten particles had a composite structure with flat surfaces possibly due to the presence of starch–oil complexes (orange arrows), whereas the structure of non-fried instant noodle products has a higher degree of friability and disorder. Afterward, a visible honeycomb-like structure accompanied with numerous small pores inside (yellow arrows) was also formed. Next, many mushroom-like structures (red arrows) can be seen in the gastrointestinal digestion. This also remained incompletely digested particles (green arrows) for fried instant noodle products. In addition, the final microstructure of instant noodle during *in vitro* digestion was obtained at 3,000 × magnification (**Figure 4B**). It is obvious that the particulates inside fried instant noodle have been digested more thoroughly, compared with the integral structure in non-fried samples. The instant noodle products with frying process also presented a honey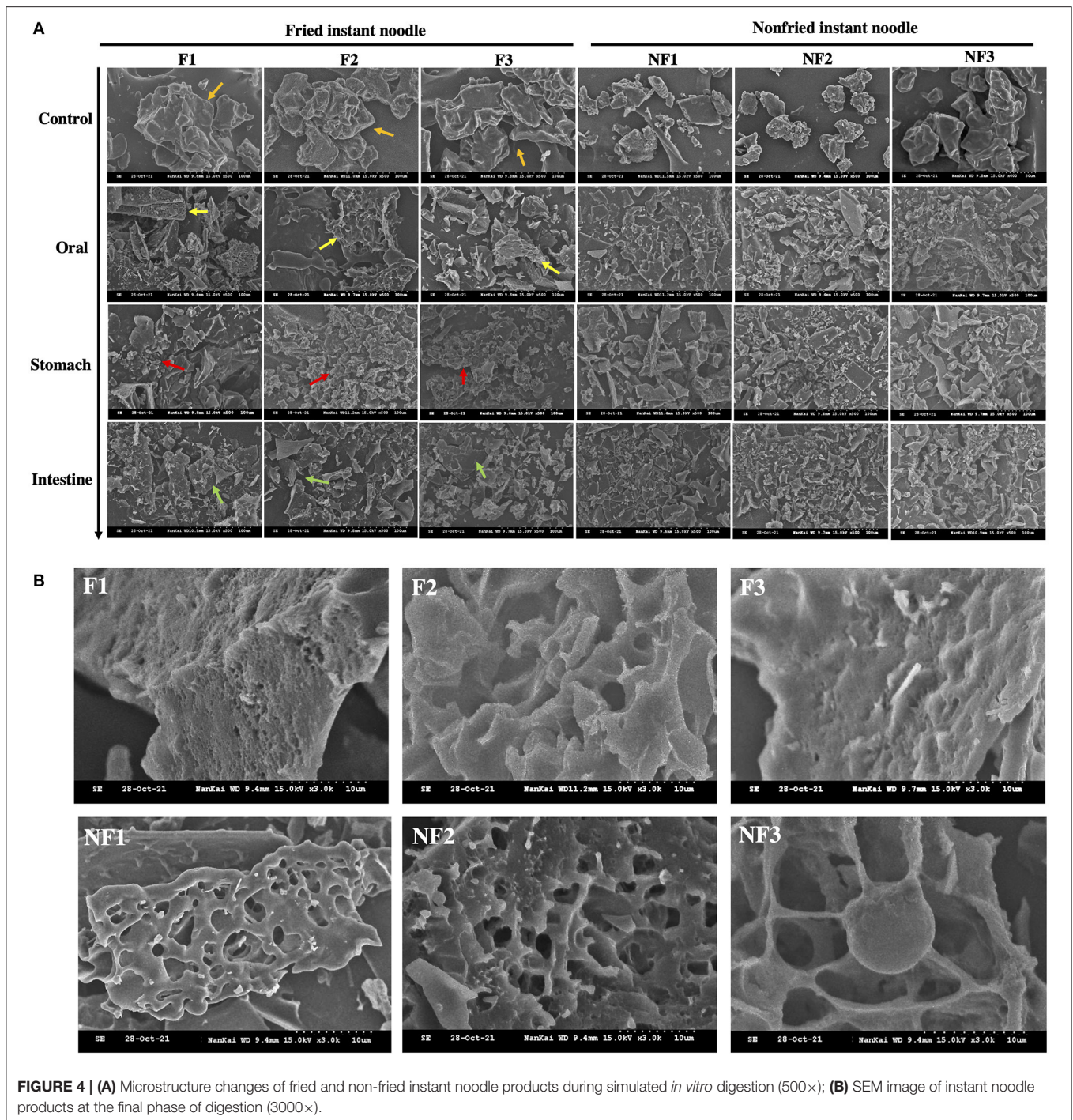comb-like appearance, whereas the surface structure of the non-fried instant noodle products had higher smoothness, uniformity, and continuity.

