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Digestion kinetics of neutral detergent fiber and chemical composition within some selected by-product feedstuffs

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Abstract

Nine by-product feedstuffs (BPF) obtained from three different sources were evaluated for nutrient composition, estimated nonstructural carbohydrate (NSC) and TDN content, and total extent and rate of digestion of DM and NDF. The nine BPF evaluated included: beet pulp (BP), rice bran (RB), almond hulls (AH), citrus pulp (CT), bakery waste (BW), wheat mill run (WMR), brewers' grains (BG), distillery grains (DG) and soy hulls (SH). Twenty-seven samples were evaluated and were a subset of a larger study reported previously. In sacco techniques were used to measure the amount of NDF and DM remaining in nylon bags after 0, 1, 2, 4, 8, 16, 24, 36, 48, and 72 h of incubation in the rumen of a rumen fistulated cow. Chemical analyses measured included ash, crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), and crude protein in the NDF (NDFCP) and ADF (ADFCP) fractions. Chemical composition differed among BPF source. This difference could be due to processing method or ingredients added to BPF during processing. The amount of CP associated with the NDF fraction varied among sources of each BPF. The amount of NDFCP also differed for each BPF. The NDFCP content of CT, 0.44%, was low compared with DG, 14.5%, which was high compared with the other BPF evaluated. Correcting for the fiber-bound protein increased the estimate of NSC slightly for most BPF, but the NSC content of DG was increased 88%. The results indicate a correction for NDFCP is necessary for an accurate estimation of NSC in BPF. Within a given BPF, the extent and rate of digestion of NDF were different for each source. The TDN content of each sample was calculated using the rate of in sacco NDF digestion for each BPF at three theoretical rates of passage from

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the rumen. By-product feedstuffs containing a high proportion of NDFCP and a low rate of NDF digestion had the greatest decrease in TDN content as passage rate increased.

Keywords: By-product feedstuffs; In sacco digestion; Neutral detergent fiber; Digestion kinetics

1. Introduction

Most by-product feedstuffs (BPF) result from the processing of commercial crops, the food processing industry, and the fiber industry. Many BPF would be discarded in landfills if they were not fed to ruminants. By-product feedstuffs in the diets of ruminants support growth and lactation and result in the production of human edible food. Consequently, BPF are becoming increasingly more important in the food and fiber system because they are available for use as livestock feeds at competitive prices relative to other commodities (Grasser et al., 1995).

The contribution of BPF to the diets of dairy cows is significant, and the utilization of BPF increases when the supplies of grain are low and grain prices are high. In California, a total of 912 000 tonnes of BPF was fed to ruminants compared with only 800 000 tonnes of grains in 1973 (Bath, 1981). During that year, by-product concentrates constituted 12% of the total feed utilized (air-dry basis) by dairy cattle. Although Bath et al. (1993) identified 355 by-product commodities used for feed, during 1992, nine selected by-products were found to account for over 27% of the total feed concentrate used in California (Grasser et al., 1995). Similarly, Lundquist (1995) reported that BPF could account for almost the entire non-forage portion of the diet of dairy cattle in the southern and western states. By-product feedstuffs, which contain little economical value as edible foods for human consumption have become major sources of dietary nutrients and energy in support of milk production and will continue to do so in the future.

Milk production was not adversely affected by the inclusion of BPF in the diet as long as the diet was formulated to meet the nutrient and energy requirements of the animal (Bath, 1981). Dietary BPF might also improve milk production (Lundquist, 1995). Consequently, knowledge of the composition of BPF fed to livestock is becoming more important and is necessary to use BPF more efficiently in the diets of high producing cows.

By-product feedstuffs are important in the food and fiber system, yet little research has characterized individual BPF. The variability in chemical composition of some BPF was recently shown to be significant (Belyea et al., 1989; Arosemena et al., 1995), and methods to incorporate variability into ration formulation for economic evaluation are developed (St. Pierre and Harvey, 1986a; St. Pierre and Harvey, 1986b; Johnson et al., 1994). The use of rates of digestion and passage to calculate discount values for net energy in ruminant feeds (Van Soest and Fox, 1992) requires accurate estimates of these kinetic parameters and knowledge of factors that may affect these estimates. These kinetic parameters are difficult to estimate, and the assumptions used are tentative.

However, relative comparisons are valuable and important to understanding the impact of the dynamic aspects of nutrient utilization.

The primary objectives were to measure the total extent and rate of digestibility for the NDF and DM components and to analyze the chemical composition of nine selected BPF. The secondary objectives were to estimate the TDN content for each BPF and to evaluate the potential impact of NDF digestion rates on the estimates of TDN.

2. Experimental methods

2.1. Sample collection and preparation

Nine different BPF were obtained from three different sources, resulting in 27 samples for evaluation. The nine BPF were beet pulp (BP), rice bran (RB), almond hulls (AH), citrus pulp (CT), bakery waste (BW), wheat mill run (WMR), brewers grains (BG), distillery grains (DG), and soy hulls (SH). The 27 samples were a subset of a larger experiment consisting of 51 samples reported previously (Arosemena et al., 1995). A description of the methods that were used for sample collection and the chemical composition of all samples were previously reported (Arosemena et al., 1995). Sources of BPF included feed mills and processing plants. The number of sources for each by-product ranged from three to nine. If a BPF was sampled from only three sources, as in the case of DG and SH, all sources were used. For BPF obtained from more than three sources, three sources of each BPF were selected randomly for in sacco evaluation. Chemical composition of the subset of BPF is presented in Table 1.

