# Advancements in Feeding Carbohydrates

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## Take Home Messages

- Carbohydrates compose the highest proportion of diets for dairy cattle, easily 70 to 75% of dietary DM.
- It is important to measure actual carbohydrate fractions in feeds, especially for forages, and some items important for consideration when formulating diets are: nonfiber carbohydrates, nonstructural carbohydrates, starch, sugar, rates of fermentation of the nonfibrous fraction, neutral detergent fiber, acid detergent fiber, physically effective fiber, effective neutral detergent fiber, neutral detergent fiber from forage, and in-vitro fiber digestibility.
- Balancing the carbohydrates should focus on maximizing digestibility of the diet, optimizing microbial protein synthesis, maintaining rumen pH and animal health, not limiting DM intake, and optimizing the efficiency of milk yield.
- Important monitoring aspects include: DM intake, milk yield, milk fat, milk protein, feed efficiency, animal health, rumination, consistency of feces, and feed bunk conditions (amount and quality of refusals and evidence of sorting).

## Introduction

Carbohydrates compose the highest proportion of diets, easily 70 to 75% of DM, and are important for meeting the energy needs of ruminal microbes and the host animals and maintaining rumen health. The primary fractions of carbohydrates are structural (fiber) and nonstructural (starch and sugar), of which forages and concentrates are the primary contributors of each, respectively. The concentrations of nonstructural and structural fractions of carbohydrates in feeds play a major role in the estimation of the energy value of feeds (NRC, 2001). With the importance of carbohydrates in the diet, measurement of the different carbohydrate fractions in feeds and diets is critical for diet formulation and relating diet and intake to animal performance. Inherent characteristics of carbohydrate sources and processing imposed on them affects ruminal and total tract digestibilities. Understanding these attributes is critical in diet formulation for optimal animal performance and health.

## ■ Measurement of Carbohydrate Fractions

The fractions of carbohydrates generally used in ration formulations for dairy cattle are provided in Figure 1. The soluble carbohydrates can be analyzed in the laboratory whereby the starch and sugar are hydrolyzed to glucose and the glucose is measured calorimetrically. This fraction of the soluble carbohydrates is referred to as nonstructural carbohydrates (NSC). Nonfiber carbohydrates (NFC) are a calculated value: NFC = 100% DM – % crude protein - % NDF - % ash - % fat; this fraction is higher than for NSC because of the organic acids that are especially present in fermented feeds (maybe as high as 10% of DM). The errors of analysis of each component of the NFC equation are compounded in the NFC value; therefore, effort in recent years has been directed to improving the accuracy of measurements of the components in the equation, especially for NDF. The NDF can be contaminated with a considerable amount of CP, thus $NDF_{N\text{-free (or CP-free)}}$ is most commonly used, which is not only important for calculation of NFC but in having a more true representation of NDF (and ADF). The protein contamination in NDF will especially be higher with heat damaged feeds and byproduct feeds high in NDF. Without this correction, the NDF is overestimated and the NFC is underestimated. If fat is determined as ether extract (EE), then some corrections need to be made because other components in addition to fat are extractable in ether. Suggested adjustments are: forages – EE * 0.55, concentrates – EE * 0.95. If fatty acids are determined in feeds, then the concentration of fatty acids should be divided by 0.90 to account for the glycerol in the triglycerides. More labs today will measure lignin in forages; since lignin is indigestible, knowing its concentration can improve the prediction of the energy concentration in the feedstuff.

