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Effect of baking on nutritional properties of starch in organic spelt whole grain products

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ABSTRACT

Consumers of organic spelt food products claim health benefits or sense of well-being from their consumption as opposed to consumption of common wheat products. This study was designed to help clarify the validity of such claims through the evaluation of nutritional properties of starch in a variety of organic spelt products, including breads, biscuits, cookies and muffins, in comparison with their respective common wheat products. Three fermented bread products, namely, yeast leavened, sour and yeast/sour dough were evaluated. Rate and extent of starch digestion were based on the measurement of starch digestion index (SDI) and rapidly available glucose (RAG). The commercial spelt variety used contained approximately eight to ten fold the amount of resistant starch (RS) as compared to common wheat, averaging 3.7% versus 0.4%, and exhibited lower SDI and RAG values. This is the first report to demonstrate high content of RS in spelt. After mixing and fermentation, RS, SDI and RAG reduced, but were still higher in spelt doughs and batters than in those of common wheat. After baking, slight differences were observed in rate and extent of starch digestion between spelt and common wheat baked products. The study showed that differences among baked products were more pronounced than those between spelt and common wheat products.

1. Introduction

Spelt (*Triticum aestivum* subsp *spelta*) is primitive wheat that is currently grown marginally and mainly for use in organic foods. It is believed that primitive wheat species are more disease-resistant and can produce healthier foods than those made from modern wheat varieties. In this respect, spelt was found to perform well under suboptimal growing conditions (Ruegger, Winzeler, & Nosberger, 1990), and to better utilize nutrients when grown in a low-input system (Moudrý & Dvořáček, 1999) and show more resistance to a number of pathogens (Kema & Lange, 1992) than common wheat. Thus spelt is recommended for organic agriculture, (i.e. no use of synthetic fertilizers, genetically modified materials, sewage sludge or pesticides). However, spelt was found to induce cellular mechanisms implicated in the pathogenesis of celiac disease, like common wheat, but monococcum and dicoccum wheat species had very few toxic effects (Vincentini et al., 2007).

Sale of organic bakery products has steadily increased over the past five years at a current value growth rate in 2005–2006 of 6.4%, 3.5% and 13.6% in Canada, UK and USA, respectively (EN, 2007). With so much interest in organic foods, organically-grown spelt finds its way to the food market. This is not a surprise, since spelt was used in bread making during the fifth century and until the beginning of the twentieth century and was subsequently replaced by higher yield free-threshing modern wheat cultivars (Abdel-Aal & Hucl, 2005). In fact, spelt cultivars have shown potential in various food applications, including bread, pasta and breakfast cereal (Abdel-Aal, Hucl, & Sosulski, 1998; Abdel-Aal, Hucl, & Sosulski, 1999; Abdel-Aal, Sosulski, & Hucl, 1998; Marconi, Carcea, Graziano, & Cubadda, 1999; Marconi, Carcea, Schiavone, & Cubadda, 2002). At present, organic spelt is being used in making a wide array of traditional and specialty food products. These products are well perceived by consumers who claim a sense of well-being when they consume spelt products.

Starch is the main constituent in cereal foods, including spelt. It also provides the majority of the energy in the diets of most people. Thus, nutritional and health properties of starch would be of great interest to consumers and food processors. Starch can be found in various physical and chemical forms in foods, which influence rate and extent of digestion and consequently its nutritional and health properties. The FAO/WHO expert consultation on carbohydrates in human nutrition recommends the consumption of foods that possess low glycemic index or slow digestion, i.e. promote slow release of glucose in the body (FAO/WHO., 1998). In other words, carbohydrate foods that exhibit lower rate and extent of starch digestion would be preferable, due to their physiological functions and impact on health, including reduction of the glycemic and

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insulinemic responses (Jenkins et al., 1987), hypocholesterolemic effects (De Deckere, Kloots, & Van Amelsvoort, 1995) and protective effects against colon–rectal cancer (Cassidy, Bingham, & Cummings, 1994). Several factors could affect rate and extent of starch digestion, including source and composition of starch (Liu, Gu, Donner, Tetlow, & Emes, 2007), food processing (Mahadevamma & Tharanathan, 2007; Skrabanja, Elmståhl, Kreft, & Björck, 2001) and storage time (Rendon-Villalobos, Bello-Prérez, Osorio-Díaz, Tovar, & Paredes-López, 2002).

The present study was designed to evaluate rate and extent of starch digestion of several organic whole grain spelt food products, e.g. breads, biscuits, cookies and muffins, based on the measurement of rapidly digestible starch, slowly digestible starch, starch digestion index and rapidly available glucose *in vitro*. In addition, effects of fermentation and baking on the formation of resistant starch in these products were also investigated.

2. Materials and methods

2.1. Wheat grains and products

Representative samples of organic spelt and common wheat grain, whole grain flour, dough, bread, cookie, biscuit and muffin were obtained from Birgit's Best Bakery (Owen Sound, ON, Canada). The two wheats were organically-grown in Ontario, Canada. In addition, five spelt cultivars, two spring-type (CDC Nixon and PGR 8801) and three winter-type (Rotkorn, Frankencorn and Heritage), were included in the study to verify the level of resistant starch in spelt. Dough samples were shipped to the research centre in a frozen form and kept in a deep freezer at −20 °C prior to further preparation and analysis. The bread products were prepared for analysis according to the procedure of the AACC Approved Method 62-05 (AACC, 2000). Immediately after processing, samples of dough, bread, biscuit, cookie and muffin were cut or crushed into small pieces and freeze-dried. The freeze-dried products were then ground and sieved to pass through a 1 mm sieve prior to analysis. Spelt and common wheat grains were ground into whole grain flours using a Cyclone Sample Mill (UDY Corp., Fort Collins, CO) equipped with a 1 mm sieve. The ground materials were kept in a refrigerator until analysis.