2.2. In sacco digestion

A nonlactating, nonpregnant Holstein cow (650 kg of body weight) surgically fitted with a ruminal cannula was fed approximately 20 kg (as-fed basis) of a basal diet once daily at 07.00 h (Fadel, 1992). Care of the cow was established under a protocol for animal use and care approved by the Animal Use and Care Administrative Advisory Committee of the University of California at Davis. The diet contained on an as-fed basis 5.0% cracked corn, 5.0% WMR, 5.0% CT, 5.0% BP, 5.0% RB, 5.0% molasses, 15.0% chopped lucerne hay, 54.05% chopped oat hay, 0.5% fat (yellow grease), and 0.45% trace-mineral salt. The diet contained on a DM basis 9.5% ash, 12.3% CP, 28.4% ADF, 45.0% NDF, 3.3% ether extract, and 3.7% lignin. The cow had free access to water.

Multifilament nylon bags, 5 × 12 cm in size with a pore size of approximately 50 μm (Ankom Co., Fairport, NY), were used in a series of in sacco ruminal incubations. Bags were weighed and air dried, and approximately 1.0 g of sample was weighed into each bag to provide a ratio of sample weight to surface area of approximately 8.3 mg cm^{-2}. Bags were then heat sealed with a Nyclone impulse heat sealer (Lorvic Corp., St. Louis,

Table 1
Chemical composition as a percentage of DM and calculated nonstructural carbohydrates and TDN for different by-product feeds

BPF [a]	S [b]	ASH	NDF	ADF	LIG [c]	EE [c]	CP	NDFCP [c]	ADFCP [c]	TDN [d]	NSCa [e]	NSCb [e]
BP	1	6.86	42.18	21.97	1.92	0.31	8.57	4.30	0.88	68.63	42.09	46.39
	2	5.34	37.58	20.08	1.53	0.74	6.03	3.95	0.51	72.58	50.31	54.26
	3	9.55	33.22	17.21	1.12	0.75	9.61	2.92	0.40	70.26	46.87	49.79
RB	1	6.46	20.12	9.38	3.10	18.40	12.94	1.99	0.40	96.02	42.08	44.07
	2	6.47	21.54	10.39	4.31	20.79	13.19	2.10	0.40	97.16	38.01	40.11
	3	6.97	21.49	9.12	3.41	24.25	14.39	2.20	0.45	102.20	32.90	35.10
AH	1	4.76	34.98	25.96	9.20	2.41	6.36	1.82	1.53	64.85	51.50	53.32
	2	5.25	31.88	23.71	8.47	2.42	5.06	1.55	1.53	66.18	55.39	56.94
	3	5.06	35.39	29.14	12.75	2.61	6.50	2.09	2.32	61.45	50.45	52.54
CT	1	7.31	18.98	18.06	0.99	1.14	5.84	0.35	0.28	76.22	66.73	67.08
	2	2.85	14.86	13.85	0.78	1.14	6.60	0.24	0.29	82.09	74.55	74.79
	3	7.54	22.43	21.60	0.88	1.10	6.87	0.74	0.42	75.37	62.06	62.80
BW	1	3.81	17.89	7.51	2.21	4.46	11.91	3.92	1.23	83.29	61.93	65.85
	2	3.57	15.27	6.45	1.86	6.35	11.38	1.48	0.64	86.55	63.44	64.92
	3	3.49	7.52	4.96	1.69	11.70	12.99	0.96	0.44	96.12	64.30	65.26
WMR	1	4.24	38.54	10.75	3.78	7.71	20.27	3.54	0.41	78.55	29.24	32.78
	2	4.86	44.05	13.12	3.98	4.39	18.37	3.92	0.43	71.86	28.33	33.25
	3	3.32	29.91	8.06	2.69	5.31	18.64	2.95	0.33	80.44	42.82	45.77
BG	1	4.19	54.95	20.10	4.66	7.49	26.92	9.23	3.72	73.52	6.45	15.68
	2	2.92	38.72	15.50	4.02	4.96	23.82	4.71	1.73	76.19	29.58	34.29
	3	3.76	51.36	20.06	6.17	5.52	26.23	5.23	2.82	69.16	13.13	18.36
DG	1	4.81	36.29	15.87	3.24	9.27	29.52	12.81	7.46	83.54	20.11	32.92
	2	4.20	38.87	21.17	4.63	11.20	30.12	13.93	9.30	83.99	15.61	29.54
	3	4.05	42.53	22.01	6.35	10.79	29.06	16.75	11.97	80.82	13.57	30.32
SH	1	4.85	58.77	43.79	1.71	3.66	13.73	3.99	0.81	71.00	18.99	22.98
	2	5.05	57.13	49.11	1.82	3.79	10.62	4.05	0.92	71.10	23.41	27.46
	3	5.52	56.51	43.39	1.90	5.75	14.60	3.76	0.91	73.13	17.63	21.39

[a] BPF: By-product feedstuffs—BP, beet pulp; RB, rice bran; AH, almond hulls; CT, citrus pulp; BW, bakery waste; WMR, wheat mill run; BG, brewers' grains; DG, distillery grains; and SH, soy hulls.

[b] S: Sources are denoted 1, 2, and 3.

[c] LIG: Lignin; EE: ether extract; NDFCP: CP associated with NDF, and ADFCP: CP associated with ADF.

[d] Calculated according to Eq. 14 of W.P Weiss et al., 1992.

[e] NSCa = (100 − (ASH + CP + EE + NDF)): nonstructural carbohydrate; NSCb = (100 − (ASH + CP + EE + (NDF − NDFCP))): nonstructural carbohydrate accounting for NDFCP.

MO). Nylon bags containing BPF samples were placed into two large, weighted mesh bags (20 × 35 cm) and were incubated in the ventral sac of the rumen.

One in sacco incubation constituted triplicate bags for two BPF incubated in the rumen for 0, 1, 2, 4, 8, 16, 24, 36, 48, and 72 h. Five series of in sacco incubations were conducted with no interval between each incubation series.

Bags were placed in the rumen at different times and were retrieved as a group (Nocek, 1988). Upon removal from the rumen, bags were immediately submerged into a cool water bath to stop microbial activity, and then washed under tap water until the rinse fluid was clear. Bags were then rinsed with deionized water, drained, dried for 48 h at 55°C, cooled in a desiccator, and weighed for determination of DM.

