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The enrichment of Asian noodles with fiber-rich fractions derived from roller milling of hull-less barley

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Abstract: Fiber-rich fractions (FRF) derived from roller milling of waxy (W) and high amylose (HA) starch hull-less barley genotypes were evaluated for suitability as functional ingredients in fresh and dried white salted (WSN) and fresh yellow alkaline (YAN) noodles. FRF-W and FRF-HA both contained over 300 g kg^{-1} dietary fiber, and over 200 g kg^{-1} of β-glucans. Replacement of 250 g kg^{-1} Canada Prairie Spring White (cv AC Vista) wheat patent flour with the FRF posed no problems in noodle processing, although water absorption had to be substantially increased. All three noodle types enriched with the FRF were significantly darker and contained more brown specks than the wheat flour control noodles. The presence of the FRF reduced cooking time of fresh YAN and WSN by ∼50%. The addition of FRF improved cooked YAN texture, as evidenced by increased firmness and resistance to compression. FRF-enriched fresh WSN were comparable to the wheat flour control noodles for those parameters, whereas enrichment of dry WSN by FRF imparted less firmness and less chewiness. FRF-enriched fresh YAN and WSN offer consumer convenience due to shorter cooking time, improved nutritional quality and acceptable cooking quality. These features might make FRF-enriched noodles sufficiently attractive to health-conscious consumers to overcome the negative effects of color and appearance

Keywords: arabinoxylans; barley; dietary fiber; functional foods; β-glucans; noodles

INTRODUCTION

Noodles are the second most common food items, next to rice dishes, consumed in southeast Asia.[1] Over the last decade, noodle consumption in Western countries has also grown considerably due to the increasing popularity of ethnic dishes and convenience foods among consumers.[2,3]

There are two major types of noodles, white salted (WSN) and yellow alkaline (YAN), which may be further modified to suit regional preferences and/or economic means of manufacturers. In Japan, white salted Udon noodles have unique texture characteristics attributable to wheat flour with high swelling starch, and with low protein content (80–100 g kg^{-1}), yet strong gluten. In China, where a different type of salted noodle is preferred, the protein content ranges from 95 to 110 g kg^{-1},[4] with noodle hardness and chewiness being key textural properties.[5]

YAN are made using, in addition to flour and water, some alkaline salts. The alkaline salt composition is normally a combination of sodium and potassium carbonates with their ratio varying to meet local consumer preferences. The introduction of the alkali serves to toughen the noodle and impart the characteristic yellow color, aroma and firm texture.[6] YAN are normally made from flour with protein content from 115 to 145 g kg^{-1}. The ash content of the various noodle flours has been shown to range from 3.0 to 5.5 g kg^{-1}, depending upon the economic climate of the area and consumer preferences.

To accommodate consumer preferences as to texture, taste and flavor of noodles, and to respond to the current nutritional recommendations, wheat flour noodles have been fortified with various ingredients. For example, the addition of microbial transglutaminase has been shown to increase shear strength of boiled Chinese noodles and to improve bite resistance,[7] whereas the incorporation of partial waxy starch into the white salted noodles resulted in a softer, less adhesive but more cohesive noodle texture.[8] Fortification of wheat flour with minerals and/or vitamins, and incorporation of whey protein

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concentrate or bean flour to increase the proportion of essential amino acids in noodles is becoming more common in many countries.[9–12]

Current knowledge about the health benefits of dietary fiber in relation to prevention of constipation, reduction of the risk of colorectal cancer and promotion of colonic health by stimulating the growth of beneficial gut microflora (prebiotics) has also roused interest in increasing the fiber content in noodles.[13,14] Although the dietary fiber content in different types of noodles may vary, YAN or WSN, made from white wheat flour, are not considered a good source of fiber. Attempts to incorporate fiber-rich ingredients, such as soy, rice bran, legume flours and psyllium, into noodles have been made in several studies.[15–18] The consequences of addition of dietary fiber usually depend on the amount of fiber added. Kim *et al*[16] reported that addition of 30–60 $\mathrm{g\,kg^{-1}}$ rice bran to wheat flour had no significant effect on appearance, taste and acceptability of noodles; however, addition of 90 $\mathrm{g\,kg^{-1}}$ rice bran significantly reduced all sensory scores compared with the control noodles.

The interest in increasing the content of dietary fiber in traditional carbohydrate-rich food items also originates from the desire to decrease the digestibility of carbohydrates (glycaemic response) by altering the food microstructure. It has been shown, for instance, that the enrichment of pasta with guar gum has a reductive effect on glucose release during *in vitro* degradation.[19,20] The authors of these studies postulated that the presence of dietary fiber restricted the enzyme accessibility to the food either by compacting the food structure or by physically entrapping starch granules in its mucilaginous matrix. However, finding natural ingredients with appropriate functional properties, and creating food products that would meet the nutritional and sensory demands of consumers in the twenty-first century, still remains a challenge to the cereal industry.

Barley grain is an excellent source of both soluble and insoluble dietary fiber with clinically proven health benefits.[21,22] β-Glucans, the major fiber constituents in barley, have been shown to lower plasma cholesterol, reduce glycaemic index and reduce risk of colon cancer.[23] The nutritional value of other fiber components in barley, such as arabinoxylans, arabinogalactans and galactomannans, has not yet been investigated. Incorporation of barley in various food applications, including bread, granola bars, muffins, pasta, noodles, and chapatis has been accomplished with moderate success. For instance, replacement of 200 $\mathrm{g\,kg^{-1}}$ wheat flour in quick bread by barley flour did not significantly reduce the loaf volume and produced a softer bread with a smooth, attractive crust.[24] Knuckles *et al*[25] found that breads and pasta containing 200 $\mathrm{g\,kg^{-1}}$ dry milled/sieved β-glucan-enriched barley fraction had acceptable eating quality, increased fiber and reduced calories per serving compared with their non-substituted counterparts. Yokoyama *et al*[26] reported that incorporation of barley β-glucans in pasta resulted in lower glycaemic index. Sensory analysis of cereal-based products with the addition of barley fractions has revealed acceptable, and in some cases improved, flavor.[27,28]