DISCUSSION

Effect of Frying on Quality Evaluation of Instant Noodle

During the frying process, high temperature and oil mass transfer can affect the composition, structure, and physicochemical properties of the various ingredients in food (30). The lower content of carbohydrates in fried products indicates the flow of free sugar from food to oil during the frying process, which is in agreement with previous results (31). In terms of the protein, their spiral and folded structure might breakdown, and internal molecules might be degraded during frying. This also indicated that non-fried noodle is a better source of protein and fiber than fried noodle that can be used for the development of various functional food products (32). Although there is no significant difference in the ash content of fried and non-fried products, the similarly low ash content of these two kinds of instant noodle was noticed. This problem can be solved by supplementing the raw material and seasoning package with higher mineral content, suggesting an important direction for future research. Optical property is another one of the most efficient ways to evaluate the sensory quality, directly affecting consumer acceptance. More color changes of fried instant noodle may be caused by the Maillard reaction of the sugars and protein, and also due to the color polymer formed in the fat oxidation reaction during the frying process, so fried instant noodle presents a darker color with lower a* and higher b*.

The frying process also decreased the levels of cooking time, water absorption, and cooking loss of instant noodle products. The lowered degree of water absorption capacity of fried instant noodle products mainly depended on the levels of starch gelatinization and decomposition of the molecular structure (33). Whereas non-fried instant noodle products have stronger water absorption capacity, which is likely due to the undamaged

FIGURE 4 | (A) Microstructure changes of fried and non-fried instant noodle products during simulated *in vitro* digestion (500×); **(B)** SEM image of instant noodle products at the final phase of digestion (3000×).

double helical structure and multiple spiral polymer secondary structure with higher water holding capacity. The decreased cooking loss for fried instant noodle might be attributed to the higher damaged starch of the flour blends and the formation of starch-lipid complexes, consistent with the previous study (12). It is also reported that the degree of cooking loss is related to solid leaching from the boiled noodles, which is considered an indicator of their overall cooking quality (14). In addition, for fried instant noodle, water can penetrate to the noodle inside

from the pore structure formed during the frying process. Since the non-fried drying method cannot form a continuous and uniform pore structure, the water can only migrate from the surface layer of the noodle to the center with a lower degree of starch gelatinization and more difficulty for rehydration, leading to the shorter cooking time for fried instant noodle products.

The effect of frying process on the degree of gelatinization and decomposition of the starch complex can be seen from the higher To, Tp, and ΔH of fried instant noodle products. Previous studies

have shown that the thermal transition temperatures of palm oil and wheat protein were around 40 and 60 °C, respectively (34). However, within the temperature scanning range of fried instant noodle products, there was no thermal transition peak, which meant that the free fatty acids and the wheat proteins had been decomposed. Once being fried, the starch gelatinization peak disappeared and a new peak can be found around 100 °C, indicating that the samples were gelatinized, and starch–lipid complexes were formed. Based on the calorimetry results, two distinctive peaks were obtained in the range of 89.48–96.42°C and 149.38–158.02 °C, respectively, presenting the formation of type I and type IIb complexes through melting and recrystallization, which showed a higher level of thermal stability compared with the non-fried samples (35). The increased peak temperature of instant noodle products, probably because of protein denaturation, would lead to structural extension, prevent the interaction between starch and other molecules, and thus interfere with the endothermic melting process of starch–lipid complexes. Furthermore, the melting enthalpy (ΔH) of the starch–lipid complex could reflect the amount of complex and the degree of order within the complex (36). The higher level of ΔH for fried instant noodle products indicated that the frying process provides more energy to activate the interaction between starch and lipid molecules, resulting in the formation of more starch–lipid complexes with higher stability and order.

