Microstructural, textural, and sensory properties of whole-wheat noodle modified by enzymes and emulsifiers

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A B S T R A C T

With the utilization of enzymes including endoxylanase, glucose oxidase (GOX) and transglutaminase (TG), and emulsifiers comprising sodium stearoyl lactate (SSL) and soy lecithin, the microstructural, textural, and sensory properties of whole-wheat noodle (WWN) were modified. The development time and stability of whole-wheat dough (WWD) were enhanced by TG due to the formation of a more compact gluten network, and by SSL resulting from the enhanced gluten strength. Microstructure graphs by scanning electron microscopy (SEM) verified that TG and SSL promoted the connectivity of gluten network and the coverage of starch granules in WWN. TG increased the hardness and elasticity of cooked WWN, while two emulsifiers increased the noodle cohesiveness. Additionally, TG and SSL improved the sensory properties of noodle such as bite, springiness, and mouth-feel. The results suggest that TG and SSL are effective ingredients in enhancing the gluten strength of WWD and improving the qualities of WWN.

1. Introduction

Whole grains comprise intact, ground, cracked, or flaked caryopses, in which all components (bran, germ, and endosperm) are present in the same relative proportions as in the intact grain. Thus, they contain all naturally occurring and essential substances of the entire seed (Ye, Chacko, Chou, Kugizaki, & Liu, 2012). In the U.S., whole grains may include whole wheat, oats, brown rice, rye, corn, barley, millet, and sorghum. Whole-grain flour can be obtained by grinding the kernels into flour using several milling techniques such as stone mill, hammer mill, and roller mill (Posner, 2009). Nowadays, consumers worldwide have shown increasing interests in reducing disease risks and managing chronic diseases by consuming health-promoting dietary ingredients. Whole-wheat flour (WWF), as one of the most important whole grains, acts as a rich source of dietary fiber and phytochemicals (Hirawan, Ser, Arntfield, & Beta, 2010). Many epidemiological and clinical studies have shown that the long-term intake of whole-wheat products can provide many benefits for the patients suffering from chronic diseases such as obesity, diabetes, and cancer (Giacco, Della Pepa, Luongo, & Riccardi, 2011). However, the addition of wheat bran not only causes rough surfaces and gritty mouth-feel but also negatively affects the formation of gluten network in bran-contained products, leading to undesirable product quality. Much effort is being made to improve the quality characteristics of whole-wheat products. Liu et al. (2015) improved the steamed bread making performance of WWF by different milling processes and found that the bran recombining grinding process provided a larger height/diameter ratio and specific volume than the entire grain grinding process. Li, Hou, Chen, and Gehring (2013) enhanced the baking quality of whole-wheat saltine cracker by including endoxylanase, vital wheat gluten, and gum Arabic, and reported that these ingredients increased the stack height and specific volume of the crackers.

Noodles account for approximately 20–50% of the total wheat consumed in Asia, and the popularity of noodles has expanded to many countries outside of Asia (Hou, 2010). In view of this, introduction of Asian noodles made from WWF can be an effective way to promote the high-fiber food consumption and increase the health benefits for consumers around the world. Several studies have been conducted to investigate the effects of bran on noodle quality and improve the textural and sensory properties of whole-wheat noodle (WWN). Jiang, Martin, Okot-Kotber, and Seib (2011) reported that dark wheat bran reduced the lightness of noodle sheet. Song, Zhu, Pei, Ai, and Chen (2013) noted that...
the presence of bran decreased the connectivity between starch granules and gluten in noodle structure. Vijayakumar and Boopathy (2014) included tapioca flour and soy flour in noodle formula and improved the cooking qualities and sensory properties of WWN. In our previous studies, the influences of wheat bran particle size and grinding methods on the properties of WWF and its noodle qualities were investigated (Niu, Hou, Lee, & Chen, 2014a; Niu, Hou, Wang, & Chen, 2014b). The reduction of wheat bran or WWF particle sizes provided beneficial effects on the quality improvement of WWN. Alternatively, the use of special inorganic phosphate salts improved the color and textural properties of WWN (Niu, Li, Wang, Chen, & Hou, 2014c). Despite some attempts have been made to improve the color, texture, and sensory properties of WWN, the use of functional ingredients that are commonly used in baking industry has not been reported.

