13 Carbohydrate Chemistry and Feed Processing

NONSTRUCTURAL CARBOHYDRATES

The more readily digestible carbohydrates in animal feeds lack a satisfactory system of classification, even though they represent the major energy yielding components of feedstuffs. The lack of an adequate definition is partly a function of the diversity of the chemical fraction as well as lack of basic research into their specific nutritive characteristics. The nonstructural carbohydrates are those carbohydrates not included in the cell wall matrix and they are not recovered in NDF. By this definition, the nonstructural carbohydrates are comprised of sugars, starches, organic acids, and other reserve carbohydrates such as fructans.

Nonstructural carbohydrates can be classified as water-soluble (including monosaccharides, disaccharides, oligosaccharides, and some polysaccharides) and larger polysaccharides that are insoluble in water. Water soluble nonstructural carbohydrates, such as sugars (glucose and fructose) and disaccharides (sucrose and lactose) are rapidly fermented in the rumen and comprise a significant fraction of certain feeds (molasses, sugar beets, high sugar corn grain, and whey). Sugar content of fresh grasses and legumes is variable and may exceed 10 percent of the dry matter (DM), but hay and silage have lower concentrations because of losses from fermentation and respiration. Temperate grasses store fructans in leaves and stems as water-soluble levan. Fructosan is increased by cool weather and may increase to as much as 30 percent of the DM for cool season perennial ryegrass (Van Soest, 1983). Although water-soluble carbohydrates may be high in individual feeds, concentrations are generally low in ruminant diets. Galactans are the storage carbohydrate of leguminous plants, and the B-glucan gums are found in the bran of barley, oats, and rye, and the cell wall of grasses (Aman and Hesselman, 1985). Pectins are associated with the cell wall but are not covalently linked to the lignified portions and are almost completely digested (90 to 100 percent) in the rumen. Pectin concentrations on a DM basis are high in citrus and beet pulps, soybean hulls, and dicotyledonous legume forages but are low in grasses (Allen and Knowlton, 1995). Starch is the major storage carbohydrate in most cereal grains. It is composed of two major molecules: amylose and amylopectin. Amylose is a linear polymer of α 1-4, D-glucose units while amylopectin is a branched polymer with linear chains of α D-glucose that has a branch point every 20 to 25 glucose units (French, 1973). Most forages contain little starch with the exception of small grain silage (10 to 20 percent of DM), grain sorghum silage (25 to 35 percent), and corn silage (25 to 35 percent of DM). The ruminal degradation of starch is variable ranging from 40 to over 90 percent depending on source, processing, and other factors.

ANALYTIC PROCEDURES

Neutral Detergent Fiber

The accuracy of feed composition data and requirements for NDF and NSC is compromised by the lack of standard methods. The neutral detergent fraction includes cellulose, hemicellulose, and lignin as the major components. There are three major modifications of the NDF method, each of which generates different values depending upon the feed that is analyzed. The original NDF method (Van Soest and Wine, 1967, Goering and Van Soest, 1970) used sodium sulfite to remove contaminating proteins from NDF by cleaving disulfide bonds and dissolving many crosslinked proteins. It was discovered that the original method did not adequately remove starch from grains and corn silage. The neutral detergent residue modification was developed that included a heat-stable amylase in the procedure to remove starch, however, sulfite was removed from the procedure because of concerns about the possible loss of lignin and phenolic compounds (Van Soest et al., 1991). The amylase-treated NDF modification (aNDF) was developed to measure NDF in all types of feeds and uses both heat-stable amylase and sodium sulfite to obtain NDF with minimum contamination by either starch or protein. It has been adopted as the reference method for NDF by the National Forage Testing Association (Undersander et al., 1993), and is being evaluated in a collaborative study for AOAC approval as an official method. The use of sodium sulfite is crucial for the removal of nitrogenous contamination from heated feeds (Hintz et al., 1996). If the objective is to accurately measure total fiber in feeds with minimum contamination by digestible protein or starch the aNDF method is preferred. Sodium sulfite improves the filtration of fiber residues during the NDF procedure and allows the method to be used on all types of feeds and feed mixtures, including heated feeds and protein supplements. The aNDF method cannot be used to measure the slowly degraded protein (B3) fraction in feeds in the Net Protein and Carbohydrate Model which is defined as the difference between neutral detergent insoluble crude protein (measured without the use of sulfite) and acid detergent insoluble crude protein. When NDF is measured without the use of sodium sulfite it probably should be corrected for protein contamination. However, for routine analysis the aNDF procedure will provide an accurate estimate of NDF with minimum contamination by protein or starch. The NDF concentrations shown in Table 15-1 were determined using amylase and sulfite.

Neutral Detergent Insoluble Nitrogen

The nitrogen associated with NDF is mostly cell wall-bound protein plus other nitrogen compounds and includes indigestible nitrogen found in the acid-detergent residue. A major cell-wall associated protein is extensin that is covalently linked to hemicellulosic carbohydrate (Fry, 1988). The nitrogen insoluble in neutral detergent solution (NDIN), but soluble in acid detergent, is digestible and consists of slowly degraded protein (Licitra et al., 1996). Pichard (1977) reported a positive correlation between the slowly solubilized pool of nitrogen and NDIN in forage samples. Krishnamoorthy et al. (1982) demonstrated that over 30 percent of total nitrogen in forages and fermented grains was NDIN (sulfite was not used).

Protein contamination of NDF for unheated forages is not a major problem, but neutral detergent insoluble CP (NDICP) is still in the range of 8 to 12 percent of the NDF with sulfite. For certain concentrate feeds such as distillers' and brewers' grains, CP contamination can greatly inflate NDF values. The concentration of NDICP (as a percentage of NDF) for brewers' and distillers' grains can be as high as 40 percent (Weiss et al., 1989). Adding sulfite to the NDF solution reduces CP contamination but does not quantitatively remove all the contamination (Dong and Rasco, 1987). Standardization of procedures for nitrogen fractionation of ruminant feeds has been reviewed by Licitra et al. (1996).

Acid Detergent Fiber

The acid detergent fiber (ADF) fraction of feedstuffs includes cellulose and lignin as primary components and should be analyzed according to AOAC (1973). The residue also contains variable amounts of ash and nitrogen compounds.