The texture profile analysis is one of the most effective methods to evaluate the edible quality of cooked noodle products. This is probably because the starch–lipid complexes formed during the frying process could disrupt the regular gluten network structure in the dough, thus weakening the hardness of fried samples. The association between texture and protein and fiber content of fried instant noodle was observed, probably because the monomeric molecules inside the protein had a significant positive relationship with the hardness of cooked instant noodle (37), whereas higher fiber content has been confirmed to increase the strength of the dough by interacting with the gluten system, leading to increased hardness of non-fried cooked noodles (38). Moreover, chewiness and resilience are affected by starch properties (total amount, molecular structure, and distribution within the tuber), starch swelling pressure, and gelatinization properties (39, 40). These might be the reasons why fried noodle showed a downward trend in the performance of hardness, and an upward trend in the performance of chewiness and resilience, compared with non-fried instant noodle.

In terms of sensory evaluation, fried instant noodle products have more acceptable performance than non-fried products. Some of the possible reasons are as follows: Dough of fried instant noodle containing starch and protein is usually cooked at a high temperature above 130°C at which Maillard and caramelization reaction will occur, producing more flavors and pigments, which contributes to the preliminary evaluation of instant noodle products (41). Many of these end-products are fat-soluble, easily dissolving in the fried products after the frying process, and so the aroma might be more lasting and softer (42). The oil itself could also produce the fragrant substance, such as 2, 4-decadienal after thermal decomposition, which produces a unique flavor for instant noodle products (43). Additionally, the presence of more fat for instant noodle after the frying process could have a positive effect on the smoothness, uniformity, and continuity of the noodle surface, thus improving the overall sensory performance of instant noodles (44).

Effect of Frying on Starch Digestibility of Instant Noodle

The performance of starch for instant noodle products, including the rate and degree of hydrolysis, components, and eGI, represents the capacity of energy supply, sugar regulation, and intestinal absorbance. First, the frying process downregulated the starch hydrolysis. This might be attributed to the formation of the starch–lipid complex that is considered RS type 5 (45). This type of complex obtained after the frying process showed higher RS, which stays in line with the results shown in **Table 3**. Besides, the frying process significantly decreased the TS content of instant noodle, possibly due to the degradation of the starch molecules during deep-frying, as observed in other studies (46). The lower levels of TS content brought by the frying process would result in changes in the thermodynamic, crystalline, and pasting properties of the starch (47), which is another one of the reasons leading to lower starch digestibility for instant noodle products. Apart from this, compared with standard starch, the higher RDS content of instant noodle products may be due to the dilution effect on starch gelatinization and the enhancement of starch–protein interaction caused by the frying process (48). Frying treatment could reduce the SDS content and increase the RS content. Although higher RS content of fried instant noodle products cannot be absorbed in the small intestine, it could be fermented and metabolized by intestinal microorganisms in the large intestine and promote human health by regulating the lipid metabolism, cholesterol synthesis, fatty acid oxidation, and other physiological processes in a variety of ways (49), so the higher RS content can been recognized as one of the nutritional attributes of instant noodle products, compared with other wheat-made food.

According to the WHO, foods with a GI value less than 55 are recognized as low-GI foods and those with over 70 are high-GI foods (50). All these high-GI foods, especially those with GI values of over 90, can enter the gastrointestinal tract with a rapid digestible rate, thus raising the blood sugar rapidly. Interestingly, our results showed a significant reduction in GI when the instant noodle products were fried, compared to non-fried products. This GI variation might be negatively correlated with RS, and this contributes to the nutritional properties for fried noodle products because the diet with high-GI food has been considered as one the of risk factors leading to Type 2 diabetes (51, 52), whereas non-fried instant noodle is still the priority on the diet for marathon runners and patients with hypoglycemia when the body urgently needs energy, and this can quickly supply energy and raise the blood sugar.