2.2. Preparation of baked products

Commercially-milled flours were used in making the baked products. Baked products were made in three batches; the size of each batch varied from 3 to 5 kg, depending on product type. Bread doughs were prepared by mixing the required ingredients in proportions included in the baking formulas (Table 1), using a Hobart dough mixer (Hobart Corporation, Troy, OH) to obtain a consistent dough, i.e., the optimal mixing times were 7 min for spelt and 9 min for common wheat. In our previous study, spelt flours required shorter mixing time than did common wheat flours (Abdel-Aal et al., 1999). The dough samples were divided into individual pieces having an approximate weight of 450 g and fermented under controlled conditions at 37 °C and relative humidity of 85%. The dough pieces were sheeted and rolled on a Hobart Sheeter/Roller Model 8 (Bakery Equipment Services Ltd, Brantford, ON) and then proofed prior to baking at 190 °C for 45 min. The total fermentation time was 6 h for spelt yeast leavened bread, 5 h for spelt sour dough bread and 7 h for spelt yeast/sour dough bread, including the 1 h proofing time. The fermentation time for common wheat breads was lower than those of spelt by about 2 h. The sour dough sponge was prepared by mixing whole grain flour, sour dough starter and water in a proportion given in Table 1. The mixture was kept at ambient temperature (25 °C) for 24 h and stored in a refrigerator for not more than 2 days prior to use.

For biscuit making, whole grain flour (100 g), baking powder (0.7 g), cream of tartar (0.1 g), salt (0.3 g), and canola oil (3 g) were blended. Then the required amount of water (51 ml for spelt and 55 ml for common wheat) was added to the mixture and mixed for 3 min in a Hobart dough mixer (Hobart Corporation, Troy, OH). For cookie making, butter (70 g), sugar (43 g) and dry whole egg (7 g) were creamed for 3 min and then whole grain flour (100 g), baking powder (0.7 g) and water (21 ml for spelt and 24 ml for common wheat) were added and mixed for 2 min. The dough was cut into balls, shaped and rested for 30 min before baking at 190 °C for 15 min.

Muffin was made by mixing whole grain flour (100 g), brown sugar (43 g), canola oil (35 ml), fresh eggs (6), baking powder (1.7 g), salt (1.0 g) and water (70 ml) in a Hobart dough mixer (Hobart Corporation, Troy, OH) for 3 min. The muffin batter was spooned into a muffin tin and rested for 40 min prior to baking at 190 °C, for 20 min.

Table 1
Composition of spelt and common wheat bread formulas

Ingredients	Yeast leavened	Sour dough	Yeast/sour dough	Sour dough sponge
Whole grain flour	100	100	100	100
Water	66 (71)[a]	66 (71)[a]	70 (73)[a]	63
Instant dry yeast	1.4	–	0.5	–
Salt	0.5	0.5	0.6	–
Honey	4.5	6.1	8.0	–
Sour dough sponge	–	26	40	–
Sour dough starter	–	–	–	28

g/100 g flour basis.
[a] Common wheat.

2.3. Composition and digestibility tests

Moisture content of the whole grain flours, breads, biscuits, cookies and muffins was determined using the modified vacuum-oven method of the AACC Approved Method 44-40 (AACC, 2000). Soluble starch was measured as outlined by Miller and Hoseney (1997), using a total starch assay kit (Megazyme Int. Ireland Ltd., Wicklow, Ireland). The procedure was modified to measure soluble starch rather than total starch. Flours were slurried in distilled water (1:10, w/v) for 2 min and, after that, were centrifuged at 1,000*g* for 15 min. The supernatant, which contained the soluble starch, was collected and used for starch measurement. Starch damage was measured using the Megazyme assay procedure (Megazyme Int. Ireland Ltd., Wicklow, Ireland). The method is based on hydration and breakdown of damaged starch granules to maltosaccharides plus α-limit dextrins by carefully controlled treatment with fungal α-amylase. Aliquots of the hydrolyzate were treated with amyloglucosidase to give complete degradation of dextrins to glucose.