Commercial enzymes, such as transglutaminase (TG) and glucose oxidase (GOX), have been tested in refined noodle products to improve their quality. Transglutaminase facilitates the formation of the isopeptide bond, thereby leading to polymers of high molecular weight. Bellido and Hatcher (2011) reported that TG could polymerize the protein network and increase the stiffness, elasticity and firmness of yellow alkaline noodles. Choy, Hughes, and Small (2010) noted that the addition of TG into instant noodle formula enhanced the noodle hardness and improved the continuity of protein network. Gan, Wenhevi, Leemin, and Easa (2009) found that inclusion of TG yielded higher tensile strength and elasticity for noodles containing soy protein isolate. GOX causes the oxidation of free sulfhydryl units in gluten proteins and promotes the formation of disulfide linkages. COX has been reported to improve the microstructure and storage quality of frozen noodle when used together with other ingredients (α-amylase and guar gum) (Lv et al., 2014). Endoxylanase, another commercial enzyme, is capable of reducing the water holding capacity of arabinoxylans (AX) and redistributes water in flour-based products, but few studies have reported its application in noodle product.

Sodium stearoyl lactylate (SSL), as a kind of anionic emulsifier, can cause gluten aggregation and increases dough strength by its interactions with gluten during mixing (Gomez, Ferrer, Anon, & Puppo, 2013). SSL was reported to enhance the structure development of instant fried noodle (Choy et al., 2010). Lecithin is a naturally occurring mixture of phosphatidyl choline with diverse fatty acid side chains such as stearic, oleic, and palmitic acids. It has been used to modify the lipid digestion of instant noodles by producing small droplets (Hur, Lee, Lee, Bahk, & Kim, 2015). Ugačić-Hardi, Jukić, Komlenić, Sabo, and Hardi (2007) included soy lecithin in noodle formula and found it could reduce noodle cooking loss.

These functional ingredients, commonly used in baking industry, have shown their effectiveness in improving the structure, cooking quality, and textural property of refined noodle products except endoxylanase. But, none of them has been experimented with in WWN dough system. The aim of the study was to investigate the influences of enzymes (endoxylanase, GOX, and TG) and emulsifiers (SSL and soy lecithin) on the quality attributes of WWN. This study was expected to demonstrate the interactions between these ingredients and flour components in WWN, and provide more effective methods and valuable guidance for further improvement of WWN.

2. Materials and methods

2.1. Materials

Ultrafine hard white whole-wheat flour (WWF) was kindly provided by Ardent Mills (Denver, Colorado, US). This special WWF was produced by the steps of roller milling and separating wheat kernels into refined and millfeed fractions, fine grinding of the millfeed fractions to mean particle size of small than 150 μm, and recombining the ground millfeeds with the refine flour. The moisture, protein, and ash content of WWF were 11.20%, 12.67% (14% moisture basis, mb), and 1.52% (14% mb), respectively. Pentopan Mono BG (EC 3.2.1.8, 2500 U/g, lyophilized powder) is a purified (1, 4)-β-xylosidase and was provided by Novozenzyme Company (Franklinton, NC). Glucose oxidase (EC 1.1.3.4, 300 U/g, lyophilized powder) was purified from Aspergillus niger, transglutaminase (EC 2.3.2.13, 100 U/g, lyophilized powder) was purified from guinea pig liver, and both enzymes were from Mühlenchemie (Ahrensburg, Germany). The enzyme unit, one U, is defined as the amount of enzyme that catalyzes the conversion of one micromole of substrate per minute at a temperature of 25 °C and the optimal pH and substrate concentration that yield the maximal substrate conversion rate. Soy lecithin was manufactured by WillPowder (Miami Beach, Florida, US), and Sodium Stearoyl Lactate (SSL) was purchased from INRFood (Durham, North Carolina, US). All ingredients used in the study were food grade.

The usage levels of each ingredient were selected based on the manufacturers’ recommendations and our screening experiments. The addition levels for the three enzymes were 0.30, 0.75, and 1.50 U per gram of WWF. The addition levels were 0.10%, 0.30%, and 0.50% (w/w, flour basis) for soy lecithin, and 0.25%, 0.50%, and 0.75% (w/w, flour basis) for SSL, respectively.