Digestibility of NDF was determined by placing approximately 55 bags in a 5 L beaker and refluxing for 1 h with neutral detergent solution added to provide at least 50 ml of solution per bag. After 1 h, bags were rinsed six times with hot deionized water. Bags were then placed on trays, dried at 100°C for 24 h, cooled in a desiccator, and weighed. The NDF remaining at each incubation time was calculated as the difference between the final dry weight of the bag with NDF and the initial weight of the bag without the feed sample divided by the amount of the initial DM sample.

The rumen environment consistency across different in sacco incubation series was evaluated by measuring ruminal pH and the concentration of volatile fatty acids and ammonia N as well as including lucerne as a reference standard. Ruminal fluid pH, volatile fatty acids, and ammonia N were measured to characterize the ruminal conditions across the incubation series. A sample of ruminal fluid was collected each time bags were placed into the rumen. Ruminal fluid was strained through cheese cloth, and the pH was immediately measured using a digital pH/mV/ORP meter (Cole-Palmer Instrument Co., Chicago, IL). A 10 ml sample of ruminal fluid was acidified with 2 ml of 25% metaphosphoric acid (wt/vol), frozen, and analyzed for acetic, propionic, butyric, isovaleric, and valeric acids by gas liquid chromatography (Baker, 1966). Ammonia nitrogen of ruminal fluid was determined according to Marsh et al. (1957) and Skeggs (1957). Lucerne samples were prepared as other BPF samples and incubated, in triplicate, at selected times during each incubation series. In addition to the reference standard, empty bags were placed into the rumen, in triplicate, at different times to correct for any change in initial bag weight.

2.3. Chemical analysis

Methods of analysis for crude protein (CP; 6.25 × %N), ash, ether extract (EE), NDF, and ADF were previously reported (Arosemena et al., 1995) with the exception of determination of fiber associated N. The NDF and ADF residues were ashed and reported on a DM basis. The CP associated with the NDF (NDFCP) and ADF (ADFCP) fractions was determined by Kjeldahl analysis of the NDF and ADF fractions. Nonstructural carbohydrate (NSC) was calculated either as $\mathrm{NSCa} = 100 - (\mathrm{ash} + \mathrm{CP} + \mathrm{EE} + \mathrm{NDF})$ or $\mathrm{NSCb} = 100 - (\mathrm{ash} + \mathrm{CP} + \mathrm{EE} + (\mathrm{NDF} - \mathrm{NDFCP}))$, where NSCb accounts for the NDF bound protein and avoids double counting of some CP.

2.4. Statistical method

One-way analysis of variance (Snedecor and Cochran, 1980) was performed for DM and NDF for each BPF incubation time using standard procedures (Statistical Analysis Systems Institute Inc., 1987). A mathematical model described by Robinson et al. (1986) was used to determine the rate of disappearance (k_d) for DM and NDF:

$$f(t) = A^{*} e^{-k_d t} + U$$

where: $f(t)$ is substrate remaining at time t (h); A is size of degradable fraction (%); k_d is rate constant for degradation (h^{-1}); U is size of undegradable fraction (%).

This model assumes that substrate degradation is a first-order process, and that all substrate is available for degradation at $t = 0$ (Robinson et al., 1986). Lag models and multipool models were tested, and little improvement in fit was observed for all BPF.

The time required for half of the substrate to disappear, $T_{1/2}$, was calculated using the equation $\ln(2)/k_d$. The TDN contents of BPF were determined using an equation developed by Weiss et al. (1992) which includes a NDF fraction adjusted for associated CP referred to here as NDF_N where $NDF_N = NDF - NDFCP + 0.4 * ADFCP$ which accounts for the CP associated with the NDF and ADF constituents in a feedstuff. These TDN estimates were subsequently discounted by substituting the digestion coefficient 0.75 for NDF_N minus lignin in equation of Weiss et al. (1992) with $k_d/(k_d + k_p)$ where k_p was equal to 0.02, 0.04, or 0.06, and k_d was estimated from the in sacco data using the model described previously.

3. Results and discussion

3.1. Nutrient composition

The chemical composition of a given BPF varied with source of the feedstuff (Table 1). For example, the NDF content of BP ranged from 33.22 to 42.18%, and the NDF content of CT ranged from 14.86 to 22.43%. The NDF composition of RB was less variable, but the content of EE ranged from 18.40 to 24.25%. In the case of RB, the variability in the content of EE could pose a problem because this BPF is often included in the ration as a source of fat. The CP content of BG and DG, which were categorized as protein by-products (Bath, 1981), varied little among sources of each feedstuff. Consequently, the variability in composition for a given BPF must be evaluated with respect to how the feedstuff is used in the diet formulation. For example, a feedstuff may be considered a source of fiber, protein, or fat.

Few estimates of the NDFCP and ADFCP fractions of BPF are reported. Less CP was associated with the ADF than with the NDF fraction for most feedstuffs (Table 1). Within a BPF, the NDFCP percentage was similar, except for BW, which had a low of 0.96% and a high of 3.92% for source of the feedstuff; 30% to 66% of the CP in BP was associated with the NDF fraction. The importance of NDFCP in BP and CT is unknown because both feedstuffs are not included typically in rations as protein sources and information on the digestibility of the fiber associated CP is not known. In contrast, DG and BG often are fed as protein supplements so fiber associated protein might be a concern. For DG, 43 to 58% and for BG, 20 to 34% of the CP was associated with the NDF. Firkins (1995) reported that BG contained more than 25% of the CP in NDF, which is comparable with the estimates observed in the present study. The digestibility of the CP associated with the NDF and ADF fractions was not determined in the present study, and limited data describe the availability of this protein.

