Carbohydrate Digestibility of Laboratory-Extruded Cereal Grains

KALEE M. DAHLIN[1,2] and KLAUS J. LORENZ[1]

ABSTRACT

Whole-grain cereals (wheat, rye, corn, millet, and low- and high-tannin sorghum) and quinoa were examined to determine the effects of laboratory-extrusion processing on in vitro carbohydrate digestibility. Extrusion variables included cereal variety, extrusion temperature, screw speed, and feed moisture. Samples were incubated with human saliva, and products of digestion were quantified spectrophotometrically. Extrusion product temperatures of 100/150°C had the greatest influence on improving in vitro carbohydrate digestibility for all cereals studied, as did 25% feed moisture and 100-rpm screw speed. Improving carbohydrate digestibility during extrusion processing appears to depend very strongly upon cereal type. Further studies are needed to assess optimal processing conditions for improved carbohydrate digestibility of particular cereal grains.

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It is well established that, in general, cooking improves the digestibility of starches in cereals by the process of gelatinization (Snow and O'Dea 1981). Extrusion has been shown to thoroughly gelatinize starch even at very low food-moisture levels, thus also enhancing starch digestibility (Gomez and Aguilera 1983).

Extrusion processing to produce a more digestible starch fraction has the potential to replace enzymatic methods presently used for production of the linear maltodextrins used in infant foods and fermentable sugars for the brewing industry. Breakfast cereals and cereal-based soup mixes and drinks are also potential applications for extrusion cooking. This process produces favorable starch digestibility properties while maintaining availability of other nutrients (Camire et al 1990). The production of a more digestible starch fraction also involves an understanding of what components interfere with starch availability. Subsequent destruction of these components during processing could have implications in the dietary management of diabetes and other malabsorptive impairments (Jenkins et al 1987). This indicates a need to identify the form and structure of the food as well as the processing conditions required to optimize end-use effectiveness.

[1]Graduate research assistant and professor, respectively, Department of Food Science and Human Nutrition, Colorado State University, Fort Collins.
[2]Present address: Nutritional Foods, Amway Corporation, Ada, MI.

Enzymatic assays are one means of measuring protein and carbohydrate digestibility. In vitro enzymatic determination of protein and starch digestibility correlates very well with in vivo studies (Hsu et al 1977, Holm et al 1985, Lee et al 1985). Although in vitro systems are not as physiologically complex as in vivo systems, they provide models for examining characteristics of foods and processing conditions that may affect digestibility and, possibly, rates of absorption (Snow and O'Dea 1981, Lee et al 1985). In vitro methods are also less expensive and time-consuming than methods using humans or animals, and they provide a means of routine analysis for many food materials.

Accordingly, this investigation was undertaken to study the effects of grain type and laboratory-extrusion process conditions on in vitro carbohydrate digestibility as well as to determine optimum extrusion-process conditions required for improving carbohydrate digestibility characteristics in a wide variety of whole-grain cereals and quinoa.

MATERIALS AND METHODS

Sample Identification

Rye, winter wheat, corn, millet, and quinoa were obtained from the Colorado State University Agronomy Department. Low- and high-tannin sorghums were obtained from Texas A&M University.

Cultivar types, growing season, and location where each grain

was grown are as follows. The rye cultivar used was Maton grown at the Irrigated Desert Research Station, Brawley, CA, on a Holtville, silty clay soil. The winter wheat was a composite obtained from the winter wheat nursery and grown in the 1989 growing season in Fort Collins, CO. There was only one available line of quinoa (*Chenopodium quinoa* Willd.) in the United States. This cultivar was Colorado D407, a Chilean land race, grown during the 1987 growing season in experimental plots located in the San Luis Valley of Colorado. The corn cultivar used was CC-136 grown during the 1988 growing season in Fort Collins. The millet cultivar used was Colorado-135 grown during the 1989 growing season in Fort Collins. The low-tannin sorghum cultivar used was a white food-grade sorghum (Dorado) grown during the 1989 growing season in College Station, TX. The high-tannin sorghum cultivar used was brown, ATX623 × SC103-12E, also grown during the 1989 growing season in College Station.

