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In Vitro Digestion Characteristics of Unprocessed and Processed Whole Grains and Their Components

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Chemical composition and in vitro digestion properties of select whole grains, before and after processing, and their components were measured. Substrates included barley, corn, oat, rice, and wheat. In addition to whole grain flours, processed substrates also were tested as were corn bran, oat bran, wheat bran, and wheat germ. Processing of most substrates resulted in higher dry matter and digestible starch and lower resistant starch concentrations. Dietary fiber fractions varied among substrates with processing. Digestion profiles for most substrates correlated well with their chemical composition. Corn bran and rice substrates were the least fermentable. Extrusion rendered barley, corn, and wheat more hydrolytically digestible and barley and oat more fermentatively digestible. Except for corn bran, all components had greater or equal fermentability compared with their native whole grains. Understanding digestion characteristics of whole grains and their components will allow for more accurate utilization of these ingredients in food systems.

KEYWORDS: In vitro digestion; in vitro fermentation; whole grain; starch; fiber

INTRODUCTION

Epidemiological studies have reported that whole-grain (WG) cereal consumption is protective against cardiovascular disease, cancer, diabetes, and obesity (*1*−*3*). Potential mechanisms for this protection are diverse because WGs are rich in nutrients and phytochemicals. The known health effects of these individual nutrients and phytochemicals can aid in the evaluation of the mechanisms by which WGs are protective against chronic disease. It appears to be a synergy among the wide range of protective compounds in WGs, suggesting that the whole is greater than the sum of the parts (*4*). Also, WGs are believed to be nutritionally superior to refined grains. Historically, Americans have consumed ever-increasing amounts of refined grain products and fewer servings of WGs. The most recent USDA/HHS Dietary Guidelines recommend at least 3 servings of WG per day (*5*). Food availability and food intake data show that most Americans are not following these guidelines.

Whole-grain cereals comprise three main fractions: the endosperm, germ, and bran. The grain endosperm is composed mainly of starch, the digestibility of which will be affected by food processing (e.g., heating, drying, acid/enzymatic digestion), and small amounts of proteins and B vitamins. Germ, the smallest part of the grain, contains lipids, proteins, and some soluble carbohydrates along with trace minerals, vitamins E and B, antioxidants, and phytonutrients. The bran is rich in nondigestible, mainly insoluble and poorly fermented, carbohydrates, B vitamins, and trace minerals (*6*).

Whole grains are valuable sources of fermentable carbohydrates such as dietary fibers, resistant starch (RS), and oligosaccharides (*4*). The beneficial effects of carbohydrate fermentation through the production of short-chain fatty acids (SCFA) have been well documented (*7*). Especially, RS fermentation in the large bowel leads mainly to butyrate production, which has a strong protection effect against colorectal cancers and other diseases (*8*). Resistant starch has been reported to contribute to the health benefits associated with WG consumption (*9*). In particular, cornstarch has been shown to be a good butyrate producer compared with other fermentation substrates including oat bran and wheat bran (*10*). However, to the best of our knowledge, the fermentation profile of several native WGs and their components has never been compared in a single study. Also, as part of their large-bowel effects, it is hypothesized that WGs may contribute to health via a beneficial effect on the human gut microbiota. Recently, an in vivo study showed a pronounced prebiotic effect of WG wheat on human gut microbiota composition compared with wheat bran (*6*).

It has been reported that the physical form of barley grains affects the digestion of its starch in the human small intestine (*1*). In this particular study, the authors reported that starch remaining undigested after finely milled barley ingestion was 8 times lower than after flaked barley ingestion. Nevertheless, very few studies have examined the effects of processing on the digestion/fermentation profiles of WGs. The present study

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aimed to compare the composition and in vitro digestion/fermentation of several common WGs, before and after processing, and their components.