The NSC content (Table 1) of each BPF was calculated using two similar methods with the major difference being that NSCb accounts for the CP in the NDF whereas NSCa does not. The NSCa underestimated the content of NSC content because it did not account for the NDFCP fraction. When accounting for NDFCP using NSCb, NSC estimates increased 20, 39, and 88% for SH, BG, and DG. The content of NSC in BP increased approximately 8% when the NDFCP was considered. Firkins (1995) recently discussed the use of non-forage fiber BPF to dilute the dietary concentration of rapidly fermentable ruminal starch as a method to maintain high DM intake and reduce perturbations of ruminal fermentation balance. Failing to account for the NDFCP of a BPF underestimates NSC. The implications of under estimating NSC of BPF in regard to production performance of ruminants is unknown.

3.2. *In sacco determinations*

The changes in ruminal fluid pH, the ratio of acetate to propionate, and ammonia N concentration at each sampling time across incubation series were similar (Table 2), suggesting that fermentation conditions were similar for all five incubation series. Although not shown, molar proportions of acetate, propionate, butyrate, isovalerate, and valerate did not differ between incubation series. Disappearance of DM and NDF for the reference sample of lucerne was consistent throughout the five in sacco incubation series. Comparisons across in sacco incubation series were possible because the ruminal measurements were consistent. Corrections were necessary for the NDF remaining in the bag after it was determined that the control bags lost an average of 7×10^{-3} g following treatment with neutral detergent solution. No correction for DM was made because there was no loss in bag weight.

The proportion of NDF remaining in nylon bags for each BPF was used to determine the amount of NDF remaining after in sacco digestion. The amount of NDF remaining at each time interval varied by source of the individual BPF for all BPF studied, although the differences between sources within RB, DG, and SH were smaller than observed for other BPF as incubation time increased (Table 3). Beet pulp is often thought to vary little from source to source in chemical composition and feeding value. However, the proportion of NDF remaining at each time interval suggests that considerable NDF variability existed in this BPF. For BG, two sources (1 and 3) were similar in the amount of NDF remaining at each time interval while source 2 was distinctly different from the other two sources ($P < 0.05$). Variation in ruminal disappearance of NDF from each source within a given BPF could have been due to the differences in processing methods used, for example BP and RB; due to the ingredients used during processing, as in the case of BW; due to the season of harvest for BPF such as CT; or due to the differences in the original plant material, as with AH (Arosemena et al., 1995).

Standard deviation was used as a measure of the variability within a BPF for the digestion parameters estimated in sacco (Table 4). Considerable variability was found in the percentage degradable (A) and undegradable (U) NDF for all BPF. The variability in the percentage of degradable NDF and NDF digestion rate (k_d) was large for BW compared with the other BPF evaluated. However, BW is low in NDF content and

Table 2
Ruminal ammonia, pH, and the ratio of acetate to propionate for five independent in sacco incubation series

	Time (h) *	24-h clock †	Series					Mean	SD
			1	2	3	4	5		
Ammonia (mg dl^{-1})	0	21	5.76	6.93	7.17	2.47	1.41	4.75	2.645
	1	20	3.64	5.88	11.90	4.94	3.88	6.04	3.378
	2	19	5.88	6.71	9.87	8.46	7.29	7.64	1.560
	4	17	8.23	5.88	4.23	6.58	7.29	6.44	1.512
	8	13	2.47	7.52	3.41	3.41	4.94	4.35	1.981
	16	5	2.82	5.76	5.41	2.71	5.29	4.40	1.501
	24	21	4.47	4.01	5.05	3.76	3.76	4.21	0.552
	36	9	6.58	13.90	7.99	6.58	14.69	9.94	4.012
	48	21	4.71	6.11	3.06	5.64	5.64	5.03	1.214
	72	21	1.67	5.76	6.93	7.17	2.47	4.80	2.564
pH	0	21	6.01	5.79	6.25	6.18	5.88	6.02	0.194
	1	20	5.92	5.90	6.29	6.04	5.88	6.01	0.171
	2	19	6.06	6.03	6.50	6.31	6.02	6.18	0.213
	4	17	6.06	6.16	6.51	5.93	6.08	6.15	0.219
	8	13	6.34	6.21	6.58	6.35	6.25	6.35	0.144
	16	5	6.64	6.69	6.67	6.20	6.61	6.56	0.205
	24	21	5.66	5.84	5.86	5.86	5.70	5.78	0.096
	36	9	6.40	6.41	6.50	6.57	6.54	6.48	0.076
	48	21	5.67	6.08	6.01	5.79	5.70	5.85	0.185
	72	21	5.95	6.01	5.79	6.25	6.18	6.04	0.184
Acetate:propionate	0	21	3.57	2.81	3.37	3.23	3.58	3.31	0.316
	1	20	3.45	3.19	3.24	3.11	3.25	3.24	0.126
	2	19	3.22	3.34	3.14	3.83	3.15	3.34	0.285
	4	17	3.31	3.61	3.48	3.80	3.93	3.62	0.247
	8	13	3.88	3.38	3.63	3.94	3.52	3.67	0.237
	16	5	4.10	4.21	4.46	3.48	4.06	4.06	0.362
	24	21	3.45	2.39	3.43	3.68	3.36	3.26	0.502
	36	9	2.93	3.41	3.74	3.62	3.39	3.42	0.309
	48	21	3.37	2.40	3.13	2.68	3.26	2.97	0.412
	72	21	3.16	3.57	2.81	3.37	3.23	3.23	0.281

* Time: hours that bags were in the rumen.
† Clock: 24-h time.

therefore, is not typically included in a dairy ration as a source of fiber. Variability in degradable NDF and NDF digestion rates was low for BP and SH. Typically these feedstuffs are included in the ration to provide fiber.