Sample Preparation

Each whole grain was milled through a 2-mm mesh screen using a Thomas-Wiley laboratory mill (model 4) before extrusion. The moisture content of each cereal was determined according to AACC method 44-15A (AACC 1983). Each analysis was performed in triplicate. After initial moisture determination, two 1,000-g samples of each grain were weighed. One 1,000-g sample was adjusted to 15% moisture. The second 1000-g sample was adjusted to 25% moisture. Moisture was added by pipetting the appropriate amount of 20°C tap water to the grains as they were mixed in a Hobart mixer (model a-120, Hobart Mfg. Co., Troy, OH). The mixtures were allowed to equilibrate for 48 hr at room temperature in airtight plastic bags. This process was repeated for each grain type to provide duplicate, moisture-adjusted samples.

Saponin Removal

To remove saponins present in quinoa samples, quinoa was mechanically abraded to remove pericarp using a barley-pearling machine modified for on-farm use.

Extrusion

We used a single-screw Brabender plasticorder extruder (model PL-V500, C. W. Brabender Instruments, Inc., South Hackensack, NJ) with a 19.05-mm barrel diameter, a 20:1 length-to-diameter ratio, and eight 0.79- × 3.18-mm longitudinal grooves. The extruder consisted of two electrically heated zones. Desired product temperature was maintained by thermostats. Compressed air-cooled collars around the barrel improved temperature control. Thermocouples monitored product temperature through contact points with the product at the inside barrel-wall surface in each zone. Each sample was extruded at two temperatures: 80/100°C and 100/150°C (at the feed and compression sections, respectively). Extruded samples were equilibrated for 2 min before collection.

The extruder was equipped with a variable-speed drive that allowed all samples to be run at two screw speeds: 100 and 150 rpm. A 4.76-mm diameter die and a 3:1 screw-compression ratio were used on all trials. All samples were run in duplicate.

TABLE I
Proximate Composition of Unprocessed Cereal Grains and Quinoa[a]

Sample	Ash	Fat	Nitrogen	Protein[b]	Neutral Detergent Fiber
Sorghum (high tannin)	2.09	3.69	2.00	12.49	7.26
Sorghum (low tannin)	1.48	3.11	1.86	11.64	6.41
Millet	4.02	4.12	1.97	12.32	13.51
Quinoa	3.53	4.88	2.77	17.34	5.49
Wheat	1.88	1.10	2.83	16.13[c]	9.73
Rye	2.45	1.83	2.57	16.06	8.56
Corn	1.36	3.80	1.75	10.92	10.17

[a] Determinations made from 0.5-g samples, % dry basis; all analyses performed.
[b] Nitrogen conversion factor = 6.25.
[c] Nitrogen conversion factor = 5.7.

Proximate Analysis

Before analysis, all samples were ground through a 1-mm mesh screen using a Udy Cyclone sample mill (Udy Corp., Fort Collins, CO). Proximate analyses were performed on unprocessed samples of each cereal and quinoa (Table I). All analyses were performed in duplicate. Moisture, crude fat, and ash were determined according to approved methods (AACC 1983). Protein was determined on 0.5-g samples by the micro-Kjeldahl method with the boric acid modification (AACC 1983). The nitrogen conversion factor used was 6.25 for all samples except wheat, which was calculated using 5.7. Neutral detergent fiber was determined by the method described by Van Soest (1963).

In Vitro Carbohydrate Digestibility

To ensure particle-size uniformity for in vitro digestibility studies, all extruded and nonextruded samples milled to 1-mm mesh were passed through two U.S. standard testing sieves (W. S. Tyler, Inc., Mentor, OH), mesh sizes 80 and 40, to determine approximate grain particle size. A representative sample showed that approximately 70% of all grain particles used for digestibility trials were 180–420 μm.

In vitro carbohydrate digestibility was determined using a modification of the method described by Jenkins et al (1987). One-gram available-carbohydrate portions from each cereal and quinoa were placed into 13-cm dialysis bags cut from dialysis tubing (4.5-cm width, 4.8-nm pore diameter, and 12,000 molecular weight cutoff [Fischer Scientific, Pittsburgh, PA]). Human saliva was collected daily from student volunteers and stored under refrigeration in sealed vials until needed. Pooled, fresh human saliva (5 ml) and distilled water (10 ml) were added to the dialysis tubing, and the slurry was massaged gently to mix. The dialysis tubing was placed into separate water baths containing 800 ml of distilled water at 37°C with continuous agitation. At 1, 2, and 3 hr, 4 ml of dialysate was pipetted into a 100-ml volumetric flask, diluted to volume with distilled water, and thoroughly shaken. Total carbohydrate content was analyzed using the phenol-sulfuric acid method (Dubois et al 1956). The diluted solutions (2 ml) were pipetted into test tubes, and 1 ml of 5% phenol solution and 5 ml of concentrated H_2SO_4 were added. Each test tube was thoroughly mixed and left to stand for 25 min to permit color development. Absorbance was measured at 490 nm on a Bausch and Lomb Spectronic 20.