Effect of Frying on *in vitro* Protein Digestibility of Instant Noodle

The frying process can change the protein digestibility, internal structure, and external interaction for instant noodle products by regulating the degree and rate of protein hydrolysis and

the proportion of secondary conformation. During the *in vitro* protein digestion, the lower digesting rate of fried instant noodle at an early stage might be since the frying process allows the lipid to enter the noodle products, which can quickly remove the moisture and create small pores carrying the air, thus inhibiting the rapid contact between pepsin and the noodle surface. The lower digesting terminal point of fried instant noodle might be related to protein oxidative modification caused by the pores carrying the air, just as demonstrated before. This would easily lead to the intermolecular cross-linking and protein aggregation, and weaken the combination of digestive enzymes and proteins, thus reducing protein digestibility. Moreover, the protein hydrolysis could release peptide chain and hydrophilic molecules, most of which are hydrophilic and likely to prevent further contact of the protein with trypsin in the presence of oil after the frying process. To sum up, although the frying process reduced the protein digestibility, IVPD of both these products reached a high level after gastrointestinal digestion. Proteins with high IVPD are usually regarded as high-quality proteins because proteolysis facilitates the release of amino acids from the protein backbone, which means they can be better digested and absorbed (53).

Besides, based on the irregular peaks of fried instant noodle products in the results of FT-IR, the wave number of 3,000–3,500 cm^{-1} represents the amide-A and free hydroxyl groups, indicating the interaction of protein molecules with water (54). This increased spectrum peak change of fried instant noodle products is probably because of some structural modifications caused by the frying process. While the absorption peaks in the wavelength of 1,150 and 850 cm^{-1} represent C–O stretching and C–H deformation vibration, respectively, (55), the degradation and new interactions of protein molecules might be responsible for these different peaks of the spectrum. As for the protein secondary structure, the lowered content of β-turns of fried instant noodle products indicated that protein continuously unfolded, allowing the protein to aggregate to the molecular scale. An increment in β-sheets content of fried instant noodle products was also observed, which was a sign of molecular aggregation (56). The higher levels of β-turns, random coil, and lower percentages of α-helixes of fried instant noodle could interrupt the structure of hydrogen bonds, affect the dehydration of gluten, and prevent direct contact between protein molecules and enzymes, thus negatively affecting the final protein digestibility.

Effect of Frying Process on Microstructure of Instant Noodle

The SEM was applied to detect the structural changes, formation of lipid–starch complex, and the levels of hydrolysis during *in vitro* stimulated digestion. The frying process promoted the generation of pores in the interior of the noodles, and this might be attributed to the formation of larger vapor pressure when water evaporates at the early stage of the frying process, which destroyed the internal structure and produced numerous pores. The honeycomb-like structure accompanied with numerous small pores inside observed after oral digestion was formed probably because of the glassy transition and the uneven shrinkage during the frying process (57). These pores created by the frying process allow digestive enzymes to enter inside, so that the noodles can be digested quickly afterward, while the existence of complete gluten structure in non-fried instant noodle made it difficult to digest with an outside-in approach. This is one of the reasons why fried instant noodle products have a higher digestion rate at the beginning. While during the gastrointestinal digestion, structural modifications caused by the frying process prevented continuous digestion, mushroom-like structures were formed that attributed to the incompletely digested particles for fried instant noodle products, thus reducing the final hydrolysis rate.

CONCLUSION

The effect of frying process on the nutritional property, physicochemical quality, and *in vitro* digestibility of instant noodle products was investigated in this study. Results clearly revealed that frying reduced the proportion of carbohydrate, protein, fiber, ad also TS and DS, but increased the content of fat and RS. The results also suggested that the frying process decreased the *in vitro* digestibility of starch and protein, and the levels of expected glycemic index because frying was confirmed to promote the interaction between starch and lipid molecules, resulting in the formation of type I and type IIb complexes through melting and recrystallization. We have also observed that the frying process could form a honeycomb-like structure, prevent continuous contact with digesting enzymes, and thus intervene in the *in vitro* digestion of instant noodle products through generating starch–lipid complexes, changing the degree of gelatinization, and transforming the protein structure. Accordingly, the frying process conferred more acceptable texture, color, and sensory attributes to the final consumer products, accompanied with better cooking quality including shorter term of cooking time and lower cook loss during rehydration, resulting from the properties of protein and starch (total amount, molecular structure, and digestibility), presence of the lipid, and higher levels of fat-soluble color polymer. Taken together, this study will contribute to the innovative evaluation of the frying process on instant noodles and other various starch-based prepared food products, and further research is necessary to address the mechanisms underlying the involved intermolecular interaction and provide further development of fried products based on optimized frying process.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