Starch nutritional fractions and digestibility indices were determined as described by Englyst, Kingman, and Cummings (1992) with some modifications, e.g. glucose in the hydrolyzates was measured on a YSI glucose analyzer model 2700 (YSI Incorporated, Yellow Springs, OH, USA). The method is based on using controlled enzyme accessibility under specific conditions of temperature and solubilization reagents. The nutritional fractions and indices include total starch (TS), rapidly digested starch (RDS), slowly digested starch (SDS), starch digestion index (SDI) and rapidly available glucose (RAG). Total starch was measured as the glucose released by enzymatic degradation following gelatinization in boiling water and treatment with potassium hydroxide to disperse the retrograded amylose. The RDS and SDS were measured after incubation with pancreatic amylase and amyloglucosidase at 37 °C for 20 min and a further 100 min, respectively. The effects of fermentation and baking on the formation of resistant starch were evaluated using a direct measurement for resistant starch, as outlined in the Megazyme assay kit (Megazyme Int. Ireland Ltd., Wicklow, Ireland). This method is based on removal of non-resistant starch by hydrolysis with α-amylase and amyloglucosidase for 16 h at 37 °C, and RS was then recovered as a pellet by centrifugation, washed with ethanol and dissolved in potassium hydroxide solution, and was quantitatively hydrolyzed to glucose with amyloglucosidase. The accuracy of the determination of RS was checked with standard materials of corn flakes (2.27% RS) and kidney bean (4.58% RS). The relative accuracy values of the method were 97–98%. Soluble sugars were twice extracted with 70% ethanol and then determined on a Dionex HPLC system (DIONEX Corporation). The amount of digestible sugars was used in the determination of rapidly available glucose.

2.4. Statistical analyses

All analyses were carried out in triplicate determinations and the data were expressed as mean ± standard deviation (SD). Analysis of variance was performed to compare the different variables of spelt products using Minitab Software (version 12, Minitab Inc., State College, PA). Differences were considered to be significant when $p < 0.05$. Multiple regression and Pearson correlation analyses were performed to determine relationships between starch nutritional fractions and digestion parameters.

3. Results and discussion

3.1. Total and soluble starches in spelt products

Moisture contents of the whole grain flours were quite similar in all the evaluated spelt and common wheat grains milled either commercially or in the laboratory (Table 2). Total, soluble (water soluble fraction) and damaged (mechanically-damaged granules) starches were measured in the whole grain flours (Table 2). Total starch contents were somewhat similar in the four evaluated flours, averaging about 62% of the dry matter. In a previous study, starch content in five spring spelt accessions varied from 61–66% compared to 62% in common wheat grown side by side with the spelt lines (Abdel-Aal, Hucl, & Sosulski, 1995). Soluble and damaged starch accounted for small portions of starch in both wheats, ranging from 0.41% to 0.69% and 2.3–5.0%, respectively. Common wheat had significantly high levels of soluble and damaged starches perhaps due to the variation in kernel hardness. These differences may have consequences on rate and extent of starch digestion, as well as functionality of starch, due to their distinct characteristics. In this respect, damaged starch granules were more accessible to enzymes (Mahadevamma & Tharanathan, 2007), and the high levels of insoluble damaged starch and soluble starch were responsible for poor cookie quality made from hard wheat flours, e.g. cookie spread rate (Miller & Hoseney, 1997).

The moisture contents of organic spelt and common wheat bread products ranged from 40% to 44%, respectively (Table 3). There were significant differences between spelt and common wheat products, moisture contents being higher in common wheat products. In other words, the dry matter in fresh spelt bread products averaged 60% versus 57% in common wheat breads. Approximately 61% of the dry matter of spelt bread was starch, compared to 58% in common wheat bread products, indicating slight variation in starch content. Soluble starch was found to be at relatively low concentrations in both wheats, ranging from 0.41% to 0.69% (Table 2). After mixing, fermentation and baking, soluble starch significantly increased in spelt and common wheat products. Additionally, significant differences in soluble starch were observed between breads fermented by different methods (e.g. yeast versus sour fermentation). Sour dough breads had lower contents of soluble starch than had yeast leavened breads. This might be attributed to the conditions of sour dough fermentation which cause an increase in the amylase activity (Arendt, Ryan, & Bello, 2007) that breaks down soluble starch due to its higher enzyme accessibility compared to non-soluble starch. Sour dough fermentation was also found to improve textural quality and mineral bioavailability of bread due to increased enzyme activity and reduced phytate content (Arendt et al., 2007).

Moisture contents of spelt and common wheat biscuit and muffin products were quite close, ranging 25–30%, but cookie products had relatively low levels of moisture of approximately 5% (Table 4). In general, spelt and common wheat cookie, biscuit and muffin products contained lower amounts of total and soluble starch than did bread products (Tables 3 and 4). There were no significant differences in total starch between spelt and common wheat cookies, muffins or biscuits, but significant differences were observed among baked products. On average, cookies had the lowest amount of total starch (24.8%) followed by muffins (33.0%) and finally

Table 2
Total, soluble and damaged starches of organic spelt and common wheat whole grain flours

Wheat	Moisture	Total starch	Soluble starch	Damaged starch
Spelt, lab milled	13.5 ± 0.2	62.4 ± 1.8	0.41 ± 0.04	2.3 ± 0.1
Spelt, commercially milled	13.1 ± 0.2	62.2 ± 2.1	0.47 ± 0.03	2.8 ± 0.1
Wheat, lab milled	13.6 ± 0.2	61.9 ± 1.2	0.48 ± 0.02	3.3 ± 0.1
Wheat, commercially milled	13.7 ± 0.4	61.1 ± 1.5	0.69 ± 0.06	5.0 ± 0.2
LSD[a]	0.67	1.53	0.23	0.57

Mean ± SD, % dry basis.
[a] Least significant difference values at $p < 0.05$.