The roller milling of barley has been shown to fractionate this grain into flour and a fiber-rich fraction.[29] The fiber-rich fraction holds promise as a natural and functional food ingredient, as it is especially enriched in the non-starch polysaccharides from the endosperm cell walls (ie β-glucans and arabinoxylans) and is obtained via a natural, chemical-free process. Fiber-rich barley roller milling fractions have been incorporated into durum wheat semolina to produce satisfactory pasta containing substantially more total dietary fiber and β-glucans.[30] The objective of this study was to incorporate the fiber-rich fractions (FRF), derived from roller milling of high amylose and waxy hulless barley cultivars, into WSN and YAN, and to evaluate their potential as an enrichment ingredient in noodles. The high amylose and waxy barleys were chosen for this study because of their higher content of β-glucan compared with barley with normal starch characteristics.

MATERIALS AND METHODS

Materials

A 600 $\mathrm{g\,kg^{-1}}$ extraction patent Canada Prairie Spring White (CPSW) wheat flour (cv Vista) was produced on the Grain Research Laboratory pilot mill[31] and used as both the control and base wheat flour for all noodle production. Two hulless barley (HB) samples, a two-row HB waxy genotype, SR93135, and a six-row high-amylose (HA) genotype, CDC-92-55-06-48, were bred at the Crop Development Centre (CDC), University of Saskatchewan (Saskatoon, Saskatchewan, Canada).

Barley was tempered to 145 $\mathrm{g\,kg^{-1}}$ moisture and pearled 20% (type TM, Satake, Hiroshima, Japan), prior to roller milling by the HB long flow roller milling procedure outlined by Izydorczyk *et al*,[30] to obtain the FRF. The FRF, which is coarse discard material coming from a shorts duster at the end of the mill flow, originates mainly from endosperm cell walls, unlike wheat shorts which are comprised primarily of fine bran.

Sample characterization

Protein content (N × 5.7) was determined by combustion nitrogen analysis (model FP-248 Leco Dumas CNA analyzer, St. Joseph, USA) calibrated with EDTA according to AACC (2000) Approved Method 46-30.[32] Ash and starch damage were determined using AACC (2000) Approved Methods 08-01 and 76-31, respectively.[32] The color of the HB FRF was determined by a Minolta Chroma CR-200 Meter with a CR-231 head (Minolta, Mississauga, Ontario, Canada). Starch pasting characteristics of the FRF–wheat flour blends were determined with a Rapid-Visco Analyzer (RVA, Newport Scientific, Warriewood, Australia). Samples (3.5 g, 140 g kg^{-1} mb) were suspended in 25 ml of a 0.05 M solution of silver nitrate to inactivate any α-amylase present in the sample.

Polyphenol oxidase (PPO) and peroxidase (PO) activities were determined according to the methods of Hatcher and Kruger[33] and Hatcher and Barker.[34]

Total starch, β-glucan (BG) and arabinoxylan (AX) analyses are reported on a dry matter basis as an average of three measurements. Total starch and BG contents of the flour were determined enzymically using Megazyme kits [Megazyme International, Bray, Ireland, according to AACC (2000) Approved Methods 76-13 and 32–33, respectively[32]]. Total arabinoxylan content was determined colorimetrically by the phloroglucinol reaction method of Douglas.[35] BG and AX were solubilized by shaking a suspension of 1 g flour in 10 ml of distilled deionized water (2 h) with a Burrell wrist action shaker (Burrell Corp, Pittsburgh, PA, USA) in a temperature-controlled chamber (40 °C). Total dietary fiber was determined using a Total Dietary Fiber Assay Kit (Sigma, St Louis, MO, USA) according to the AOAC Official Method 985.29.[36]

Samples were prepared for SEM by mounting them onto aluminum stubs covered with double-sided carbon adhesive discs and allowed to set for 24 h. The mounted samples were placed in a Hummer VII (Anatech Ltd, Alexandria, USA) sputter coater, coated with 50 nm of gold, examined with a Jeol (Tokyo, Japan) JSM-6400 scanning electron microscope at 10 kV and photographed on Kodak TMAX 100 black and white professional 120 roll film.

Noodle preparation

FRF were added to the wheat flour at the 250 g kg^{-1} replacement level prior to mixing. The appropriate amount of a 10 g kg^{-1} salt (NaCl) or *kansui* solution (9:1 sodium and potassium carbonates dissolved in water) was added during a 5 min mixing regime using a Hobart mixer (N50, Hobart Canada, North York, Ontario, Canada) as per Kruger *et al*.[37] The moist crumb aggregate mixture was fed between the temperature-controlled rollers (28 °C) of an Ohtake Laboratory noodle machine (Ohtake, Tokyo, Japan) with an initial gap setting of 3 mm. The noodle sheet was cut into a representative 25 cm long section and underwent seven successive reduction passes within 4.5 min, ending with a final gap width of 1.10 mm. The resulting noodle sheet was cut into three sections, with two portions held at ambient temperature (24 °C) in sealed plastic containers for color and image analysis. The other noodle sheet was cut into strands using a No B22 cutter (Ohtake, Tokyo, Japan) and held in sealed plastic containers at ambient temperature (24 °C) for 1 h prior to cooking. Work requirements during processing were determined as per Hatcher *et al*.[38]

Fresh WSN, placed on wooden dowels, were dried over a 16 h period in a drying cabinet (Conviron, Winnipeg, Canada) using the following temperature–humidity profile: 25 °C–55% RH (1 h), 25 °C–90% RH (7.5 h), 35 °C–90% RH (5.5 h), 25 °C–70% RH (2 h). Dried noodles were placed in non-sealed plastic bags and allowed to cure and equilibrate to atmospheric conditions for a minimum of 2 weeks at room temperature prior to further analysis.

