Composition and in Vitro Digestibility of Monosaccharide Constituents of Selected Byproduct Feeds

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Nonforage byproduct feeds, including distillers dried grains (DDG), corn gluten feed (CGF), wheat bran (WB), beet pulp (BP), soybean hulls (SH), and dried citrus pulp (DCP), were examined for monosaccharide composition and in vitro digestibility by ruminal liquor. The dicotyledonous feeds (BP, SH, and DCP) contained more galactose, pectin, and NDF glucans and less NDF-xylan and NDF-arabinose than the monocotyledonous ones (DDG, CGF, and WB). The lowest values of lignin were found in CGF, SH, and DCP. Digestibility of total carbohydrate was around 90% in CGF, DCP, BP, and SH and around 80% in DDG and WB. Digestibility of total NDF polysaccharides was 86% in CGF and SH, 78−84% in DDG, DCP, and BP, and 56% in WB. In all byproducts, digestibility of NDF glucose and arabinose was higher than that of NDF xylose and uronic acids.

Keywords: *Monosaccharides; carbohydrate degradability; NDF polysaccharides; distillers dried grains; corn gluten feed; wheat bran; beet pulp; soybean hulls; citrus pulp*

INTRODUCTION

Interest in byproduct feeds, such as distillers dried grains (DDG), corn gluten feed (CGF), wheat bran (WB), sugar beet pulp (BP), soybean hulls (SH), and dried citrus pulp (DCP), as alternative feeds for dairy cows has increased over the past decade. Byproducts of the grain utilization industries have a combination of energy sources for ruminal microbes including both nonstructural carbohydrate and a readily digestible NDF fraction (*17*, *20*, *33*). Therefore, these nonforage fiber byproducts have been used for replacement in rations of lactating cows of either concentrated grains (*5*, *6*, *29*) or roughage NDF (*5*, *18*, *35*). Such feedstuffs may contain different cell-wall types, ranging from thin primary nonlignified, readily digestible cell walls, to thick secondary, hardly digestible cell walls which are often lignified (*14*). Knowledge of the composition of whole byproduct and its cell-wall carbohydrate constituents and their potential digestion by ruminal population is needed to optimize feed utilization by dairy cattle.

Most of the research on the composition and in vivo digestibility of total and cell-wall monosaccharide constituents has been done on forage crops such as alfalfa (*8*, *23*), wheat or corn silages (*24*, *25*, *30*), grasses (*7*, *31*, *13*), and straw (*22*), which are rich in lignified secondary cell walls. However, less attention has been paid to cell-wall carbohydrate constituents of byproduct feeds, which may contain cell wall degradability obstacles of a different nature.

The methodology commonly used to evaluate forage composition is based on the detergent fractionation system of Van Soest et al. (*34*) that estimates cellulose, hemicellulose, and lignin content of the cell walls. However, there is lack of knowledge about carbohydrate composition of byproduct feeds analyzed by the detergent system in comparison with analysis down to the individual monosaccharide constituents level.

The objective of this study was to examine both the amount and type of total and cell wall monosaccharide and lignin constituents of several byproducts of the feed industry, and to determine the potential of ruminal population to degrade the individual monosaccharide constituents.

MATERIALS AND METHODS

Byproducts Used in This Study. The byproducts examined were collected in three replicates, each from different origins described below including (i) distillers' dried grains (DDG), which is the byproduct from the yeast fermentation of corn grains for the production of ethyl alcohol; DDG was sampled from batches imported from Bulgaria and Romania or manufactured in Israel; (ii) corn gluten feed (CGF), which is a dried byproduct from the mechanical and chemical extraction of corn starch and corn syrup; CGF was sampled from batches imported from Bulgaria and Romania or manufactured in Israel; (iii) wheat bran (WB) which is a byproduct of milling of wheat grains for flour and contains predominantly the seed coat; WB was sampled from batches imported from Italy and USA or manufactured in Israel; (iv) beet pulp (BP), which is the residue from manufacturing sugars from sugarbeets that was dried and pelleted; BP was sampled from batches imported from USA, Brazil, and Romania; (v) soybean hulls (SH), which are a byproduct of the oil industry; SH was sampled from batches imported from Canada and USA or manufactured in Israel; and (vi) dried citrus pulp (DCP), which is a mixture of peels, inside portions, and cull fruits of the orange, dried and ground to some extent; DCP samples were imported from Spain and USA or manufactured in Israel. These byproduct foodstuffs in their dry form were ground to pass a 1-mm sieve prior to their chemical analysis and in vitro digestibility examinations.

