Food Chemistry 324 (2020) 126858

Contents lists available at ScienceDirect

Food Chemistry

journal homepage: www.elsevier.com/locate/foodchem

The contribution of β-glucan and starch fine structure to texture of oat-fortified wheat noodles

Thoa T.L. Nguyen[a], Robert G. Gilbert[a,b,*], Michael J. Gidley[a], Glen P. Fox[a,c]

[a] Queensland Alliance for Agriculture and Food Innovation (QAAFI), Centre for Nutrition and Food Sciences, The University of Queensland, Qld 4067, Australia
[b] Joint International Research Laboratory of Agriculture and Agri-Product Safety, College of Agriculture, Yangzhou University, Yangzhou 225009, Jiangsu Province, China
[c] Department of Food Science and Technology, University of California Davis, CA 95616, USA

ARTICLE INFO

Keywords:
Oat
Noodles
Hardness
β-glucan
Size exclusion chromatography
Starch
Physicochemical properties

ABSTRACT

Wheat flour noodles are sometimes fortified with β-glucan for nutritional value, but this can decrease eating quality. The contributions of β-glucan and starch molecular fine structure to physicochemical properties of wholemeal oat flour and to the texture of oat-fortified white salted noodles were investigated here. Hardness of oat-fortified noodles was controlled by the longer amylopectin chains (DP ≥ 26) and amount of longer amylose chains (DP ≥ 1000). Higher levels of β-glucan, in the range from 3.1 to 5.2%, result in increased noodle hardness. Pasting viscosities of wholemeal oat flour positively correlate with the hardness of oat-fortified noodles. The swelling power of oat flour is not correlated with either pasting viscosities of oat flour or noodle hardness. Longer amylopectin chains and the amount of longer amylose chains both control the pasting viscosities of oat flour, which in turn affect noodle texture. This provides new means, based on starch and β-glucan molecular structure, to choose oats with optimal starch structure and β-glucan content for targeted oat-fortified noodle quality.

1. Introduction

Around 20–50% of the total wheat flour consumption in many Asian countries is for noodle making (Hou, 2011). The last few decades have witnessed significant increase in noodle consumption in Asia and in other parts of the world. Asian wheat noodles are mainly divided into two distinct categories based on the existence or absence of alkaline salt. White salted noodles (WSN) are made from flour, sodium chloride and water, while yellow alkaline noodles (YAN) are made from wheat flour, water and alkaline salts such as sodium or potassium carbonate. The wheat flours for noodle making are refined flours which are low in dietary fiber, vitamins, minerals and other important nutrients (Slavin, Martini, Jacobs, & Marquart, 1999).

Wheat flour noodles have been fortified with various ingredients to enhance health benefits for consumers. The substitution of wheat flour with banana flour and β-glucan showed an increase in essential minerals and total dietary fiber together with a decrease in glycemic index and the starch digestibility rate in noodles (Choo & Aziz, 2010). Some attempts to fortify fiber-rich sources such as psyllium, oat-bran powder, wheat bran and arabinoxylans into noodles has been reported (Czuchajowska, Paszczynska, & Pomeranz, 1992; Fan, Ma, Wang, & Zheng, 2016; Mohamed, Rayas-Duarte, Xu, Palmquist, & Inglett, 2005; Song, Zhu, Pei, Ai, & Chen, 2013). Although the addition of arabinoxylan enhances the nutritional benefits, it may contribute to changes in the textural and sensory properties of noodles, resulting in undesirable product quality. The presence of wheat bran reduced the lightness of noodle dough sheets (Jiang, Martin, Okot-Kotber, & Seib, 2011) and the surface connectivity between starch granules and gluten, which may further affect the texture of cooked noodles (Song et al., 2013). The addition of arabinoxylan was found to alter all textural parameters of cooked noodles. This is ascribed (Fan et al., 2016) to interactions between proteins and xylans through covalent and noncovalent bonding, and water absorption and water holding through hydrogen bonding, both of which affect the hardness of cooked noodles through plasticization. In addition, the viscous properties of xylans influence the springiness, resilience and adhesiveness of cooked noodles by changing the interactions between various macromolecules.

Increased long-term consumption of dietary fiber and whole grains has been associated with reduction in the risk of obesity, type 2 diabetes and cardiovascular disease, prevention of constipation, and stimulation of the growth of beneficial gut microflora. Whole-grain oat is an excellent source of dietary fiber (especially β-glucan), and of quality

* Corresponding author at: Queensland Alliance for Agriculture and Food Innovation (QAAFI), Centre for Nutrition and Food Sciences, The University of Queensland, Qld 4067, Australia.
E-mail address: b.gilbert@uq.edu.au (R.G. Gilbert).

https://doi.org/10.1016/j.foodchem.2020.126858
Received 27 November 2019; Received in revised form 3 April 2020; Accepted 17 April 2020
Available online 21 April 2020
0308-8146/

protein with good amino-acid balance, lipids (especially unsaturated fatty acids), minerals, vitamin and phytochemicals (Martinez-Villaluenga & Peñas, 2017). Whole grain oat flours have been incorporated into wheat noodles (Mitra, James, Fenton, Cato, & Solah, 2016; Wang, Huang, Kim, Liu, & Tilley, 2011). However, these studies either only focused on investigating the effects of different proportions of oat flour on the quality parameters of noodles such as cooking quality, texture and sensory properties, and suggesting the appropriate level of added oat flour that satisfies the overall quality of noodles or considered other suitable high protein additives to improve the properties of noodles.

Starch is the major component of oat flour. It is a glucose polymer comprising two types of polymers, amylopectin and amylose. Amylopectin is highly branched with many short chains and has a high molecular weight ($10^{7\text{-}8}$), while amylose is largely linear with a few long-chain branches and smaller molecular weight ($10^{6\text{-}7}$). Starch plays important roles in the eating quality of noodles. Amylose content, pasting viscosity and swelling power of starch have all been reported to be closely correlated to eating characteristics of noodles (Baik & Lee, 2003; Crosbie, 1991; Kaur et al., 2016). Starch with high peak paste viscosity and low amylose content is desirable for soft-bite and more cohesive white salted noodles (Baik & Lee, 2003; Crosbie, 1991), while low starch-paste viscosity is suitable for Chinese-type noodles (Guo, Jackson, Graybosch, & Parkhurst, 2003).

The molecular fine structure of starch in the present paper means the chain length distributions (CLDs) of debranched starch (the fine structure of amylose and amylopectin) and the molecular size distributions of whole branched starch molecules. Knowledge about the effect of starch fine structure on the physicochemical and texture properties of noodles is still limited, although the molecular fine structure of starch is known to be the main contributor for some functional properties of starch and flour (Srichuwong, Sunarti, Mishima, Isono, & Hisamatsu, 2005; Tao, Li, Yu, Gilbert, & Li, 2019).

Oat groat has from 12 to 24% protein. Although protein content is quite high in oat, the contribution of protein to pasting and thermal properties of wholemeal oat flour, which are the key factors for the texture of oat-based food products, is much less than that of β-glucan and starch (Liu, Bailey, & White, 2010; Zhou, Robards, Glennie-Holmes, & Helliwell, 2000). This work focuses on the impact of β-glucan and starch rather than protein on the texture of oat-fortified noodles.