MATERIALS AND METHODS

Substrates. Substrates, including five cereal grains (barley, corn, oat, rice, and wheat), were tested in their native forms and after processing. The processed samples were prepared from the same batch as the native WG samples. For each substrate, the WG flour was mixed into dough with trisodium phosphate and water (30−40% dough moisture). The mixed dough was cooked for 1 h at 95 °C with agitation using a Farinograph. The cooked dough was pelletized using a piston extruder. Pellets were dried for approximately 1 h at 100 °C and expanded with hot air (2−6% final moisture). In addition to native and processed substrates, corn bran, oat bran, wheat bran, and wheat germ were tested. All substrates were first ground through a 2 mm screen in a Wiley mill in preparation for chemical analysis, and then a 1 mm screen was used to obtain the substrates used for the in vitro digestion experiment. Three standards were included in the in vitro fermentation experiment: cellulose (Solka Floc, International Fiber Corp., Urbana, OH), inulin (Ultra-FOS ST, Encore Technologies Inc., Minnetonka, MN), and pectin (Pectin HM Rapid, Tic Gums, Belcamp, MD).

Chemical Analysis. Substrates were analyzed for dry matter (DM) and organic matter (OM) using Association of Official Analytical Chemists (AOAC) (*12*) methods. Dietary fiber concentrations [total (TDF), soluble (SDF), and insoluble (IDF) fractions] were determined according to the method of Prosky et al. (*13, 14*). The substrates were analyzed in duplicate, and the error between duplicate samples was determined; if >5%, the assay was repeated.

In Vitro Digestion: Starch Fractions. The method of Muir and O'Dea (*15, 16*) was used to determine the amount of starch digested in the stomach and small intestine by measuring glucose in the supernatant resulting from acid-enzyme digestion of the substrate. Briefly, 0.2 g of each substrate was weighed in triplicate and exposed to pepsin/hydrochloric acid, amyloglucosidase, and α-amylase. Tubes containing reagents but no substrate were run as blanks. All tubes were incubated for 15 h at 37 °C and then centrifuged for 15 min. Glucose concentrations in the supernatant were determined by reading the absorbance of individual samples at 450 nm on a DU 640 spectrophotometer (Beckman Instruments, Schaumburg, IL) and comparing those values against a glucose standard curve. Digestible starch (DS) was determined by subtracting (free glucose × 0.9) from (total glucose/original sample weight) present in the supernatant after 15 h of digestion. The 0.9 value used in the calculation of DS is a correction factor for the difference in weight between a free glucose (FG) unit and a glucose residue in starch. Because the measurement of glucose was used to determine starch content, the correction factor was needed. Total starch (TS) content of samples was determined using the method of Thivend et al. (*17*) with amyloglucosidase. Resistant starch (RS) was calculated by subtracting [DS + (FG × 0.9)] from TS.

The released glucose value corresponds to the amount of glucose resulting from hydrolytic starch digestion that is available for absorption in vivo. Because it is not possible to extract glucose from the tubes after the in vitro digestion stage, matching blanks were prepared for each sample by adding the appropriate amount of glucose to an extra set of tubes to be run in the in vitro fermentation experiment. For each substrate, all variables measured after the 12 h in vitro fermentation were corrected with the appropriate blank tube value.

Donors and Collection Method. Three human fecal samples, from male volunteers, were pooled to serve as the source of inoculum for the in vitro fermentation experiment. All donors consumed their normal diet, were over the age of 18, were free of gastrointestinal disease, and had not received antibiotics for at least 3 months prior to or during the study. The experimental protocol was approved by the University of Illinois at Urbana−Champaign Institutional Review Board, and all subjects signed an informed consent prior to initiation of the experiment.

On the morning of the experiment, each donor provided a fresh fecal sample, collected using a Commode Specimen Collection System (Sage Products, Crystal Lake, IL). Samples were brought to the laboratory within 15 min of defecation to ensure viability of microbial populations.

Medium Composition and Substrate Fermentation. The substrate remaining after simulated stomach and small intestinal digestion (in vitro hydrolytic digestion) was used in a model that simulated large bowel fermentation (*18*). The composition of the in vitro medium has already been presented elsewhere (*19*). All components except vitamin and short-chain fatty acid (SCFA) mixes were added before autoclave sterilization of the medium. Filter-sterilized vitamin solutions were added just before the medium, which was maintained under anaerobic conditions at all times after preparation, was dispensed. An aliquot (25 mL) of the medium was aseptically transferred to appropriate tubes containing the substrate remaining after simulated hydrolytic digestion. All tubes were stored at 4 °C for approximately 12 h to enable hydration of the substrates before initiating fermentations. Tubes were placed in a 37 °C water bath approximately 30 min before inoculation.