Table 3
Total and soluble starches of organic spelt and common wheat whole grain flour, dough and bread products

Wheat product	Moisture	Total starch	Soluble starch
Yeast leavened dough			
Spelt, after mixing	46.2 ± 0.7	61.8 ± 2.2	3.7 ± 0.2
Spelt, after fermentation	45.4 ± 1.3	60.8 ± 2.5	3.8 ± 0.2
Wheat, after mixing	49.4 ± 0.9	58.5 ± 1.4	3.9 ± 0.2
Wheat, after fermentation	49.1 ± 0.7	59.5 ± 1.7	4.1 ± 0.3
Sour dough			
Spelt, after mixing	47.3 ± 1.1	63.9 ± 3.1	2.5 ± 0.1
Spelt, after fermentation	46.8 ± 0.9	61.6 ± 2.0	2.9 ± 0.2
Wheat, after mixing	49.8 ± 1.2	62.2 ± 2.2	2.7 ± 0.2
Wheat, after fermentation	47.8 ± 1.2	60.4 ± 1.9	3.9 ± 0.1
Yeast/sour dough			
Spelt, after mixing	47.4 ± 0.9	56.9 ± 2.3	2.3 ± 0.1
Spelt, after fermentation	44.3 ± 1.2	58.9 ± 2.1	4.3 ± 0.2
Wheat, after mixing	51.1 ± 1.3	55.1 ± 2.5	2.7 ± 0.1
Wheat, after fermentation	48.1 ± 1.2	56.6 ± 2.7	5.0 ± 0.3
LSD[a]	2.18	3.51	0.21
Bread			
Yeast leavened spelt	40.5 ± 0.9	60.4 ± 1.4	4.3 ± 0.1
Sour dough spelt	40.7 ± 0.8	61.6 ± 1.9	3.9 ± 0.1
Yeast/sour dough spelt	40.2 ± 1.0	60.3 ± 2.1	4.0 ± 0.1
Yeast leavened wheat	43.6 ± 1.0	58.2 ± 2.5	4.8 ± 0.2
Sour dough wheat	42.9 ± 0.8	59.3 ± 2.3	3.7 ± 0.1
Yeast/sour dough wheat	41.9 ± 0.8	57.3 ± 1.8	3.9 ± 0.2
LSD[a]	1.03	3.67	0.53

Mean ± SD, % dry basis.
[a] Least significant difference values at $p < 0.05$.

Table 4
Total and soluble starches of organic spelt and common wheat whole grain biscuit, cookie and muffin doughs and products

Wheat product	Moisture	Total starch	Soluble starch
Biscuit			
Spelt dry mix	13.3 ± 0.1	55.1 ± 2.0	0.47 ± 0.02
Wheat dry mix	11.4 ± 0.1	54.8 ± 1.7	0.37 ± 0.01
Spelt dough	39.6 ± 0.8	45.4 ± 1.5	1.69 ± 0.10
Wheat dough	39.1 ± 0.7	44.4 ± 1.8	1.80 ± 0.10
Spelt biscuit	30.4 ± 0.7	45.6 ± 1.4	0.97 ± 0.07
Wheat biscuit	29.8 ± 0.7	45.1 ± 1.3	1.15 ± 0.09
LSD[a]	1.32	0.79	0.38
Cookie			
Spelt dough	14.4 ± 0.3	24.4 ± 1.1	1.31 ± 0.07
Wheat dough	15.9 ± 0.2	23.7 ± 1.1	0.96 ± 0.03
Spelt cookie	5.3 ± 0.1	24.7 ± 0.8	1.22 ± 0.05
Wheat cookie	4.3 ± 0.1	24.8 ± 1.0	1.05 ± 0.09
LSD[a]	0.95	0.66	0.39
Muffin			
Spelt batter	36.9 ± 1.1	32.5 ± 1.5	1.64 ± 0.11
Wheat batter	38.5 ± 1.1	32.7 ± 1.3	1.77 ± 0.09
Spelt muffin	27.5 ± 0.6	33.6 ± 1.2	1.90 ± 0.13
Wheat muffin	25.1 ± 0.7	32.4 ± 1.3	1.76 ± 0.11
LSD[a]	0.97	1.21	0.29

Mean ± SD, % dry basis.
[a] Least significant difference values at $p < 0.05$.

Table 5
Effects of milling and baking on the formation of resistant starch (RS) in organic spelt and common wheat products, as determined by direct measurement

Wheat product	RS	Wheat product	RS
Milling		*Bread* (continued)	
Spelt, lab milled	3.25 ± 0.03	Sour dough wheat	1.21 ± 0.01
Spelt, commercially milled	4.12 ± 0.05	Yeast/sour dough wheat	1.16 ± 0.01
Common, lab milled	0.39 ± 0.01	*Biscuit*	
Common, commercially milled	0.40 ± 0.01	Spelt dry mix	0.37 ± 0.01
Mixing		Spelt dough	0.59 ± 0.02
Spelt, yeast leavened	1.64 ± 0.01	Spelt biscuit	0.66 ± 0.01
Spelt, sour dough	2.55 ± 0.02	Wheat dry mix	0.33 ± 0.01
Spelt, yeast/sour dough	0.92 ± 0.01	Wheat dough	0.44 ± 0.01
Wheat, yeast leavened	0.40 ± 0.01	Wheat biscuit	0.69 ± 0.02
Wheat, sour dough	0.49 ± 0.01	*Cookie*	
Wheat yeast/sour dough	0.39 ± 0.01	Spelt dough	0.25 ± 0.01
Fermentation		Spelt cookie	0.22 ± 0.01
Spelt, yeast leavened	1.21 ± 0.02	Wheat dough	0.26 ± 0.01
Spelt, sour dough	2.20 ± 0.03	Wheat cookie	0.28 ± 0.01
Spelt, yeast/sour dough	0.84 ± 0.01	*Muffin*	
Wheat, yeast leavened	0.29 ± 0.01	Spelt batter	0.22 ± 0.01
Wheat, sour dough	0.39 ± 0.01	Spelt muffin	0.60 ± 0.02
Wheat yeast/sour dough	0.35 ± 0.01	Wheat batter	0.27 ± 0.01
Bread		Wheat muffin	0.79 ± 0.02
Yeast leavened spelt	1.35 ± 0.01	*Reference materials*	
Sour dough spelt	1.04 ±0.01	Corn flakes	2.27 ± 0.07 (2.26)[a]
Yeast/sour dough spelt	1.17 ± 0.01	Kidney bean	4.58 ± 0.18 (4.50)
Yeast leavened wheat	1.25 ± 0.01		