The hypothesis of this work is that β-glucan content and the fine structure of amylose and amylopectin are significant determinants of functional properties of oat noodles. Using wholemeal flour from various oat cultivars grown in different locations in Australia, the aim of this study is to examine the correlations between β-glucan content, starch molecular fine structure, the physicochemical properties of wholemeal oat flour and the texture of oat-fortified white salted noodles. We select samples with different growth locations and environmental conditions so as to have a wide variety of starch structures and β-glucan contents. Starch molecular fine structure, specifically the chain-length distribution (CLD) of debranched starch, was determined by size-exclusion chromatography (*SEC*). Biosynthetic models were used to fit the CLDs of amylopectin and of amylose. The pasting and gelatinization properties of wholemeal oat flour were measured by rapid visco analysis (RVA) and differential scanning calorimetry (DSC). The texture properties of noodles were determined by instrumental texture profile analysis.

2. Materials and methods

2.1. Materials

Thirty-two oat samples (eight genotypes: Williams, Mitika, Kowari, Bannister, Wombat, Yallara, Durack, Dunnart) were grown in each of four locations (Turretfield (South Australia), Riverton (South Australia), Pingelly (Western Australia), and Cunderdin (Western Australia)) in 2015 were used for this study. The wholemeal oat flours from these were provided by AEGIC (Australia Export Grains Innovation Centre), Perth, Australia.

Protease from Streptomyces (type XIV) (3.5 units/mg solid), LiBr (ReagentPlus) and isoamylase (from Pseudomonas sp.) (1000 units/ml) were purchased from Sigma-Aldrich Pty. Ltd. (Castle Hill, NSW, Australia). A series of pullulan standards with peak molecular weights ranging from 342 to 2.35 × 106 were from Polymer Standards Services (PSS) GmbH (Mainz, Germany). Dimethyl sulfoxide (DMSO, GR grade for analysis) was from Merck Co. Inc. (Kilsyth, Vic., Australia). Total starch (AA/AMG) assay kit, β-glucan (mixed linkage) assay kit and starch damage kit were purchased from Megazyme International, Ltd. (Wicklow, Ireland)

2.2. Total starch content, β-glucan content and starch damage

Total starch content in oat groats was determined using the total starch assay kit (Megazyme International Ltd., Wicklow, Ireland) following AACC approved method 76-13.01.

The β-glucan content in oat flour was determined with a mixed-linkage β-glucan kit (Megazyme International Ltd., Wicklow, Ireland) using AACCI approved method 32-23.01.

Starch damage in oat flour was measured using the starch damage kit (Megazyme International Ltd., Wicklow, Ireland) following AACC approved method 76-31.01.

2.3. Starch molecular structure characterization

All starch samples were extracted from wholemeal flour and then enzymatically debranched using a procedure described in detail previously (Nguyen, Mitra, Gilbert, Gidley, & Fox, 2019). The structure of debranched starch was characterized using size-exclusion chromatography (*SEC*), which separates polymer molecules by molecular size, viz., the hydrodynamic radius Rh, as described previously, with the same experimental setting (Nguyen et al., 2019). The distribution of the weight of polymers with a given size, $w(\log R_h)$ was obtained from *SEC* with a refractive-index detector as described elsewhere (Vilaplana & Gilbert, 2010). For linear polymers (linear chains after debranching starch, in the present case), there is a unique relation between size and molecular weight. Therefore, $w(\log R_h)$ can be converted to $w(\log X)$, which is the weight distribution of degree of polymerization X (the number of glucose units in the chain): the weight chain length distribution (CLD)

Amylopectin and amylose CLDs from *SEC* were fitted with two models for starch biosynthesis, one for amylopectin and one for amylose; these represent the CLDs in terms of a small number of biosynthesis-related parameters. The model used for fitting amylopectin CLDs (Wu, Morell, & Gilbert, 2013) assumes that the CLDs of amylopectin chains are produced by the action of three core classes of starch biosynthesis enzymes: starch synthase (SS), starch branching enzyme (SBE), and starch debranching enzyme (DBE). In a given DP region, the CLD is controlled mainly but not exclusively by an enzyme set which comprises one each of an isoform of SS, SBE and DBE. The overall CLD is the sum of the contribution of CLDs synthesized from each enzyme set. Two parameters obtained from the fitting are $\beta A_{p,i}$, the ratio of the activity of SBE to that of SS in enzyme set i, and the relative contribution of enzyme set i to the entire amylopectin CLD, $hA_{p,i}$ (the subscript A_p is for amylopectin). The parameters $\beta A_{p,i}$, $hA_{p,i}$, $\beta A_{p,iii}$ and $hA_{p,iii}$ govern chain lengths and amounts of amylopectin chains over DP 7–28 (i) and DP 30–60 (iii). For example, samples with higher values of $\beta A_{p,i}$ have more shorter amylopectin chains while a high value of $hA_{p,i}$ means high amounts of amylopectin chains in the range DP 7–28. Similarly, $\beta A_{m,ii}$ and $hA_{m,ii}$ govern chain-length and content of amylose chains respectively in the long amylose chain region. A high value of $\beta A_{p,i}$ indicates high activity of SBE and/or low activity of SS in enzyme set (i), leading to low rate of chain elongation for chains in a single

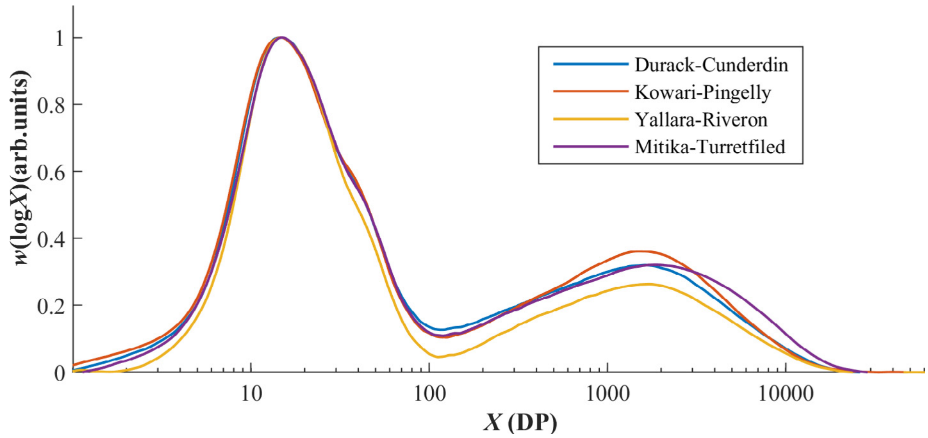

Fig. 1. *SEC* weight distribution, $w(\log X)$, in arbitrary units but normalized the the maximum of each distribution, of four representative samples of debranched oat starches. The $w(\log X)$ distributions for all 32 samples are shown in the Supplementary Information.

lamella ($X \leq 26$) and thus less long amylopectin chains in the single lamella region. Samples with high $hA_{p,i}$ values have a high amount of short amylopectin chains in a single lamella synthesized from enzyme set (i).