Acid Detergent Insoluble Nitrogen

The concentration of acid detergent insoluble nitrogen (ADIN) is used to determine protein availability in heated feeds. Tannins, if present, are one possibility for increased insoluble protein associated with the plant cell wall. Another is the Maillard or nonenzymatic browning reaction caused by heating and drying. The nitrogen in these fractions has low biologic availability and tends to be recovered in ADF (Van Soest, 1965b; Van Soest and Mason, 1991). Heat drying of forages at temperatures above 60°C results in significant increases in yields of lignin and fiber. The increased yield of ADF can be accounted for largely by the production of artifact lignin via nonezymatic Browning Reaction (Van Soest, 1965b). The ADIN can be a sensitive assay for nonenzymatic Browning Reaction due to overheating of certain feeds (Van Soest and Mason, 1991). The ADIN concentration in forages has a strong negative correlation to apparent protein digestibility (Thomas et al., 1982). Nakamura et al. (1994), however, demonstrated a weak correlation between ADIN concentrations in eight different nonforage fiber sources and nitrogen digestibility. Their results indicated that ADIN values in nonforage sources of protein predicted more protein damage than that measured by in vivo nitrogen digestibility. The chemical composition of ADIN (Weiss et al., 1986) and the relationship between ADIN concentrations and digestibility are different between concentrates and forages, therefore the use of a single equation to relate ADIN to nitrogen digestibility for all feeds is not correct.

Lignin

Lignin is a noncarbohydrate, high molecular weight compound that constitutes a diverse class of phenolic compounds (Van Soest, 1983). The acid detergent lignin (ADL) procedure of Van Soest (1965a) includes both hydrolytic (sulfuric acid) and oxidative (potassium permanganate) methods; the sulfuric acid variant of ADL is the most popular (Jung et al., 1997). The Klason lignin is the residue remaining after a two stage sulfuric acid hydrolysis that is commonly used to determine the neutral sugar components of cell wall polysaccharides (Theander and Westerlund, 1986). Differences in the ADL and Klason lignin methods (i.e., order of acid strength use, detergent in the ADF step, and addition of the filtration step to the ADL procedure) account for the difference in lignin values as measured by these two methods (Lowry et al., 1994). Klason lignin values are typically two to four times greater for grasses than the sulfuric ADL estimates and 30 percent higher for legumes (Jung et al., 1997). Hatfield et al. (1994) concluded that the Klason lignin is a more accurate estimate of plant cell wall lignin content than is ADL. Other evidence suggests that an acid soluble lignin fraction is lost in the ADF step of the ADL procedure, thereby resulting in underestimates of lignin content by the ADL method (Lowry et al., 1994).

The Klason lignin procedure was approved by the AOAC (1973) at the same time as ADF. Klason lignin is a better marker for digestibility than permanganate lignin; however, Klason lignin followed by treatment with permanganate yields lignin by difference that is more recoverable in feces (Van Soest et al., 1991). The fraction resistant to both 72 percent sulfuric acid detergent lignin and permanganate is cutin, which is in many seed hulls. The correlation between forage digestibility and concentrations of 72 percent sulfuric acid detergent lignin and Klason lignin were compared by Jung et al. (1997). Thirty-six forages, including C3 legumes and C3 and C4 grasses, were analyzed for sulfuric acid detergent lignin, Klason lignin, and in vitro digestibilities of DM and NDF. Twenty of these forages were also fed to lambs at restricted intake for measurement of DM and NDF digestibilities. Lignin concentrations determined by the two lignin methods were positively correlated, and the Klason lignin value was always greater than the acid detergent lignin concentration. The largest differences were observed for grass forages. In vivo and in vitro digestibilities of DM and NDF in forages were negatively correlated with both lignin measurements. The degree of correlation for the two lignin methods with digestibility was generally similar across all forages and within forage classes. Slopes of linear regressions of digestibility on lignin concentration did not differ between legumes and grasses. Although the sulfuric acid detergent lignin and Klason lignin procedures gave very different estimates of the lignin concentration in forage, they were similarly correlated with digestibility.

Total Nonstructural Carbohydrates

Total nonstructural carbohydrates (NSC) include starch, sugar, and fructan measured using the procedure of Smith (1981) when modified to use ferriccyanide as the colorimetric indicator. The method of Salomonsson et al. (1984) as modified by Herrera-Saldana et al. (1990) measures only starch by an enzymatic method. Crude enzyme preparations such as taka-diastase (derived from Aspergillis oryzae) represents more than 30 different enzymatic functions, including amylolytic, proteolytic, and lipolytic (Nocek, 1991). Considerable variation may be associated with the specificity and/or lack of specificity of enzymes used in the starch and NSC analysis. In most cases the starch and modified Smith (1981) procedure are synonymous. The difference calculation usually accounts for more carbohydrate types (mainly pectin), especially for forages and byproduct feeds. Table 4-1 provides a summary of several common feed sources with measured values for NSC and calculated NFC values as a percentage of DM.

Generally, wheat has the highest content of starch for the grains (77 percent of the DM; ranging from 66 to 82 percent), followed by corn and sorghum (72 percent of the DM; ranging from 65 to 80 percent) and then by barley (57 percent of the DM; ranging from 55 to 75 percent), and oats (58 percent of the DM; ranging from 45 to 69 percent); (Nocek and Tamminga, 1991; Huntington, 1994). Starch content of corn silage (35 percent of the DM) is a function of plant maturity and proportion of grain in the whole plant. Corn silage with 32 percent grain should contain about 22 percent starch. Alfalfa hay or silage contains from 2.7 to 20 percent starch and protein supplements such as soybean meal and cottonseed meal contain from 2.5 to 27 percent starch (Nocek and Tamminga, 1991).