JW and AL designed this study, performed the experiments, and prepared the manuscript. JH, BZ, and JL coordinated the laboratory work and prepared the tables and figures. SW and YZ aided in the analysis and interpretation of the data. All authors agree to be accountable for the content of the work and approve the manuscript.

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REFERENCES

1. Li M, Chung SJ. Flavor principle as an implicit frame: its effect on the acceptance of instant noodles in a cross-cultural context. *Food Qual Prefer.* (2021) 93:104293. doi: 10.1016/j.foodqual.2021.104293

2. Wu J, Aluko RE, Corke H. Partial least-squares regression study of the effects of wheat flour composition, protein and starch quality characteristics on oil content of steamed-and-fried instant noodles. *J Cereal Sci.* (2006) 44:117–26. doi: 10.1016/j.jcs.2006.05.008

3. Wong YH, Goh KM, Nyam KL, Cheong LZ, Wang Y, Nehdi IA, et al. Monitoring of heat-induced carcinogenic compounds (3-monochloropropane-1,2-diol esters and glycidyl esters) in fries. *Sci Rep.* (2020) 10:15110. doi: 10.1038/s4s1598-020-72118-z

4. Yang Y, Wang L, Li Y, Qian HF, Zhang H, Cheng Wu G, et al. Investigation the molecular degradation, starch-lipid complexes formation and pasting properties of wheat starch in instant noodles during deep-frying treatment. *Food Chem.* (2019) 283:287–93. doi: 10.1016/j.foodchem.2019.01.034

5. Adejuwon OH, Jideani AIO, Falade KO. Quality and public health concerns of instant noodles as influenced by raw materials and processing technology. *Food Rev Int.* (2020) 36:276–317. doi: 10.1080/87559129.2019.1642348

6. Ruocco C, Ragni M, Rossi F, Carullo P, Ghini V, Piscitelli F, et al. Manipulation of dietary amino acids prevents and reverses obesity in mice through multiple mechanisms that modulate energy homeostasis. *Diabetes.* (2020) 69:2324–39. doi: 10.2337/db20-0489

7. Chen X, He X, Fu X, Zhang B, Huang Q. Complexation of rice starch/flour and maize oil through heat moisture treatment: structural, *in vitro* digestion and physicochemical properties. *Int J Biol Macromol.* (2017) 98:557–64. doi: 10.1016/j.ijbiomac.2017.01.105

8. Kawai K, Takato S, Sasaki T, Kajiwara K. Complex formation, thermal properties, and in-vitro digestibility of gelatinized potato starch–fatty acid mixtures. *Food Hydrocoll.* (2012) 27:228–34. doi: 10.1016/j.foodhyd.2011.07.003

9. Park CS, Baik BK. Relationship between protein characteristics and instant noodle making quality of wheat flour. *Cereal Chem.* (2004) 81:159–64. doi: 10.1094/CCHEM.2004.81.2.159

10. Gong X, Hui X, Wu G, Morton JD, Brennan MA, Brennan CS. *In vitro* digestion characteristics of cereal protein concentrates as assessed using a pepsin-pancreatin digestion model. *Int Food Res J.* (2021):110715. doi: 10.1016/j.foodres.2021.110715

11. Cao X, Zhou S, Yi C, Wang L, Qian H, Zhang H, et al. Effect of whole wheat flour on the quality, texture profile, and oxidation stability of instant fried noodles. *J Texture Stud.* (2017) 48:607–15. doi: 10.1111/jtxs.12274

12. Xu M, Hou GG, Ma F, Ding J, Deng L, Kahraman O, et al. Evaluation of aleurone flour on dough, textural, and nutritional properties of instant fried noodles. *LWT.* (2020) 126:109294. doi: 10.1016/j.lwt.2020.109294