Fitting amylose number CLDs was performed with the model of Nada et al. (Nada, Zou, Li, & Gilbert, 2017; Tao et al., 2019). Similar to the fitting of amylopectin CLDs, this model also assumes that different enzyme environments control different regions of amylose CLDs, which can be seen as peaks or shoulders in data with good *SEC* separation. The amylose fitting parameters are equivalent to those of the amylopectin model, and are denoted $\beta A_{m,i}$ and $hA_{m,i}$ (the subscript Am is for amylose). There are two methods for doing this; here the “subtractive” method was used. The fitting for both models is performed with publicly available code (Nada et al., 2017; Wu et al., 2013).

2.4. Functional properties of oat flour

Gelatinization properties, pasting properties and swelling power of oat flour were investigated in this study and were measured as described in detail previously (Nguyen et al., 2019).

The swelling power of oat flour was determined as described elsewhere with some modification (Konik-Rose et al., 2001). Oat flour with approximate weight of 0.1 g (dry basis, A) was carefully suspended and mixed well in 10 mL distilled water in a tared centrifuge tube, containing a small stirrer magnet bar. The flour suspension was incubated at 92.5 °C for 30 min in a water bath and a magnetic stirrer set at 100 rpm. After being cooled at room temperature with continuous magnetic stirring for 30 min, sample was centrifuged at 2000 × *g* for 20 min. The supernatant was collected and the residue (B) was weighed. The flour swelling power was calculated as:

Flour swelling power = 100 × weight of residue (B)/dry weight of flour (A)

2.5. Noodle making

Noodles were supplied by AEGIC. The mixing and sheeting method was used for the preparation of fresh raw noodles as described in detail elsewhere (Mitra et al., 2016). They contained more than 50% of wholemeal oat flour, the rest being wheat flour and other ingredients to compensate for diluted gluten (this is a very high oat content, which is nutritionally advantageous given the beneficial effects of oat; the detailed recipe and manufacturing process are commercially confidential information) were used to make oat-based white salted noodles. The final thickness of the noodle sheet was 1 mm, and this sheet was cut into 2.5 mm wide strips. The dried raw noodles were stored in plastic bags at ambient temperature before analysis.

2.6. Texture profile analysis

Textural profile analysis (TPA) of cooked noodles was measured with a texture analyzer (TA-XTPlus Texture Analyzer, Texture Technology Corp., Scarsdale, NY), following a method described elsewhere (Hou, 2010). Noodles were cooked to the optimum cooking time, which was that when the inner core in the noodle was still present but not visible to the naked eye (based on AACC Method 66-50). The optimum cooking time of noodles was measured by the AEGIC oat team (cooking time of all samples is provided in Table S1). After cooking, noodles were rinsed with 25 °C water for 10 s with stirring and then placed in a steel strainer. The excess water on the surface of the cooked noodles was removed by tapping the strainer for 10 s on the edge of a sink. The drained noodles were placed in a covered container to prevent them from drying out. 5–6 noodle strands with a length of ~6.0 cm were randomly collected and put side by side on the base plate. TA 47 W Pasta Blade (5 mm thickness flat blade) equipped with a 5 kg load cell was used in the test. The standard settings for the TPA were Pre-test speed 4.0 mm/s, Test speed 1.0 mm/s, Post-test speed 1.0 mm/s, Target mode Strain, Strain 70%, Time 1.0 s, Trigger force 10.0 g. The textural parameters measured were hardness, springiness, cohesiveness and resilience. There were 4 replicates in each measurement.

2.7. Statistical analysis

Minitab 17 (Minitab, Inc., State College, PA) was used to calculate the mean value and standard deviation. Analysis of variance (ANOVA) with Tukey’s pairwise comparisons ($p < 0.05$) was used for significant difference analysis.

3. Results

3.1. Starch molecular structure

Typical *SEC* weight distributions, $w(\log X)$, of the debranched starches from oat flours, normalized to the height of the amylopectin peak, are shown in Fig. 1. In the main text, 4 among the total of 32 samples are chosen to illustrate typical *SEC* weight distributions, $w(\log X)$; $w(\log X)$ the data for all 32 samples (8 genotypes grown in 4 locations) are provided in Fig. S1.

These show similar features as reported in many other studies, e.g. (Nguyen et al., 2019; Tao et al., 2019). There is an initial large peak followed by a smaller shoulder, these features going up to DP ~ 100, and then a wide component with a smaller separate maximum above DP 1000, in which a small feature at a smaller DP, ~300, can just be distinguished. Chains with DP ≤ 100 are taken as belonging to

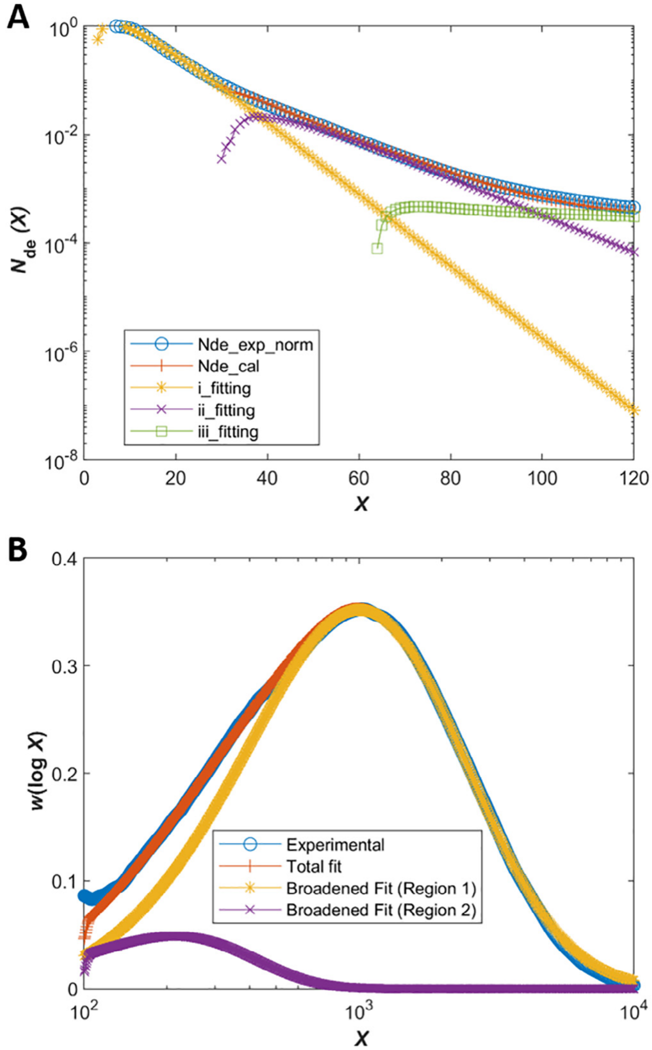

Fig. 2. Experimental data and results of model fitting for (A) oats amylopectin CLD;, Nde_exp_norm and Nde_cal are the experimental and fitted number distributions $N_{de}(X)$; i_fitting, ii_fitting, iii_fitting are the CLD fits to single-lamella chains, type –1 trans-lamella chains and type – 2 trans-lamella chains respectively; (B) oats amylose CLDs, showing the two broadened components using the subtractive method. Regions 1 and 2 refer to region of higher and lower DP respectively. The fits in regions 1 and 2 corrected for band broadening refer to broadened fit region 1 (gray) and 2 (light blue).

amylopectin and above that to amylose. The shorter amylopectin chains in the first peak are confined to only one crystalline lamella while the DPs from the shoulder and beyond are longer amylopectin chains which can span more than one crystalline lamella.