EFFECTS OF PROCESSING ON ENERGY IN FEED

Sources of Starch

BARLEY GRAIN

Cows digest whole barley poorly because of the cutinous nature of the seed husk (Nordin and Campling, 1976). Less than 10 percent of DM from whole barley is digested after 48 hours of in situ incubation in the rumen (McAllister et al., 1990). When grains were broken into halves or quarters, in situ DM digestibility was about 60 percent after 24 hour of incubation. Treatment of barley with an aqueous solution of NaOH (30 to 40 g of NaOH/kg of barley) can substitute for mechanical processing (Ørskov and Greenhalgh, 1977). Barley treated with NaOH has higher concentrations of ash (corresponding to the Na added); the concentrations of the other nutrients are reduced because of ash dilution (McNiven et al., 1995). Dry matter digestibility of NaOH-treated barley in the total tract was similar, digestibility of NDF was higher, and digestibility of starch was lower than for rolled barley. Ruminal digestibility of CP and DM was reduced about 30 percent by NaOH treatment (McNiven et al., 1995). Cows fed NaOH-treated barley or rolled barley produced similar amounts of milk in a 10-week study (Bettenay, 1980), but fat and protein concentrations in milk were reduced when NaOH-treated barley was fed in a short-term study (McNiven et al., 1995).

Milk production and digestibility of DM were similar when cows are fed rolled high-moisture barley or dry rolled barley (Kennelly et al., 1988; Christen et al., 1996). Heat-treatment of dry barley (exit temperatures of 135 or 175° C) has little effect on its gross nutrient composition, energy value, or milk production compared with dry rolled barley (Robinson and McNiven, 1994; McNiven et al., 1995). High producing cows fed twice daily produced more milk when fed heat-treated barley than when fed rolled barley but when cows were fed seven times per day no differences were observed (Robinson and McNiven, 1994).

CORN GRAIN

Mechanical processing (grinding) significantly increases the digestibility of dry corn. The digestibility of whole corn was increased approximately 25 percent by either rolling (Clark et al., 1975) or cracking (Moe et al., 1973). Ground dry corn has 4 to 6 percent more digestible energy than either rolled or coarsely cracked corn (Moe et al., 1973; Knowlton et al., 1996; Wilkerson et al., 1997). Most of the difference in digestibility between cracked and ground corn is caused by a 7 to 10 percent improvement in digestibility of starch (or nonfiber carbohydrate), but part of the increase is offset by a reduction in digestibility of NDF (Knowlton et al., 1996; Wilkerson et al., 1997). The site of digestion of starch is affected more by grinding than is the digestibility of starch in the total tract. Based on in situ studies, approximately 44 percent of the starch in coarsely cracked corn is digested in the rumen compared with 60 to 65 percent for finely ground corn (Cerneau and Michalet-Doreau, 1991; Lykos et al., 1997).

Because of changes in the site of digestion, the difference in measured NE_L concentrations between cracked and ground corn should be less than the differences in digestibility. The difference in measured NE_L concentrations between cracked and ground dry corn is between 0 and 4 percent (Moe et al., 1973; Wilkerson et al., 1997). Milk production increased 3.5 to 6 percent when high producing (35 kg/d) cows were fed ground dry corn compared with dry cracked corn (Mitzner et al., 1994; Knowlton et al., 1996; Wilkerson et al., 1997). Milk composition was not consistently affected by the fineness of the grind of dry corn. Based on production and calorimetry data, average dry ground corn should have about 6 percent more NE_L than average cracked corn when fed at 3 X maintenance (Table 15-1).

Dry matter digestibility of steam-flaked corn is not consistently higher than that of rolled or ground dry corn when fed to cows (Joy et al., 1997; Crocker et al., 1998; Yu et al., 1998). Plascencia and Zinn (1996) however, reported a 10 percentage unit increase (15 percent) in digestibility of OM between steam-flaked and dry-rolled corn when fed to lactating cows. In that study, digestibility of the dry-rolled corn diet was much lower than would be expected. Generally steam-flaking increases digestibility of starch by 10 to 20 percent but digestibility of NDF decreases by a similar amount (Plascencia and Zinn, 1996; Joy et al., 1997; Crocker et al., 1998; Yu et al., 1998; Dann et al., 1999). Digestibility of starch in the total tract was consistently increased as the density of the corn following steam-flaking was reduced (Chen et al., 1994; Plascencia and Zinn, 1996; Joy et al., 1997; Yu et al., 1998). However, variable responses of flake density have been found for digestibility of OM because digestibility of NDF usually decreases as flake density is reduced. Steam-flaking generally increased the proportion of starch digestion occurring in the rumen. The optimal flake density based on milk production is about 0.36 kg/L (28 lbs/bushel).

The average response in yield of fat-corrected milk was 4.5 percent when steam-flaked corn replaced dry ground corn (Chen et al., 1994; Plascencia and Zinn, 1996; Joy et al., 1997; Yu et al., 1998; Dann et al., 1999). Milk fat percentage was either not affected or tended to decrease and milk protein percentage was either not affected or tended to increase when steam-flaked corn replaced dry rolled corn. Based on milk production and changes in digestibility, the NE_L value for average steam-flaked corn is about 11 percent higher than that for average dry cracked corn and about 4 percent higher than that for average dry finely ground corn when fed at 3 X maintenance (Table 15-1). Theurer et al. (1999) calculated that steam-flaked corn had 18 percent more NE_L than cracked corn. These differences are highly related to DMI and differences between cracked corn and other forms of corn should increase as DMI increases.

The chemical composition of high-moisture corn is similar to that of dry corn except that high moisture corn contains two to three times more soluble CP (Prigge et al., 1976). The concentration of NDF tends to be higher in high moisture corn probably because of contamination by the cob. On average, high-moisture corn was about 9 percent more digestible than dry corn when fed to lactating cows (Tyrrell and Varga, 1987; Wilkerson et al., 1997). When similar diets were fed to nonlactating cows (at approximately maintenance) the difference in digestibility was $<$1 percent (McCaffree and Merrill, 1968; Tyrrell and Varga, 1987). Grinding high-moisture corn increased the digestibility of energy or organic matter of diets about 5 percent compared with diets with rolled high moisture corn (Ekinci and Broderick, 1997; Wilkerson et al., 1997).