Few estimates of NDF degradation rates are available for comparison. The rates of NDF digestion ranged from 0.073 to 0.090 h^{-1} for BP and 0.036 to 0.039 h^{-1} for SH (Table 4). In contrast, Firkins (1995) reported a much larger range in NDF digestion for both BP, 0.055 to 0.116 h^{-1}, and SH, 0.011 to 0.077 h^{-1}. Soy hulls often replace a portion of the BP in dairy rations when economics favor this substitution. Beet pulp, like SH, was high in both NDF content and degradable NDF and low in undegradable NDF

Table 3
Neutral detergent fiber remaining by time interval during in sacco incubation

Time (h)											
BPF [*]	S [†]	0	1	2	4	8	16	24	36	48	72
BP	1	42.45^{a}	41.37^{a}	39.96^{a}	39.82^{a}	34.12^{a}	8.75	5.69^{a}	4.68^{a}	4.57^{a}	4.27^{a}
	2	37.07^{b}	35.94^{b}	35.92^{b}	34.35^{b}	24.41^{b}	6.97	4.57^{ab}	4.17^{a}	3.97^{b}	3.78^{b}
	3	32.89^{c}	32.66^{c}	32.09^{c}	29.54^{c}	19.52^{c}	6.24	3.52^{b}	3.22^{b}	2.96^{c}	2.78^{c}
SE		0.348	0.299	0.332	0.752	1.112	1.151	0.417	0.211	0.089	0.044
RB	1	19.19	18.30^{b}	18.22	17.54	15.62	12.30	11.98	11.53^{a}	10.82	10.34^{a}
	2	18.73	19.17^{a}	18.57	17.17	16.15	11.69	11.24	10.49^{b}	10.15	9.25
	3	19.35	19.31^{a}	18.83	18.24	15.99	12.83	11.84	11.56^{a}	10.63	9.86
SE		0.327	0.213	0.368	0.352	0.586	0.274	0.504	0.239	0.547	0.399
AH	1	33.68^{a}	33.26^{a}	32.76^{a}	31.94^{a}	29.14^{a}	24.14^{a}	19.30^{a}	16.99^{b}	16.46^{b}	16.11^{a}
	2	29.97^{b}	27.87^{b}	22.79^{c}	22.35^{c}	19.16^{c}	19.81^{b}	16.31^{b}	17.64^{b}	12.84^{c}	9.53^{b}
	3	31.08^{b}	29.00^{b}	27.50^{b}	26.98^{b}	24.52^{b}	24.40^{a}	20.88^{a}	20.27^{a}	18.31^{a}	16.50^{a}
SE		0.637	0.472	0.578	0.253	0.851	0.962	0.627	0.757	0.319	0.339
CT	1	23.49^{a}	20.91^{a}	18.56^{b}	18.14^{b}	14.48^{b}	2.36	1.24^{b}	1.11^{b}	1.13^{b}	1.44^{b}
	2	19.19^{b}	16.24^{b}	15.64^{c}	14.27^{c}	12.05^{c}	1.58	0.96^{c}	0.93^{b}	0.95^{b}	1.02^{c}
	3	24.22^{a}	23.00^{a}	22.22^{a}	20.78^{a}	18.44^{a}	2.30	2.25^{a}	1.86^{a}	1.74^{a}	1.93^{a}
SE		0.650	0.652	0.281	0.556	0.517	0.213	0.067	0.110	0.051	0.063
BW	1	15.20^{a}	13.25^{a}	12.19^{a}	11.82^{a}	10.32^{a}	8.17^{a}	5.49^{a}	4.62^{b}	4.71	3.63^{b}
	2	11.87^{b}	11.49^{b}	10.13^{b}	9.27^{b}	8.77^{b}	7.89^{a}	6.02^{a}	5.43^{a}	4.92	4.20^{a}
	3	7.74^{c}	7.00^{c}	6.31^{c}	5.86^{c}	5.48^{c}	4.24^{b}	3.32^{b}	3.54^{c}	3.32	3.08^{c}
SE		0.457	0.355	0.178	0.343	0.268	0.389	0.252	0.059	0.766	0.158
WMR	1	38.90^{b}	36.77^{b}	32.45^{b}	28.69^{b}	25.88^{b}	22.75^{b}	20.98^{b}	19.68^{b}	18.72^{b}	15.31^{b}
	2	44.04^{a}	41.98^{a}	37.17^{a}	34.46^{a}	30.57^{a}	25.89^{a}	25.34^{a}	22.02^{a}	21.24^{a}	18.87^{a}
	3	30.84^{c}	29.40^{c}	25.27^{c}	23.22^{c}	17.08^{c}	16.31^{c}	15.00^{c}	13.63^{c}	13.12^{c}	10.84^{c}
SE		0.148	0.230	0.310	0.439	0.459	0.670	0.296	0.086	0.465	0.175
BG	1	53.12^{a}	51.46^{a}	47.01^{a}	43.85^{a}	35.67	31.17^{a}	27.26^{a}	23.84^{a}	21.33^{a}	18.50^{a}
	2	38.91^{b}	37.34^{b}	37.21^{b}	32.45^{b}	29.92	21.36^{b}	19.95^{b}	16.52^{b}	16.59^{b}	13.75^{b}
	3	53.32^{a}	48.98^{a}	47.99^{a}	43.80^{a}	40.02	30.09^{a}	27.53^{a}	22.86^{a}	20.11^{a}	18.54^{a}
SE		0.840	0.854	0.724	0.903	2.323	0.347	1.242	0.297	0.726	0.589
DG	1	35.26^{b}	34.11^{b}	33.04	30.78	22.67	13.54	12.66	10.36^{a}	7.84^{a}	5.10
	2	36.59^{b}	34.29^{b}	33.40	32.19	21.83	18.08	13.56	7.86^{b}	6.30^{b}	5.71
	3	39.76^{a}	38.14^{a}	35.31	30.40	24.37	15.39	14.79	10.89^{a}	8.51^{a}	6.79
SE		0.620	0.591	0.885	1.119	1.043	1.090	0.992	0.679	0.321	0.487
SH	1	57.08	55.58^{a}	56.71	53.10^{b}	46.31^{b}	34.04	27.46^{a}	16.19	5.42	4.16
	2	59.30	58.24^{a}	56.70	56.44^{a}	50.40^{a}	36.88	27.69^{a}	10.48	5.54	4.20
	3	55.34	51.69^{b}	53.31	50.68^{c}	45.81^{b}	31.34	20.67^{b}	14.72	5.00	4.36
SE		1.086	0.921	0.918	0.303	0.526	2.333	1.136	1.695	0.307	0.133

[*] BPF: By-product feedstuffs—BP, beet pulp; RB, rice bran; AH, almond hulls; CP, citrus pulp; BW, bakery waste; WMR, wheat mill run; BG, brewers' grains; DG, distillery grains; and SH, soy hulls.