2.2. Starch pasting properties

The starch pasting properties of WWF samples added with ingredients were determined with a Rapid Visco Analyzer (RVA, Model Super-3, Newport Scientific, Australia), using the AACC International Approved Method 76-21 (American Association of Cereal Chemists, 2010). A sample of 3.5 g WWF (14% mb), 25 mL of distilled water, and a defined addition level of each ingredient were mixed to form a slurry that was manually homogenized using a plastic paddle to avoid lump formation before the RVA test. The tests were conducted in a programmed heating and cooling cycle for 13 min. The parameters recorded were expressed in rapid visco units (RVU).

2.3. Dough mixing properties by Mixolab

The dough mixing properties of WWF were determined with a Mixolab (Chopin Technologies, Villeneuve la Garenne, France). A constant dough weight (75 g) method was used. An exact amount of each WWF sample with each ingredient was weighed and placed into the mixer as specified by the Mixolab software. The settings of the heating and cooling circles were first maintained at 30 °C for 8 min, increasing at 4 °C/min until the mixer temperature reached 90 °C, decreasing at the same speed until the temperature reached 50 °C after an 8-min holding period at 90 °C, and finally holding at 50 °C for 6 min. The parameters obtained from the recorded curve were water absorption (the percentage of water required for the dough to produce a torque of 1.1 ± 0.07 Nm), dough development time (the time required to obtain C1), stability (the time during which the torque produced is >C1-11%), peak torque (the maximum torque produced during the heating stage), setback (the difference between the torque before cooking at 50 °C and the torque after the holding time at 90 °C), and hot-gel stability (the ratio of the torque after the holding time at 90 °C and the maximum torque during the heating period). The measurements were performed in triplicate for each sample.

2.4. Preparation of noodles

The fresh raw noodles were prepared through mixing and sheeting on a pilot-scale noodle line, according to the procedure.
described by Hou (2010). Each enzyme or emulsifier was pre-
dissolved in half of the water, and salt was dissolved in the remain-
ing water. The correct amount of solution was added to achieve a
flour-water-salt weight ratio of 100:35:1.2. The final thickness of
the noodle-dough sheet was calibrated to 1.20 ± 0.03 mm, and
the noodle sheet was slit into 2.5 mm-wide and 300 mm-long
strands with a #12 square-type slitter. The fresh raw noodles were
stored in plastic bags at room temperature before analyses.

2.5. Scanning electron microscopy (SEM)
The SEM study of the cross-section structure of raw noodle was
conducted as described by Niu et al. (2014c), using a scanning
electron microscope (Sigma VP, ZEISS International, Germany).
The fresh noodles were soaked in glutaraldehyde solution (2.5%) for
2 h and rinsed with phosphate buffer (0.1 mol/L), followed by a
secondary fixation in osmium tetroxide solution (1%) for 1.5 h.
Then, the samples were eluted in graded ethanol series (30%, 50%, 70%, 90%, and 100%) and isoamyl acetate was used to remove
the ethanol. After being supercritical dried, dehydrated samples
were mounted on an aluminum stub using a double-sided tape
and coated with 50 nm of gold, then observed at an accelerating
voltage of 15 kV. The micrographs were taken at 600 × magnifica-
tion. During preparation, the mounting solutions were kept uncon-
taminated and the steps of sample sticking and coating were
performed as quickly as possible to avoid possible contamination
from operating environment.

2.6. Color measurement
A Chroma meter (Konica Minolta CR-410, Japan) equipped with
D50 illuminant was used to measure the color of raw noodle sheets
following the methods of Hou (2010). An average of eight readings
was calculated for each measurement. Duplicate noodle prepara-
tions were conducted on two different days. Noodle sheets were stored
in sealed plastic bags at room temperature until the measurements
were taken.