Fecal samples were maintained at 37 °C until inoculum was prepared (within 10 min). Equal amounts of each fecal sample were mixed together and diluted 1:10 (w/v) in anaerobic dilution solution (*20*) by blending for 15 s in a Waring blender under a stream of CO_2. Blended, diluted feces were filtered through four layers of cheesecloth and sealed in 125 mL serum bottles under CO_2.

Appropriate samples and blank tubes were aseptically inoculated with 4 mL of diluted feces. Tubes were incubated at 37 °C with periodic mixing for 12 h. After 12 h, tubes were removed from the 37 °C incubator and processed immediately for analyses. First, the pH of the tube contents was measured with a standard pH-meter (Denver Instrument Co., Arvada, CO). Finally, a 2 mL subsample was taken from each tube for SCFA and lactate analyses.

Short-Chain Fatty Acid and Lactate Analyses. The 2 mL aliquot of fluid removed from the sample tubes for SCFA and lactate analyses was immediately added to 0.5 mL of 25% metaphosphoric acid, precipitated for 30 min, and centrifuged at 20000*g* for 20 min. The supernate was decanted and frozen at −20 °C in microfuge tubes. After freezing overnight, the supernate was thawed and centrifuged at 10000*g* for 10 min. Concentrations of acetate, propionate, and butyrate were determined in the supernate using a Hewlett-Packard 5890A series II gas chromatograph (Palo Alto, CA) and a glass column (180 cm × 4 mm i.d.) packed with 10% SP-1200/1% H_3PO_4 on 80/100+ mesh Chromosorb WAW (Supelco Inc., Bellefonte, PA). SCFA concentrations were corrected for blank tube production of SCFA. The supernates were also analyzed for lactate concentration according to the spectrophotometric method described by Barker and Summerson (*21*). All samples were run in duplicate, and an error between duplicates of ≤5% was considered to be acceptable.

Statistical Analysis. Data were analyzed as a completely randomized design using the Proc Mixed procedure of SAS (SAS Institute, Inc., Cary, NC). The statistical model was as follows:

$$Y = \mu + S + e \quad (1)$$

where Y denotes the observed variable, μ is the overall mean, S represents the effect of substrate, and e is the experimental error. Least-squares means were reported along with the pooled SEM for all response criteria. When significant ($P < 0.05$) differences were detected, individual means were compared using the least significant difference method of SAS (*22*).

RESULTS AND DISCUSSION

Chemical Composition. The chemical composition of the substrates is presented in **Table 1**. Dry matter concentrations were lower for the native WG substrates compared to the processed WG and components and ranged from 88.0% (WG wheat) to 98.7% (processed WG oat). On average, the increase in DM concentrations after processing was approximately 6% among substrates, with the lowest increase for rice substrates (4%) and the highest for the oat and wheat substrates (7% for

Table 1. Chemical Composition of Native and Extruded Cereal Grains and Components[a]

substrate	% DM	% DMB OM	TDF	IDF	SDF
barley					
native WG	88.5	98.5	14.2	6.4 (45)	7.9 (55)
processed WG	94.7	97.9	17.6	8.1 (46)	9.5 (54)
corn					
native WG	88.6	98.7	14.7	7.1 (48)	7.6 (52)
processed WG	95.4	98.1	13.9	10.2 (73)	3.7 (27)
bran	94.8	98.8	85.6	82.0 (96)	3.6 (04)
oat					
native WG	91.4	97.9	12.8	5.9 (46)	6.9 (54)
processed WG	98.7	97.5	13.5	5.9 (44)	7.5 (56)
bran	91.9	96.8	22.3	12.4 (56)	9.9 (44)
rice					
native WG	90.3	98.4	7.4	4.3 (57)	3.2 (43)
processed WG	94.6	98.1	6.3	4.1 (66)	2.2 (34)
wheat					
native WG	88.0	98.2	14.2	12.3 (87)	1.9 (13)
processed WG	95.3	97.6	17.2	11.7 (68)	5.6 (32)
bran	89.6	94.9	40.8	36.5 (89)	4.4 (11)
germ	90.9	95.3	23.5	19.0 (81)	4.5 (19)

[a] Values in parentheses are individual fractions expressed as a percentage of TDF. WG, whole grain; DM, dry matter; OM, organic matter; TDF, total dietary fiber; IDF, insoluble dietary fiber; SDF, soluble dietary fiber; DMB, dry matter basis.