[†] S: Sources are denoted 1, 2, and 3.

[a,b,c] Different superscripts for Sources 1, 2, and 3 within a specific time for each BPF differ ($P < 0.05$).

Table 4
Estimated and calculated in sacco digestion parameters for DM and NDF

BPF *	S †	DM					NDF				
		A ‡	k_d	U	$T_{1/2}$	R^2	A	k_d	U	$T_{1/2}$	R^2
BP	1	70.6	0.075	1.1	9.2	0.94	44.3	0.073	1.8	9.5	0.94
	2	65.2	0.086	1.7	8.1	0.96	38.3	0.085	2.1	8.2	0.96
	3	53.7	0.092	1.4	7.5	0.97	34.6	0.090	1.5	7.7	0.97
Mean		63.1	0.084	1.4	8.3	0.95	39.1	0.083	1.8	8.5	0.96
SD		8.6	0.009	0.3	0.9	0.02	4.9	0.009	0.3	0.9	0.02
RB	1	36.8	0.092	16.6	7.5	0.98	8.8	0.075	10.5	9.2	0.96
	2	35.2	0.081	15.2	8.6	0.97	10.1	0.068	9.4	10.2	0.94
	3	26.6	0.073	18.5	9.5	0.96	9.8	0.065	10.0	10.6	0.98
Mean		32.8	0.082	16.8	8.5	0.97	9.6	0.070	10.0	10.0	0.96
SD		5.5	0.010	1.7	1.0	0.01	0.7	0.005	0.6	0.7	0.02
AH	1	34.5	0.058	16.8	11.9	0.98	19.9	0.051	14.7	13.6	0.98
	2	28.3	0.072	14.4	9.7	0.93	16.3	0.040	10.4	17.4	0.83
	3	24.9	0.055	20.1	12.6	0.94	13.2	0.039	16.2	17.6	0.93
Mean		29.2	0.062	17.1	11.4	0.95	16.5	0.043	13.8	16.2	0.91
SD		4.9	0.009	2.9	1.5	0.03	3.3	0.007	3.1	2.2	0.07
CT	1	63.6	0.082	0.0	8.5	0.94	23.5	0.094	0.3	7.4	0.96
	2	50.2	0.080	0.0	8.6	0.94	19.0	0.094	0.2	7.4	0.96
	3	74.9	0.085	0.0	8.2	0.92	25.5	0.083	0.5	8.3	0.94
Mean		62.9	0.082	0.0	8.4	0.94	22.7	0.091	0.3	7.7	0.95
SD		12.4	0.002	0.0	0.2	0.01	3.3	0.006	0.2	0.6	0.01
BW	1	30.6	0.122	7.8	5.7	0.96	10.6	0.063	3.7	10.9	0.95
	2	33.8	0.114	8.4	6.1	0.96	7.1	0.054	7.9	12.9	0.95
	3	31.8	0.189	8.0	3.7	0.94	4.2	0.097	3.2	7.2	0.95
Mean		32.1	0.142	8.1	5.1	0.95	7.3	0.071	5.0	10.3	0.95
SD		1.6	0.041	0.3	1.3	0.01	3.2	0.023	2.6	2.9	0.00
WMR	1	36.4	0.135	20.2	5.1	0.98	19.6	0.117	18.3	5.9	0.96
	2	37.8	0.118	23.1	5.9	0.98	21.9	0.097	20.9	7.1	0.97
	3	35.9	0.153	14.5	4.5	0.97	17.8	0.150	13.1	4.6	0.96
Mean		36.7	0.135	19.3	5.2	0.98	19.8	0.122	17.5	5.9	0.96
SD		1.0	0.018	4.4	0.7	0.01	2.1	0.026	4.0	1.2	0.01
BG	1	47.0	0.057	23.0	12.2	0.96	32.2	0.072	20.2	9.6	0.96
	2	34.5	0.069	15.7	10.1	0.98	24.8	0.068	14.4	10.3	0.98
	3	48.1	0.063	22.4	11.0	0.99	33.4	0.060	18.5	11.6	0.99
Mean		43.2	0.063	20.4	11.1	0.98	30.1	0.067	17.7	10.5	0.98
SD		7.6	0.006	4.1	1.1	0.01	4.7	0.006	3.0	1.0	0.01
DG	1	45.3	0.059	13.6	11.9	0.96	30.0	0.071	6.3	9.8	0.98
	2	45.6	0.054	14.3	12.9	0.97	31.8	0.059	4.9	11.7	0.98
	3	42.6	0.066	17.5	11.5	0.98	31.8	0.080	8.0	8.6	0.99
Mean		44.5	0.058	15.1	12.1	0.97	31.2	0.070	6.4	10.0	0.98
SD		1.7	0.003	2.1	0.7	0.01	1.1	0.010	1.6	1.5	0.01

Table 4 (continued)

BPF [*]	S [†]	DM					NDF				
		A [‡]	k_d	U	$T_{1/2}$	R^2	A	k_d	U	$T_{1/2}$	R^2
SH	1	86.4	0.044	0.0	15.7	0.99	59.5	0.036	0.0	19.2	0.98
	2	90.3	0.047	0.0	14.9	0.98	62.5	0.038	0.0	18.2	0.97
	3	85.0	0.050	0.9	14.0	0.99	56.9	0.039	0.0	17.8	0.98
Mean		87.2	0.047	0.3	14.8	0.99	59.7	0.038	0.0	18.4	0.98
SD		2.7	0.003	0.5	0.8	0.00	2.8	0.001	0.0	0.7	0.01

[*] BPF: By-product feedstuffs—BP, beet pulp; RB, rice bran; AH, almond hulls; CT, citrus pulp; BW, bakery waste; WMR, wheat mill run; BG, brewers' grains; DG, distillery grains; and SH, soy hulls; R^2 values represent the coefficient of multiple determination for the full model.