13. AOAC. *Official Methods of Analysis, 19th ed*. Association of Official Analytical Chemist (2012).

14. Song Y, Yoo SH. Quality improvement of a rice-substituted fried noodle by utilizing the protein-polyphenol interaction between a pea protein isolate and green tea (*Camellia sinensis*) extract. *Food Chem.* (2017) 235:181–7. doi: 10.1016/j.foodchem.2017.05.052

15. Guo XN, Wu SH, Zhu KX. Effect of superheated steam treatment on quality characteristics of whole wheat flour and storage stability of semi-dried whole wheat noodle. *Food Chem.* (2020) 322:126738. doi: 10.1016/j.foodchem.2020.126738

16. Zhang M, Zhang L, Li M, Sun Q. Inhibitory effects of sorbitol on the collapse and deterioration of gluten network in fresh noodles during storage. *Food Chem.* (2021) 344:128638. doi: 10.1016/j.foodchem.2020.128638

17. Li M, Sun QJ, Han CW, Chen HH, Tang WT. Comparative study of the quality characteristics of fresh noodles with regular salt and alkali and the underlying mechanisms. *Food Chem.* (2018) 246:335–42. doi: 10.1016/j.foodchem.2017.11.020

18. Sofi SA, Singh J, Mir SA, Dar BN. *In vitro* starch digestibility, cooking quality, rheology and sensory properties of gluten-free pregelatinized rice noodle enriched with germinated chickpea flour. *LWT.* (2020) 133:110090. doi: 10.1016/j.lwt.2020.110090

19. Wang S, Wang S, Liu L, Wang S, Copeland L. Structural orders of wheat starch do not determine the *in vitro* enzymatic digestibility. *J Agric Food Chem.* (2017) 65:1697–706. doi: 10.1021/acs.jafc.6b66b0b4044

20. Englyst HN. Kingman, S M, Cummings, J H. Classification and measurement of nutritionally important starch fractions. *Eur J Clin Nutr.* (1992) 46:33–50.

21. Hur SJ, Lee SJ, Lee SY, Bahk YY, Kim CG. Effect of emulsifiers on microstructural changes and digestion of lipids in instant noodle during *in vitro* human digestion. *LWT - Food Sci Technol.* (2015) 60:630–6. doi: 10.1016/j.lwt.2014.07.036

22. Jadhav SB, Gaonkar T, Rathi A. *In vitro* gastrointestinal digestion of proteins in the presence of enzyme supplements: Details of antioxidant and antidiabetic properties. *LWT.* (2021) 147:111650. doi: 10.1016/j.lwt.2021.111650

23. Wang R, Li M, Chen S, Hui Y, Tang A, Wei Y. Effects of flour dynamic viscosity on the quality properties of buckwheat noodles. *Carbohydr Polym.* (2019) 207:815–23. doi: 10.1016/j.carbpol.2018.09.048

24. Fevzioglu M, Ozturk OK, Hamaker BR, Campanella OH. Quantitative approach to study secondary structure of proteins by FT-IR spectroscopy, using a model wheat gluten system. *Int J Biol Macromol.* (2020) 164:2753–60. doi: 10.1016/j.ijbiomac.2020.07.299

25. Khatkar AB, Kaur A, Khatkar SK, Bala M, Maan S, Tyagi SK. Valorization of ultrasound assisted restructured soy protein: Impact on the quality characteristics of instant noodles. *LWT.* (2021) 147:111599. doi: 10.1016/j.lwt.2021.111599

26. Butterworth PJ, Warren FJ, Ellis PR. Human α-amylase and starch digestion: an interesting marriage. *Starch - Stärke.* (2011) 63:395–405. doi: 10.1002/star.201000150

27. Chung HJ, Liu Q, Hoover R, Warkentin TD, Vandenberg B. *In vitro* starch digestibility, expected glycemic index, and thermal and pasting properties of flours from pea, lentil and chickpea cultivars. *Food Chem.* (2008) 111:316–21. doi: 10.1016/j.foodchem.2008.03.062

28. Zhou R, Sun J, Qian H, Li Y, Zhang H, Qi X, et al. Effect of the frying process on the properties of gluten protein of you-tiao. *Food Chem.* (2020) 310:125973. doi: 10.1016/j.foodchem.2019.125973