Mean ± SD, % dry basis.
[a] True value.

biscuits (45.4%). Soluble starch contents were also somewhat similar in spelt and common wheat cookie, biscuit or muffin; muffin products had the highest level of soluble starch, followed by cookie and biscuit. These results indicate that differences in total and soluble starches among baked products are more pronounced than those between spelt and common wheat products.

3.2. Effect of baking on the formation of resistant starch

The commercial spelt grains used in the study were found to contain about eight to ten fold more resistant starch (RS), i.e. on average spelt had 3.7% versus 0.4% in normal wheat (Table 5). Several samples from the same commercial spelt variety, as well as other spelt cultivars, were assessed to further investigate this finding. Five spelt cultivars varied significantly in their contents of RS, ranging from 0.45% to 5.21%, compared to 0.3% in common wheat. The cultivars included were two spring-type CDC Nixon (0.45% RS) and PGR 8801 (0.53% RS) and three winter-type spelt, Rotkorn (5.21% RS), Frankencorn (3.97% RS) and Heritage (0.52% RS). CDC Nixon and PGR are spelt hybrid, whereas Rotkorn and Frankencorn are pure spelt. This is the first report to reveal the high content of RS in spelt wheat. The wide range of RS content in spelt grains could be related to various starch structures and warrant further investigation. The precision and accuracy of the RS method were high, as indicated by lower CV values (0.7–2.7%) for wheat samples and high relative accuracy values (97–98%) based on reference materials. The high content of RS in spelt would impact processing and nutritional quality to spelt products. Resistant starch is the portion of starch and starch degradation products escaping digestion and not absorbed in the small intestine of healthy humans, being considered as part of the dietary fibre. Consumption of diets high in RS or amylose reduced blood lipid levels in hamsters (Ranhotra, Gelroth, & Glaser, 1996) and postprandial glycemic and insulinemic responses in human subjects (Behall & Schoofield, 2005).

After mixing and fermentation, RS in spelt diminished by about 22–72%, depending upon type of dough, but RS in common wheat remained unchanged. The RS contents in spelt doughs were still considerably higher than those in common wheat doughs. After baking, RS levels were quite similar in spelt and common wheat bread products. In the case of common wheat bread, RS increased by about 195% (from 0.4% to 1.2%), whereas it decreased by about 63% in spelt breads (from 3.3% to 1.2%). This phenomenon requires further investigation to elucidate effects of baking on spelt starch. RS contents in a variety of food products were 0.9% in white bread, 0.3% in whole wheat bread, 1.8% in multi-grain bread, 0.7% in wheat bran flakes and 0.4% in wheat crackers (Ranhotra, Gelroth, & Leinen, 1999). The contents of RS in biscuit, cookie and muffin doughs and end-products were less than 1% showing little nutritional impact. Research on molecular characterization of RS in spelt cultivars with high level of RS would help to understand changes occurring in RS during fermentation and baking.

3.3. Nutritional fractions of starch in spelt products

The rate and extent of starch digestion vary in foods, depending on several intrinsic and extrinsic factors, including physical form of food and food composition (Englyst et al., 1992). Thus, carbohydrate-rich foods, e.g. wheat products having the same amount of starch, may not have similar rates and extents of digestion, and accordingly different glycemic and insulinemic responses. In the present study, the relative rate of starch digestion was measured by starch digestion index and the rapid release of glucose was measured as rapidly available glucose. These measurements are based on chemical assays, including the determination of total starch, starch digestible fractions (SDS and RDS) *in vitro* and total soluble sugars in foods. RAG is the sum of free glucose, glucose from sucrose and glucose released from RDS or starch digested for 20 min of incubation, while SDI is the ratio between RDS and TS multiplied by 100. Since the RAG value measures RDS and free sugars, it is a better indicator of blood glucose and insulin response than is the SDI (Englyst et al., 1992). Indeed, the measurement of carbohydrate digestion and absorption *in vivo,* to evaluate food quality in relation to glycemic response, is more effective and efficient than *in vitro* methods but it is costly and time-consuming. Such *in vivo* measurements include glycemic index (GI) and glycemic load (GL) (Schulze et al., 2004). The GI parameter measures and ranks the impact of carbohydrates on postprandial plasma glucose by determining the rise in blood glucose after eating a food against a standard of glucose or white bread in the same subject, while the GL measure takes into account the quality and quantity of carbohydrates in food and is estimated by multiplying GI value of a food by the quantity of carbohydrate per serving and divided by 100. The relationship between *in vitro* (e.g. SDI, RAG) and *in vivo* (e.g. GI, GL) measurements would be of interest and useful for the evaluation of food nutritional quality.