Chemical Analysis and in Vitro Digestibility Determination. Ground samples of the byproducts were assayed for dry matter (DM) and organic matter (OM) content (*3*). Total N content was determined according to the Kjeldahl method (*3*) and fructose analyzed colorimetrically as described previ-

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Table 1. Chemical Composition of Selected Byproduct Feedstuffs (% of dry matter ± SE)

component	distillers dried grains	corn gluten feed	wheat bran	beet pulp	soybean hulls	dried citrus pulp
organic matter	93.0 ± 1.82	92.4 ± 1.61	93.4 ± 1.92	89.7 ± 1.22	95.0 ± 2.44	91.2 ± 1.65
crude protein	29.2 ± 0.31	25.1 ± 0.43	17.3 ± 0.56	8.77 ± 0.13	10.1 ± 0.35	6.70 ± 0.14
neutral detergent fiber (NDF)	47.3 ± 1.05	41.0 ± 0.61	51.3 ± 0.91	45.9 ± 0.61	68.6 ± 1.63	21.6 ± 0.32
acid detergent fiber (ADF)	28.3 ± 0.44	12.5 ± 0.32	15.8 ± 0.62	33.0 ± 0.43	52.7 ± 1.27	21.2 ± 0.53
acid detergent lignin (ADL)	11.1 ± 0.23	0.32 ± 0.02	2.84 ± 0.07	3.35 ± 0.18	1.48 ± 0.08	0.31 ± 0.03
NDF-phenolics	4.87 ± 0.13	6.60 ± 0.11	6.51 ± 0.18	4.87 ± 0.17	4.19 ± 0.12	1.56 ± 0.06
hemicellulose (NDF-ADF)	19.0 ± 0.52	28.5 ± 0.63	35.5 ± 0.16	12.9 ± 0.12	15.9 ± 0.63	0.40 ± 0.04
cellulose (ADF-ADL)	17.2 ± 0.36	12.2 ± 0.54	13.0 ± 0.34	29.7 ± 0.23	51.2 ± 1.45	20.9 ± 0.86

Table 2. Monosaccharide Composition of Selected Byproduct Feedstuffs (% of dry matter ± SE)

component	distillers dried grains	corn gluten feed	wheat bran	beet pulp	soybean hulls	dried citrus pulp
glucose	22.8 ± 0.13	25.7 ± 1.48	37.0 ± 2.35	28.0 ± 0.25	39.5 ± 0.13	29.0 ± 0.79
xylose	8.90 ± 0.17	14.9 ± 0.91	17.4 ± 1.17	3.07 ± 0.06	8.79 ± 0.12	2.14 ± 0.09
arabinose	6.31 ± 0.04	10.3 ± 0.72	11.3 ± 0.67	21.4 ± 0.23	5.55 ± 0.03	6.80 ± 0.10
galactose	2.95 ± 0.07	2.97 ± 0.13	1.43 ± 0.14	6.84 ± 0.01	4.80 ± 0.04	6.57 ± 0.36
mannose	2.56 ± 0.13	1.02 ± 0.10	0.68 ± 0.06	1.73 ± 0.02	7.55 ± 0.04	2.62 ± 0.01
uronic acids	3.0 ± 0.19	4.63 ± 0.12	2.48 ± 0.05	15.2 ± 0.12	14.8 ± 0.12	21.5 ± 0.41
total carbohydrate[a]	46.5 ± 0.45	59.5 ± 3.19	70.3 ± 4.28	76.2 ± 0.46	81.0 ± 0.25	79.0* ± 1.11
ND-soluble uronic acids	1.34 ± 0.02	2.40 ± 0.06	0.63 ± 0.06	12.7 ± 0.21	11.0 ± 0.15	20.7 ± 0.42
ND-soluble glucans	9.30 ± 0.12	12.8 ± 0.71	22.7 ± 0.68	6.11 ± 0.16	2.95 ± 0.03	16.2 ± 0.41