29. Gómez AV, Ferrer EG, Añón MC, Puppo MC. Changes in secondary structure of gluten proteins due to emulsifiers. *J Mol Struct.* (2013) 1033:51–8. doi: 10.1016/j.molstruc.2012.08.031

30. Chen L, Zhang H, McClements DJ, Zhang Z, Zhang R, Jin Z, et al. Effect of dietary fibers on the structure and digestibility of fried potato starch: a comparison of pullulan and pectin. *Carbohydr Polym.* (2019) 215:47–57. doi: 10.1016/j.carbpol.2019.03.046

31. Ikanone CEO, Oyekan PO. Effect of boiling and frying on the total carbohydrate, Vitamin C and mineral contents of Irish (Solanun tuberosum) and Sweet (*Ipomea batatas*) Potato Tubers. *Nigerian Food J.* (2014) 32:33–9. doi: 10.1016/S0S189-7241(15)301155-6

32. Abdul-Hamid A, Luan YS. Functional properties of dietary fibre prepared from defatted rice bran. *Food Chem.* (2000) 68:15–9. doi: 10.1016/S0S308-8146(99)001455-4

33. Castellanos-Gallo L, Galicia-García T, Estrada-Moreno I, Mendoza-Duarte M, Márquez-Meléndez R, Portillo-Arroyo B, et al. Development of an expanded snack of rice starch enriched with Amaranth by

extrusion process. *Molecules*. (2019) 24: 2430. doi: 10.3390/molecules2s4132430

34. León A, Rosell CM, Benedito de. Barber C. A differential scanning calorimetry study of wheat proteins. *Eur Food Res Technol*. (2003) 217:13–6. doi: 10.1007/s0s0217-003-0699-y

35. Putseys JA, Lamberts L, Delcour JA. Amylose-inclusion complexes: Formation, identity and physico-chemical properties. *J Cereal Sci*. (2010) 51:238–47. doi: 10.1016/j.jcs.2010.01.011

36. Wang J, Ren F, Yu J, Copeland L, Wang S. Octenyl Succinate modification of starch enhances the formation of starch–lipid complexes. *J Agric Food Chem*. (2021) 69:14938–50. doi: 10.1021/acs.jafc.1c11c0c5816

37. Hu XZ, Wei YM, Wang CMIPK. Quantitative assessment of protein fractions of Chinese wheat flours and their contribution to white salted noodle quality. *Food Res Inter*. (2007) 40:1–6. doi: 10.1016/j.foodres.2006.05.003

38. Mitra S, James AP, Fenton HK, Cato L, Solah VA. The impact of oat quality on white salted noodles containing oat flour. *Cereal Chem*. (2016) 93:282–92. doi: 10.1094/CCHEM-05-15-0100-R

39. Thybo AK, Christiansen J, Kaack K, Petersen MA. Effect of cultivars, wound healing and storage on sensory quality and chemical components in pre-peeled potatoes. *LWT - J Food Sci Technol*. (2006) 39:166–76. doi: 10.1016/j.lwt.2004.11.010

40. Botero-Uribe M, Fitzgerald M, Gilbert RG, Midgley J. Effect of pulsed electrical fields on the structural properties that affect french fry texture during processing. *Trends Food Sci Technol*. (2017) 67:1–11. doi: 10.1016/j.tifs.2017.05.016

41. Wang Z, Cai R, Yang X, Gao Z, Yuan Y, Yue T. Changes in aroma components and potential Maillard reaction products during the stir-frying of pork slices. *Food Control*. (2021) 123:107855. doi: 10.1016/j.foodcont.2020.107855

42. Bi S, Wang A, Lao F, Shen Q, Liao X, Zhang P, et al. Effects of frying, roasting and boiling on aroma profiles of adzuki beans (Vigna angularis) and potential of adzuki bean and millet flours to improve flavor and sensory characteristics of biscuits. *Food Chem*. (2021) 339:127878. doi: 10.1016/j.foodchem.2020.127878