Raw spelt and common wheat grains had relatively low RDS, SDS, SDI and RAG values compared to their end-products (Table 6). Significant differences in SDS and SDI were observed between spelt and common wheat whole grain flours. Spelt exhibited lower values of the nutritional starch fractions, possibly because of the high content of RS found in raw spelt. Spelt and common wheat grains milled in the laboratory also showed lower values of the nutritional starch fractions compared to those commercially milled. This indicates impact of the milling process on starch granules which may lead to changes in their functionality and nutritional properties. No significant variations were found in total starch content determined by the Englyst method versus that determined by the Megazyme method (Tables 2 and 6).

When spelt and common wheat whole grain flours were converted into doughs, slight increases occurred in the starch nutritional fractions, leading to an increase in SDI and RAG values before and after fermentation, with the fermented doughs exhibiting higher digestion parameters (Table 6). The changes in starch digestion were influenced by type of dough and wheat subspecies. Starch digestion of spelt doughs had significantly lower rate and extent compared to that of common wheat. Flours fermented by the sour dough method exhibited lower rate and extent of starch digestion, i.e. lower SDI and RAG values than did those of yeast fermented doughs. Following baking, SDI and RAG values of spelt breads were insignificantly different from those of common wheat breads. The bread-making process resulted in an increase in SDI and RAG in spelt and common wheat products, but at different extents. In other words, the effect of baking on spelt was greater than that on common wheat. Thus differences in starch digestion between spelt and wheat grains disappeared after baking. These results are in agreement with those reported by Skrabanja et al. (2001) who found insignificant differences in starch hydrolysis index and predicted GI between spelt whole grain bread and common wheat bread, while spelt white bread had a significantly higher starch hydrolysis index. In addition, glycemic response of spelt white bread was not different from that of common wheat white bread, having a GI value of about 93 ± 9 (Marques et al., 2007). However, another study found that spelt bread had higher RSD and SDI than had common wheat bread (Bonafaccia et al., 2000). This discrepancy might be due to differences in genetics and composition of wheat materials, baking formulas and baking conditions.

The nutritional starch fractions, and their digestion indices, of spelt biscuit and muffin products were somewhat close to those of common wheat products (Table 7). Both biscuit and muffin products were made from simple recipes and contained relatively high amounts of water for better starch gelatinization during the baking step compared to cookie recipes. For cookie products, significant differences in rate and extent of starch digestion were observed between spelt and common wheat. Spelt cookie

Table 6
Effects of milling and bread-making on nutritional starch fractions and indices of freeze-dried organic spelt and common wheat

Wheat product	TS	RDS	SDS	SDI	RAG
Whole grain flour					
Spelt, lab milled	62.1 ± 1.9	5.2 ± 0.1	7.5 ± 0.2	8.5 ± 0.3	6.3 ± 0.2
Spelt, commercially milled	62.3 ± 2.1	8.4 ± 0.2	10.4 ± 0.4	13.5 ± 0.3	9.2 ± 0.4
Common, lab milled	61.7 ± 1.9	8.8 ± 0.2	13.9 ± 0.5	14.2 ± 0.4	9.3 ± 0.4
Common, commercially milled	61.1 ± 2.3	11.9 ± 0.3	15.4 ± 0.5	19.5 ± 0.5	12.4 ± 0.3
LSD[a]	1.12	0.89	1.01	0.98	0.55
Yeast leavened dough					
Spelt, after mixing	62.1 ± 1.7	7.4 ± 0.1	9.9 ± 0.3	11.9 ± 0.3	12.1 ± 0.3
Spelt, after fermentation	60.8 ± 1.3	8.1 ± 0.1	11.1 ± 0.3	13.3 ± 0.4	12.4 ± 0.2
Wheat, after mixing	58.9 ± 1.9	14.1 ± 0.3	15.2 ± 0.5	23.8 ± 0.6	19.1 ± 0.5
Wheat, after fermentation	59.1 ± 1.7	14.2 ± 0.2	16.3 ± 0.4	24.1 ± 0.5	19.7 ± 0.5
Sour dough					
Spelt, after mixing	62.5 ± 2.5	6.8 ± 0.1	9.6 ± 0.2	10.4 ± 0.2	8.8 ± 0.2
Spelt, after fermentation	61.2 ± 1.9	7.5 ± 0.1	9.5 ± 0.2	12.2 ± 0.3	9.1 ± 0.2
Wheat, after mixing	62.1 ± 2.3	12.3 ± 0.2	15.5 ± 0.6	19.8 ± 0.6	15.0 ± 0.3
Wheat, after fermentation	60.4 ± 2.1	12.1 ± 0.3	15.9 ± 0.6	20.0 ± 0.6	16.1 ± 0.3
Yeast/sour dough					
Spelt, after mixing	55.2 ± 1.5	13.1 ± 0.4	15.6 ± 0.3	23.7 ± 0.6	19.5 ± 0.5
Spelt, after fermentation	56.8 ± 1.2	10.0 ± 0.3	11.9 ± 0.3	17.6 ± 0.4	15.1 ± 0.4
Wheat, after mixing	55.1 ± 1.3	15.2 ± 0.5	16.1 ± 0.4	27.6 ± 0.7	18.1 ± 0.5
Wheat, after fermentation	56.3 ± 1.2	8.9 ± 0.3	15.4 ± 0.6	15.8 ± 0.3	14.5 ± 0.2
LSD[a]	1.05	0.78	0.87	0.79	0.76
Bread					
Yeast leavened spelt	61.1 ± 2.1	42.3 ± 1.4	6.5 ± 0.1	69.1 ± 1.0	48.0 ± 1.1
Sour dough spelt	60.1 ± 2.5	41.9 ± 1.5	5.1 ± 0.1	69.7 ± 1.2	47.2 ± 1.3
Yeast/sour dough spelt	56.1 ± 1.8	41.4 ± 2.0	7.3 ± 0.2	73.8 ± 1.9	46.1 ± 2.0
Yeast leavened wheat	58.7 ± 1.9	41.9 ± 1.7	5.8 ± 0.1	71.1 ± 1.5	46.9 ± 1.4
Sour dough wheat	59.3 ± 2.0	41.3 ± 1.3	5.0 ± 0.1	69.6 ± 1.1	47.5 ± 1.1
Yeast/sour dough wheat	55.8 ± 1.7	41.7 ± 1.5	7.1 ± 0.1	74.7 ± 1.6	46.8 ± 1.7
LSD[a]	1.59	0.91	0.59	1.05	1.12