[†] S: Sources are denoted 1, 2, and 3.

[‡] A: Degradable fraction (%); U: Undegradable fraction (%); k_d: rate constant for degradation (h^{-1}); and $T_{1/2}$: half life (h).

content (Table 4). However, degradation rates of DM and NDF observed in the present study were slower for SH than for BP which could influence DM intake and nutrient utilization in the rumen. Beet pulp exhibited a much higher mean rate of NDF digestion ($k_d = 0.083$ h^{-1}) than did SH ($k_d = 0.038$ h^{-1}). This difference was also reflected in the 8.5 h half-life of NDF for BP compared with 18.4 h for SH. The extent of ruminal NDF digestion observed at 72 h of incubation was high for both BP and SH (Table 3). The implications of differences in extent and rate of NDF digestion between BPF, for example BP and SH, in practical feeding programs are unknown. However, Firkins (1995) reported that the NDF of BP was more effective in stimulating chewing than the NDF of oat hulls, but the NDF of oat hulls was more effective in promoting milk fat than the NDF of BP.

Half-life ($T_{1/2}$) estimates of DM and NDF disappearance exhibited considerable variability within a given BPF similar to estimates of k_d (Table 4). Half-life of NDF disappearance was longest for SH (18.4 h) and shortest for WMR (5.9 h).

The TDN content of BPF was estimated using an equation developed by Weiss et al. (1992), which assumed a rate of passage of $k_p = 0.02$ h^{-1} which was equivalent to a maintenance level of feed intake and a constant digestion coefficient ($k_d/(k_d + k_p)$) of 0.75 (Table 5). To assess the potential implications of the digestion rate of NDF on the estimation of TDN, the digestion coefficient of 0.75 was replaced by $k_d/(k_d + k_p)$, where k_d of each BPF was obtained from in sacco measurements (Table 4). The rate of passage included 0.02, 0.04, or 0.06 h^{-1} to evaluate TDN based on the intake at maintenance and two levels above maintenance. The TDN estimates determined according to the equation of Weiss et al. (1992) were similar to the TDN estimates obtained using the k_d of NDF for each individual BPF (TDN1) and a k_p of 0.02 h^{-1}, except for WMR and SH. As k_p increased, estimates of TDN decreased for all BPF. However, the depression in TDN with increasing k_p was greatest for SH. Soy hulls were high in NDF content, but the average k_d of NDF was 0.038 h^{-1} and higher only than the k_p for maintenance. In contrast, TDN estimates of WMR, BW, and CT changed less with increasing k_p. Wheat mill run although high in NDF content contained NDF with a high average k_d, but BW and CT contained NDF with lower k_d and NDF content than

Table 5

Calculated TDN using N adjusted NDF (NDF_N) and digestion coefficients from literature (TDN) or coefficients based on in sacco NDF rates of digestion (k_d) and increasing rates of passage

BPF [*]	S [†]	NDF (% DM)	NDF_N (% DM)	k_d h^{-1}	TDN [‡] (%)	TDN1 [$] (%)	TDN2 [$] (%)	TDN3 [$] (%)
BP	1	42.18	38.23	0.073	68.63	69.75	65.40	62.36
	2	37.58	33.83	0.085	72.58	74.26	70.60	67.95
	3	33.22	30.46	0.090	70.26	72.03	68.74	66.33
RB	1	20.12	18.29	0.075	96.02	96.45	95.01	93.99
	2	21.54	19.60	0.068	97.16	97.38	95.99	95.03
	3	21.49	19.47	0.065	102.20	102.37	100.77	99.68
AH	1	34.98	33.77	0.051	64.85	64.39	62.14	60.70
	2	31.88	30.94	0.040	66.18	65.08	62.91	61.61
	3	35.39	34.23	0.039	61.45	60.55	58.82	57.79
CT	1	18.98	18.74	0.094	76.22	77.37	75.49	74.11
	2	14.86	14.73	0.094	82.09	82.99	81.52	80.42
	3	22.43	21.86	0.083	75.37	76.41	73.99	72.24
BW	1	17.89	14.46	0.063	83.29	83.38	82.09	81.22
	2	15.27	14.05	0.054	86.55	86.35	84.94	84.03
	3	7.52	6.74	0.097	96.12	96.36	96.00	95.72
WMR	1	38.54	35.16	0.117	78.55	81.09	78.45	76.41
	2	44.05	40.30	0.097	71.86	74.13	70.68	68.11
	3	29.91	27.09	0.150	80.44	82.97	81.19	79.75
BG	1	54.95	47.20	0.072	73.52	74.62	69.95	66.69
	2	38.72	34.70	0.068	76.19	76.70	73.34	71.03
	3	51.36	47.26	0.060	69.16	69.14	64.56	61.50
DG	1	36.29	26.46	0.071	83.54	84.06	81.59	79.88
	2	38.87	28.66	0.059	83.99	83.96	81.41	79.72
	3	42.53	30.57	0.080	80.82	81.61	79.51	78.02
SH	1	58.77	55.11	0.036	71.00	65.86	57.72	52.97
	2	57.13	53.44	0.038	71.10	66.75	58.99	54.39
	3	56.51	53.11	0.039	73.13	69.02	61.38	56.82

[*] BPF: By-product feedstuffs—BP, beet pulp; RB, rice bran; AH, almond hulls; CT, citrus pulp; BW, bakery waste; WMR, wheat mill run; BG, brewers' grains; DG, distillery grains; and SH, soy hulls.

[†] S: Sources are denoted 1, 2, and 3.