Measured NE_L of diets containing rolled high-moisture corn is about 5 percent higher than that of diets containing rolled dry corn when fed to lactating cows (Tyrrell and Varga, 1987; Wilkerson et al., 1997). If no associative effects are assumed, the NE_L value of rolled high-moisture corn was 12 to 13 percent higher than that for rolled dry corn. When the corn was ground, diets with high-moisture corn had 13 percent more NE_L than did diets with dry corn. Assuming no associative effects, the NE_L of the ground high-moisture corn was 32 percent higher than that for the ground dry corn (Wilkerson et al., 1997). The difference in NE_L values between high-moisture and dry corn was about twice as large as the difference in digestibility. Ruminal digestibility of starch is 15 to 25 percent higher when rolled high-moisture corn is fed to high producing cows than when rolled dry corn is fed (Aldrich et al., 1993; Knowlton et al., 1998). Energetic losses should be higher when starch is digested in the rumen rather than the small intestine; NE_L values should differ less than digestibility.

Clark (1975) reviewed the early literature and found no difference in dry matter intake (DMI) (ca. 17 kg/d) or FCM production (ca. 20 kg/d) between cows fed high-moisture or dry corn. In short term studies (Lykos et al., 1997; Wilkerson et al., 1997), DMI was not affected, but milk production increased about 5 percent when dry corn was replaced with high-moisture corn in diets of high producing cows. In a longer term study (Dhiman and Satter, 1995), with diets based on alfalfa and corn silage, cows fed high-moisture corn (either rolled or finely ground) produced 6 percent more 3.5 percent fat-corrected milk (34.2 vs. 32.2 kg/d) than cows fed dry-rolled corn. Conversely, Knowlton et al. (1998) reported that DMI (23.5 kg/d), milk production (35 kg/d), and milk composition were not different between cows fed high-moisture or dry corn. Diets in that study were the same as those used in the calorimetry study conducted by Wilkerson et al. (1997).

Based on digestibility, measured NE_L values, and milk production data, rolled high-moisture corn averages about 7 percent higher in NE_L than dry cracked corn at 3X maintenance. Based on similar criteria, ground high-moisture corn has about 11 percent more NE_L than cracked dry corn at 3X maintenance (Table 15-1).

CORN SILAGE

Based on limited data, digestibility of starch from normal corn silage (ca. 35 percent DM) is similar to that of cracked corn but digestibility of starch from mature corn silage is about 10 percent less when fed to cows at approximately 3X maintenance (Harrison et al., 1996; Bal et al., 1997). Mechanical rolling of corn silage (i.e., kernel processing) increased digestibility of starch in the total diet by about 6 percent (Bal et al., 1998; Weiss and Wyatt, 2000; Bal et al., 2000). Digestibility of energy in a diet with processed mature corn silage (27 percent of DM) was about 7 percent higher than for a diet with mature unprocessed corn silage, but processing did not affect digestibility of energy in diets with less mature corn silage (Johnson et al., 1998). In another study, processing increased the TDN of one hybrid of corn silage by about 8 percent but had essentially no effect on another hybrid (Weiss and Wyatt, 2000). Milk yield of high producing cows has not been consistently affected by processing corn silage (Bal et al., 1998; Bal et al., 2000; Weiss and Wyatt, 2000). Because of the paucity of published data with lactating cows, an appropriate factor to adjust the energy value of processed corn silage cannot be developed at this time.

OAT GRAIN

More than 90 percent of the starch in oats is soluble and almost 100 percent of the starch in ground oats disappeared in situ within 4 hour of incubation (Herrera-Saldana et al., 1990). The DM digestibility of diets containing 25 percent whole or rolled oats was not different when fed to lactating cows and milk production was similar (Moran, 1986). Current data do not support extensive processing of oat grain for feeding to moderately producing dairy cows or changing the NE_L value of processed oats.

SORGHUM GRAIN

Whole sorghum is poorly digested (Nordin and Campling, 1976). The digestibility of starch from dry rolled sorghum is 7 to 18 percent less than that of ground or steam-rolled corn (Oliveira et al., 1993), and barley (Herrera-Saldana and Huber, 1989) when fed to lactating cows. In those studies, yield of solid or fat-corrected milk was slightly (ca. 2 percent) lower when cows were fed dry-rolled sorghum rather than when fed steam-flaked corn, finely ground corn, or barley. Milk production was similar for cows fed dry-rolled sorghum and rolled corn (Mitzner et al., 1994).

Steam-flaked sorghum has consistently higher digestibility of starch than dry rolled sorghum when fed to lactating cows. In three studies, digestibility of starch from diets based on steam-flaked sorghum was 8 percent higher than that for starch from diets based on dry-rolled sorghum (Chen et al., 1994; Santos et al., 1997a; Simas et al., 1998). Another study indicated a 27 percent increase in digestibility of starch when sorghum was steam-flaked (Moore et al., 1992), but the digestibility of the starch in the dry-rolled sorghum diet was very low. On average, digestibility of starch for diets based on stream-flaked sorghum was 98 percent. The digestibility of DM or OM for diets with steam-flaked sorghum was about 8 percent higher than for diets based on dry rolled sorghum (Moore et al., 1992; Chen et al., 1994; Santos et al., 1997a; Simas et al., 1998). The degree to which steam flaking increases the feeding value of sorghum is primarily a function of flake density. The optimal density of steam-flaked sorghum is about 0.36 kg/L (Chen et al., 1994; Plascencia and Zinn, 1996; Santos et al., 1997a; Santos et al., 1997b). Extremely thin flakes (density < 0.3 kg/L) often result in reduced DMI and lower production (Moore et al., 1992; Santos et al., 1997a).

Milk production and gross efficiency of feed utilization (FCM yield/DMI) when steam-flaked sorghum was fed was about 10 percent higher than when dry-rolled sorghum was fed (Moore et al., 1992; Chen et al., 1994; Santos et al., 1997a; Simas et al., 1998). Based on milk production and DM digestibility data, the NE_L value of steam-flaked sorghum is about 13 percent higher than for dry-rolled sorghum. Compared with cracked corn, dry rolled sorghum contains about 4 percent less NE_L at 3X maintenance (a function of less fat and lower starch digestibility). Steam-flaked sorghum (mainly because of improved digestibility of starch) has about 9 percent more NE_L than cracked corn at 3X maintenance (Table 15-1). This difference is less than the difference (16 percent) calculated by Theurer et al. (1999).