The amylopectin and amylose CLDs were fitted to biosynthesis models to obtain a small number of biosynthesis-related parameters. Some fitted CLDs of amylopectin and amylose are shown in Fig. 2, and the fitted parameters from these biosynthesis models are presented in Table 1. There is variation in the structural parameters among different growing locations. It is also noted that the parameters for fitting the small low-DP feature in the amylose region have a large uncertainty, but this small feature is real; the data cannot be fitted with a single feature. The effect of environmental conditions on structural parameters of oat starch is not the subject of this study, although growth conditions such as rainfall, temperature during grain development affect starch biosynthesis enzymes (Fang et al., 2019; Thitisaksakul, Jiménez, Arias, & Beckles, 2012) which in turn control the starch structure.

3.2. β-glucan content, starch content and functional properties of oat flour

Paste viscosity and swelling power are frequently used to predict noodle texture in industry. In addition, the crystalline structure within noodles is considered to influence noodle eating qualities. As well as starch concentration and starch fine structure, the pasting properties of oat wholemeal flour are affected by other components, predominantly β-glucan with high viscosity (Colleoni-Sirghie, Jannink, Kovalenko, Briggs, & White, 2004; Liu et al., 2010). All these are measured here.

The β-glucan content in these samples here is within the range reported for oats (Redaelli et al., 2013). The oat flours in this study have higher pasting viscosities and pasting temperature as compared to other cereals, in agreement with other reports (Berski, Krystyjan, Buksa, Zięć, & Gambuś, 2014; Punia et al., 2020). The gelatinization temperatures (onset and peak temperatures) of oat flours are higher, while the enthalpy is lower, than in another report (Punia et al., 2020); this is because the oat flours used here were heat-moisture treated, and the reasons for these differences have been explained elsewhere (Nguyen et al., 2019).

The starch damage level ranges from 3.28 to 5.00%, which is higher than in a previous study (Mitra et al., 2016). The present study used the heat-moisture treated oat flour, which is probably slightly degraded during milling, causing some starch damage (Nguyen et al., 2019). The swelling power value in this present study ranges from 5.10 to 7.14%, which is lower than in wheat flour (Blazek & Copeland, 2008) and purified oat starch (Tester & Karkalas, 1996).

As shown in Tables S2 and S3 in the Supporting Information, there are significant variations in β-glucan content, gelatinization properties, pasting properties, swelling power and starch damage among different cultivars and growing locations. Since the objective of this study is to investigate and explore the mechanism of starch structure and β-glucan controlling functional properties in oat flour, which in turn controls the texture quality of noodles, effects of genotype and environment on β-glucan content and functional properties of oat flour are not discussed.

3.3. Texture profile analysis of cooked noodles

In uncooked noodles, starch is present in granular form and is surrounded by a protein polymeric network. During cooking, the starch granules absorb a higher amount of water than the protein network, and become gelatinized to yield moist and soft-textured cooked noodles.

Pasting viscosity has a significant impact on texture of cooked noodles. 24 flour samples with a wide range of pasting properties (see Table S1 in the Supplementary Information) were chosen to make noodles. We select samples with different and wide-spread growth locations and varieties so as to have a wide range of starch structures and groat compositions. All noodle samples were cooked to their optimum cooking time, as with longer cooking time, noodles will take up more water, which influences noodle thickness and firmness (Hatcher, 2010). As shown in Table S4, cooked noodles from different oat cultivars grown in different locations display significant variations in their hardness and cohesiveness but with similar resilience.

3.4. Structure – functional properties – texture relations

The coefficients from Pearson correlation tests between starch fine structure parameters from model fitting, β glucan content and functional properties are given in Table 2.

The parameters $\beta A_{p,i}$, $hA_{p,i}$, $\beta A_{p,iii}$ and $hA_{p,iii}$ govern chain lengths and amounts of amylopectin chains over DP 7–28 (i) and DP 30–60 (iii). For example, samples with higher values of $\beta A_{p,i}$ have more shorter amylopectin chains while a high value of $hA_{p,i}$ means high amounts of amylopectin chains in the range DP 7–28. Similarly, $\beta A_{m,ii}$ and $hA_{m,ii}$ govern chain-length and content of amylose chains respectively in the long amylose chain region. Table 2 shows that $\beta A_{p,i}$ and $\beta A_{p,iii}$ are

Table 1
Starch structure parameters from model fitting to amylopectin and amylose CLDs.