A blank for each cereal was prepared in the same manner, except that 5 ml of boiled saliva was used to eliminate the effects of naturally occurring starch digestion products. Each analysis was performed in duplicate.

A standard curve was prepared using solutions containing known concentrations of maltose (0, 10, 20, 30, 40, 60, and 100 μg). Graphpad (ISI Software, San Diego, CA) was used to plot the standard curve and to calculate the concentrations of starch

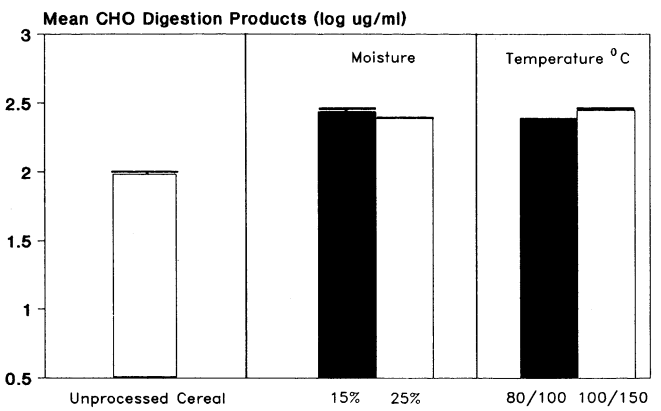

Fig. 1. In vitro carbohydrate digestibility of extruded corn. Effect of feed moisture and extrusion temperature. Values are least significant means pooled over a 3-hr incubation period (aliquots taken at 1, 2, and 3 hr). Least significant difference = 0.0387. $n = 8$ for each treatment variable (SEM ±0.012). $P < 0.05$.

digestion products in test solutions. Total starch digestion products released into the dialysate during in vitro digestion of cereals were expressed as log microgram per milliliter per hour.

Experimental Design and Statistical Analysis

The experimental design was a split-split-plot arranged in block fashion with extruder barrel temperature functioning as the main plot, screw speed as the split-plot, and feed moisture as the split-split-plot. As previously described, each processing variable was run using two levels, resulting in eight extrusion-process conditions.

The data were analyzed using the statistical analysis system, general linear models procedure (SAS 1987). When the split-plot and split-split-plot error terms were not different, they were pooled. Actual mean comparisons were performed using least significant differences to determine significance of cereal variety, extrusion temperature, screw speed, and feed moisture on in vitro carbohydrate digestibility.

RESULTS AND DISCUSSION

Because of individual cereal differences observed when comparing effects of extrusion-process conditions on in vitro carbohydrate digestibilities, each cereal was evaluated separately to assess which extrusion combinations most favorably alter carbohydrate digestibility.

Carbohydrate digestibility of corn improved significantly after extrusion processing (Fig. 1). The most favorable improvement was attributed to two conditions with significant ($P < 0.05$) influences on the carbohydrate digestibility of corn: 15% feed moisture and 100/150°C extrusion product temperatures.

Millet, although slightly less carbohydrate-digestible than corn in the unprocessed state, had an almost identical pattern of improvement in digestibility (Fig. 2). As in corn, the 15% feed moisture and 100/150°C extrusion product temperatures significantly ($P < 0.05$) influenced carbohydrate digestibility of millet.

Previous studies demonstrated that low-moisture (20%) and low-temperature (100°C) extrusion resulted in maximal fragmentation of starch present in corn meal (Wen et al 1990). Other studies have demonstrated increased enzyme susceptibility of whole-ground corn after low-moisture extrusion, presumably because of gelatinization and dextrinization or fragmentation of the polysaccharide chain (Gomez and Aguilera 1983).

Three conditions significantly ($P < 0.05$) influenced improvement in carbohydrate digestibility of rye (Fig. 3): 25% feed moisture, 100/150°C extrusion product temperatures, and 100-rpm screw speed.