WHEAT GRAIN

Data on the effects of processing wheat fed to dairy cows are lacking. In situ DM disappearance of intact wheat is low but once the kernel is broken, particle size does not greatly affect extent or rate of DM disappearance (McAllister et al., 1990). In a study with nonlactating cows fed a diet with 33 percent wheat, OM digestibility of the diet was increased by 30 percent when the wheat was rolled rather than when fed whole (Nordin and Campling, 1976). The digestibility of OM was 88 percent for rolled wheat and 41 percent for whole wheat grain. Based on that study, wheat should undergo some mechanical processing prior to feeding to dairy cows. Ground wheat to supply up to 33 percent of dietary DM has been fed to moderately producing cows (ca. 30 kg/d) without negative effects (Faldet et al., 1989). The benefits, if any, of feeding ground wheat rather than rolled wheat to dairy cows are not known.

Oilseeds

COTTONSEED

The majority of cottonseed fed in the United States is not processed; however, the effects of mechanical processing and heat-treatment of cottonseeds have been investigated (Arieli, 1998). The DM digestibility of diets with 15 percent intact, cracked, or ground Pima cottonseed (naturally delinted) was not different when fed to lactating cows although approximately 12 percent of the intact seeds (weight basis) were excreted in the feces (Sullivan et al., 1993a,b). Digestibility of fiber tended to be reduced and digestibility of crude fat was increased by cracking or grinding. Based on the digestibility data in those experiments, the TDN of cracked and ground Pima seeds would be about 7 percentage units higher (ca. 10 percent) than that of intact Pima seeds. Milk production and gross efficiency of feed utilization were not different when cows were fed intact or cracked Pima cottonseed but gross efficiency was 9 percent higher for the diet with ground Pima seeds compared with the diet that contained intact cottonseed (Sullivan et al., 1993a,b). Similar to the data with Pima cottonseed, 11 percent of the acid delinted cottonseeds consumed by lactating cows were voided in the feces compared with <1 percent of whole linted cottonseed (Coppock et al., 1985). Because of lack of dilution by lint, delinted seeds generally have higher ether extract concentrations than linted seeds; therefore differences in TDN are less than differences in digestibiilty. However, based on the data of Coppock et al. (1985) whole delinted cottonseeds have about 10 percent less TDN than whole linted seeds. When the delinted seeds were cracked TDN values were slightly higher than those for whole linted seeds (Coppock et al., 1985). Grinding linted cottonseeds had little effect on extent and site of digestibility of most nutrients or on milk production when fed to low producing cows (Pires et al., 1997).

The effect of heat-treatment of whole linted cottonseed on OM digestibility has been inconsistent. Heat-treatment of cottonseeds has either not affected OM digestibility (Pena et al., 1986) or decreased it (Pires et al., 1997). In the Pires et al. (1997) study, digestibility of NDF and CP was reduced but digestibility of fatty acids was not affected by heat-treatment. When heat-treated cottonseeds were ground, digestibility of OM was similar to that for raw cottonseeds (Pires et al., 1997). Feed intake and milk production were not different when low to moderate producing cows were fed raw or heat-treated cottonseed (Smith and Vosloo, 1994; Pires et al., 1997). Pires et al. (1997) reported increased milk protein when heat-treated cottonseed was fed.

Currently available data do not support adjusting the NE_L value of linted cottonseeds when they are ground or cracked. Grinding significantly increases the energy value of delinted cottonseeds. Even though chemical data suggest that delinted cottonseeds would have more energy than linted seeds, based on digestibility, linted seeds have approximately 10 percent more available energy than delinted seeds when intact seeds are fed.

SOYBEANS

Heat-treatment of soybeans generally consists of heating the whole seed to 120 to 140° C and steeping for 30 to

120 minutes. Digestibility of diets with 10 to 18 percent soybeans were not different when roasted or raw soybeans were fed to dairy cows or steers (Bernard, 1990; Tice et al., 1993; Aldrich et al., 1995), but one study (Scott et al., 1991) found that OM digestibility of a diet that contained 16 percent soybeans was reduced (69 vs. 60 percent) when roasted soybeans were fed compared with raw soybeans. Roasting soybeans has not consistently altered crude fat or fatty acid digestibility (Aldrich et al., 1995; Bernard, 1990; Scott et al., 1991; Tice et al., 1993).

Milk production was generally, but not always, increased when cows were fed roasted soybeans compared with cows fed raw soybeans. Two studies (Bernard, 1990; Scott et al., 1991) with cows producing approximately 30 kg/d of milk indicated no difference between raw and roasted soybeans. Four other studies (Faldet and Satter, 1991; Tice et al., 1993; Chouinard et al., 1997; Dhiman et al., 1997) indicated that cows fed roasted soybeans produced 10 to 16 percent more milk than did cows fed raw soybeans. Source of forage did not seem to influence the results. Some of the inconsistency could be caused by different heat-treatments.

Digestibility of OM from diets that contained whole, cracked, or ground roasted soybeans was not different (Tice et al., 1993). Milk production (38.5 vs. 37.2 kg/d) was higher for cows fed coarsely cracked roasted soybeans than for cows fed ground roasted soybeans (Dhiman et al., 1997). With low-producing cows (19 kg/d) mechanical processing of roasted soybeans did not affect milk production (Tice et al., 1993).

Data comparing the digestibility of diets that contained extruded soybeans with diets that contained raw or roasted soybeans are limited. Scott et al. (1991) reported similar digestibility of diets that contained either 16 percent extruded or roasted soybeans and both were lower than the digestibility of the diet that contained raw soybeans. Milk production by cows fed extruded soybeans was similar or higher than that of cows fed raw or roasted soybeans (Guillaume et al., 1991; Scott et al., 1991; Chouinard et al., 1997). Digestibility data do not support adjusting NE_L concentrations when soybeans are roasted, or extruded, or when roasted soybeans are mechanically processed.

REFERENCES

Aldrich, C. G., N. R. Merchen, and J. K. Drackley. 1995. The effect of roasting temperature applied to whole soybeans on site of digestion by steers: 1. Organic matter, energy, fiber and fatty acid digestion. J. Anim. Sci. 73:2120–2130.

Aldrich, J. M., L. D. Muller, G. A. Varga, and J. L. C. Griel. 1993. Nonstructural carbohydrate and protein effects on rumen fermentation, nutrient flow, and performance of dairy cows. J. Dairy Sci. 76:1091–1105.