2.7. Noodle cooking yield
The cooking yield was determined according to the method
described by Hou (2010). A sample of 100 g raw noodle was cooked
in boiling water for 5 min and rinsed in 26-27 °C water for 10 s
with stirring. The noodles were then placed in a plastic strainer,
and the excess water on the surface of the cooked noodles was
drained by tapping the strainer forcefully 10 times (for about
10 s) on the edge of a sink. The weight of the cooked noodle sample
was recorded, and the cooking yield was calculated as the mass
ratio before and after cooking.

2.8. Textural properties
Textural profile analysis (TPA) of cooked noodle was deter-
mined as described by Hou (2010), using a TA-XTPlus Texture Ana-
lyzer (Texture Technology Corp., Scarsdale, NY). Cooked noodles
were prepared using the same procedures as noodle cooking yield in
Section 2.7. After the excess water on noodle surface was
removed, the drained noodles were placed in a covered container
and three uniform long noodle strands were taken and cut to a
length of 6.0 cm. Five short strands were randomly selected and
placed side by side on the base plate, and compressed with a TA-
47 W Pasta Blade (5-mm thickness flat blade) by using a 5 kg load
cell. The pre-test speed, test speed, and post-test speed were
4 mm/s, 1 mm/s, and 1 mm/s, respectively. The compression strain
was 70% of the noodle thickness, and the averages of at least eight
analyses were calculated. Four textural parameters, including
hardness, springiness, cohesiveness, and resilience, were recorded from the TPA.

2.9. Sensory evaluation
The sensory qualities of cooked noodle were determined
according to the method described by Fu and Malcolmson
(2010), using a quantitative descriptive analysis (QDA). All pan-
elists consume Asian noodles regularly. Before conducting formal
descriptive analysis, panelists were given several training sessions
on the attributes and procedures they must follow for assessing
the noodle products. During training, panelists received instruc-
tions and samples varying in the intensities of the attributes being
assessed. The training continued until panelists were in agree-
ment with each other on their ratings, and they were able to repro-
duce their judgments from one session to another. Eight trained
panelists were included for the analyses and a ten-point hedonic
scale was used. The sensory analyses included two steps. The first
step began immediately after the noodles were cooked, and the
second step began when the noodles were soaked in a hot water
for 5 min after cooking. The attributes evaluated were bite, springi-
ness, mouth-feel, integrity, and total score. The control group was
without added ingredient, and the score of each quality parameter
was set at 7.0. The test samples were scored against the control
sample.

2.10. Statistical analysis
All measurements were performed at least in triplicate. Statisti-
cal analyses were carried out with SPSS 16.0 for Windows, using
one-way analyses of variance (ANOVA). P < 0.05 was considered
to be significant by using Duncan’s test.