[a] Including 10.2% fructose found only in DCP.

ously (*10*). Neutral detergent fiber (NDF) of the byproducts and their in vitro degradation residues were determined and prepared by the method of Van Soest et al. (*34*) employing the amylase procedure. Cell wall fractions of the byproducts including acid detergent fiber (ADF) and acid detergent lignin (ADL) were determined according to Van Soest et al. (*34*). Hemicellulose was calculated as NDF-ADF, cellulose was determined by acid hydrolysis (72% H_2SO_4) of ADF, and lignin was determined as ADL after subtracting silica. The acetyl bromide method (*26*) was also used to measure total phenolics in NDF fractions.

Monosaccharide components of the freeze-dried byproducts and their NDF preparations were determined after hydrolysis with 24 N H_2SO_4 for 1 h at 21 °C followed by 1 N H_2SO_4 for 5 h at 100 °C, as described by Ben-Ghedalia and Miron (*8*). The free sugars released were converted to alditol acetates and determined by gas liquid chromatography (*11*), and results are presented on an anhydro-sugar basis. Uronic acids in the hydrolysates were determined colorimetrically (*12*). On the basis of the monosaccharide analysis, α-glucans (starch) content in the byproducts was estimated as ND-soluble glucose, and pectin as ND-soluble uronic acids, and the cell wall polysaccharides were divided into cellulose = NDF-glucose and hemicellulose = NDF-non-glucose polysaccharides (NGP).

In vitro digestibility of byproducts by ruminal population was determined (in four tubes = replicates) by the two stage fermentation technique of Tilley and Terry (*32*). Residual DM, NDF, and monosaccharide components remaining in each fermentation tube were determined as described above.

RESULTS AND DISCUSSION

The byproducts which are manufactured by the processing of grains for starch utilization (i.e., DDG, CGF, WB) or beans for oil extraction (i.e., SH) were high in NDF, originating from grain or bean envelopes, as shown in Table 1. Notwithstanding, the citrus pulp, which is a mixture of peels, inside portions, and cull fruits of the orange juice industry, contained less NDF (21.6%) than the other byproducts. The monocotyledonous byproducts of the starch industry (DDG, CGF, and WB) contained more protein and hemicellulose and less ADF and cellulose than the dicotyledonous BP and SH. High content of ADL (11.1%) was found in DDG, whereas, CGF contained only traces of ADL. The large difference between the values of ADL and NDF-phenolics contents in DDG (Table 1) is probably associated with the presence of nonphenolic constituents, such as cutin, in the ADL fraction of DDG. The high content of ether-extract in DDG supports this suggestion (*2*). The chemical extraction of starch from corn grains, during the manufacturing of CGF, removes part of the cutin originally found in the grains, whereas yeast fermentation of corn starch to ethanol, during DDG manufacturing, does not remove cutin. The values shown in Table 1 coincide well with those of NRC (*28*), Macgregor (*20*), and Arosemena et al. (*2*).

Table 2 shows the monosaccharide composition of the whole byproducts. The monocotyledonous byproducts of the starch industry (DDG, CGF, and WB) contained more residual starch and less uronic acids and pectin than the dicotyledonous BP and SH. In DDG, CGF, WB, and SH, most of the total carbohydrates originated from NDF polysaccharides (68, 68, 63, and 75%, respectively), whereas in BP and DCP, most of the total carbohydrates originated from the ND-soluble fraction (54 and 75%, respectively). In the DCP, α-glucans, pectin, and fructose plus soluble arabinose and galactose contributed together up to 98% of total ND-soluble carbohydrate. In general, SH, DCP, and BP were high in total carbohydrates (around 80%), whereas DDG was the lowest in carbohydrate content (47%); CGF and WB were in an intermediate position (60 and 70%, respectively).