Noodle quality analysis

Raw and cooked noodle colors were evaluated at 0, 1, 2 and 24 h after processing with a spectrocolorimeter (Labscan II, HunterLab, Reston, VA, USA) equipped with a D65 illuminant using the CIE 1976 L^*, a^* and b^* color scale. Three measurements were taken at two different locations on the dough sheet and the readings averaged. Images of the raw noodle sheets (25 cm^2) were captured at 1, 2 and 24 h after processing using a commercial scanner (model 4700, Microteck International Inc, Toronto, Canada) and analyzed using in-house developed software based upon KS-400 software (Carl Zeiss Vision, Echting, Germany) as per Hatcher and Symons.[39]

Optimum cook time, swelling index and solid loss were determined using previously described methods.[40] The cooking water of the noodles containing the FRF was analyzed in order to determine the portion of β-glucans solubilized and lost during cooking.

Texture

Twenty-five grams of noodles were cooked in 400 ml of boiling distilled water to optimum cooking time 1 h after completion of processing. The cooked noodles were drained, rinsed for 1 min with distilled water (20 °C), shaken to release any free water and placed in sealed plastic containers for 10 min. The maximum cutting stress (MCS) test was performed at this time with the compression,[41] texture profile analysis (TPA)[42,43] and stress relaxation tests[44] being performed at 8, 16 and 24 min after the commencement of the cutting test, respectively. Texture measurements were performed using the TA-XT2i Texture Analyzer (Texture Technologies Corp., Scarsdale, NY, USA/Stable Micro Systems, Godalming, Surrey, UK). All texture tests were performed on five sets of three noodles.

Differential scanning calorimetry (DSC) and *in vitro* digestibility of starch

The DSC analyses of dry and ground WSN were carried out with a DSC 2920 (TA Instruments, New Castle, DE, USA). Samples were mixed with water (400 g kg^{-1} solid) and hermetically sealed in DSC pans (TA Instruments). After 1 h equilibration, the samples were heated from 25 to 130 °C (10 °C/min). The empty pan was used as a reference. The gelatinization peak (T_p), completion (T_c) temperatures, and enthalpy change (ΔH) were obtained using the TA analysis software (TA Instruments).

Samples of cooked noodles were cut into pieces of $\sim$1 mm^3, and 15 g of each sample were mixed with α-amylase (*Bacillus licheniformis*, Megazyme, Bray, Ireland) in a buffer (0.1 M ammonium acetate, pH 6.0) to provide the enzyme concentrations of 100 U g^{-1} starch. The mixtures were incubated at 37 °C for 30, 60 and 90 min. After centrifugation (6000 *g*, 10 min), the amount of solubilized carbohydrates was determined by further digestion with thermostable α-amylase (*Bacillus licheniformis*, Ankom Tech Corp, Fairport, NY, USA) and amyloglucosidase (*Aspergillus niger*, Boehringer Mannheim, Laval, Quebec, Canada). The resulting glucose contents in the supernatants were measured with a Gluco-quant assay kit (Boehringer Mannheim), according to the procedure of Salomonsson *et al.*[45] The results indicate the amount of solubilized carbohydrates expressed as milligrams of glucose per gram of starch available in the sample.

Statistical analysis

All statistical analyses were performed using SAS statistical software version 8 (SAS Institute Inc, Cary, NC, USA). Analysis of variance (ANOVA) and Proc GLM were performed to determine significant differences. Replicated results are reported as means; coefficient of variation was less than 5% for all tests. Noodle samples were prepared using a randomized design. All differences were considered significant at $p \leqslant 0.05$ unless otherwise stated.

RESULTS AND DISCUSSION

Physicochemical properties of FRF

The FRF obtained via roller milling of high amylose and waxy hulless barley were composed mainly of the fragments of the endosperm cell walls (Fig 1). The diameter of the fiber particles ranged from $\sim$150 to $\sim$300 µm and the particles had irregular shape and uneven and porous structure. The particle size of the FRF from waxy barley was slightly larger than that from high amylose barley. Compared with the wheat flour and the whole barley grain, the FRF contained much more dietary fiber and were enriched especially in β-glucans and arabinoxylans (Table 1). Fiber fractions obtained from waxy (FRF-W) and high amylose (FRF-HA) barleys contained comparable amounts of total β-glucans. However, the FRF-HA had a greater proportion of soluble β-glucans and total arabinoxylans than the FRF-W. The solubility of arabinoxylans from FRF was much lower compared with that of β-glucans. The addition of FRF into noodles at the 250 g kg^{-1} level was chosen with an intention to substantially increase the content of BG and dietary fiber in noodles. Since a common serving size of most noodle products ranges from 85 to 100 g, the enrichment of noodles with the FRF resulted in $\sim$4.25–5 g of BG and $\sim$7.2–8.5 g of dietary fiber per serving. In addition to β-glucans and arabinoxylans, other fiber constituents, such as arabinogalactans, cellulose and galactomannans, were probably present in the FRF, although they were not specifically quantified in this study. The starch granules, most likely entrapped in the porous structure of the fiber particles, still constituted a considerable

Table 1. Content and composition of dietary fiber in the barley fiber-rich fractions

Sample	TDF (g kg^{-1})	β-Glucans (g kg^{-1})		Arabinoxylans (g kg^{-1})	
		Total	Soluble	Total	Soluble
Control wheat flour	ND	7.2b	3.5c	16.9c	4.5a
FRF-W	338 ± 11[a]	220.2a	91.0b	42.1b	7.1a
FRF-HA	353 ± 9	221.4a	118.1a	59.3a	10.9a

Means followed by different letters in columns are significantly different at $p \leqslant 0.05$.