Table 2. Starch Fractions of Native and Extruded Cereal Grains and Components[a]

substrate	% DMB DS	RS	TS
barley			
native WG	60.7 (83)	12.2 (17)	73.0
processed WG	59.8 (87)	8.7 (13)	68.6
corn			
native WG	57.5 (78)	16.3 (22)	73.7
processed WG	67.2 (93)	5.3 (07)	72.5
bran	9.6 (100)	0.00	9.2
oat			
native WG	57.1 (87)	8.7 (13)	65.8
processed WG	58.5 (93)	4.4 (07)	62.8
bran	48.3 (85)	8.3 (15)	56.6
rice			
native WG	76.0 (93)	5.4 (07)	81.4
processed WG	76.0 (93)	5.7 (07)	81.7
wheat			
native WG	54.3 (77)	16.4 (23)	70.6
processed WG	62.8 (90)	6.7 (10)	69.5
bran	33.4 (97)	1.1 (03)	34.5
germ	29.1 (97)	0.8 (03)	30.0

[a] Values in parentheses are individual fractions expressed as a percentage of TS. WG, whole grain; DS, digestible starch; RS, resistant starch; TS, total starch (TS = DS + RS).

both). Wheat bran and wheat germ had the lowest OM concentrations (94.9 and 95.3%, respectively). Except for these two substrates and despite some differences among substrates, OM concentrations were very similar to each other and differed by approximately two percentage units. We found similar OM concentrations as Murray et al. (*19*) for barley, corn, rice, and wheat substrates and lower DM concentrations for the native WG substrates. These investigators found no effect of extrusion processing on DM and OM concentrations of various cereal grains whenever the substrates were extruded at low or high temperature. In the present study, we observed a slight increase in DM and a decrease in OM concentrations after extrusion of the native WG substrates. The increase in DM was expected as the native grains were cooked at 95 °C and dried at 100 °C during processing.

Rice substrates had the lowest total dietary fiber concentrations (7.4 and 6.3%, respectively, for native and processed WG rice). Extrusion processing had no effect on the TDF concentrations of the oat substrates, but increased slightly the TDF percentage in the barley and wheat substrates and decreased the TDF percentage in the corn substrates. Among sources, the TDF percentage was higher in the components (from 22.3% for oat bran to 85.6% for corn bran). Corn bran had the highest TDF content among substrates. The higher TDF content of wheat bran compared with native WG wheat is in accordance with Costabile et al. (*6*).

Slavin (*4*) reported that a comparison of the dietary constituents of various WG showed that oat and barley contained about one-third SDF, that wheat was lower in SDF than most grains, and that rice contained virtually no soluble fiber. Our results confirmed the low SDF content of wheat and rice and showed that barley and oat contained about 55% SDF, both before and after processing. It is well-known that the SDF content of oat and barley cereals is significant compared to other WGs (*23*). The association between the intake of WGs and the decreased incidence of coronary heart disease has been attributed to the soluble fibers of WGs such as oat and barley rather than the insoluble fibers of WGs such as wheat and rice (*23*). In particular, the hypocholesterolemic effects of β-glucan soluble fiber from oat and barley have motivated a health claim from the U.S. Food and Drug Administration (*24*). Despite some small differences among substrates, our results showed that IDF and SDF concentrations were generally not affected by processing. The greatest changes were noted for the corn and wheat substrates (4% decrease and 4% increase in SDF concentrations after processing, respectively).