[‡] Calculated according to the equation of Weiss et al., 1992.

[$] TDN1, TDN2, and TDN3: 0.75 digestion coefficient for NDF_N minus lignin in equation 14 by Weiss et al., 1992, replaced by $k_d/(k_p + k_d)$, where k_d is in sacco NDF rate of digestion and k_p is rate of passage at 0.02, 0.04, and 0.06 h^{-1} for TDN1, TDN2, and TDN3, respectively.

WMR. On a practical basis, the previous estimates of TDN would suggest that although SH often replace BP in diet formulations when cost dictates such a substitution, production performance might be compromised especially at higher rates of passage.

4. Summary

The chemical composition of nine selected BPF varied with source of the feedstuff. The variation in chemical composition with source of the BPF could be related to the processing methods used, to the ingredients used during processing, or to differences in the original plant material. The NDF fraction of the BPF studied was found to contain CP, and the proportion of the total CP found in the NDF fraction varied for BPF. For DG, 43 to 58% of the total CP was associated with the NDF. As much as 66% of the CP in BP was associated with the NDF fraction while a maximum of 11% was observed for CT. The proportion of CP associated with the NDF influenced the estimate of NSC in the BPF. Since NSC is often calculated as NSC = 100 − (ash + CP + EE + NDF), not correcting for the CP in the NDF fraction will result in an underestimation of the NSC of the BPF. The greater the NDFCP in the BPF, the greater is the underestimation of the NSC content.

Estimates of NDF degradation rates obtained from in sacco digestion varied for source of the BPF. Some BPF demonstrated large variation while other BPF were more similar across sources of the feedstuff. The estimation of TDN content of the BPF varied when the rate of NDF digestion for each BPF was used at three rates of passage. As the rate of passage from the rumen increased, estimates of TDN decreased for all BPF. However, the depression in TDN was greatest with increasing rate of passage for those BPF which displayed the lowest rate of NDF digestion and the highest NDF content.

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References

Arosemena, A., DePeters, E.J. and Fadel, J.G., 1995. Extent of variability in nutrient composition within selected by-product feedstuffs. Anim. Feed Sci. Technol., 54: 103–120.

Baker, R.A., 1966. Volatile fatty acids in aqueous solution by gas liquid chromatography. J. Gas Chromatogr., 4: 418–419.

Bath, D.L., 1981. Feed by-products and their utilization by ruminants. In: J.T. Huber (Editor). Upgrading Residues and By-products for Animals. CRC Press, Boca Raton, FL.

Bath, D., Dunbar, J., King, J., Berry, S. and Olbrich, S., 1993. By-products and unusual feedstuffs. (Ref. Issue). Feedstuffs, 65: 32–37.

Belyea, R.L., Stevens, B.J., Restrepo, R.J. and Clubb, A.P., 1989. Variation in composition of by-product feeds. J. Dairy Sci., 72: 2339–2345.

Fadel, J.G., 1992. Application of theorectical optimal sampling schedule designs for fiber digestion paarameter estimation in sacco. J. Dairy Sci., 75: 2184–2189.

Firkins, J.L., 1995. Fiber value of alternative feeds. In: M.L. Eastridge (Editor). Alternative Feeds for Dairy and Beef Cattle. Proc. 2nd Natl. Alternative Feeds Symp., Ohio State Univ.

Grasser, L.A., Fadel, J.G., Garnett, I. and DePeters, E.J., 1995. Quantity and economic importance of nine selected by-products used in California dairy rations. J. Dairy Sci., 78: 962–971.

Johnson, H.A., Fadel, J.G. and Howitt, R.E., 1994. Evaluating the cost of nutrient variance and risk of meeting the animal's requirements using linear and nonlinear programming techniques. Proc. Western Sec. J. Anim. Sci., 45: 330–333.

Lundquist, R., 1995. Current uses of traditional co-products. In: M.L. Eastridge (Editor). Alternative Feeds for Dairy and Beef Cattle. Proc. 2nd Natl. Alternative Feeds Symp., Ohio State Univ.

Marsh, W.B., Fingerhut, B. and Kirch, E., 1957. Determination of urea nitrogen with diacetyl method and an automated dialyzing apparatus. Am. J. Clin. Pathol., 28: 681–688.

Nocek, J.E., 1988. In situ and other methods to estimate ruminal protein and energy digestibility: a review. J. Dairy Sci., 71: 2051–2069.

Robinson, P.H., Fadel, J.G. and Tamminga, S., 1986. Evaluation of mathematical models to describe neutral detergent soluble residue in terms of its susceptibility of degradation in the rumen. Anim. Feed Sci. Technol., 15: 249–271.

Statistical Analysis Systems Institute Inc., 1987. SAS User's Guide: Statistics, Version 6.04 edn. 1987. SAS Inst. Inc., Cary, NC.

Snedecor, G.W. and Cochran, W.G., 1980. Statistical methods. Iowa State Univ. Press, Ames, IO.

Skeggs, L.T., 1957. An automated method for colorimetric analysis. Am. J. Clin. Pathol., 28: 311–322.

St. Pierre, N.R. and Harvey, W.R., 1986a. Incorporation of uncertainity in composition of feeds into least cost ration models. 1. Single chance constrained programming. J. Dairy Sci., 69: 3051–3062.

St. Pierre, N.R. and Harvey, W.R., 1986b. Incorporation of uncertainity in composition of feeds into least cost ration models. 1. Joint chance constrained programming. J. Dairy Sci., 69: 3063–3073.

Van Soest, P.J. and Fox, D.G., 1992. Discounts for net energy and protein-fifth revision. Proc. Cornell Nutrition Conference for Feed Manufacturers, 1992, Rochester, NY. Cornell University, Ithaca, NY, pp. 40–68.

Weiss, W.P., Conrad, H.R. and St. Pierre, N.R., 1992. A theoretically-based model for predicting total digestible nutrient values of forages and concentrates. Anim. Feed Sci. Technol., 39: 95–110.