Mean ± SD, % dry basis.
TS, total starch; RSD, rapidly digestible starch; SDS, slowly digestible starch; SDI, starch digestion index; RAG, rapidly available glucose.
[a] Least significant difference values at $p < 0.05$.

Table 7
Nutritional starch fractions and indices of organic spelt and common wheat whole grain biscuit, cookie and muffin doughs and products

Wheat product	TS	RDS	SDS	SDI	RAG
Biscuit					
Spelt dry mix	45.1 ± 2.1	6.0 ± 0.2	6.3 ± 0.2	13.3 ± 0.3	7.1 ± 0.2
Wheat dry mix	45.5 ± 1.6	5.8 ± 0.1	5.9 ± 0.1	12.7 ± 0.2	6.9 ± 0.1
Spelt dough	44.4 ± 1.8	5.4 ± 0.1	5.1 ± 0.1	12.2 ± 0.2	9.3 ± 0.1
Wheat dough	41.3 ± 1.7	5.4 ± 0.1	5.9 ± 0.1	13.1 ± 0.1	9.2 ± 0.2
Spelt biscuit	45.6 ± 2.1	18.8 ± 0.3	16.7 ± 0.5	41.2 ± 0.7	23.4 ± 0.6
Wheat biscuit	44.2 ± 2.0	18.4 ± 0.4	15.8 ± 0.6	41.1 ± 0.9	23.2 ± 0.7
LSD[a]	2.62	0.89	0.91	1.11	1.02
Cookie					
Spelt dough	22.6 ± 0.9	2.1 ± 0.1	3.4 ± 0.1	9.2 ± 0.2	14.8 ± 0.3
Wheat dough	23.2 ± 1.0	2.8 ± 0.1	5.1 ± 0.2	12.1 ± 0.3	15.9 ± 0.4
Spelt cookie	24.7 ± 1.1	5.5 ± 0.3	12.9 ± 0.3	22.1 ± 0.5	18.9 ± 0.3
Wheat cookie	23.9 ± 1.2	8.7 ± 0.3	9.1 ± 0.3	36.1 ± 0.5	22.6 ± 0.4
LSD[a]	0.87	0.71	0.69	0.88	0.91
Muffin					
Spelt batter	32.3 ± 1.3	4.7 ± 0.1	3.9 ± 0.1	14.5 ± 0.3	14.8 ± 0.2
Wheat batter	32.7 ± 1.4	5.0 ± 0.2	4.1 ± 0.1	15.2 ± 0.4	17.1 ± 0.2
Spelt muffin	33.7 ± 1.2	21.2 ± 0.7	5.3 ± 0.1	62.9 ± 0.9	33.2 ± 0.6
Wheat muffin	32.3 ± 1.1	20.4 ± 0.5	5.1 ± 0.1	63.1 ± 1.1	32.8 ± 0.5
LSD[a]	1.01	1.33	0.89	2.01	1.71

Mean ± SD, % dry basis.
TS, total starch; RSD, rapidly digestible starch; SDS, slowly digestible starch; SDI, starch digestion index; RAG, rapidly available glucose.
[a] Least significant difference values at $p < 0.05$.