3. Results and discussion
3.1. Starch pasting properties
Three enzymes showed little effect on the starch pasting prop-
erties of WWF (data not shown), which might be due to the short
duration within the suitable temperature range (20–65 °C) of the
enzymes in the standard RVA test cycle. Enzymes generally require
45 to 60 min of incubation time to act on the wheat flour dough.
The 13-min of RVA testing cycle only had 3 min within the suitable
temperature range of the enzymes, which were too short for the
enzymes to show their effects on the starch gelatinization and ret-
gradation in WWF. Table 1 shows the starch pasting properties
of WWF added with emulsifiers. Soy lecithin decreased the peak
viscosity (PV) of WWF. Starch pasting involves post-pasting gran-
ule swelling, granule disruption, carbohydrates leaching, formation
of a three-dimensional network of leached molecules, and interac-
tions between granule remnants and leached material. The starch
viscosity reaches the peak value when starch granules swell to
the maximum volume, then followed by the granule disruption
and a reduction in viscosity. High swelling power is generally
related to high starch viscosity (Hirsch & Kokini, 2002). Soy lecithin
is a group of phospholipids with HLB (hydrophilic-lipophilic bal-
ance) value of smaller than 10, and are composed of phosphoric
acid with choline, glycerol or other fatty acids. Amylose can be
easily associated with phospholipids to form amylose-lipid com-
plexes, and the complexes restrict swelling of the starch granules
and reduce the pasting viscosity (Sasaki, Yasui, & Matsuki, 2000).
Therefore, the reduced peak viscosity by soy lecithin was mainly
attributed to its interaction with amylose, which interrupted the
granule swelling during pasting.
Contrary to soy lecithin, SSL increased the PV of WWF, and there was an upward trend with the increased addition level. Similar results were observed by Ali and Hasnain (2013a), who noted that SSL increased the PV of oxidized white sorghum starch. However, Azizi and Rao (2005) reported that the PV and trough of wheat starch were reduced when SSL was added; only PV was increased. The discrepancies in these studies could be caused by the differences in starch concentration, chemical structure, and compositions in the tested samples (Ali & Hasnain, 2013b; Van Steertegem et al., 2013). As a hydrophilic surfactant, SSL tends to mechanically cover starch granules due to the interactions with water molecules and restricts the entry of water into the granules, thereby prolonging the arrival of PV during the heating period (Eliasson, Larsson, & Miezis, 1981). But, this covering layer is unstable under heat; once the coverage is disrupted by heating, SSL can facilitate the water absorption by its polar ends. As SSL binds with starch molecules, coverage is formed by cleaving the glycosidic bonds; more exposure of hydrophilic groups in AX promotes bindings with water and increases water absorption. Soy lecithin showed a small increase in water absorption and further amylose exudation takes place. The setback value represents the degree of retrogradation in starch. Soy lecithin decreased the breakdown value and setback value of WWF, which was mainly due to its interaction with amylose that reduced the amylose leaching and recrystallization. SSL reduced the breakdown value, but increased the peak time and setback value. As mentioned above, SSL tends to cover starch granules and restricts the entry of water into the granules, thereby increasing the peak time. It is interesting to note that SSL is generally used in bread baking to retard staling during storage; the increased setback value observed here seems to contradict its typical function. Nevertheless, many previous studies also showed that SSL increased the setback value of sorghum starch, wheat starch, and wheat flour in RVA profiles (Ali & Hasnain, 2013a; Van Steertegem et al., 2013). According to Van Steertegem et al. (2013), SSL induced a viscosity increase upon cooling and increased the setback value because of its complexation with amylose, leading to increased amylose aggregation. The mechanism by which SSL retards bread staling is attributed to its capacity of forming complexes with amylose and amylopectin. Upon cooling, these complexes do not participate in the crystal formation and texture firming, and the staling process is thus inhibited. Therefore, it can be seen that the increased setback value by SSL in apparent viscosity profiles is not contradictory to its function in retardation staling; instead, both of them are associated with the cross-linking ability of SSL. The report of Collar (2003) confirms this explanation that suitable viscosity trends for retardation bread staling include delayed pasting temperature, high viscosities, and high setback values in starch pasting profiles.

### 3.2. Mixolab parameters

The dough mixing properties of WWF and starch pasting properties of WWD measured by Mixolab represent the behaviors of protein and starch when subjected to both mechanical stress and temperature changes. In a typical Mixolab curve, the early stage (0–23 min) demonstrates the properties of gluten, and the latter stage (24–45 min) displays the characteristics of starch (Huang et al., 2010). Compared to the starch pasting properties measured by the RVA test in flour–water slurry, the latter stage of the Mixolab test exhibits the starch pasting properties in a dough system. Therefore, the results from these two methods show different traits of starch pasting and may not be directly compared with. Table 2 shows the Mixolab parameters of WWF with addition of enzymes or emulsifiers. Each ingredient showed slightly but significantly (p < 0.05) higher water absorption than the control group, except for SSL: endoxylanase exhibited the highest water absorption value. Endoxylanases transform water-insoluble AX into soluble forms by cleaving the glycosidic bonds; more exposure of hydrophilic groups in AX promotes bindings with water and increases water absorption. Soy lecithin showed a small increase in water absorption, mainly because of water-binding activity of its hydrophilic ends. As SSL binds with starch molecules, coverage is formed on starch granules; it interrupts the water entering into the granules and reduces the water absorption at low temperature (30°C). Both TG and SSL increased the development and stability times of WWD, confirming their ability to enhance gluten strength. In another study, Choy et al. (2010) also reported that TG and SSL strengthened the structure of dough prepared for instant fried noodle. TG can modify the rheological behavior of dough by promoting the formation of a more compact gluten matrix and conferring a greater degree of orientation to the gluten network (Autio et al., 2005). SSL interacts with hydrophobic regions of the gluten proteins by its lipophilic groups and forms hydrogen bonds with the amino groups of glutamine, thus promoting the aggregation of proteins and yielding stronger dough (Gomez et al., 2013). An enhancement to gluten strength by these two ingredients is responsible for the increases in the development time and stability of WWD.