Variable		Amylopectin fitting parameters				Amylose fraction	Amylose fitting parameters			
Location	Genotype	100 $\beta A_{p,i}$	100 $hA_{p,i}$	100 $\beta A_{p,iii}$	100 $hA_{p,iii}$		1000 $\beta A_{m,i}$	100 $hA_{m,i}$	1000 $\beta A_{m,ii}$	100 $hA_{m,ii}$
Cunderdin	Bannister	9.90a	109abcd	5.17a	2.48a	0.34bcde	85.17a	4.33ab	11.6a	25.8a
	Dunnart	9.98a	109abcd	5.16a	2.35a	0.33bcde	74.70a	5.74ab	11.3a	25.1a
	Yallara	10.05a	110abcd	5.14a	2.34a	0.32de	78.35a	4.94ab	12.0a	23.6a
	Wombat	10.05a	113ab	5.36a	2.29a	0.35abcde	89.12a	3.00ab	11.5a	26.0a
	Durack	9.93a	107abcde	5.03a	2.45a	0.34bcde	83.78a	5.23ab	10.5a	24.2a
	Kowari	9.69a	107abcde	5.05a	2.70a	0.36abcde	85.82a	3.00ab	10.3a	28.1a
	Mitika	9.90a	110abcd	5.09a	2.61a	0.35abcde	63.77a	5.45ab	9.30a	27.0a
	Williams	9.82a	106abcde	4.98a	2.71a	0.36abcde	62.72a	8.03ab	8.88a	27.2a
Turretfield	Bannister	9.51a	107abcde	4.89a	2.51a	0.34bcde	78.18a	5.28ab	10.5a	28.0a
	Dunnart	9.64a	111ab	4.94a	2.38a	0.35abcde	80.21a	4.35ab	10.1a	25.0a
	Yallara	9.54a	108abcd	4.86a	2.46a	0.32de	82.21a	4.86ab	10.7a	25.7a
	Wombat	9.75a	109abcd	5.08a	2.31a	0.36abcd	84.28a	3.12ab	10.4a	26.4a
	Durack	9.51a	109abcd	4.82a	2.52a	0.34abcde	80.20a	5.22ab	10.2a	24.4a
	Kowari	9.38a	105abcde	4.71a	2.75a	0.35abcde	86.74a	6.87ab	9.64a	29.2a
	Mitika	9.48a	108abcd	4.75a	2.71a	0.37abc	88.40a	5.48ab	9.57a	27.4a
	Williams	9.56a	108abcd	4.87a	2.76a	0.36abcde	110.47a	3.38ab	10.2a	27.2a
Riverton	Bannister	9.66a	115a	5.22a	2.51a	0.32cde	72.88a	2.94ab	9.20a	27.6a
	Dunnart	9.63a	109abcd	4.95a	2.65a	0.32de	90.10a	4.27ab	11.8a	29.3a
	Yallara	9.57a	112ab	4.92a	2.42a	0.33cde	69.25a	4.09ab	10.4a	23.1a
	Wombat	9.41a	97.7de	4.86a	2.43a	0.39ab	92.65a	5.69ab	10.7a	31.8a
	Durack	9.58a	110abcd	5.02a	2.50a	0.36abcde	80.96a	3.91ab	10.5a	25.3a
	Kowari	9.25a	107abcde	4.74a	2.85a	0.40a	92.23a	4.58ab	10.5a	35.7a
	Mitika	9.20a	94.9e	4.57a	2.79a	0.34bcde	119.11a	8.38a	11.0a	30.8a
	Williams	9.87a	97.8cde	4.99a	2.58a	0.33cde	101.68a	6.16ab	11.4a	31.5a
Pingelly	Bannister	9.94a	104abcde	5.13a	2.36a	0.31e	95.79a	3.51ab	10.8a	22.2a
	Dunnart	10.03a	106abcde	5.21a	2.25a	0.32de	89.28a	2.68ab	11.3a	22.7a
	Yallara	9.89a	103abcde	5.21a	2.33a	0.32de	108.79a	2.14b	11.8a	22.8a
	Wombat	10.13a	110abc	5.31a	2.20a	0.33cde	78.35a	3.05ab	9.34a	23.1a
	Durack	9.80a	101bcde	4.96a	2.37a	0.33cde	99.23a	5.18ab	10.7a	23.6a
	Kowari	9.85a	103abcde	5.03a	2.62a	0.34bcde	98.27a	4.51ab	10.8a	25.9a
	Mitika	9.89a	109abcd	5.38a	2.60a	0.36abcde	94.40a	2.86ab	10.7a	28.8a
	Williams	9.94a	106abcde	5.16a	2.63a	0.35abcde	90.82a	3.83ab	10.36a	28.01a

Data based on duplicate measurements. Values with different letters in the same column are significantly different at $p < 0.05$.

negatively correlated with peak, trough and final viscosities and with peak time, while $hA_{p,iii}$ shows a positive correlation with these parameters. $hA_{p,iii}$ is also positively correlated with onset and gelatinization temperatures (To and Tp). Amylose content has a negative correlation with breakdown and setback viscosity and enthalpy (ΔH) but a positive correlation with To and Tp. $hA_{m,ii}$ is positively correlated with peak, trough viscosities, peak time, T_o and T_p but negatively correlated with ΔH. These correlations are in agreement with our previous results (Nguyen et al., 2019). β-glucan content shows positive correlations with peak, trough, final viscosities, T_o and T_p, but negative correlations with peak temperature and ΔH. Starch content is negatively correlated with all pasting and gelatinization parameters, excepted setback viscosity and ΔH. Interestingly, the flour swelling power is not correlated with either starch structural parameters or pasting and gelatinization parameters.

As shown in Table 3, the hardness of cooked noodles have significant and positive correlation with peak, trough and final viscosities. There is also a positive correlation between hardness and β-glucan content. Damage starch and swelling power show no significant correlation with any texture parameters. Hardness is negatively correlated with $\beta A_{p,i}$ and $\beta A_{p,iii}$ but positively correlated with $hA_{m,ii}$. The cohesiveness and resilience are not significantly correlated with any pasting or gelatinization parameters. The hardness is positively correlated with cohesiveness but negatively correlated with resilience.

4. Discussion

The influence of starch molecular fine structural parameters on the functional properties of flour, particularly pasting and gelatinization properties, examined here is consistent with that in our previous work (Nguyen et al., 2019), where mechanistic explanations were put forward, and thus will not be discussed here.

The novelty in the present studies is the influence of β-glucan. The negative correlation between starch content and β-glucan content is well documented and explained (Lim et al., 2020). It is found here that pasting viscosities significantly and positively correlate to β-glucan content (Table 2). With its high-water binding property, β-glucan would compete for free water and increase the viscosity of flour paste. Positive correlations between β-glucan concentration and the pasting properties have been found elsewhere (Colleoni-Sirghie et al., 2004; Liu et al., 2010). It has been reported that pasting viscosity increases with starch concentration (Srichuwong et al., 2005). However, a negative correlation between starch concentration and pasting viscosities was observed in this study. This shows that other effects beyond starch concentration (β-glucan concentration in this case) contribute to the pasting viscosities of oat flour. This is manifest in the negative correlation between starch content and β-glucan content, and the positive correlation between β-glucan and pasting viscosity.

When starch is heated in water at and above the glass transition temperature, gelatinization is initiated by the molecular hydration and mobility in amorphous regions first, which then spread into the crystalline regions. Water is a plasticizer of the amorphous regions of starch granules. It also facilitates rupture of hydrogen bonds and formation of new hydrogen bonds between itself and the dissociated starch chains. The restriction of water content reduces the hydration and mobility of the amorphous regions, resulting in higher gelatinization temperature (Tester & Sommerville, 2003). Due to its hydrophilic nature, β-glucan can be considered as an “anti-plasticizer” which is likely to limit water availability for starch hydration during gelatinization, which will increase gelatinization temperatures. The anti-plasticizing effect of non-

Table 2
Pearson correlation between starch structural parameters and functional properties of flour samples.

Parametersb		BGC	Amylose fitting		AC	SP	Pasting parameters (Viscosities in cP)							Gelatinization parameters		
			βAm,ii	hAm,ii			PV	TV	BV	FV	SV	PT(s)	PT(0C)	To (°C)	Tp (°C)	ΔH (J g^{-1})
Amylopectin fitting	$hA_{p,i}$	−0.28	−0.22	−0.34	−0.04	−0.31	−0.21	−0.22	0.03	−0.18	0.03	−0.13	0.26	−0.19	−0.19	0.04
	$\beta A_{p,i}$	−0.54	0.22	−0.59***	−0.49	0.33	−0.74***	−0.72***	0.02	−0.55***	0.19	−0.67***	0.00	−0.23	−0.22	0.57
	$hA_{p,iii}$	0.53	−0.30	0.72***	0.51**	−0.35	0.56***	0.6***	−0.29	0.42*	−0.23	0.64***	−0.22	0.76***	0.72***	−0.30
	$\beta A_{p,iii}$	−0.42	0.19	−0.46**	−0.37	0.23	−0.65***	−0.64***	0.11	−0.48**	0.19	−0.61***	0.13	−0.22	−0.22	0.41
Amylose content		0.33	−0.38	0.64***		−0.22	0.27	0.3	−0.47***	0.07	−0.46**	0.54	−0.09	0.49**	0.51**	−0.35*
Amylose fitting	$\beta A_{m,ii}$	−0.28		−0.08	−0.38	0.40*	−0.27	−0.31	0.15	−0.19	0.18	−0.43*	0.07	−0.33	−0.36*	0.14
	$hA_{m,ii}$	0.57	−0.07		0.64***	−0.17	0.46**	0.5**	−0.31	0.33	−0.24	0.57***	−0.24	0.63***	0.61***	−0.45**
β-glucan content		−0.28	0.57***	0.33	−0.12	0.81***	0.82***	0.21	0.81***	0.22	0.49**	−0.44*	0.41*	0.43*	−0.43*	
Starch content		−0.71***	0.38*	−0.49	−0.52	0.4*	−0.71***	−0.75***	0.22	−0.50**	0.35*	−0.76***	0.12	−0.34*	−0.38*	0.67***
Swelling power		−0.12	0.40	−0.17	−0.22		−0.12	−0.18	0.47	−0.01	0.33	−0.35	0.03	−0.21	−0.22	0.47