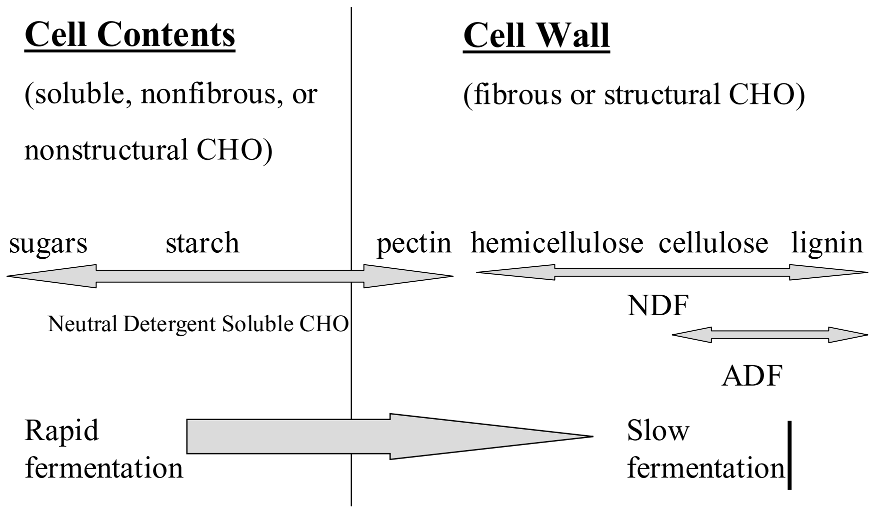


**Figure 1. Fractions of carbohydrates (CHO) in plants.**

The NDF fraction is very important as it is highly related to feed intake and energy availability from the feedstuff. The ADF fraction is more correlated to feed digestibility than NDF because the indigestible fraction of lignin has been concentrated in the ADF fraction. As illustrated in Figure 1, hemicellulose is more digestible than cellulose and can be estimated in feeds by: NDF minus ADF. Hemicellulose is higher in grasses than legumes and is rather high in several of the nonforage fiber sources (Table 1).

**Table 1. Carbohydrate composition of some selective feeds (NRC, 2001).**

| Item | NDF (%) | ADF (%) | HCELL[1] (%) | Lignin (%) | PAF[2] | $NE_L$-4X[3] (Mcal/kg) | NDICP[4] (%) | ADICP[5] (%) | eNDF[6] (% of NDF) | PEF[7] |
|---|---|---|---|---|---|---|---|---|---|---|
| Barley, rolled | 20.8 | 7.2 | 13.6 | 1.9 | 1.04 | 1.76 | 1.8 | 0.5 | 40.0 | -- |
| Corn, dry ground | 9.5 | 3.4 | 6.1 | 0.9 | 1.00 | 1.90 | 0.7 | 0.3 | 40.0 | -- |
| Corn, steam flaked | 9.5 | 3.4 | 6.1 | 0.9 | 1.04 | 1.98 | 0.7 | 0.3 | 20.0 | -- |
| Corn silage | 45.0 | 28.1 | 16.9 | 2.6 | 0.94 | 1.38 | 1.3 | 0.8 | 95.0 | 0.85 |
| Distillers grains w solubles | 38.8 | 19.7 | 19.1 | 4.3 | 1.00 | 1.87 | 8.6 | 5.0 | 30.0 | 0.40 |
| Grass, cool season, hay, mid maturity (13.3% CP) | 57.7 | 36.9 | 20.8 | 4.3 | 1.00 | 1.16 | 3.9 | 1.2 | 100.0 | 1.00 |
| Legume, hay, immature (22.8% CP) | 36.3 | 28.6 | 7.7 | 5.9 | 1.00 | 1.30 | 2.7 | 1.6 | 95.0 | 0.95 |
| Legume, hay, mid maturity (20.8% CP) | 42.9 | 33.4 | 9.5 | 6.4 | 1.00 | 1.20 | 2.5 | 1.6 | 95.0 | 0.95 |
| Soybean hulls | 60.3 | 44.6 | 15.7 | 2.5 | 1.00 | 1.37 | 3.5 | 1.0 | 20.0 | 0.40 |
| Wheat middlings | 36.7 | 12.1 | 24.6 | 4.2 | 1.00 | 1.58 | 2.8 | 0.5 | 50.0 | 0.40 |

[1]HCELL = Hemicellulose; calculated as NDF – ADF; [2]PAF = Processing adjustment factor.

[3]Net energy of lactation at 4-times maintenance intake.

[4]NDICP = Neutral detergent insoluble crude protein

[5]ADICP = Acid detergent insoluble crude protein

[6]eNDF = Effective NDF, described as roughage value by Mertens (1992).