TG at 1.50 U/g reduced the setback value of WWD, whereas SSL increased it. Starch retrogradation occurs during cooling and storage. The amylopectin portion of the starch crystallizes within hours, while amylepectin crystallization contributes to the long-term staling during the storage (Nunes, Moore, Ryan, & Arendt, 2009). The results indicated that TG inhibited the amylose recrystallization in WWD, which were directly related to its interactions with starch molecules and interference on the connections between amylose chains. However, this phenomenon was not observed in the RVA test, probably due to different systems (flour–water slurry for the RVA test vs. dough for Mixolab). As mentioned in Section 3.1, SSL can complex with amylose and increase the viscosity.
during gelatinization. In the Mixolab test, the increase of starch viscosity in WWD induces the enhancement of WWD torque. Although SSL binds with starch molecules and inhibits the crystal formation, the increase in WWD torque occurred upon cooling and therefore indicated increased setback value. In addition, both TG and SSL increased hot-gel stability of WWD, probably due to the interactions with amylose that retarded the amylose exudation after starch granules physically disrupted. Unlike TG and SSL, other ingredients showed no significant effect on Mixolab parameters (Table 2). Previous studies have reported the strengthening effect of lecithin on wheat dough (Selmaïr & Koehler, 2009). Lecithin can interact with proteins by its fatty acid chains, and thereby reduce protein solubility and promote the protein aggregation. Soy lecithin exhibited little impact on the WWD strength probably due to the low usage or the dilution of gluten proteins in WWD system. Although endoxylanases promoted the water absorption of WWD, they did not exert significant influence on gluten formation. It was likely that the water was still held by AX rather than transferred into gluten due to low dosage of endoxylanases used, thereby making little contribution to gluten development.

### 3.3. SEM images

As displayed in Fig. 1, the control group showed a more open and porous structure compared with the groups added with ingredients, except for the GOX group. Starch granules can be easily identified and are not completely covered by gluten matrix in the control group. As for the three enzymes, TG showed the thickest and most compact gluten structure of WNN, which was most likely associated with enhanced dough strength and mixing stability caused by TG, as indicated in Section 3.2. Bellido and Hatcher (2011) also reported the reinforcing properties of TG in the thickness of protein layer and starch granules coverage of refined yellow alkaline noodle. However, an even more disaggregated structure compared to the control group was observed with an inclusion of GOX. This observation was contrary to its typical function in baking. Previous studies have demonstrated that GOX increases the content of gluten macromolecule polymers and reinforces the strength of wheat dough (Steffolani, Ribotta, Perez, & Leon, 2010), but our results (Fig. 1C) showed GOX disrupted the interaction between the protein and starch in WNN. The adverse effect of GOX on the structure of WNN needs further investigation. Inappropriate addition levels and/or interference of wheat bran particles in our whole-wheat noodle dough system are speculated for causing this discrepancy in results.

Both soy lecithin and SSL increased the thickness of the protein layer and the coverage of starch granules in WNN. Compared to soy lecithin, the SSL group exhibited a larger degree of connectivity in the gluten network of WNN, which was in agreement with the Mixolab dough mixing properties (Table 2). Due to the amphiphilic properties, SSL propels the aggregation of gluten proteins and binds with starch granules, thereby promoting proteins-starch interactions in noodle dough. These interactions facilitate the development of a gluten-starch-lipid complex and generate a more compact structure (Mettler & Seibel, 1993). Choy et al. (2010) also reported a more continuous matrix with the addition of 0.5% SSL in instant noodle formula, but SSL exhibited a more connectivity of gluten network than TG, which was discrepant with the present study. The discrepancy in observed results was probably caused by the different cross-linking abilities of SSL and TG within the two different noodle formulations (instant noodle made from refined flour vs. white raw noodle made from WWF). In overall, TG and SSL showed more favorable impacts on the structural characteristics of WNN.