[a] Average ± standard deviation; $n = 3$.

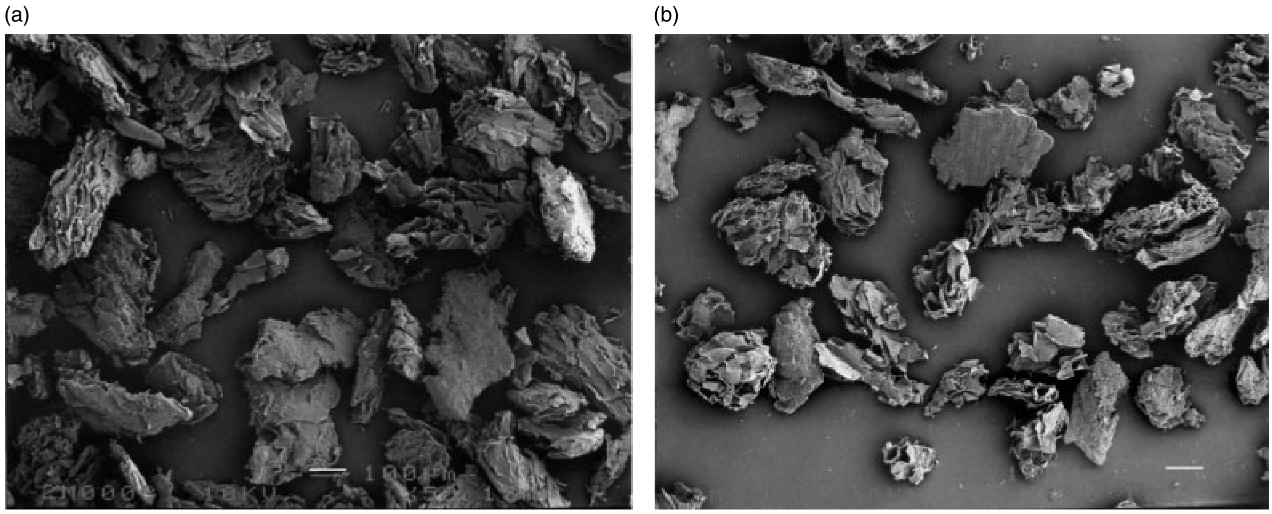

Figure 1. SEM micrographs of the FRF-W (a) and FRF-HA (b). The bar at the bottom of each micrograph represents 100 µm.

Table 2. Color and composition[a] of wheat flour and FRF

Sample	Color			Starch ($\mathrm{g\,kg^{-1}}$)	Protein[b] ($\mathrm{g\,kg^{-1}}$)	Ash ($\mathrm{g\,kg^{-1}}$)	PPO[c]	PDO[d]
	L^*	a^*	b^*					
Control-wheat flour	92.7	−0.72	9.01	755	123	4.4	17	176
FRF-W	90.4	−0.57	9.54	463	121	10.6	247	29
FRF-HA	89.8	0.12	6.28	431	131	9.8	16	63

[a] Values are expressed on a dry matter basis.

[b] N × 5.7.

[c] Polyphenol oxidase values expressed in nmol $\mathrm{g^{-1}\,min^{-1}}$.

[d] Peroxidase values expressed in pyrogallol units $\mathrm{mg^{-1}}$.

portion (430–460 $\mathrm{g\,kg^{-1}}$) of the FRF (Table 2). The protein content of FRF was comparable to the proteins in the control wheat flour, but the ash content was much higher. Both FRF had lower peroxidase levels than the wheat flour control. The FRF-W had a higher level of polyphenol oxidase than the FRF-HA and the control wheat flours.

The color parameters for the barley fractions and wheat flour are listed in Table 2. The FRF had only slightly lower L^* values than the wheat flour control. The FRF-W more closely resembled the wheat flour in terms of redness, a^*, and yellowness, b^*, than did the FRF-HA. However, significant differences in the particle size between the FRF (150–300 µm) and wheat flour (<150 µm) prevent accurate comparisons. In general, the FRF were more brown and less uniform in color than the wheat patent flour.

The replacement of 250 $\mathrm{g\,kg^{-1}}$ of wheat flour with FRF significantly increased the RVA peak viscosity, holding strength, breakdown viscosity, final viscosity and setback, relative to the wheat flour control (Fig 2). These results are indicative of the great swelling and water holding capacity of the FRF, most likely due to their porous structure and large surface area (Fig 1). Other factors which could contribute to the increased viscosity of the blends probably include the large particle size of the FRF as well as partial solubilization of the non-starch polysaccharides, known for their water adsorbing and viscosity-enhancing properties.

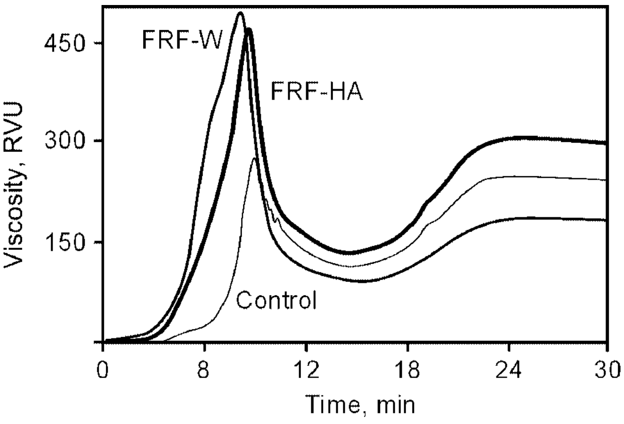

Figure 2. RVA pasting profiles of the control wheat flour (AC Vista) and the 250 $\mathrm{g\,kg^{-1}}$ blends of wheat and the FRF.

The FRF-W–wheat flour blend exhibited faster and greater viscosity development than the FRF-HA–wheat blend. The presence of the waxy starch and the larger particle size of the FRF-W could have contributed to the observed differences.