In vitro carbohydrate digestibility of wheat was very similar to that of rye. Two-way interactions of processing variables significantly ($P< 0.05$) influenced carbohydrate digestibility of wheat (Fig. 4). This suggests that carbohydrate digestibility does not

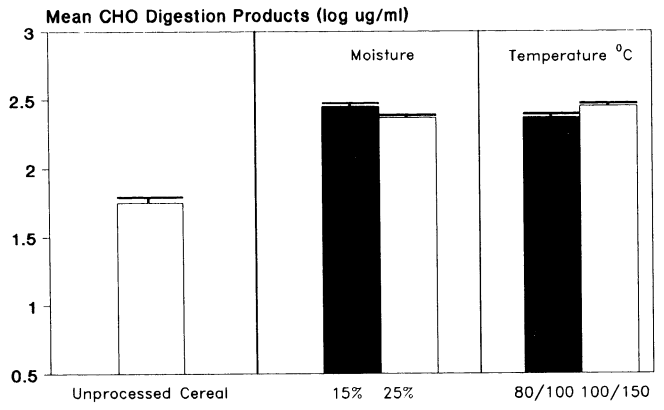

Fig. 2. In vitro carbohydrate digestibility of extruded millet. Effect of feed moisture and extrusion temperature. Values are least significant means pooled over a 3-hr incubation period (aliquots taken at 1, 2, and 3 hr). Least significant difference = 0.0452. $n = 8$ for each treatment variable (SEM ±0.014). $P < 0.05$.

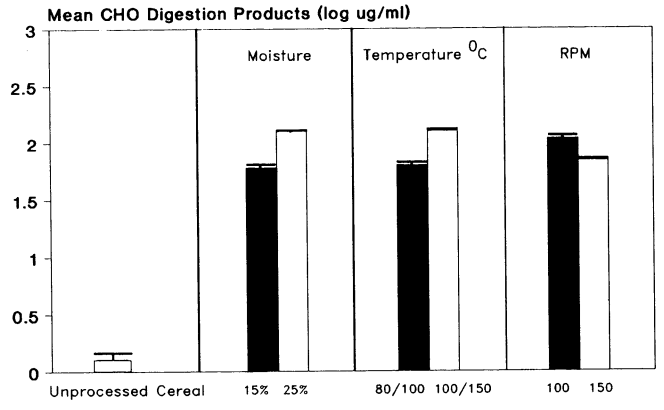

Fig. 3. In vitro carbohydrate digestibility of extruded rye. Effect of feed moisture, extrusion temperature, and screw speed. Values are least significant means pooled over a 3-hr incubation period (aliquots taken at 1, 2, and 3 hr). Least significant difference = 0.0906. $n = 6$ for 15% feed moisture, 80/100°C, 100 rpm (SEM ±0.028); $n = 8$ for 25% feed moisture, 100/150°C, 150 rpm (SEM ±0.024). $P < 0.05$.

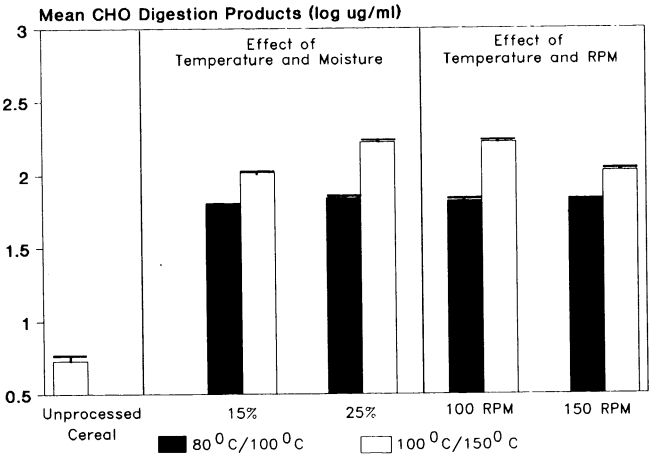

Fig. 4. In vitro carbohydrate digestibility of extruded wheat. Effect of feed moisture × extrusion temperature interaction and screw speed × extrusion temperature interaction. Values are least significant means pooled over a 3-hr incubation period (aliquots taken at 1, 2, and 3 hr). Least significant difference = 0.0428. $n = 4$ for each treatment interaction (SEM ±0.013). $P < 0.05$.