Starch Fractions. Concentrations of starch fractions of substrates (expressed as percentages of DM and TS) are presented in **Table 2**. Processing had no effect on DS concentrations for barley, oat, and rice substrates, but increased DS concentrations by about 10% in corn and wheat substrates. This indicates that processing rendered corn and wheat more hydrolytically digestible. The highest DS value was 76% for native and processed rice, followed by processed corn (67%), whereas corn bran had the lowest DS value (9.6%). Except for rice substrates, RS concentrations decreased after processing, but to a lesser extent than that reported by Murray et al. (*19*), who used more severe processing conditions than those used here.

Except for the rice and wheat substrates, TS concentrations decreased slightly after processing and ranged from 63% (processed WG oat) to 82% (processed WG rice) among substrates. As expected, the bran substrates had lower TS concentrations than the native WG substrates (corn, oat, and wheat), because starches are more concentrated in the endosperm of grains (*6*). The lowest TS value was 9% for corn bran, with 100% of the starch being digestible.

Second Stage in Vitro Released Glucose. Percentage of released glucose values are presented in **Table 3**. As expected, these values reflect the digestible portion of the substrate. For example, corn bran, which had the highest amount of TDF (85%), had the lowest percentage of released glucose (9.1%). In the same way, the highest released glucose values were 81 and 80% for native and processed WG rice, respectively, which had the lowest TDF concentrations (7.4 and 6.3%, respectively). Also, the percentage of released glucose reflected the DS fraction of all substrates. The greatest discrepancy occurred for barley, for which the released glucose percentage was approximately 6% higher for processed WG barley than for native WG barley, whereas DS values were similar (59.8 and 60.7%, respectively).

Table 3. Percentage of Released Glucose after the Second Stage in Vitro (Dry Matter Basis)[a]

substrate	% released glucose
barley	
native WG	61.7
processed WG	67.8
corn	
native WG	60.6
processed WG	72.5
bran	9.1
oat	
native WG	64.5
processed WG	63.0
bran	52.5
rice	
native WG	81.1
processed WG	80.1
wheat	
native WG	57.4
processed WG	67.6
bran	30.6
germ	26.2

[a] WG, whole grain.

It has been reported in a previous study that a possible explanation for the low glycemic index of barley might be that starch escapes small intestinal digestion (*11*). The authors suggested that starch within cereal cells is protected from digestion by surrounding cell walls. They found that only 2% of starch remained undigested after milled barley was eaten, but 17% resisted digestion after flaked barley ingestion. The authors concluded that possibly, botanical origin of cereals and, certainly, processing are important determinants of starch digestibility. In our study, a part of the DS from native WG barley would have remained undigested and this could explain why less glucose was released with native WG barley compared with processed WG barley, despite a similar DS fraction.

Third Stage in Vitro Fermentation. Table 4 reports the pH change, total short-chain fatty acid (tSCFA), and individual SCFA production after 12 h of in vitro fermentation. The two highly fermentable controls, inulin and pectin, exhibited the largest ($P < 0.0001$) pH decreases (−1.78 and −1.44, respectively). The substrates that had the greatest changes in pH ($P < 0.05$) were the barley substrates, the native WG wheat, wheat bran, and wheat germ. In general, the pH change reflected tSCFA production but, because the pH values are expressed on a log scale, the range of values for the change in pH was not of the same order of magnitude as the tSCFA production differences among substrates.