Processing requirements

An optimum water absorption of 350 and 370 $\mathrm{g\,kg^{-1}}$ was determined for the wheat flour WSN and YAN control doughs, respectively, based upon aggregate particle size, consistency and crumb feel. When either YAN or WSN was enriched with FRF-W or FRF-HA, a 500 $\mathrm{g\,kg^{-1}}$ water absorption level was required to attain the proper crumb aggregate characteristics. The porous structure and large surface area of the particles in the FRF as well as the hygroscopic nature of β-glucans and arabinoxylans increased the water requirements in the blended noodles. The ability to introduce 500 $\mathrm{g\,kg^{-1}}$ water into the production process, for either noodle type, offers a strong financial incentive to the fresh noodle manufacturer; however, if noodles need to be dried, the higher water content in fresh noodles may actually be a disadvantage.

Work requirements to process the WSN or YAN noodle sheets were not significantly different for the wheat flour control compared with the FRF–wheat blends (Table 3). Previous research has shown that the increased water absorption during the processing of wheat flour noodles significantly decreases the amount of work input required.[38] Since the blended flours required significantly more water, yet no reduction in work input was observed for either noodle type, it can be suggested that the FRF are very active in binding and competing with other dough constituents for the available water. It is also possible that partial solubilization of the non-starch polysaccharides increased the viscosity of noodle dough. Normally, dilution of the functional wheat gluten upon replacement of wheat flour with another filler/ingredient would result in weakening of the noodle dough and in decreasing the power requirements. Our results suggest that the FRF cannot be considered as an inert filler dispersed in the wheat flour viscoelastic matrix, but rather as an active component affecting the water partitioning and the overall viscoelastic properties of the dough system.

Table 3. Processing and cooking characteristics of wheat flour control and the FRF-enriched noodles

Noodle type/blend	Energy requirement (work g^{-1})	Optimum cook time (min)	Swelling index ($gH_2O\,g^{-1}$)	Solid loss ($g\,g^{-1}$)	β-Glucan loss[a]
YAN					
Control	19.3a	7.0a	1.016a	0.105a	—
FRF-W	18.8a	3.5b	0.767b	0.042b	2.6 ± 0.3
FRF-HA	17.4a	3.0b	0.740b	0.047b	2.6 ± 0.3
WSN					
Control	12.6a	11.0a	1.526a	0.060a	—
FRF-W	14.1a	6.0b	1.033b	0.044b	2.5 ± 0.2
FRF-HA	13.8a	5.5b	0.972c	0.046b	2.1 ± 0.3
Dry WSN					
Control		13.0c	2.044a	0.0735a	—
FRF-W		14.0b	2.081a	0.0735a	3.4 ± 0.5
FRF-HA		16.0a	2.182a	0.090a	3.8 ± 0.6

[a] Fraction (%) of total β-glucans in noodles.

Means followed by different letters in columns are significantly different at $p \leqslant 0.05$.

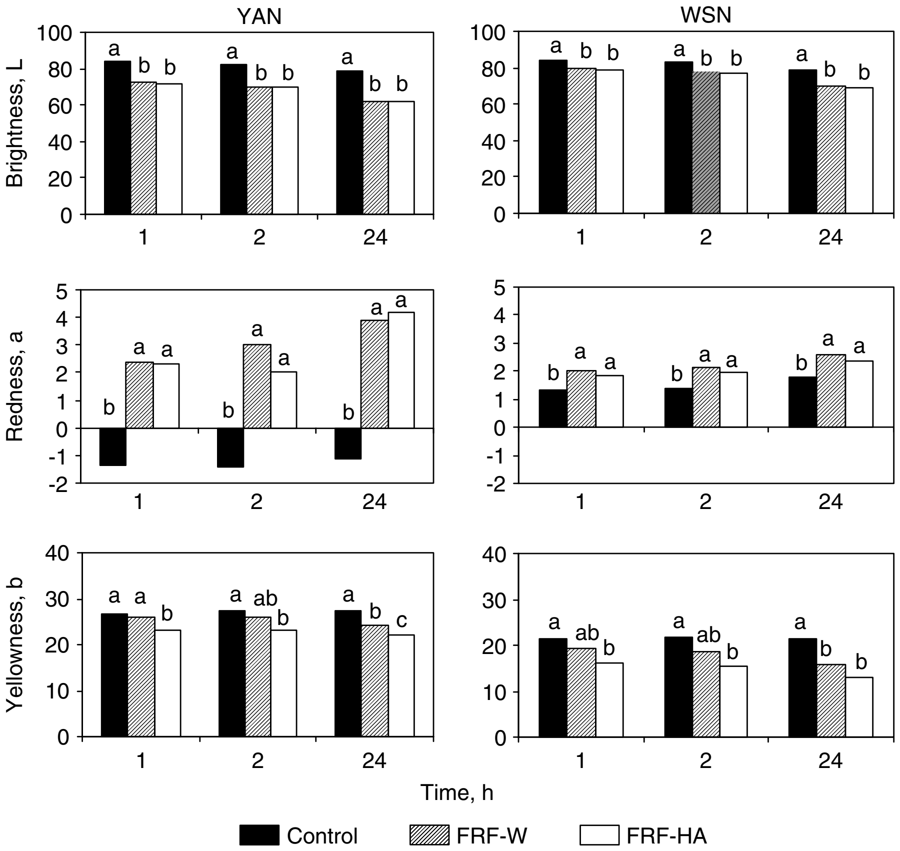

Figure 3. Time-dependent changes in color of fresh YAN and WSN with 250 g kg^{-1} addition of FRF. Different letters above the bars within each time group indicate significant differences at $p \leqslant 0.05$.