43. Sun X, Wang Y, Li H, Zhou J, Han J, Wei C. Changes in the volatile profile, fatty acid composition and oxidative stability of flaxseed oil during heating at different temperatures. *LWT*. (2021) 151:112137. doi: 10.1016/j.lwt.2021.112137

44. Ding S, Yang J. The influence of emulsifiers on the rheological properties of wheat flour dough and quality of fried instant noodles. *Trends Food Sci Technol*. (2013) 53:61–9. doi: 10.1016/j.lwt.2013.01.031

45. Bello-Perez LA, Flores-Silva PC, Agama-Acevedo E, Tovar J. Starch digestibility: past, present, and future. *J Sci Food Agric*. (2020) 100:5009–16. doi: 10.1002/jsfa.8955

46. Chen L, Tian Y, Sun B, Cai C, Ma R, Jin Z. Measurement and characterization of external oil in the fried waxy maize starch granules using ATR-FTIR and XRD. *Food Chem*. (2018) 242:131–8. doi: 10.1016/j.foodchem.2017.09.016

47. Chen L, McClements DJ, Yang T, Ma Y, Ren F, Tian Y, et al. Effect of annealing and heat-moisture pretreatments on the oil absorption of normal maize starch during frying. *Food Chem*. (2021) 353:129468. doi: 10.1016/j.foodchem.2021.129468

48. Shumoy H, Van Bockstaele F, Devecioglu D, Raes K. Effect of sourdough addition and storage time on *in vitro* starch digestibility and estimated glycemic index of tef bread. *Food Chem*. (2018) 264:34–40. doi: 10.1016/j.foodchem.2018.05.019

49. Sun H, Fan J, Tian Z, Ma L, Meng Y, Yang Z, et al. Effects of treatment methods on the formation of resistant starch in purple sweet potato. *Food Chem*. (2022) 367:130580. doi: 10.1016/j.foodchem.2021.130580

50. Kumar A, Panda PA, Lal MK, Ngangkham U, Sahu C, Soren KR. et al. Addition of pulses, cooking oils, and vegetables enhances resistant starch and lowers the glycemic index of rice (Oryza sativa L) *starch*. *Stärke*. (2020) 72:1900081. doi: 10.1002/star.201900081

51. Naseer B, Naik HR, Hussain SZ, Zargar I. Beenish, Bhat TA, et al. Effect of carboxymethyl cellulose and baking conditions on in-vitro starch digestibility and physico-textural characteristics of low glycemic index gluten-free rice cookies. *LWT*. (2021) 141:110885. doi: 10.1016/j.lwt.2021.110885

52. Teymoori F, Farhadnejad H, Moslehi N, Mirmiran P, Mokhtari E, Azizi F. The association of dietary insulin and glycemic indices with the risk of type 2 diabetes. *Clin Nutri*. (2021) 40:2138–44. doi: 10.1016/j.clnu.2020.09.038

53. Mir NA, Riar CS, Singh S. Structural modification in album (Chenopodium album) protein isolates due to controlled thermal modification and its relationship with protein digestibility and functionality. *Food Hydrocoll*. (2020) 103:105708. doi: 10.1016/j.foodhyd.2020.105708

54. Perisic N, Afseth NK, Ofstad R, Kohler A. Monitoring protein structural changes and hydration in bovine meat tissue due to salt substitutes by fourier transform infrared (FTIR) microspectroscopy. *J Agric Food Chem*. (2011) 59:10052–61. doi: 10.1021/jf2f01578b88b

55. Gu FL, Kim JM, Abbas S, Zhang XM, Xia SQ, Chen ZX. Structure and antioxidant activity of high molecular weight Maillard reaction products from casein–glucose. *Food Chem*. (2010) 120:505–11. doi: 10.1016/j.foodchem.2009.10.044

56. Wang P, Zou M, Gu Z, Yang R. Heat-induced polymerization behavior variation of frozen-stored gluten. *Food Chem*. (2018) 255:242–51. doi: 10.1016/j.foodchem.2018.02.047

57. Yang S, Zhang MN, Shan CS, Chen ZG. Evaluation of cooking performance, structural properties, storage stability and shelf life prediction of high-moisture wet starch noodles. *Food Chem*. (2021) 357:129744. doi: 10.1016/j.foodchem.2021.129744

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