Table 3 shows the composition of NDF-polysaccharides. Glucose, xylose, and arabinose were the main monosaccharide constituents of the cell walls of monocotyledonous byproducts (DDG, CGF, and WB). The cell walls of the dicotyledonous; BP, SH and DCP were higher in glucose and lower in xylose and arabinose, as compared to monocotyledonous cell walls. The content of matrix polysaccharides in monocotyledonous byproducts (DDG, CGF and WB) was higher than that of cellulose (NDF β-glucans). The compositional pattern of dicotyledonous feedstuffs (BP, SH, and DCP) was converse to the above-mentioned.

Comparison of the concentrations of cellulose and hemicellulose based on individual monosaccharide assay (Table 3) with the data obtained from detergent fractionation (Table 1) shows some discrepancy, particularly with respect to the content of cellulose in BP, DDG, DCP, and SH, and hemicellulose in WB, SH, and DCP.

Table 3. NDF Monosaccharide Composition of Selected Byproduct Feedstuffs (% of NDF ± SE)

component	distillers dried grains	corn gluten feed	wheat bran	beet pulp	soybean hulls	dried citrus pulp
glucose	27.9 ± 0.39	31.4 ± 1.01	27.9 ± 0.96	47.7 ± 0.4	53.3 ± 2.39	54.5 ± 1.75
xylose	17.5 ± 0.37	34.2 ± 0.60	31.1 ± 0.10	5.28 ± 0.06	12.7 ± 0.61	8.70 ± 0.09
arabinose	12.5 ± 0.46	21.3 ± 0.69	20.7 ± 0.16	9.47 ± 0.01	6.61 ± 0.30	4.92 ± 0.02
galactose	3.49 ± 0.23	4.97 ± 0.13	1.71 ± 0.02	5.17 ± 0.06	3.28 ± 0.15	7.48 ± 0.07
mannose	1.92 ± 0.03	1.17 ± 0.07	0.90 ± 0.01	3.24 ± 0.06	6.78 ± 0.16	7.65 ± 0.09
uronic acids	3.52 ± 0.09	5.44 ± 0.08	3.61 ± 0.06	5.37 ± 0.73	5.58 ± 0.19	3.58 ± 0.12
total carbohydrate	66.8 ± 1.24	98.5 ± 2.16	85.9 ± 1.86	76.2 ± 1.8	88.2 ± 3.40	91.8 ± 1.59
NGP[a] (g/100 g dm)	18.4 ± 0.42	27.5 ± 1.02	29.8 ± 0.42	13.1 ± 0.9	24.0 ± 1.13	6.98 ± 0.15
NDF-glucans (g/100 g dm)	13.2 ± 0.23	12.9 ± 0.57	14.3 ± 0.53	21.9 ± 0.3	36.6 ± 1.66	11.8 ± 0.45

[a] NGP = NDF − non-glucose polysaccharides.

Table 4. In Vitro Digestibility of the Monosaccharide Components of Selected Byproduct Feedstuffs (% ±SE)