Allen, M. S., and K. F. Knowlton. 1995. Non-structural carbohydrates important for ruminants. Feedstuffs, April 17, 1995, pp. 13–15.

Aman, P. and K. Hesselman. 1985. An enzyme method for analysis of total mixed linkage beta glucans in cereal grains. J. Cereal Sci. 3:231–237.

Association of Official Analytical Chemists. 1973. Official Methods of Analysis. Washington, D.C.

Arieli, A. 1998. Whole cottonseed in dairy cattle feeding: a review. Anim. Feed Sci. Tech. 72:97–110.

Bal, M. A., J. G. Coors, and R. D. Shaver. 1997. Impact of the maturity of corn for use as silage in the diets of dairy cows on intake, digestion, and milk production. J. Dairy Sci. 80:2497–2503.

Bal, M. A., R. D. Shaver, K. J. Shinners, and L. D. Satter. 1998. Effect of mechanical processing on the utilization of whole-plant corn silage by lactating dairy cows. J. Dairy Sci. 81(Suppl. 1):334 (abstr.).

Bal, M. A., R. D. Shaver, A. G. Jirovec, K. J. Shinners, and J. G. Coors. 2000. Crop processing and chop length of corn silage: effects on intake, digestion, and milk production by dairy cows. J. Dairy Sci. 83:1264–1273.

Bernard, J. K. 1990. Effect of raw or roasted whole soybeans on digestibility of dietary nutrients and milk production of lactating dairy cows. J. Dairy Sci. 73:3231–3236.

Bettenay, R. A. 1980. Comparison of caustic soda-treated barley and rolled barley in the ration of dairy cows. Austral. J. Exp. Ag. Anim. Husb. 20:394–397.

Cerneau, P., and B. Michalet-Doreau. 1991. In situ starch degradation of different feeds in the rumen. Reprod. Nutr. Dev. 1:65–72.

Chen, K. H., J. T. Huber, C. B. Theurer, R. S. Swingle, J. Simas, S. C. Chan, Z. Wu, and J. L. Sullivan. 1994. Effect of steam flaking of corn and sorghum grains on performance of lactating cows. J. Dairy Sci. 77:1038–1043.

Chouinard, P. Y., V. Girard, and G. J. Brisson. 1997. Performance and profiles of milk fatty acids of cows fed full fat, heat-treated soybeans using various processing methods. J. Dairy Sci. 80:334–342.

Christen, S. D., T. M. Hill, and M. S. Williams. 1996. Effects of tempered barley on milk yield, intake, and digestion kinetics of lactating Holstein cows. J. Dairy Sci. 79:1394–1399.

Clark. 1975. Utilization of high moisture grains by dairy and beef cattle. Proc 2nd Int'l Silage Res. Conf. 2:205–238.

Clark, J. H., W. J. Croom, and K. E. Harshbarger. 1975. Feeding value of dry, ensiled, and acid treated high moisture corn fed whole or rolled to lactating cows. J. Dairy Sci. 58:907–921.

Coppock, C. E., J. R. Moya, J. W. West, D. H. Nave, J. M. Labore, and C. E. Gates. 1985. Effect of lint on whole cottonseed passage and digestibility and diet choice on intake of whole cottonseed by Holstein cows. J. Dairy Sci. 68:1198–1206.

Crocker, L. M., E. J. DePeters, J. G. Fadel, H. Perez-Monti, S. J. Taylor, J. A. Wyckoff, and R. A. Zinn. 1998. Influence of processed corn grain in diets of dairy cows on digestion of nutrients and milk composition. J. Dairy Sci. 81:2394–2407.

Dann, H. M., G. A. Varga, D. E. Putnam, and J. L. C. Griel. 1999. Improving energy supply to late gestation and early postpartum dairy cows. J. Dairy Sci. 82:1765–1778.

Dhiman, T. R., and L. D. Satter. 1995. Particle size and moisture content of corn grain and their effect on dairy cow performance. J. Dairy Sci. 78(Suppl. 1):210(abstr.).

Dhiman, T. R., A. C. Korevaar, and L. D. Satter. 1997. Particle size of roasted soybeans and the effect on milk production of dairy cows. J. Dairy Sci. 80:1722–1727.

Dong, F. M., and B. A. Rasco. 1987. The neutral detergent fiber, acid detergent fiber, crude fiber, and lignin contents of distiller's grains with solubles. J. Food Sci. 52:403–410.

Ekinci, C., and G. A. Broderick. 1997. Effects of processing high moisture ear corn on ruminal fermentation and milk yield. J. Dairy Sci. 80:3298–3307.

Faldet, M. A., T. Nalsen, L. J. Bush, and G. D. Adams. 1989. Utilization of wheat in complete rations for lactating cows. J. Dairy Sci. 72:1243–1251.

Faldet, M. A., and L. D. Satter. 1991. Feeding heat-treated full fat soybeans to cows in early lactation. J. Dairy Sci. 74:3047–3054.

French, D. 1973. Chemical and physical properties of starch. J. Anim. Sci. 37:1048–1061.

Fry, S. C. 1988. The Growing Plant Cell Wall: Chemical and Metabolic Analysis, Wiley, p. 352. Longman Scientific & Technical:New York, Wiley.

Goering, H. K., and P. J. Van Soest. 1970. Forage fiber analysis. U.S. Department of Agriculture Handbook, No. 379, Washington, D.C.

Guillaume, B., D. E. Otterby, M. D. Stern, J. G. Linn, and D. G. Johnson. 1991. Raw or extruded soybeans and rumen-protected methionine and lysine in alfalfa-based diets for dairy cows. J. Dairy Sci. 74:1912–1922.

Harrison, J. H., L. Johnson, R. Riley, S. Xu, K. Loney, C. W. Hunt, and D. Sapienza. 1996. Effect of harvest maturity of whole plant corn silage on milk production and component yield and passage of corn grain and starch into feces. J. Dairy Sci. 79(Suppl. 1):149(Abstr.).

Hatfield, R. D., H. G. Jung, J. Ralph, D. R. Buxton, and P.J. Weimer. 1994. Comparison of the insoluble residues produced by the Klason lignin and acid detergent lignin procedure. J. Sci. Food Ag. 65:51–58.