Raw noodle color and appearance

The addition of 250 g kg^{-1} FRF significantly decreased YAN brightness (L^*) and increased redness (a^*) at all time intervals (Fig 3). The source of FRF had no significant effect on either L^* or a^* of YAN. The FRF-HA reduced b^* more than the FRF-W. A similar trend was observed when the FRF were added to WSN (Fig 3), although the decrease in brightness and increase of redness upon addition of the FRF were less pronounced in WSN than in YAN. The higher pH of YAN could contribute to the more prominent brown/red color of fiber-supplemented YAN. Discoloration of food products containing barley occurs due to the complex oxidative polymerization of the numerous phenolic compounds (polyphenols, phenolic acids, proanthocyanidins and catechins) present in this grain.[46,47]

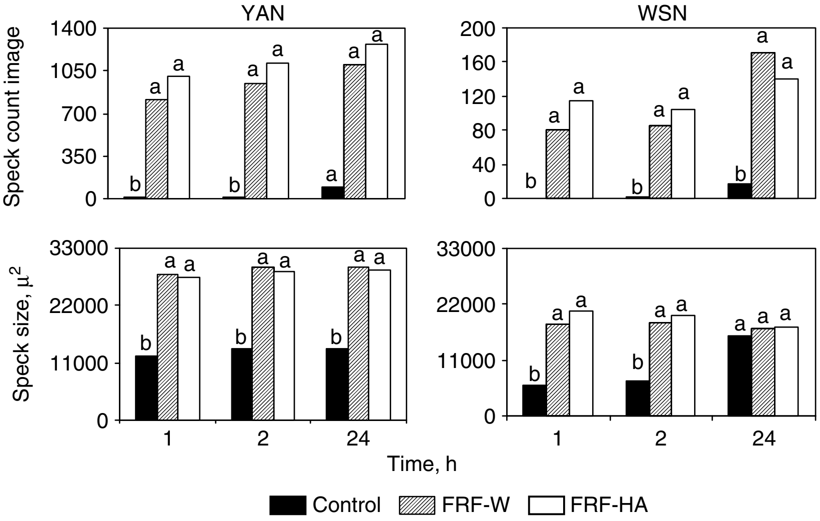

Figure 4. Time-dependent changes in speck count and size in YAN and WSN with addition of FRF. Different letters above the bars within each time group indicate significant differences at $p \leqslant 0.05$.

Enrichment of YAN with either FRF significantly increased the number of specks per unit area at all time intervals examined (Fig 4). On average, YAN-enriched fiber fractions exhibited speck counts $\sim$150 times greater than the wheat flour control. The average size of specks in YAN enriched by either FRF was more than twice that of the wheat flour control (Fig 4). YAN enriched with the FRF-HA displayed more specks but of smaller dimensions than YAN enriched with FRF-W, which is consistent with slightly smaller particle size of the former (Fig 1).

WSN enriched by either FRF displayed a significantly greater number of specks than the control noodles at all time periods. Specks in FRF-enriched WSN were significantly larger at 1 and 2 h, but not at 24 h after processing compared with the control WSN (Fig 4). WSN supplemented with FRF were significantly less specky than FRF-enriched YAN (Fig 4), probably because the complex reactions leading to speck formation and/or exposition are more pronounced in an alkaline environment.[39] The specks in the FRF-supplemented noodles clearly originated from the fragments of the endosperm cell walls aleurone, bran and testa, embedded within the noodle cast (Fig 5). Micrographs of the control raw noodles show, on the other hand, a much more uniform and continuous protein–starch matrix.

Cooking quality

The addition of FRF dramatically reduced optimum cooking time of YAN from 7 min for the control noodles to 3.0 and 3.5 min for YAN containing FRF-W and FRF-HA, respectively (Table 3). A

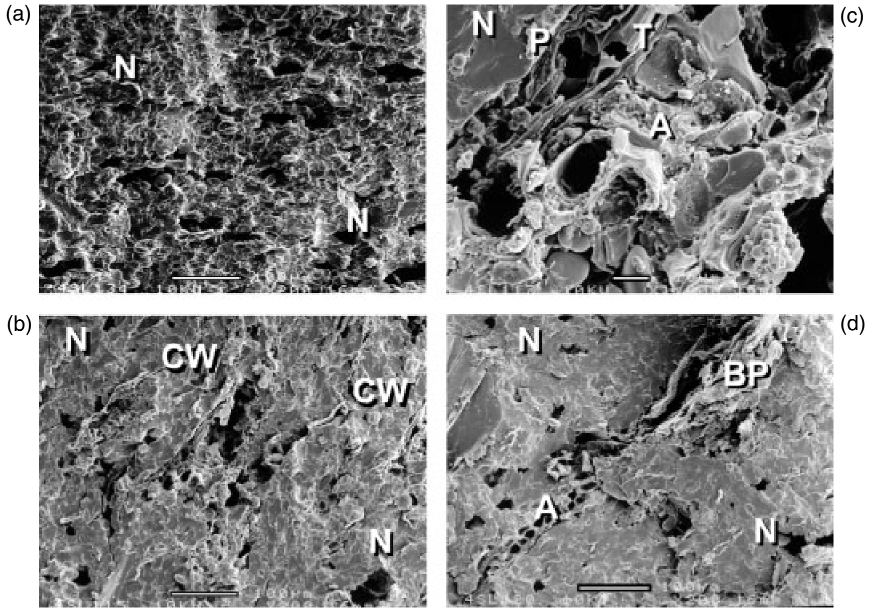

Figure 5. SEM micrographs of dried WSN: (a) control wheat flour noodle; (b, c) noodle with FRF-W; (d) noodle with FRF-HA. N, noodle; P, pericarp; A, aleurone; CW, cell walls; BP, bran particle; T, testa. The bar at the bottom of each micrograph represents 100 μm.

significant reduction in cooking time was also seen with the addition of FRF to WSN. The higher water absorption level of the noodles containing the FRF is believed to be the primary factor involved in the reduced cooking times. The addition of the FRF appeared also to disrupt the continuity of the wheat protein matrix (Fig 5), which probably resulted in faster heat/moisture penetration and shorter cooking time.