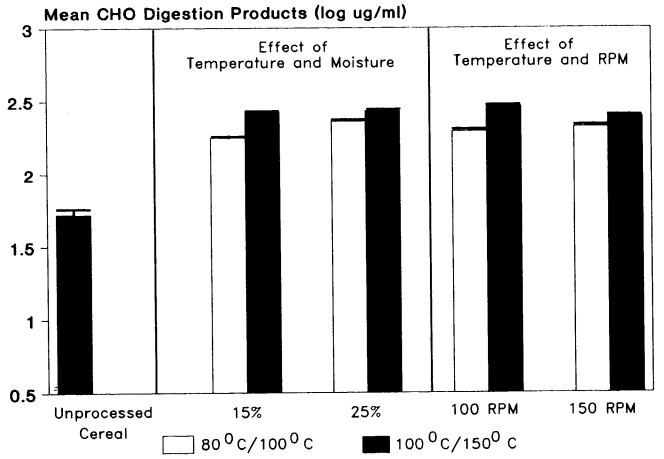

Fig. 5. In vitro carbohydrate digestibility of extruded high-tannin sorghum. Effect of extrusion temperature × feed moisture interaction and effect of extrusion temperature × screw speed interaction. Values are least significant means pooled over a 3-hr incubation period (aliquots taken at 1, 2, and 3 hr). Least significant difference = 0.0468. $n = 4$ for each treatment interaction, except $n = 2$ for 80/100°C × 15% feed moisture and 80/100°C × 100 rpm (SEM ± 0.013). $P < 0.05$.

respond uniformly across moisture levels and temperatures. Specific combinations of extruder operating conditions produce the highest carbohydrate digestibility. A significant temperature-moisture interaction indicated that the most favorable increase in digestibility for wheat occurred at product temperatures of 100/150°C and feed moisture of 25%. A temperature-screw speed interaction also revealed most favorable improvement in digestibility of wheat at product temperatures of 100/150°C and screw speed of 100 rpm. As with extruded rye, wheat improved most with regard to carbohydrate digestibility when extruded at 25% feed moisture, 100/150°C product temperatures, and 100-rpm screw speed.

High-tannin sorghum behaved similarly to wheat after extrusion in that two-way interactions significantly ($P < 0.05$) influenced carbohydrate digestibility of this grain over other extrusion conditions (Fig. 5). Extrusion product temperatures of 100/150°C had the most beneficial effect on digestibility. High-tannin sorghum showed a significant ($P < 0.05$) decrease in carbohydrate digestibility when extruded at low-moisture (15%), low-temperature (80/100°C) combinations. A temperature-screw speed interaction also significantly ($P < 0.05$) influenced carbohydrate digestibility of high-tannin sorghum (Fig. 5). As with rye and wheat, carbohydrate digestibility improved most when high-tannin sorghum was extruded at 100/150°C and 100 rpm.

Increased screw speeds have been shown to adversely affect carbohydrate digestibility (Chiang and Johnson 1977). This finding could be attributed to increased shear force resulting in an increase in reducing groups due to hydrolysis of starch. Subsequently, digestibility would decrease as sugars participate in the Maillard reaction. A lower screw speed, such as that found beneficial to carbohydrate digestibility in this study, allows enough residence time for the gelatinization and solubilization of starch to occur.

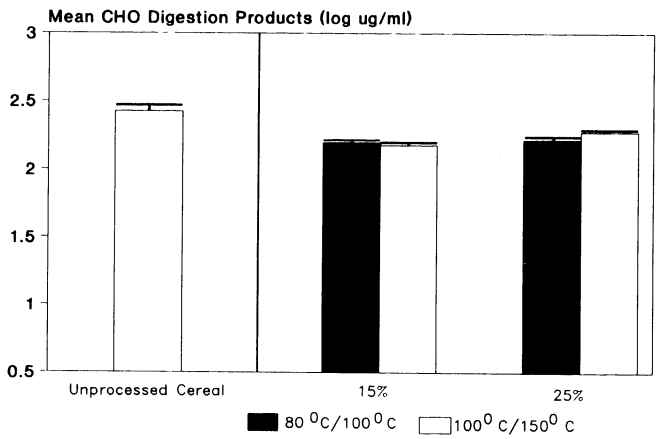

Fig. 6. In vitro carbohydrate digestibility of extruded quinoa. Effect of extrusion temperature and feed moisture. Values are least significant means pooled over a 3-hr incubation period (aliquots taken at 1, 2, and 3 hr). Least significant difference = 0.0583. $n = 4$ for each treatment variable (SEM ±0.017). $P < 0.05$.