### 3.4. Noodle color and cooking yield

As shown in Table 3, endoxylanase at 1.50 U/g decreased the L24h-value, and increased the values of a24h, b24h, and ΔL* in WNN. On the contrary, TG and GOX increased the value of L24h at 0.75 and 1.50 U/g, respectively, and the ΔL* value was reduced by TG and SSL. These results demonstrated that TG and GOX enhanced the color quality of WNN, and discoloration was inhibited by TG and SSL. Noodle discoloration is generally associated with polyphenol oxidases (PPO), phenolic substrates, and the surrounding environment parameters such as pH and ionic strength (Asenstorfer, Appelbee, & Mares, 2009). TG and SSL had minor changes on the pH and ionic strength of WWD (data not shown), thus the reduced discoloration (smaller ΔL*) might result from the fact that TG and SSL interacted with phenolic substances and reduced the contact between PPO and its substrates. Furthermore, soy lecithin exhibited no significant impact on the L24h-value, but increased the value of a24h and reduced the ΔL* value at level of 0.50%. In summary, TG, SSL, and soy lecithin interfered with the color browning of WNN. GOX showed little effect on the ΔL* value but increased the L24h-value, therefore also improving the color quality of WNN.

Cooking yield is commonly regarded as one of the most important indicators that represent the cooking performance of noodles by both consumers and industry. High cooking yield is generally considered as desired quality. Noodle cooking yield is mainly determined by starch gelatinization and swelling of gluten network (Mazloomi, Ostovan, & Farahnaky, 2011). Of all ingredients tested, only SSL showed significant (p < 0.05) effect on the cooking yield of WNN at levels of 0.50% and 0.75%. SSL reduced the cooking yield as the addition level was increased. In general, the increase in starch pasting viscosity results in increased cooking yield, mostly due to higher swelling power. In the present study, SSL increased the starch pasting viscosities of WWF, but the noodle cooking yield was reduced. It was speculated that due to the protection from the physical structure, the coverage on starch granules formed by SSL was probably more difficult to disrupt under heating in WNN, compared to that in flour-water slurry (RVA test), and the more stable covering layer restricted the WNN swelling during cooking. Previous studies have reported that SSL induces a low entry of
water into the starch granules by covering the starch granules (Ali & Hasnain, 2013b; Eliasson et al., 1981). As indicated by our results, SSL revealed the emulsifying property in WWN by yielding reduced cooking yields. Moreover, the result was also supported by the Mixolab results (Table 2), in which SSL reduced water absorption primarily because of its interference with the water entering into starch granules. Ugarcˇic´-Hardi et al. (2007) reported that soy lecithin increased the water uptake of refined noodle during cooking. However, the water-binding activity of soy lecithin was probably interfered by WWF, and therefore little increase in cooking yield was observed in the present study.

3.5. Textural properties

Table 4 shows the textural properties of cooked WWN added with ingredients. Both TG and soy lecithin increased the hardness value of cooked WWN. It has been reported previously that the firmness of yellow alkaline noodles increased with TG supplementation (Bellido & Hatcher, 2011). Choy et al. (2010) also reported that TG addition increased the hardness of instant noodle by 65% and 58%, respectively, at two different water addition levels (35% and 40%). In the present study, TG enhanced the hardness of cooked WWN only by 8%, 13%, and 17%, respectively, at three addition levels. The discrepancy in noodle hardness increase between these two studies was probably due to different noodle strand size, formulation, and/or the interference of wheat bran. Lecithin can interact with gluten proteins and increase dough strength, and the enhanced noodle hardness results from its dough strengthening property. However, soy lecithin demonstrated little strengthening effect on WWD as indicated by Mixolab results (Table 2). The varying influences of soy lecithin on WWD and WWN might be related to different moisture contents in the two systems. In contrast with TG and soy lecithin, SSL significantly (p < 0.05) reduced the hardness of WWN at the addition level of 0.75%. As discussed in Section of 3.2, SSL enhanced the gluten strength in WWD by promoting the aggregation of gluten proteins and forming a strong protein network. The higher gluten strength usually yields harder noodle texture. Meanwhile, SSL also significantly (p < 0.05) increased starch peak viscosity at 0.75% addition level (Table 1), and higher starch peak viscosity generally caused softer noodle texture (Wang, Hou, Hsu, & Zhou, 2011). Therefore, it can be concluded that the net effect on noodle hardness by SSL is