Herrera-Saldana, R., and J. T. Huber. 1989. Influence of varying protein and starch digestibilities on performance of lactating cows. J. Dairy Sci. 72:1477–1483.

Herrera-Saldana, R. E., J. T. Huber, and M. H. Poore. 1990. Dry matter, crude protein, and starch degradability of five cereal grains. J. Dairy Sci. 73:2386–2393.

Hintz, R.W., D. R. Mertens, and K. A. Albrecht. 1996. Effects of sodium sulfite on recovery and composition of detergent fiber and lignin. J. AOAC Int. 1996 79:16–22.

Huntington, G. B. 1994. Ruminant starch utilization progress has been extensive. Feedstuffs 66:16–18, 38–43.

Johnson, L. M., J. H. Harrison, R. E. Riley, and A. Tintzman. 1998. Effect of maturity and mechanical processing of corn silage on energy content of corn silage based total mixed rations. J. Dairy Sci. 81(Suppl. 1): 199(abstr.).

Joy, M. T., E. J. DePeters, J. G. Fadel, and R. A. Zinn. 1997. Effects of corn processing on the site and extent of digestion in lactating cows. J. Dairy Sci. 80:2087–2097.

Jung, H. G., D. R. Mertens, and A. J. Payne. 1997. Correlation of acid detergent and Klason lignin with digestibility of forage dry matter and neutral detergent fiber. J. Dairy Sci. 80:1622–1628.

Kennelly, J. J., D. L. Dalton, and J. K. Ha. 1988. Digestion and utilization of high moisture barley by lactating dairy cows. J. Dairy Sci. 71:1259–1266.

Knowlton, K. F., M. S. Allen, and P. S. Erickson. 1996. Lasalocid and particle size of corn grain for dairy cows in early lactation. 1. Effect on performance, serum metabolites and nutrient digestibility. J. Dairy Sci. 79:557–564.

Knowlton, K. F., B. P. Glenn, and R. A. Erdman. 1998. Performance, ruminal fermentation, and site of starch digestion in early lactation Holstein cows fed corn grain harvested and processed differently. J. Dairy Sci. 81:1972–1985.

Krishnamoorthy, U., T. V. Muscato, C. J. Sniffen, and P. J. Van Soest. 1982. Nitrogen fractions in selected feedstuffs. J. Dairy Sci. 65:217–225.

Licitra, G., T. M. Hernandez, and P. J. Van Soest. 1996. Standardization of procedures for nitrogen fractionation of ruminant feeds. Anim. Sci. Feed Tech. 57:347–358.

Lowry, J. B., L. L. Conlan, A. C. Schlink, and C. S. McSweeney. 1994. Acid detergent dispersible lignin in tropical grasses. J. Sci. Food Ag. 65:41–49.

Lykos, T., G. A. Varga, and D. Casper. 1997. Varying degradation rates of total nonstructural carbohydrates: effects on ruminal fermentation, blood metabolites, and milk production and composition in high producing Holstein cows. J. Dairy Sci. 80:3341–3355.

McAllister, T. A., L. M. Rode, D. J. Major, K.-J. Cheng, and J. G. Buchanan-Smith. 1990. Effect of ruminal microbial colonization on cereal grain digestion. Can. J. Anim. Sci. 70:571–579.

McCaffree, J. D., and W. G. Merrill. 1968. High moisture corn for dairy cows in early lactation. J. Dairy Sci. 51:553–560.

McNiven, M. A., M. R. Weisbjerg, and T. Hvelplund. 1995. Influence of roasting or sodium hydroxide treatment of barley on digestion in lactating cows. J. Dairy Sci. 78:1106–1115.

Mitzner, K. C., F. G. Owen, and R. J. Grant. 1994. Comparison of sorghum and corn grains in early and midlactation diets for dairy cows. J. Dairy Sci. 77:1044–1051.

Moe, P. W., H. F. Tyrrell, and J. N. W. Hooven. 1973. Physical form and energy value of corn grain. J. Dairy Sci. 56:1298–1304.

Moore, J. A., M. H. Poore, T. P. Eck, R. S. Swingle, J. T. Huber, and M. J. Arana. 1992. Sorghum grain processing and buffer addition for early lactation cows. J. Dairy Sci. 75:3465–3472.

Moran, J. B. 1986. Cereal grains in complete diets for dairy cows: a comparison of rolled barley, wheat and oats and of three methods of processing oats. Anim. Prod. 43:27–36.

Nakamura, T., T. J. Klopfenstein, and R. A. Britton. 1994. Evaluation of acid detergent insoluble nitrogen as an indicator of protein quality in nonforage proteins. J. Anim. Sci. 72:1043–1048.

Nocek, J. E. 1991. New concepts in carbohydrate nutrition for high producing cows. Prof. Anim. Sci. 8:5–16.

Nocek, J. E., and S. Tamminga. 1991. Site of digestion of starch in the gastrointestinal tract of dairy cows and its effect on milk production. J. Dairy Sci. 74:3598–3629.

Nordin, M., and R. C. Campling. 1976. Digestibility studies with cows given whole and rolled cereal grains. Anim. Prod. 23:305–315.

Oliveira, J. S., J. T. Huber, D. Ben-Ghedalia, R. S. Swingle, C. B. Theurer, and M. Pessarakli. 1993. Influence of sorghum grain processing on performance of lactating dairy cows. J. Dairy Sci. 76:575–581.

Ørskov, E. R., and J. F. D. Greenhalgh. 1977. Alkali treatment as a method of processing whole grain for cattle. J. Ag. Sci. (Camb.) 89:253–255.

Pena, F., H. Tagari, and L. D. Satter. 1986. The effect of heat treatment of whole cottonseed on site and extent of protein digestion in dairy cows. J. Anim. Sci. 62:1423–1433.

Pichard, D.G. R. 1977. Forage nutritive value. Continuous and batch in vitro rumen fermentations and nitrogen solubility. Ph.D. dissertation. Cornell Univ., Ithaca, NY.

Pires, A. V., M. L. Eastridge, J. L. Firkins, and Y. C. Lin. 1997. Effects of heat treatment and physical processing of cottonseed on nutrient digestibility and production performance by lactating cows. J. Dairy Sci. 80:1685–1694.