constituent	distillers dried grains	corn gluten feed	wheat bran	beet pulp	soybean hulls	dried citrus pulp
glucose	78.2 ± 0.12	89.0 ± 0.28	85.9 ± 0.12	84.2 ± 0.91	88.1 ± 0.34	89.7 ± 1.36
xylose	76.8 ± 0.13	87.1 ± 0.37	65.5 ± 0.21	53.8 ± 3.29	85.8 ± 0.36	68.8 ± 2.46
arabinose	86.4 ± 0.07	91.1 ± 0.26	69.4 ± 0.26	86.5 ± 0.20	89.2 ± 0.28	95.4 ± 0.57
galactose	80.1 ± 0.10	79.0 ± 0.52	68.8 ± 0.29	87.5 ± 0.42	91.1 ± 0.18	93.7 ± 0.77
mannose	89.0 ± 0.05	67.9 ± 0.67	61.9 ± 0.36	83.2 ± 0.64	95.5 ± 0.10	89.0 ± 1.30
uronic acids	82.9 ± 0.09	87.6 ± 0.33	37.8 ± 0.53	94.3 ± 0.33	93.4 ± 0.18	97.7 ± 0.25
total carbohydrate	80.2 ± 0.15	88.4 ± 0.21	76.4 ± 0.14	88.6 ± 0.68	89.7 ± 0.30	92.3 ± 0.80
dry matter	77.1 ± 0.29	88.4 ± 0.52	72.7 ± 0.18	83.3 ± 0.15	87.7 ± 0.73	91.5 ± 0.18

Table 5. In Vitro Degradability of NDF Monosaccharide Residues of Selected Byproduct Feedstuffs (%+SE)

NDF component	distillers dried grains	corn gluten feed	wheat bran	beet pulp	soybean hulls	dried citrus pulp
glucans	78.0 ± 0.93	86.4 ± 0.42	54.1 ± 1.23	87.3 ± 0.26	86.1 ± 0.46	84.5 ± 0.53
xylan	75.0 ± 1.14	85.0 ± 0.48	53.4 ± 0.90	64.5 ± 1.11	83.6 ± 0.54	68.3 ± 1.09
arabinose	83.3 ± 0.68	89.8 ± 0.35	64.7 ± 1.37	90.1 ± 0.20	88.4 ± 0.39	84.5 ± 0.50
galactose	77.3 ± 0.97	77.5 ± 0.47	54.0 ± 1.22	89.2 ± 0.22	90.6 ± 0.24	87.4 ± 0.45
mannose	88.8 ± 0.37	73.9 ± 0.48	60.7 ± 0.94	83.1 ± 0.13	93.3 ± 0.12	89.8 ± 0.36
uronic acids	74.3 ± 1.11	86.0 ± 0.43	26.1 ± 1.99	73.9 ± 0.53	85.6 ± 0.49	72.6 ± 0.96
NGP[a]	78.0 ± 0.93	85.3 ± 0.37	56.5 ± 1.17	78.8 ± 0.42	88.2 ± 0.39	80.7 ± 0.66
total NDF carbohydrate	78.0 ± 0.93	85.7 ± 0.38	55.7 ± 1.19	84.1 ± 0.32	86.9 ± 0.44	83.2 ± 0.60
NDF	76.5 ± 0.95	83.4 ± 0.57	50.8 ± 0.51	74.4 ± 0.55	83.0 ± 0.62	70.4 ± 1.28

[a] NGP = NDF-non-glucose polysaccharides.

Possible explanation to this discrepancy was given previously for forages by Morrison (*27*), who demonstrated that hemicellulose fraction determined as NDF-ADF may contain NDF-phenols and cellulose, whereas, the cellulose fraction determined by 72% acid hydrolysis of ADF may contain hemicellulose and lignin residues. Therefore, we have decided in this study to use the individual monosaccharides assay for analyzing the degradability of NDF cellulose and hemicellulose of the byproduct feeds.

Data of carbohydrate composition of DCP, BP, WB, and SH shown in Tables 1, 2, and 3 are supported in less detail by previous publications (*1, 4, 10, 16, 33*). However, we were unable to find previous publications presenting the full monosaccharide compositional spectrum of byproduct feedstuffs as presented in Tables 2 and 3.

Table 4 shows the average in vitro digestibility values of the monosaccharide components of the byproduct feedstuffs. The ruminal microorganisms degraded around 90% of total carbohydrate of CGF, BP, SH, and DCP and around 80% of total DDG and WB carbohydrate. In each substrate there were differences in the degradability of individual monosaccharide components. The lower degradable monosaccharides were xylose in DDG, BP, SH, and DCP, galactose and mannose in CGF, and uronic acids, xylose, and mannose in WB. The digestibility values of total carbohydrate were by up to 8% higher than the corresponding DM digestibility data. In general, the in vitro DM digestibility values shown in Table 4 are similar to previously reported total digestible nutrients data (*2, 20, 28*).