Fig. 1. The microstructure of whole-wheat noodles (WWN) added with ingredients. A, Control (WWN without enzymes or emulsifiers); B, WWN with additional 1.50 U/g of endoxylanase in formula; C, WWN with additional 1.50 U/g of GOX in formula; D, WWN with additional 1.50 U/g of TG in formula; E, WWN with additional 0.50% of soy lecithin in formula; F, WWN with additional 0.75% of SSL in formula. All additional levels were on a flour basis. SSG, small starch granule; LSG, large starch granule; WSG, wrapped starch granule; NSG, non-wrapped starch granule; WB, wheat bran; PM, protein matrix.
determined by the balance of improved gluten strength and increased peak viscosity, and the results clearly showed that at high addition level (0.75%), SSL contributed more to improved peak viscosity, thus making noodle texture significantly (p < 0.05) softer (Table 4).

Soy lecithin and SSL increased the cohesiveness value of cooked noodles at levels of 0.50% and 0.75%, respectively. Meanwhile, SSL contributed more to improved cohesiveness compared to soy lecithin. With regard to enzymes, GOX decreased the cohesiveness value of WWN, indicating the reduced integrity and elasticity of cooked WWN. On the contrary, TG significantly (p < 0.05) increased the springiness and resilience of WWN at 1.50 U/g, which was probably due to the formation of a more compact gluten network (Fig. 1). Additionally, endoxylanase showed no significant influence on the textural attributes of WWN.

3.6. Sensory evaluation

Table 5 illustrated the sensory properties of cooked WWN added with ingredients. Noodle sensory attributes such as bite, springiness, and integrity are highly associated with the structural covering on starch granules and reducing water uptake during cooking (Table 3), SSL probably causes more reduction in the repulsing charges on the protein surface by binding more tightly with proteins, thus allowing more protein aggregation compared to soy lecithin. With regard to enzymes, GOX decreased the cohesiveness and resilience values of WWN, indicating the reduced integrity and elasticity of cooked WWN. On the contrary, TG significantly (p < 0.05) increased the springiness and resilience of WWN at 1.50 U/g, which was probably due to the formation of a more compact gluten network (Fig. 1). Additionally, endoxylanase showed no significant influence on the textural attributes of WWN.
and textural properties of cooked noodle. Endoxylanases had no effect on the sensory properties of WWN, whereas the GOX group showed the lower scores on the properties of bite, springiness, and integrity, indicating a detrimental effect on the sensory quality of WWN. The results were consistent with the noodle microstructure examined by SEM in Section 3.3, and textural properties in Section 3.4, which indicated that endoxylanases showed little effect on noodle structure and texture, and GOX disrupted noodle structure and reduced cohesiveness and resilience values of WWN. Although soy lecithin showed some enhancements on the microstructure and texture of WWN, it did not show significant impact on the sensory attributes observed. Sensory evaluation may not be sensitive enough to detect differences in microstructure and texture as analyzed by SEM and TPA.

SSL increased the bite, mouth-feel, and total scores of WWN as evaluated by the panelists, and TG exhibited pronounced improvements in the scores of bite, springiness, mouth-feel (after 5 min), and integrity. The improvements on the noodle sensory properties by SSL and TG were directly related to the changes on the dough mixing properties and noodle texture that SSL and TG had modified.

4. Conclusions

TG and SSL were found more effective in modifying the quality characteristics of WWN. SEM analysis showed that TG and SSL enhanced the interaction between the protein matrix and starch granules in WWN. Texture profile analysis indicated that TG increased the hardness, springiness, and resilience of cooked WWN, and SSL improved the noodle cohesiveness. Additionally, sensory evaluation confirmed that TG and SSL significantly \( p < 0.05 \) improved sensory eating properties of cooked WWN. These results demonstrated that some of common baking ingredients could be used to improve the quality characteristics of WWN in combination with other options as reported.

Conflict of interest

All authors have seen and agree with the contents of the manuscript, and there is no conflict of interest to report.

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References


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