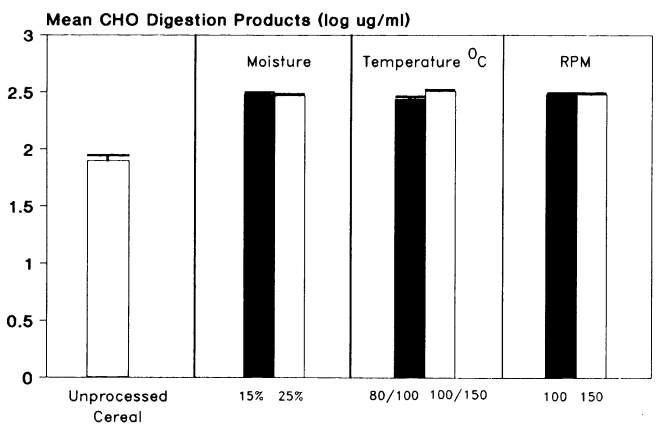

Fig. 7. In vitro carbohydrate digestibility of extruded low-tannin sorghum. Effect of feed moisture, extrusion temperature, and screw speed. Values are least significant means pooled over a 3-hr incubation period (aliquots taken at 1, 2, and 3 hr). Least significant difference = 0.0583. $n = 4$ for each treatment variable (SEM ±0.017). $P < 0.05$.

For quinoa, the most improvement in carbohydrate digestibility after extrusion processing was indicated by two-way temperature-moisture interactions. As with rye, wheat, and high-tannin sorghum, quinoa was most digestible after processing when extruded at 25% feed moisture and 100/150°C product temperatures (Fig. 6). This combination significantly ($P < 0.05$) improved carbohydrate digestibility more than other moisture-temperature combinations. Despite this, unprocessed quinoa was significantly more carbohydrate-digestible than any of the extruded quinoa samples. Quinoa is a richer source of protein than the cereal grain crops, generally containing up to 19% protein. The protein content of quinoa has an exceptionally attractive amino acid balance for human nutrition because of its high levels of lysine and methionine (Risi and Galwey 1984). It is possible that extrusion-processing conditions employed in this study decreased digestible carbohydrate by favoring carbohydrate participation in the Maillard reaction.

Mechanical abrasion of quinoa cultivar D407 further increases α-amylase activity in quinoa seeds (Lorenz and Nyanzi 1989) because of the reduction in kernel weight and removal of areas of the kernel with relatively low α-amylase content. This explains the comparatively high carbohydrate digestibility of the unprocessed quinoa. The extruded quinoa and the extruded cereal in this study all, presumably, lost amylase activity during extrusion.

It is also possible that the quantity and nature of quinoa protein negatively influenced availability of quinoa carbohydrate after extrusion processing. Protein or carbohydrate structure or interactions between carbohydrates and other components such as lipids and proteins could render the carbohydrate less available for enzymatic hydrolysis. No studies on the specific interactions of these components after extrusion have been reported.

In the present study, there was no specific extrusion condition for low-tannin sorghum that significantly influenced the improvement of in vitro carbohydrate digestibility. Although the 100/150°C extrusion product temperatures had a nonsignificant ($P > 0.05$) influence on improving digestibility, extrusion generally improved carbohydrate digestibility of this grain (Fig. 7).

Optimum Process Conditions

With the exception of quinoa, laboratory-extrusion generally improved carbohydrate digestibility of all grains studied. Extrusion product temperatures of 100/150°C had the greatest influence on in vitro carbohydrate digestibility improvement in all cereals studied. Effects of extrusion feed moisture content on carbohydrate digestibility were variable, but our study showed that grains generally favored the higher 25% moisture condition. The effect of screw speed was less pronounced and not a significant influence on improved carbohydrate digestibility; in general, screw speeds of 100 rpm were favored.

Based on these findings, optimum improvement in carbohydrate digestibility of cereal grains during laboratory-extrusion processing should take into account the type of cereal being extruded and extrusion-processing variables that might be employed. Higher extrusion temperature, higher feed moisture, and lower screw speeds appear to be overall recommendations for increasing carbohydrate digestibility.

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