The in vitro digestion system is based on degradation of plant material by rumen microorganisms followed by enzymatic solubilization of plant and microbial protein by pepsin−HCl reagent. Thus, soluble material is considered digestible (*32*). Therefore, the differences existing among byproducts with respect to individual monosaccharide digestion (Table 4) resulted from the differences in the degradation of NDF polysaccharides as shown in Table 5. Previous studies demonstrated that in the cell walls of forage plants the minor matrix sugars are located as branching monomers on the hetero-xylan, and the least digestible monosaccharide component of the heteroxylan is probably interlinked with the lignin in the matrix (*8, 9, 21*). Assuming that this is true also for cell walls of the byproducts, the data of Table 5 shows that NDF xylose and uronic acids are the least digestible components of DDG, BP, WB, and DCP, whereas in CGF and SH their digestibility values are similar to that of the NDF glucose. It is therefore suggested that lignin and NDF-phenolics (Table 1) are interlinked via uronic acids with the heteroxylan of the matrix of DDG, BP, DCP, and WB, creating accessibility and enzymatic obstacles for ruminal bacteria who lack the enzymatic capabilities to degrade these lignin−carbohydrate connections (*14*). This suggestion enables us to explain part of the relatively low digestion of hemicellulose found in DDG, BP, DCP, and even lower in WB (57%). On the other hand, in SH and CGF, the content of ADL-lignin (resembling the core lignin) was very low (0.3%, Table 1), and as such it's possible interference with hemicellulose digestion (85−88%) was limited.

The WB, whose lignin and NDF-phenolics concentrations do not differ from the values found for DDG, BP, and DCP, need special attention in order to explain the reasons for its lower NDF-polysaccharides degradation (56%). By using solid-state ^{13}C NMR of the cell walls of wheat bran, Ha (*19*) suggested that "cutin rather than lignin plays an important role in protecting wheat bran from microbial degradation in the rumen". The data of Table 1 show that ADL content in WB is 2.84% and NDF-phenolics content is 6.51%. Thus, it is unlikely that lignin plays a predominant role in the protection of WB NDF-polysaccharides from ruminal degradation as suggested by Ha (*19*). A possible explanation to the low digestibility of WB NDF-polysaccharides is that WB, unlike the other byproducts, is composed of wheat grain envelopes that were not treated by any wet chemical or microbial agent, with some associated residues of starch granules. Microscopic observations have shown that the envelopes and hulls surrounding the endosperm are composed of thick secondary cell walls coated by cutin, that were originally created for protecting the endosperm from any damage or microbial degradation (*33*). In addition, the presence of high content of ND-soluble glucose in WB (22.7%, Table 2) may interfere with cell wall degradation by ruminal bacteria, probably via the mechanism of "soluble carbohydrate inhibitory effect", as previously demonstrated by Miron et al. (*25*).

4. CONCLUSION

The byproduct feedstuffs of this study can be divided into two groups, according to their potential to replace grains or other concentrates low in NDF: CGF, DCP, BP, and SH whose total carbohydrate digestion values are around 90%; and DDG and WB whose total carbohydrate digestion is only around 80%.

When considered as forage NDF replacers, these byproducts should be evaluated not only according to their potential NDF digestibility data provided in Table 5. Additional factors including particle size and physical structure of the byproducts and of other dietary fibrous ingredients, and level of intake, may affect the NDF polysaccharides digestibility in productive ruminants.

ABBREVIATIONS USED

ADF, acid detergent fiber; ADL, acid detergent lignin; BP, beet pulp; CGF, corn gluten feed; DCP, dried citrus pulp; DDG, distillers dried grains; DM, dry matter; ND, neutral detergent; NDF, neutral detergent fiber; NGP, non-glucose polysaccharides; OM, organic matter; SE, standard error; SH, soybean hulls; WB, wheat bran.

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