While a reduction in cooking time was seen with the addition of FRF to fresh YAN and WSN, an increased cooking time was required for dry WSN containing the fiber fractions. The dehydration occurring during the drying process changed the microstructure of noodles; as seen in Fig 5, the noodle matrix surrounding the fiber inclusions in the FRF-supplemented noodles was more compact compared with the relatively porous matrix of the control noodles.

Although the FRF exhibited very high water-adsorbing and swelling properties (as indicated by high dough water absorptions and RVA parameters), both YAN and fresh WSN supplemented with the FRF showed a reduced water uptake during cooking compared with the control noodles (Table 3), due to the overriding effect of shorter cooking times for the FRF-enriched fresh noodles. The reduced cooking time of the FRF-enriched YAN and WSN would also explain their reduced swelling indices. The shorter cooking time of noodles as well as the lower water uptake during food processing are likely to be factors appealing to the consumers.

In contrast, enrichment of dried WSN with either FRF did not affect water uptake values compared with the wheat flour control. The dry WSN displayed higher water uptake values than corresponding fresh YAN or WSN, as expected from the longer cooking time of the former.

Table 3 illustrates that significantly decreased cooking losses were obtained for samples containing the FRF. These differences are probably primarily due to the shorter cooking time of the FRF-containing noodles; however, other factors could also contribute to the observed results. Normally cooking losses are attributed to the weakening and/or disruption of the protein–starch matrix.[19] Inclusion of the FRF in wheat flour clearly disrupted the uniformity of the protein starch network; however, as mentioned before, the FRF are not inert fillers. It is possible that during cooking the fiber particles swell and the partially solubilized non-starch polysaccharides form viscous networks restricting excessive swelling and diffusion of starch polymers into the cooking medium. The loss of β-glucans in the fiber-enriched noodles during cooking was very low. Under $30\,\text{g}\,\text{kg}^{-1}$ of the total β-glucan present in noodles were lost during cooking of fresh YAN and WSN, and under $40\,\text{g}\,\text{kg}^{-1}$ for dry WSN (Table 3). Very small solid and β-glucan losses appear to be supportive of the theory that the FRF, although present as distinct particles within the noodle matrix, are well fused/embodied with the other noodle constituents.

An important quality criterion of dry noodle manufacturers is product loss due to breakage after packaging. This breakage can occur during the packing of cartons, transport and consumer handling. Evaluation of dry WSN breaking strength revealed no significant differences between the control noodles and those enriched by either waxy or HA FRF (data not shown).

Cooked noodle texture

The textural characteristics of noodles generally play an essential role in determining consumer preference. However, in addition to some common preference patterns (eg firm texture YAN or soft white salted Udon noodles), deviation from these patterns is sometimes desirable, either to satisfy more individual preferences and/or to introduce traditional food items with novel properties. Results obtained in this study showed that the textural characteristics of noodles can be altered by the addition of barley FRF (Table 4).

Maximum cutting stress (MCS) measures bite, or firmness of a cooked noodle on a front tooth, whereas resistance to compression (RTC) is an estimate of the chewiness of noodles on back molars.[41] Enrichment of YAN with the FRF-HA significantly increased MCS and RTC. The FRF-W also increased these two parameters, but the increases were not statistically significant. The differences between the two FRF might be attributable to the different starch properties in these fractions. The addition of $250\,\text{g}\,\text{kg}^{-1}$ of the FRF into the wheat noodles resulted in introduction of about $100\,\text{g}\,\text{kg}^{-1}$ of either high amylose or waxy starch from the FRF-HA and FRF-W, respectively. High amylose starch is known to increase the firmness and chewiness of noodles, whereas waxy starch has the opposite effects.[40] Despite a low level of barley

Table 4. Texture parameters of the wheat flour control noodles and the FRF-enriched noodles

Noodle type/blend	MCS[a] ($\text{g}\,\text{mm}^{-2}$)	RTC[b] (%)	Chewiness	Resilience	Stress relaxation time (s)
YAN					
Control	23.22b	19.72b	300.63b	0.45a	3.31a
FRF-W	30.10ab	22.55b	295.69b	0.39b	2.45b
FRF-HA	32.12a	26.32a	360.03a	0.38b	3.12a
WSN					
Control	16.77a	15.86a	276.24a	0.45a	3.51a
FRF-W	17.47a	14.02a	225.28a	0.39b	1.77c
FRF-HA	18.59a	18.01a	271.43a	0.36c	2.42b
Dry WSN					
Control	23.33a	24.88a	419.98a	0.42b	6.70a
FRF-W	21.62b	17.34b	324.99c	0.45a	4.20b
FRF-HA	19.79c	20.06b	353.66b	0.44ab	4.39b

[a] MCS, maximum cutting stress.

[b] RTC, retention to compression.

Means followed by different letters in columns are significantly different at $p \leqslant 0.05$.

starch (~100 g kg^{-1}) in the noodles, its contribution to the overall texture cannot be ignored, especially in the YAN. TPA parameters were also affected by the addition of the FRF. The FRF-HA significantly increased the TPA chewiness of YAN, whereas both FRF decreased resilience and the stress relaxation time (although the differences between the control and the FRF-HA were not statistically significant; Table 4). Reduced stress relaxation time is indicative of reduced strength/firmness of the noodle matrix, possibly due to disruption of the gluten matrix by inclusion of FRF.

Enrichment of WSN with FRF slightly increased MSC and RTC (except for FRF-W), although the changes were not statistically significant. In contrast, FRF-enriched dried WSN were significantly less firm, had lower RTC and were less chewy than the wheat flour control noodle, which is probably associated with the longer cooking times of the dried fiber-containing noodles. The resilience and stress relaxation time parameters of the fresh WSN containing FRF were lower than those of the control noodles. The resilience of the dried WSN with fiber addition was superior to the control, but their stress relaxation time was lower.