BGC, β-glucan content; AC, amylose content; SP, swelling power; PV, Peak viscosity; TV, Trough viscosity; BV, Breakdown viscosity; FV, Final viscosity; SV, Setback viscosity; PT(s), Peak time; PT(0C), Peak temperature.
Significance level: *, ** and *** at p ≤ 0.05, 0.01 and 0.001 respectively.

Table 3
Pearson correlation between β-glucan content, starch structure parameters and functional properties of oat flour.

Parametersb	SD	SP	Pasting parameters (Viscosities in cP)							Gelatinization parameters			β-glucan (%)	Amylopectin fitting				Amylose content	Amylose fitting	
			PV	TV	BV	FV	SV	PT(s)	PT(0C)	To (0C)	Tp (0C)	ΔH (J g-1)		hAp,i	βAp,i	hAp,iii	βAp,iii		βAm,ii	hAm,ii
Hardness	0.03	−0.17	0.54**	0.58**	0.07	0.55**	0.08	0.42	−0.31	0.05	0.05	−0.41	0.56**	−0.36	−0.59**	0.23	−0.51*	0.22	−0.15	0.45*
Cohesiveness	−0.26	−0.09	0.19	0.22	0.08	0.23	0.07	0.10	−0.22	0.22	0.22	−0.02	0.35	−0.16	−0.13	0.14	−0.12	0.09	0.02	0.15
Resilience	0.02	0.35	−0.19	−0.25	0.28	−0.12	0.21	−0.38	−0.03	0.04	−0.002	0.47	−0.07	0.04	0.35	−0.09	0.36	−0.12	0.22	−0.09

SD, starch damage; SP, swelling power; PV, Peak viscosity; TV, Trough viscosity; BV, Breakdown viscosity; FV, Final viscosity; SV, Setback viscosity; PT(s), Peak time; PT(0C), Peak temperature.
Significance levels: *, ** and *** at p ≤ 0.05, 0.01 and 0.001 respectively.

starch polysaccharides, β-glucan in this case, is similar to that of sugar but to a greater extent (Tester & Sommerville, 2003). The positive correlation of β-glucan content and negative correlation of starch content with T_o and T_p in this study support the above hypothesis.

The gelatinization enthalpy (ΔH) is controlled by the melting of double helices in amylopectin in the starch grain. This is consistent with ΔH being positively correlated with starch content and negatively correlated with β-glucan content, as it reflects the higher extent of double helices in the crystalline regions.

It has been reported that pasting properties, particularly peak viscosity and swelling power, are strongly correlated in wheat flour (Blazek & Copeland, 2008; Crosbie, 1991). However, in the present case of oat flour, there was no correlation between these two properties. In fact, pasting viscosities and swelling power represent different processes (rheology and gelatinization, respectively) and are measured differently. The swelling power determines the water absorption of largely undisrupted granules in flour or starch at high temperature without the application of shear forces, while pasting viscosities are measured during the disruption of granule integrity with the application of shear and heat. In the swelling power measurement, a stir bar at 100 rpm was used. While this creates significant shear, it is very low compared to that during the measurement of pasting viscosities by RVA.

No correlation between pasting viscosities and swelling power was found here, probably because of the presence of significantly higher amounts of β-glucan in oat flour compared to that in wheat flour. The preferential hydration, aggregation and matrix formation of β-glucan would entrap starch granules in a semi-solid gel which would limit water movement to the starch granules, resulting in reduction in starch swelling and gelatinization (Brennan & Cleary, 2007). Here, it is seen that β-glucan inhibits starch swelling. This is consistent with the lack of any significant correlation between swelling power of flour and any starch fine structure or gelatinization parameters (Table 2), as is normally seen for other flours without β-glucan.

In contrast, pasting viscosities are determined under the high shear and high temperature of the RVA conditions. Starch and β-glucan are considered to form a biphasic system, with β-glucan as the continuous phase due to its high water binding (Banchathanakij & Suphantharika, 2009). During pasting, starch granules swell, leading to a decrease in the volume of the continuous phase and, as a result, an increase of β-glucan concentration in the continuous phase. Therefore, the viscosity of the continuous phase significantly increases, leading to an increase in the overall viscosity of the system. Therefore, β-glucan increases pasting viscosity and decreases swelling properties, which, if these effects approximately cancel, can result in no correlation between pasting viscosities and swelling power of oat flour.

The hardness of cooked noodles was positively correlated with peak viscosity, trough viscosity and final viscosity of flour (Table 3), which is opposite to what has been found in wheat noodles (Baik & Lee, 2003; Ross, Quail, & Crosbie, 1997), and in wheat-noodle pasta fortified with dietary fiber (Mohamed et al., 2005; Tudorica, Kuri, & Brennan, 2002), where the hardness and peak viscosity were negatively correlated. One possible explanation for this difference is the level of β-glucan in noodles. At low concentrations (as in this study), β-glucan may interact with the protein-starch matrix and develop starch-protein-polysaccharide networks, which could stabilize noodle structure and thus increase the hardness of noodles (Tudorica et al., 2002). Further, β-glucan may compete for water with starch, which would limit starch swelling (as discuss above) and water absorption. This would make the noodle harder (Rakhesh, Fellows, & Sissons, 2015). The increase in the hardness of pasta and white salted noodles with the increase of β-glucan enriched flour level was also recorded in literature (Mitra, Cato, James, & Solah, 2012; Rakhesh et al., 2015).

However, when the level of β-glucan exceeds a threshold (Mohamed et al., 2005; Tudorica et al., 2002), it may reduce the integrity of the protein-starch matrix. The disruption of that structure may explain the decreased hardness of noodles. Thus a higher concentration of β-glucan significantly decreases noodle hardness (Fan et al., 2016; Tudorica et al., 2002). In the present study, although more than 50% of oat flour was supplemented to wheat flour, two other components (one of these is hydrocolloid) were added to functional compensate for gluten network. Therefore, the integrity of protein network is still maintained. The positive correlation of β-glucan with peak viscosity, trough viscosity, final viscosity and with the hardness of oat-based noodles found here suggests that the range of β-glucan level in oat flour studied here which is possibly below the limiting threshold along with other additional supplements enhance protein-starch-polysaccharide network and stabilize noodle structure.