Table 8
Nutritional starch fractions and indices of organic spelt and common wheat whole grain fresh bread, biscuit, cookie and muffin products

Wheat product	TS	RDS	SDS	SDI	RAG
Bread					
Yeast leavened spelt	30.7 ± 0.9	22.1 ± 0.7	2.8 ± 0.1	71.8 ± 2.0	26.1 ± 0.7
Sour dough spelt	31.8 ± 1.1	24.2 ± 1.1	1.6 ± 0.1	76.1 ± 2.1	27.4 ± 0.7
Yeast/sour dough spelt	31.5 ± 0.9	24.9 ± 1.0	1.2 ± 0.1	78.9 ± 2.5	29.8 ± 0.8
Yeast leavened wheat	29.0 ± 0.7	20.1 ± 0.7	3.1 ± 0.2	69.1 ± 1.9	24.2 ± 0.7
Sour dough wheat	30.4 ± 1.1	25.4 ± 1.2	1.3 ± 0.1	83.4 ± 2.8	28.9 ± 0.6
Yeast/sour dough wheat	30.2 ± 0.9	21.6 ± 1.0	2.2 ± 0.1	71.5 ± 2.2	26.0 ± 0.6
LSD[a]	1.03	1.22	0.53	0.89	0.55
Biscuit					
Spelt	28.4 ± 0.8	12.2 ± 0.4	4.5 ± 0.2	42.9 ± 1.2	14.5 ± 0.4
Wheat	27.0 ± 0.7	11.8 ± 0.3	6.3 ± 0.2	43.7 ± 1.3	15.1 ± 0.5
LSD[a]	1.59	0.65	0.98	1.27	1.25
Cookie					
Spelt	22.5 ± 0.7	9.8 ± 0.3	2.1 ± 0.1	43.6 ± 1.2	23.7 ± 0.7
Wheat	24.7 ± 0.8	9.9 ± 0.3	4.1 ± 0.2	40.1 ± 1.2	25.9 ± 0.8
LSD[a]	1.26	1.29	0.56	5.13	1.64
Muffin					
Spelt	21.1 ± 0.8	14.4 ± 0.5	1.9 ± 0.1	68.1 ± 2.1	26.6 ± 0.9
Wheat	20.7 ± 0.9	14.3 ± 0.4	2.2 ± 0.1	69.1 ± 2.2	29.6 ± 0.8
LSD[a]	1.82	1.39	0.73	1.65	1.60

Mean ± SD, % wet basis.
TS, total starch; RSD, rapidly digestible starch; SDS, slowly digestible starch; SDI, starch digestion index; RAG, rapidly available glucose.
[a] Least significant difference values at $p < 0.05$.

Table 9
Correlation coefficients between starch fractions and digestion parameters

Fraction	TS	SS	RS	RDS	SDS	SDI
SS	0.432 (0.009)[a]	– –	– –	– –	– –	– –
RS	0.447 (0.006)	0.009 (0.958)	– –	– –	– –	– –
RDS	0.308 (0.067)	0.554 (0.000)	0.096 (0.576)	– –	– –	– –
SDS	0.362 (0.030)	0.141 (0.411)	−0.086 (0.616)	−0.140 (0.416)	– –	– –
SDI	0.069 (0.691)	0.420 (0.011)	−0.003 (0.988)	0.945 (0.000)	0.209− (0.221)	– –
RAG	0.040 (0.816)	0.520 (0.001)	−0.033 (0.850)	0.954 (0.000)	−0.233 (0.171)	0.971 (0.000)

TS, total starch; SS, soluble starch; RS, resistant starch; RSD, rapidly digestible starch; SDS, slowly digestible starch; SDI: starch digestion index; RAG, rapidly available glucose.
[a] p values, $n = 36$.

exhibited lower SDI and RAG values than did common wheat cookie. This might indicate different lipid–starch interactions between the two wheats. The low rate and extent of starch digestion in spelt cookie might also have nutritional implications in terms of glycemic response.

Fresh samples of bread, biscuit, cookie and muffin were evaluated in terms of starch digestion in order to avoid effects of frozen storage and freeze-drying during sample preparation and also to verify differences in the nutritional fractions and digestibility indices between baked products (Table 8). Analyses of fresh bread products showed significant differences in starch nutritional fractions and digestion indices. In addition, significant variations were found between bread products, with sour dough or yeast/sour dough breads being higher in starch digestion index and rapidly available glucose. For fresh biscuit products, slight differences were observed in rate and extent of starch digestion between spelt and common products, while significant differences were found for cookie and muffin products only for RAG values. These results suggest that freezing could affect starch digestibility in terms of rate and extent.

As expected, Pearson correlation analysis showed that digestion parameters (SDI and RAG) are highly significantly correlated ($r = 0.971$) (Table 9). This indicates that either parameter could be used for measuring nutritional quality of carbohydrates in foods. Multiple regression analysis indicated that both digestion parameters are significantly influenced by TS, SS and RDS, while RS and SDS had insignificant effects. This could refer to the relatively small contents of SDS starch fractions compared to the other nutritional fractions in the examined products. Significant correlation relationships were also observed between TS and SS, RS and SDS fractions. In addition, SS and RDS were significantly correlated with SDI and RAG. This would indicate a significant role for the SS fraction in starch digestibility.

4. Conclusions

In conclusion, the study results indicate that spelt whole grain flours or doughs contain significantly higher levels of RS and lower rate and extent of starch digestion, as indicated by lower values for SDI and RAG compared to common wheat products. These differences, however, were eliminated to a certain extent by baking, depending upon the baking process. Some differences were found in rate and extent of starch digestion between spelt and common wheat bread, cookie, biscuit and muffin products. The effects of the baking process differ between spelt and common wheat, particularly in the content of RS. This requires more research, particularly on molecular characterization of RS in spelt cultivars exhibiting high levels of RS, in order to explore these effects. In general, differences in starch fractions and digestion parameters among baked products were more pronounced than those between spelt and common wheat products. Within products, cookies possessed the lowest rate and extent of starch digestion, followed by biscuits and muffins, and finally breads.

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