The effects of FRF addition to wheat flour noodles follow a complex pattern. The 250 g kg^{-1} replacement of wheat flour substantially diluted the amount of functional gluten in the noodles. Furthermore, the addition of the FRF clearly disrupted the continuity of the protein–starch matrix. These two factors should normally lead to weakening of the protein network, thus lowering the noodle firmness. Yet the overall firmness of fresh YAN especially was significantly increased upon addition of the barley FRF. Other factors, therefore, must have counterbalanced the aforementioned effects. Firstly, the lower cooking times and swelling indices of the fresh YAN and WSN contributed to the increased firmness of the FRF containing noodles. Secondly, the FRF, which hydrated extensively during dough preparation, appeared to form a semisolid network which, although disrupting the integrity of wheat matrix, also contributed to noodle firmness, due to the viscoelastic and network-forming properties of the FRF constituents. The alkali environment of the YAN probably enhanced the swelling of the FRF and solubility of the non-starch polysaccharides, and contributed to a stronger network formation in YAN than in WSN. Interestingly, although the FRF were visible as distinct particles within the noodle matrix, they appeared to be well fused with the other noodle constituents, suggesting interactions between the FRF and the wheat flour constituents. The nature of these interactions, however, remains to be further explored.

Starch gelatinization and digestibility

The effects of FRF addition into noodles on starch gelatinization properties, starch degradation and carbohydrate release were investigated by DSC and *in vitro* digestion of the dry WSN. The DSC analysis revealed that additions of the FRF affected gelatinization temperatures and enthalpy values (Table 5). Both FRF-containing noodles showed increases in gelatinization temperatures (peak and completion temperatures) compared with the control samples. As such, the results were consistent with previous research.[48] This increase in gelatinization temperatures might be due to the faster hydration tendency of the FRF and uneven distribution of water within the noodle matrix, resulting in increase of the energy required for gelatinization events. As shown in this study, the FRF-wheat flour blends exhibited high water absorption and water holding capacity. The slight decrease in the enthalpy for the noodles supplemented by the FRF is probably related to the reduction of starch content due to the fiber inclusion.

The results of the *in vitro* digestibility of starch showed that the inclusion of FRF into noodles significantly decreased the glucose release (mg g^{-1} starch) at all three time intervals. The biggest differences between the control wheat flour noodles and the FRF-enriched noodles were observed at the shortest digestion period. Previous research has shown that inclusion of soluble fiber (eg guar gum) into pasta and bread decreased starch digestibility by encapsulating starch granules, thus decreasing the accessibility of starch-degrading enzymes to their starch substrate.[19,49] The FRF used in this study contained soluble non-starch polysaccharides and as discussed above, partial solubilization of these polymers probably occurs under appropriate hydro/thermal conditions. It is also clear that the presence of the FRF changed the water distribution within the dough matrix, and thus affected the structure of the protein–starch matrix. The micrographs of raw and cooked noodles appear to be supportive of the proposed explanations. The noodle matrix surrounding the fiber inclusions in the FRF-supplemented noodles, both before and after cooking, was more compact compared with the relatively porous

Table 5. Gelatinization parameters and glucose release during *in vitro* digestion of the wheat flour control noodles and the FRF-enriched noodles

Noodle type/blend	Gelatinization			Glucose release (mg g^{-1} starch)		
	T_{peak} (°C)	$T_{completion}$ (°C)	ΔH (J g^{-1})	30 min	60 min	90 min
Dry WSN						
Control	64.8b	83.1b	0.48a	51.3a	76.5a	93.0a
FRF-W	67.2a	85.2 ± a	0.45a	31.0b	63.0c	81.3b
FRF-HA	67.0a	86.6a	0.47a	30.6b	69.3b	81.9b

Means followed by different letters in columns are significantly different at $p \leqslant 0.05$.

matrix of the control noodles. Finally, the interactions between the fiber components and starch granules, which would also reduce digestibility of starch, are possible but need to be further investigated.

CONCLUSIONS

This research demonstrates the potential of using FRF, obtained via roller milling of barley grain, in various noodle products. The FRF provide a concentrated source of dietary fiber, obtained via a natural process of physical fractionation of grain without any chemical solvents. Replacement of $250\,\mathrm{g\,kg^{-1}}$ of wheat flour with the barley FRF significantly increased the total dietary fiber content in noodles and enriched them, especially in β-glucans, known for many health benefits associated with soluble dietary fiber. In addition, our results showed a potential of decreasing the amount of glucose release during *in vitro* digestion of noodles, pointing to possible reduction of the glycaemic index and, therefore, another nutritional benefit of incorporating the FRF into noodles.

The FRF-supplemented noodles exhibited somewhat darker (more brown) and more specky appearance, which may be especially appealing to health-conscious consumers who are aware that the white color of cereal-based products is achieved using refined and nutrient-depleted ingredients.[50] Consumer awareness of the origin of the darker colour of cereal products, substantiated by clinical evidence of health benefits of dietary fiber and phenolic compounds, is growing and parallels the acceptability of novel or traditional foods with different appearance and texture.

These studies also demonstrated that the supplementation of noodles with the barley FRF can be beneficial to both manufacturers and consumers in terms of processing and cooking characteristics of noodles. A high water absorption during preparation of YAN or WSN dough is attractive to the fresh noodle manufacturers, whereas short cooking time and lower water uptake during cooking might be appealing to consumers. The mechanisms by which the FRF affected cooking quality, textural attributes and starch degradation are complex and the overall effects depend on the interactions among water, protein, starch and fiber polysaccharides at the microscopic and molecular levels. Better understanding of these mechanisms will allow finer control over the processing, sensory and nutritional quality attributes of noodles with non-traditional ingredients to be achieved.

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