No correlation between swelling power and any texture parameters is expected, because β-glucan hinders starch gelatinization, as discussed above.

Starch damage was not significantly correlated with any of hardness, cohesiveness or resilience of cooked noodles. This suggests that the amount of starch damage here is not high enough to have an impact on noodle texture, as reported previously (Li, Dhital, & Wei, 2017).

A model of the internal structure of cooked noodles (Ross et al., 1997) postulated that the cooked noodle can be considered as a composite material made up of two distinct but interconnected phases: a continuous phase with gluten proteins together with amylose leached from gelatinized starch granules forming a three dimensional lattice, and a discrete phase made up of remnant swollen starch granules within the lattice. After cooking, amylose in the continuous phase could either associate with protein by hydrogen bonding, or retrograde with other amylose molecules, both of which would contribute to the rigidity of the polymer network.

The correlation between noodle hardness and $hA_{m,ii}$ was significantly positive. A higher value of $hA_{m,ii}$ means a higher amount of long amylose chains. With more bonding points, the dispersed long amylose chains could reassociate with each other or with protein to form a more stable polymeric matrix, which would result in increased hardness. In the present study, hardness was not found to be significantly correlated with amylose content, which may be because the samples used in this study had a relatively small range of amylose content.

The results showed that not only amylose content but also the CLD of amylose play a significant role in the hardness of noodles. Samples with lower value of $\beta A_{p,i}$ and/or $\beta A_{p,iii}$ have more longer amylopectin chains in regions with DP 7–28 and 30–60 respectively. The long amylopectin chains have a tendency to form more stable (longer) double-helix structures, which could cause a lower degree of swelling, leading to an increase in noodle hardness. The effect of starch fine structure on hardness of noodles in this study is consistent with other reports which investigate the effect of starch fine structure on hardness and stickiness of rice (Li, Prakash, Nicholson, Fitzgerald, & Gilbert, 2016; Tao, Yu, Prakash, & Gilbert, 2019). It can be seen that starch fine structure, particular $\beta A_{p,i}$, $\beta A_{p,iii}$ and $hA_{m,ii}$, control the pasting viscosity of flour, which in turn affects the hardness of noodles.

5. Conclusions

This study examines the relationship between β-glucan and starch molecular fine structure with physicochemical properties and texture of cooked oat-fortified noodles. We show, for the first time, that the proportions of both longer amylopectin and longer amylose chains have significant impact on the texture of cooked noodles. Unlike wheat flour, where there is positive correlation between swelling power with pasting viscosities, here there were no significant correlations between swelling power with noodle hardness, swelling power and pasting viscosity of wholemeal oat flour. Oat flours with higher pasting viscosities formed noodles with increased hardness. These results demonstrated the important contribution of β-glucan to physicochemical properties of wholemeal oat flour and the texture of cooked noodles.

This may be of use to plant breeders and noodle manufacturers to use the level of β-glucan and starch molecular fine structure to generate suitable oat genotypes for noodle products, and new assessment methods to optimize noodle eating qualities.

CRediT authorship contribution statement

Thoa T.L. Nguyen: Data curation, Formal analysis, Investigation, Methodology, Writing - original draft, Writing - review & editing. **Robert G. Gilbert:** Supervision, Writing - review & editing. **Michael J. Gidley:** Methodology, Supervision, Writing - review & editing. **Glen P. Fox:** Conceptualization, Investigation, Methodology, Project administration, Resources, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We gratefully acknowledge the funding of Australia Export Grains Innovation Centre (AEGIC) for this project. We also highly appreciate the help of the AEGIC oats team of Mark Tucek, Sabori Mitra, Regina Buswell and Nabeen Dulal, for providing noodle samples and for useful advice. Thoa T. L. Nguyen gratefully acknowledges the support of a University of Queensland International Scholarship and a Queensland Alliance for Agriculture and Food Innovation (QAAFI) Postgraduate Award. RGG gratefully acknowledges the support of 2017 Jiangsu Innovation and Entrepreneurship talents program and of a National Science Foundation of China grant C1304013151101138. A project funded by the Priority Academic Program of Jiangsu Higher Education Institutions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodchem.2020.126858.

References

Baik, B. K., & Lee, M. R. (2003). Effects of starch amylose content of wheat on textural properties of white salted noodles. *Cereal Chemistry, 80*(3), 304–309.

Banchathanakij, R., & Suphantharika, M. (2009). Effect of different β-glucans on the gelatinisation and retrogradation of rice starch. *Food Chemistry, 114*(1), 5–14.

Berski, W., Krystyjan, M., Buksa, K., Zięć, G., & Gambuś, H. (2014). Chemical, physical and rheological properties of oat flour affected by the isolation of beta-glucan preparation. *Journal of Cereal Science, 60*(3), 533–539.

Blazek, J., & Copeland, L. (2008). Pasting and swelling properties of wheat flour and starch in relation to amylose content. *Carbohydrate Polymers, 71*(3), 380–387.

Brennan, C. S., & Cleary, L. J. (2007). Utilisation Glucagel® in the β-glucan enrichment of breads: A physicochemical and nutritional evaluation. *Food Research International, 40*(2), 291–296.

Choo, C. L., & Aziz, N. A. A. (2010). Effects of banana flour and β-glucan on the nutritional and sensory evaluation of noodles. *Food Chemistry, 119*(1), 34–40.

Colleoni-Sirghie, M., Jannink, J.-L., Kovalenko, I. V., Briggs, J. L., & White, P. J. (2004). Prediction of β-glucan concentration based on viscosity evaluations of raw oat flours from high β-glucan and traditional oat lines. *Cereal Chemistry, 81*(4), 434–443.

Crosbie, G. (1991). The relationship between starch swelling properties, paste viscosity and boiled noodle quality in wheat flours. *Journal of Cereal Science, 13*(2), 145–150.

Czuchajowska, Z., Paszczynska, B., & Pomeranz, Y. (1992). Functional properties of psyllium in wheat-based products. *Cereal Chemistry, 69*, 516.

Fan, L., Ma, S., Wang, X., & Zheng, X. (2016). Improvement of Chinese noodle quality by supplementation with arabinoxylans from wheat bran. *International Journal of Food Science & Technology, 51*(3), 602–608.

Fang, L. H., Hu, Y., Wang, C., Liu, W., Ma, G., Han, Q., & Ma, D. (2019). Effects of high temperature and drought stress on the expression of genes encoding enzymes and the activity of key enzymes involved in starch biosynthesis in wheat grains. *Frontiers in Plant Science, 10*, 1414.

Guo, G., Jackson, D. S., Graybosch, R. A., & Parkhurst, A. M. (2003). Asian salted noodle quality: Impact of amylose content adjustments using waxy wheat flour. *Cereal Chemistry, 80*(4), 437–445.

Hatcher, D. W. (2010). Objective evaluation of noodles. Asian Noodles: Science, Technology, and Processing, 227-260.

Hou, G. G. (2010). Laboratory pilot-scale Asian noodle manufacturing and evaluation protocols. *Asian Noodles: Science, Technology, and Processing* (pp. 183–225). Wiley Online Library.