Inulin and pectin fermentation generated the highest ($P < 0.0001$) tSCFA production (478 and 456 mg/g DMB, respectively). Among substrates, the highest tSCFA production was noted for native WG wheat, wheat bran, and wheat germ. In particular, native WG wheat fermentation generated among the highest amounts of acetate and butyrate (58 and 54 mg/g DMB, respectively). Resistant starch fermentation has been shown to lead to great SCFA production and to favor butyrate production (*10, 25*). Therefore, the high tSCFA and butyrate production observed with WG wheat can be related to the highest RS content found in WG wheat among substrates. Wheat germ and wheat bran were as fermentable as the native WG wheat ($P > 0.05$). Given the low RS content (1.1 and 0.8%, respectively) and moderate SDF content (4.4 and 4.5%, respectively) of wheat bran and wheat germ, their high tSCFA production was surprising. Wheat bran and wheat germ had the highest TDF contents among substrates, more than twice the TDF content of native WG wheat. We can hypothesize that these two components contained more fermentable fibers in their IDF fraction than the native WG wheat. In a recent in vivo study evaluating the prebiotic effect of WG wheat cereal, no differences in SCFA production were found between WG wheat and wheat bran, but the authors reported that in a preliminary in vitro screening of three WG cereals (not specified) compared with wheat bran, the WG cereals produced more SCFA with increased concentrations of butyrate (*6*). The authors explained the differences between in vivo and in vitro results by the rapid absorption of SCFA in the large intestine. In the present in vitro study, we observed a similar ($P = 0.18$) tSCFA production between WG wheat and wheat bran, but found a higher butyrate production with native WG wheat ($P < 0.0001$) and native WG corn ($P < 0.05$) compared with wheat bran. Wheat bran was first proposed as protective in colon cancer because of its higher butyrate proportion generated by its fermentation compared with other fibers (*26*), but this was invalidated after a careful comparison of results from in vitro and in vivo studies (*27*). Our results showed that wheat bran in vitro fermentation generated one of the lowest butyrate proportions among substrates (37%) and that the majority of native tested WGs produced higher butyrate concentrations than wheat bran.

Wheat germ and wheat bran contained essentially the same digestible portion (percent released glucose), the same SDF content, and the same RS concentration. However, the tSCFA results suggest that wheat germ fibers were more fermentable ($P = 0.0007$) than wheat bran fibers (142 and 113 mg of tSCFA produced/g DMB, respectively). These results are in accordance with the reported composition of wheat germ (lipids, proteins, and mainly soluble carbohydrates) and wheat bran (nondigestible, mainly insoluble and poorly fermentable, carbohydrates such as cellulose, hemicelluloses, arabinoxylan as well as polyphenolic lignins) (*6*).

Table 4. pH Change and Acetate, Propionate, Butyrate, And Total Short-Chain Fatty Acid (tSCFA) Production following 12 h of in Vitro Fermentation of Native and Extruded Cereal Grains and Components[a]

		mg/g DMB			
substrate	pH change	acetate[b]	propionate[b]	butyrate[b]	tSCFA
barley					
native WG	−0.16	3.8 (6.50)	14.7 (24.9)	40.5 (68.6)	59.0
processed WG	−0.14	57.2 (55.0)	20.4 (19.6)	26.3 (25.3)	104.0
corn					
native WG	0.06	0.00	1.2 (2.60)	45.5 (97.4)	46.7
processed WG	−0.03	0.00	13.0 (40.3)	19.3 (59.7)	32.2
bran	0.00	0.00	10.1 (62.7)	6.0 (37.3)	16.0
oat					
native WG	0.08	5.4 (8.60)	21.3 (34.3)	35.4 (57.1)	62.0
processed WG	0.00	31.4 (32.1)	27.0 (27.6)	39.4 (40.3)	97.8
bran	−0.07	11.2 (14.2)	28.0 (35.6)	39.4 (50.2)	78.6
rice					
native WG	0.03	9.4 (27.7)	4.3 (12.8)	20.1 (59.5)	33.8
processed WG	−0.02	0.00	8.1 (62.8)	4.8 (37.2)	12.9
wheat					
native WG	−0.17	58.1 (46.7)	12.1 (9.70)	54.2 (43.6)	124.4
processed WG	−0.09	8.2 (18.4)	12.6 (28.3)	23.8 (53.3)	44.6
bran	−0.13	52.3 (46.4)	20.2 (17.9)	40.1 (35.6)	112.6
germ	−0.16	53.5 (37.7)	33.4 (23.6)	54.9 (38.7)	141.8
standards					
Solka Floc	−0.12	0.8(100)	0.00	0.00	0.8
inulin Ultra-FOS	−1.78	212.6 (44.5)	94.4 (19.7)	171.2 (35.8)	478.2
Pectin HM Rapid	−1.44	308.3 (67.6)	70.6 (15.5)	77.3 (16.9)	456.1
SEM	0.02	4.25	1.00	1.80	5.8

[a] Values are corrected for glucose release after in vitro digestion. WG, whole grain; DM, dry matter; OM, organic matter; TDF, total dietary fiber; IDF, insoluble dietary fiber; SDF, soluble dietary fiber. All values are corrected for the glucose released after the in vitro digestion and represent the true pH change, ACE, PRO, BUTY, and tSCFA production after the fermentation of undigested residues. [b] Values in parentheses are individual fractions expressed as a percentage of total SCFA.