[7]PEF = Physical effectiveness factor; NDF * PEF = physically effective NDF (Mertens, 1997)

Because not all NDF stimulates rumination, indices other than total NDF have been investigated to address the effectiveness of the fiber source to stimulate chewing or maintain milk fat percentage. Physically effective NDF (peNDF) has been defined as the physical characteristics of a fiber source (primarily particle size) that influences chewing and the two layers (ruminal mat and liquid) of ruminal contents (Mertens, 1997). The physically effective factor has been derived from chewing data or mass of particles retained on a 1.18 mm sieve (Mertens, 1997). Effective NDF (eNDF) has been described as the sum total ability of the feed to replace forage or roughage in a ration to maintain milk fat percentage (Mertens, 1997). Because forage is a good source of eNDF, forage NDF (FNDF) is often used as an indicator of effective fiber in a diet. Cows consuming diets with high levels of FNDF can tolerate a high concentration of NFC in the diet, but the inverse is also true. Therefore, as minimum FNDF drops from 19 to 16% in the diet, maximum dietary NFC must drop from 44 to 38% of the diet (NRC, 2001). Because of this relationship, the ratio of FNDF/NFC is sometimes monitored in diets. Using the Penn State Particle Size Separator to access particle size distribution is important in the field, and especially important is the proportion of particles on the two top screens. About 60 (processed) to 80% (unprocessed) of the particles (and NDF) in corn silage will be on the screen with 8 mm pores, and 85 to 90% of the NDF will be on the two top screens (Weiss, 2000). With the addition of a third screen to the Penn State Particle Size Separator at 1.18 mm, additional insights into levels of peNDF may be gained (Kononoff et al., 2003). In-vitro fiber digestibility (IVFD) is being offered by some analytical laboratories and can be useful in evaluating forages, especially in ranking forages instead of using the values as absolute measures of digestibility. The IVFD appears to be positively related to milk yield (Figure 2.)

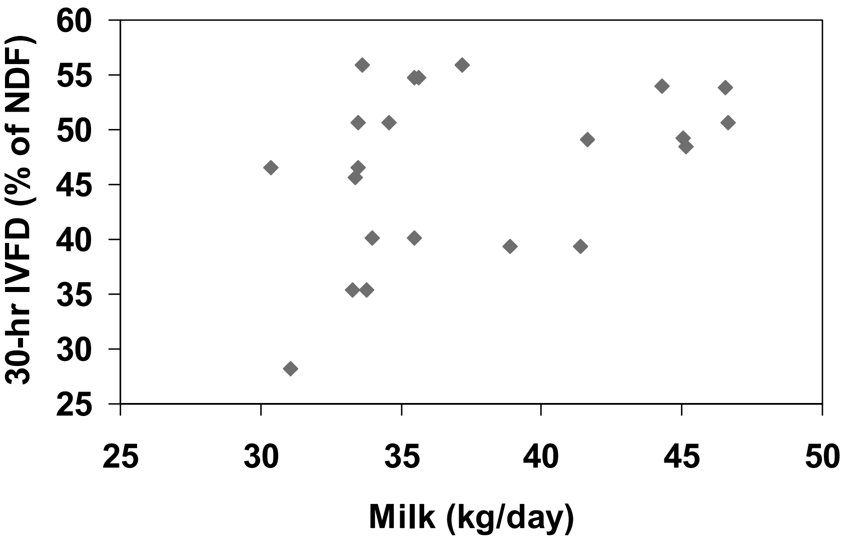


**Figure 2. Relative relationship between milk yield and in-vitro NDF digestion (IVFD; 30-hr incubation) in corn silage (taken from Oba and Allen, 2005).**