Plascencia, A., and R. A. Zinn. 1996. Influence of flake density on the feeding value of steam-processed corn in diets for lactating cows. J. Anim. Sci. 74:310–316.

Prigge, E. C., R. R. Johnson, F. N. Owens, and D. Williams. 1976. Soluble nitrogen and acid production of high moisture corn. J. Anim. Sci. 42:490–496.

Robinson, P. H., and M. A. McNiven. 1994. Influence of flame roasting and feeding frequency of barley on performance of dairy cows. J. Dairy Sci. 77:3631–3643.

Salomonsson, A,-C., O. Theander, and E. Westerlund. 1984. Chemical characterization of some Swedish cereal whole meal and bran fractions. Swed. J. Ag. Res. 14:111–118.

Santos, F. A., J. T. Huber, C. B. Theurer, R. S. Swingle, and J. M. Simas. 1997a. Response of lactating dairy cows to various densities of sorghum grain. J. Anim. Sci. 75:1681–1685.

Santos, F. A. P., J. T. Huber, C. B. Theurer, R. S. Swingle, K. H. Chen, S. C. Chan, J. Santos, and E. J. DePeters. 1997b. Comparison of barley and sorghum grain processed at different densities for lactating dairy cows. J. Dairy Sci. 80:2098–2103.

Scott, T. A., D. K. Combs, and R. R. Grummer. 1991. Effects of roasting, extrusion, and particle size on the feeding value of soybeans for dairy cattle. J. Dairy Sci. 74:2555–2562.

Simas, J. M., J. T. Huber, C. B. Theurer, K. H. Chen, F. A. P. Santos, and Z. Wu. 1998. Influence of sorghum grain processing on performance and nutrient digestibilities in dairy cows fed varying concentrations of fat. J. Dairy Sci. 81:1966–1971.

Smith, D. 1981. Removing and analyzing total non-structural carbohydrates from plant tissues. Wisconsin Ag., Exp. Stn. Rep. No. R2107, Madison.

Smith, W. A., and L. P. Vosloo. 1994. Effect of whole cottonseed, heat-treated whole cottonseed and whole cottonseed plus lanolin on milk production and composition. S. African J. Anim. Sci. 24:45–48.

Sullivan, J. L., J. T. Huber, and J. M. Harper. 1993a. Performance of dairy cows fed short staple, pima, and cracked pima cottonseed and feed characteristics. J. Dairy Sci. 76:3555–3561.

Sullivan, J. L., J. T. Huber, R. L. Price, and J. M. Harper. 1993b. Comparison of digestibility, nutritive value, and storage characteristics of different forms of cottonseed in diets fed to lactating dairy cows. J. Anim. Sci. 71:2837–2842.

Theander, O., and E. A. Westerlund. 1986. Studies on dietary fiber. 3. Improved procedures for analysis of dietary fiber. J. Ag. Food Chem. 34:330–336.

Theurer, C. B., J. T. Huber, A. DelgadoElorduy, and R. Wanderley. 1999. Invited review: Summary of steam-flaking corn or sorghum grain for lactating dairy cows. J. Dairy Sci. 82:1950–1959.

Thomas, J. W., Y. Yu, T. Middleton, and C. Stallings. 1982. Estimations of protein damage. pp. 81–98 *in* Protein Requirements for Cattle: Symposium. F. N. Owens, ed. Oklahoma State Univ. MP-109, Stillwater, OK.

Tice, E. M., M. L. Eastridge, and J. L. Firkins. 1993. Raw soybeans and roasted soybeans of different particle sizes. 1. Digestibility and utilization by lactating cows. J. Dairy Sci. 76:224–235.

Tyrrell, H. F., and G. A. Varga. 1987. Energy value for lactation of rations containing ground whole ear maize or maize meal both conserved dry or ensiled at high moisture. Eur. Assoc. Anim. Prod. 32:308–309.

Undersander, D., D. R. Mertens, and N. Thiex. 1993. Forage Analyses Procedures. National Forage Testing Association Proceedings, Omaha, NE, pp. 95–103.

Van Soest, P. J. 1965a. Use of detergents in analyses of fibrous feeds. II. A rapid method for the determination of fiber and lignin. J. Assoc. Offic. Agric. Chem. 46:829–835.

Van Soest, P. J. 1965b. Use of detergents in analysis of fibrous feeds. III. Study of effects of heating and drying on yields of fiber and lignin in feeds. J. Assoc. Offic. Agric. Chem. 48:785–791.

Van Soest, P. J. 1983. Nutritional ecology of the ruminant. Comstock, Cornell Univ. Press, Ithaca, NY.

Van Soest, P. J., and R. H. Wine. 1967. Use of detergents in the analysis of fibrous feeds. IV. J. Assoc. Offic. Agric. Chem. 50:50–55.

Van Soest, P. J., and V. C. Mason. 1991. The influence of the Maillard reaction upon the nutritive value of fibrous feeds. Anim. Feed Sci. Tech. 32:45–53.

Van Soest, P. J., J. B. Robertson, and B. A. Lewis. 1991. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. J. Dairy Sci. 74:3583–3587.

Weiss, W. P., H. R. Conrad, and W. L. Shockey. 1986. Digestibility of nitrogen in heat-damaged alfalfa. J. Dairy Sci. 69:2658–2670.

Weiss, W. P., D. O. Erickson, G. M. Erickson, and G. R. Fisher. 1989. Barley distillers grains as a protein supplement for dairy cows. J. Dairy Sci. 72:980–987.

Weiss, W. P., and D. J. Wyatt. 2000. Effect of oil content and kernel processing of corn silage on digestibility and milk production by dairy cows. J. Dairy Sci. 83:351–358.

Wilkerson, V. A., B. P. Glenn, and K. R. McLeod. 1997. Energy and nitrogen balance in lactating cows fed diets containing dry or high moisture corn in either rolled or ground form. J. Dairy Sci. 80:2487–2496.

Yu, P., J. T. Huber, F. A. P. Santos, J. M. Simas, and C. B. Theurer. 1998. Effects of ground, steam-flaked, and steam-rolled corn grains on performance of lactating cows. J. Dairy Sci. 81:777–783.