Processing increased ($P < 0.05$) tSCFA production for the barley and oat substrates. This increase was particularly significant for barley (50% increase in tSCFA production after processing) and is in agreement with Murray et al. (*19*). In our study, for both barley and oats, the increase in tSCFA production after processing was mainly due to the increase in acetate production (from 4 to 57 mg/g DMB and from 5 to 31 mg/g DMB, respectively), but these increases are not in accordance with the similar SDF content before and after processing and with the lower RS concentration found in processed barley and oats compared to native substrates. Livesey et al. (*11*) suggested a higher accessibility of starch to hydrolytic enzymes in processed cereals to explain a lower small intestinal digestion of starch in WG cereals. We can hypothesize, on the other hand, that the fiber matrix is more accessible to microbial enzymes in processed barley, rendering the fiber fraction more fermentable.

Processing decreased ($P < 0.05$) tSCFA production for rice and wheat substrates. The most significant decrease was observed with wheat substrates (from 124 to 45 mg/g DMB for native and processed WG wheat, respectively). This could be explained by the fact that 60% of the RS present in the WG wheat became digestible with processing (**Table 2**). The decrease in tSCFA production after wheat and rice processing concerned acetate and butyrate production. Generally speaking, except for the oat substrates, processing decreased ($P < 0.05$) butyrate production after 12 h of in vitro fermentation. This can be related to the observed decrease in RS after processing and a higher protection of starch in native WGs (*11*). Processed rice and corn bran fermentation generated the lowest ($P < 0.001$) amount of tSCFA (13 and 16 mg/g DMB, respectively). Given rice's low TDF contents (7.4 and 6.3%) and its high DS concentrations (76%), the low tSCFA production for the rice substrates was expected. The corn substrates fermentation produced no acetate, little propionate, and moderate amounts of butyrate and tSCFA. In a previous study carried out in our laboratory, we showed that native corn fibers are poorly fermentable (data not published). An absence of acetate production is not surprising for a low fermentable fiber source, and in our study the butyrate production reflected the RS fraction of the corn substrates. Corn bran, which contained 82% IDF and 0% RS, was the lowest fermentable substrate in the corn category.

No lactate production after 12 h of fermentation for any of the substrates was noted (data not shown). Depending on the type of substrate used in an in vitro experiment, such results can occur. The lactate produced can be rapidly processed by bacteria and not be present in tubes in sufficient amounts to be detected after 12 h of fermentation. Moreover, it is important to consider that all data presented in **Table 4** have been corrected for glucose production after the digestion stage. This correction procedure is the best way to mimic in vivo conditions using an in vitro model, but we still must consider that SCFA and lactate values could be affected by the fermentation of any residual glucose not accounted for in the blanking process.

Conclusion and Implications. As interest in WG foods increases, it is important to understand how processing affects WG chemical composition and digestion/fermentation profiles, especially in reference to grain coproducts generated as a result of normal manufacturing practices. This study provides information pertaining to this question and also compares select WG components to their native WG counterparts. Processing made barley and oat more fermentable, made wheat and corn more hydrolytically digestible, and had no major effect on rice. These effects can be related, in part, to changes observed in the starch fractions after processing of all substrates. Processing does not exert the same effect on all WGs, but it is interesting to note how native WGs and heat-processed WGs compare in composition and digestion characteristics to bran and germ fractions used in many food systems. Finally, all WGs tested in the present study were slightly to moderately fermentable. Among the WG substrates, processed WG barley, processed WG oat, and native WG wheat fermentation generated the highest amounts of SCFA. These results are of particular interest because of the well-known beneficial effects of SCFA, mainly butyrate, on digestive health. It is already believed that whole grains are more nutritious than bran and germ. Along with the prebiotic effect of WG wheat compared with wheat bran, recently demonstrated, our results should help strengthen the value of WG ingredients compared with refined grains.

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