Hou, G. G. (2011). *Asian noodles: Science, technology, and processing.* John Wiley & Sons.

Jiang, H., Martin, J., Okot-Kotber, M., & Seib, P. A. (2011). Color of whole-wheat foods prepared from a bright-white hard winter wheat and the phenolic acids in its coarse bran. *Journal of Food Science, 76*(6), C846–C852.

Kaur, A., Shevkani, K., Katyal, M., Singh, N., Ahlawat, A. K., & Singh, A. M. (2016). Physicochemical and rheological properties of starch and flour from different durum wheat varieties and their relationships with noodle quality. *Journal of Food Science and Technology, 53*(4), 2127–2138.

Konik-Rose, C. M., Moss, R., Rahman, S., Appels, R., Stoddard, F., & McMaster, G. (2001). Evaluation of the 40 mg swelling test for measuring starch functionality. *Starch-Stärke, 53*(1), 14–20.

Li, M., Dhital, S., & Wei, Y. (2017). Multilevel Structure of Wheat Starch and Its Relationship to Noodle Eating Qualities. *Comprehensive Reviews in Food Science and Food Safety*.

Li, H., Prakash, S., Nicholson, T. M., Fitzgerald, M. A., & Gilbert, R. G. (2016). The importance of amylose and amylopectin fine structure for textural properties of cooked rice grains. *Food Chemistry, 196*, 702–711.

Lim, W. L., Collins, H. M., Byrt, C. S., Lahnstein, J., Shirley, N. J., Aubert, M. K., ... Burton, R. A. (2020). Overexpression of HvCslF6 in barley grain alters carbohydrate partitioning plus transfer tissue and endosperm development. *Journal of Experimental Botany, 71*(1), 138–153.

Liu, Y., Bailey, T. B., & White, P. J. (2010). Individual and interactional effects of β-glucan, starch, and protein on pasting properties of oat flours. *Journal of Agricultural and Food Chemistry, 58*(16), 9198–9203.

Martinez-Villaluenga, C., & Peñas, E. (2017). Health benefits of oat: Current evidence and molecular mechanisms. *Current Opinion in Food Science, 14*, 26–31.

Mitra, S., Cato, L., James, A. P., & Solah, V. A. (2012). Evaluation of white salted noodles enriched with Oat flour. *Cereal Chemistry, 89*(2), 117–125.

Mitra, S., James, A. P., Fenton, H. K., Cato, L., & Solah, V. A. (2016). The impact of oat quality on white salted noodles containing oat flour. *Cereal Chemistry, 93*(3), 282–292.

Mohamed, A. A., Rayas-Duarte, P., Xu, J., Palmquist, D. E., & Inglett, G. (2005). Hard red winter wheat/nutrim-OB alkaline fresh noodles: Processing and texture analysis. *Journal of Food Science, 70*(1), S1–S7.

Nada, S. S., Zou, W., Li, C., & Gilbert, R. G. (2017). Parameterizing amylose chain-length distributions for biosynthesis-structure-property relations. *Analytical and Bioanalytical Chemistry, 409*(29), 6813–6819.

Nguyen, T. L., Mitra, S., Gilbert, R. G., Gidley, M. J., & Fox, G. P. (2019). Influence of heat treatment on starch structure and physicochemical properties of oats. *Journal of Cereal Science, 102805*.

Punia, S., Sandhu, K. S., Dhull, S. G., Siroha, A. K., Purewal, S. S., Kaur, M., & Kidwai, M. K. (2020). Oat starch: Physico-chemical, morphological, rheological characteristics and its application-A review. *International Journal of Biological Macromolecules*.

Rakhesh, N., Fellows, C. M., & Sissons, M. (2015). Evaluation of the technological and sensory properties of durum wheat spaghetti enriched with different dietary fibres. *Journal of the Science of Food and Agriculture, 95*(1), 2–11.

Redaelli, R., Del Frate, V., Bellato, S., Terracciano, G., Ciccoritti, R., Germeier, C. U., ... Sgrulletta, D. (2013). Genetic and environmental variability in total and soluble β-glucan in European oat genotypes. *Journal of Cereal Science, 57*(2), 193–199.

Ross, A., Quail, K., & Crosbie, G. (1997). Physicochemical properties of Australian flours influencing the texture of yellow alkaline noodles. *Cereal Chemistry, 74*(6), 814–820.

Slavin, J. L., Martini, M. C., Jacobs, D. R., Jr, & Marquart, L. (1999). Plausible mechanisms for the protectiveness of whole grains. *The American Journal of Clinical Nutrition, 70*(3), 459s–463s.

Song, X., Zhu, W., Pei, Y., Ai, Z., & Chen, J. (2013). Effects of wheat bran with different colors on the qualities of dry noodles. *Journal of Cereal Science, 58*(3), 400–407.

Srichuwong, S., Sunarti, T. C., Mishima, T., Isono, N., & Hisamatsu, M. (2005). Starches from different botanical sources II: Contribution of starch structure to swelling and pasting properties. *Carbohydrate Polymers, 62*(1), 25–34.

Tao, K., Li, C., Yu, W., Gilbert, R. G., & Li, E. (2019). How amylose molecular fine structure of rice starch affects functional properties. *Carbohydrate Polymers, 204*, 24–31.

Tao, K., Yu, W., Prakash, S., & Gilbert, R. G. (2019). High-amylose rice: Starch molecular structural features controlling cooked rice texture and preference. *Carbohydrate Polymers, 219*, 251–260.

Tester, R. F., & Karkalas, J. (1996). Swelling and gelatinization of oat starches. *Cereal Chemistry, 73*(2), 271–277.

Tester, R., & Sommerville, M. (2003). The effects of non-starch polysaccharides on the extent of gelatinisation, swelling and α-amylase hydrolysis of maize and wheat starches. *Food Hydrocolloids, 17*(1), 41–54.

Thitisaksakul, M., Jiménez, R. C., Arias, M. C., & Beckles, D. M. (2012). Effects of environmental factors on cereal starch biosynthesis and composition. *Journal of Cereal Science, 56*(1), 67–80.

Tudorica, C., Kuri, V., & Brennan, C. (2002). Nutritional and physicochemical characteristics of dietary fiber enriched pasta. *Journal of Agricultural and Food Chemistry, 50*(2), 347–356.

Vilaplana, F., & Gilbert, R. G. (2010). Characterization of branched polysaccharides using multiple-detection size separation techniques. *Journal of Separation Science, 33*(22), 3537–3554.

Wang, F., Huang, W., Kim, Y., Liu, R., & Tilley, M. (2011). Effects of transglutaminase on the rheological and noodle-making characteristics of oat dough containing vital wheat gluten or egg albumin. *Journal of Cereal Science, 54*(1), 53–59.

Wu, A. C., Morell, M. K., & Gilbert, R. G. (2013). A parameterized model of amylopectin synthesis provides key insights into the synthesis of granular starch. *PLoS One, 8*(6), e65768.

Zhou, M., Robards, K., Glennie-Holmes, M., & Helliwell, S. (2000). Effects of enzyme treatment and processing on pasting and thermal properties of oats. *Journal of the Science of Food and Agriculture, 80*(10), 1486–1494.