## ▪ Digestibility of Carbohydrates

Most of the starch is fermented in the rumen and is important for synthesis of microbial protein and propionic acid which is used as a precursor for glucose synthesis in the liver. The rate and extent of starch digestion in the rumen can be increased by processing of grain (e.g. decreasing of particle size or steam addition; Callison et al., 2001) and using different grain sources (e.g. barley > corn > sorghum; Firkins et al., 2001). Steam-flaking of cereal grains causes gelatization of the starch, which results in increased ruminal and total-tract digestibilities of starch (higher digestibility with low versus high flake density, e.g. 0.26 versus 0.39 kg/L), with the most pronounced results for sorghum. Ruminal starch digestibility is generally increased with the following processes (from highest to lowest): steam-flaking, steam rolling, roasted dry rolled, dry rolling, and grinding. With increased ruminal digestibility, greater risks occur for causing low ruminal pH. Also, corn grain with a high proportion of vitreous endosperm will likely have lower ruminal starch digestibility (Correa et al., 2002) and total tract digestibility of starch. Reducing particle size of corn will likely increase ruminal digestibility of starch, and although total tract digestibility of starch will likely be increased, the increase will be of less magnitude due to compensatory digestion in the hindgut (Callison et al., 2001). The increased ruminal digestion of starch may decrease ruminal NDF digestion but may have little to no effect on total tract NDF digestion because of increased NDF digestion in the hind gut (Table 2). Replacement of starch in high concentrate diets with nonforage NDF can help improve NDF digestibility by reducing the negative associative effects in the rumen (Firkins, 1997). Therefore, except for cottonseed (fiber from hulls and lint that entrap it in the rumen mat) which is high in eNDF compared to other nonforage NDF sources, nonforage NDF sources are often most useful in diluting starch from diets so DM and NDF digestibility in the total tract can be optimized.

Fiber is important for maintaining rumen health, but high dietary concentrations can limit DM intake (DMI) by increased rumen fill. Therefore, source of the NDF [physical (particle size) and chemical characteristics (e.g. proportion of hemicellulose versus cellulose versus lignin) and its corresponding rate of digestion as affected by these intrinsic properties, along with its interaction with other ingredients in the diet, will affect DMI and energy availability from the feed. This is related to why the NRC (2001) computer model does not provide a value for energy available from individual feeds but only provides energy concentration of the total diet. With a better understanding of the interactions of dietary starch and fiber and particle size of forage, rumen heath can be maintained and improved digestibility of the diet can be accomplished.

**Table 2. Digestibility of the nonstructural carbohydrates and NDF in diets varying in particle size of dry ground corn and steam rolled corn (Callison et al., 2001).**

| Item[1] | Diets[2] | | | | |
|---|---|---|---|---|---|
| | FGC | MGC | CGC | SC | SRC |
| NSC digestibility (% of total tract unless indicated otherwise): | | | | | |
| Apparent rumen[Q,L] | 71.4 | 33.8 | 38.1 | 49.4 | 54.5 |
| True rumen[Q,L] | 88.7 | 49.7 | 54.2 | 68.2 | 71.2 |
| Apparent small intestine[Q,NS] | 19.9 | 60.2 | 47.7 | 46.7 | 36.9 |
| Apparent large intestine | 8.6 | 8.4 | 14.2 | 16.1 | 8.6 |
| Total tract, % of intake[L,Q] | 98.0 | 92.2 | 91.3 | 89.3 | 95.0 |
| Rate of digestion[L,L] | 0.104 | 0.051 | 0.020 | 0.031 | 0.037 |
| NDF digestibility (% of total tract unless indicated otherwise): | | | | | |
| Rumen[L,NS] | 45.6 | 51.5 | 52.7 | 52.6 | 47.5 |
| Small intestine | 13.2 | 7.7 | 9.7 | 11.5 | 13.5 |
| Large intestine | 18.9 | 15.4 | 9.7 | 9.5 | 11.1 |
| Total tract, % of intake | 66.4 | 66.5 | 65.2 | 66.5 | 62.8 |

[1]NSC = Nonstructural carbohydrates and NDF = neutral detergent fiber.

[2]Diets contained 50% alfalfa silage and 36.6% corn: FGC = fine ground corn, MGC = medium ground corn, CGC = coarse ground corn, SC = 50% steam rolled corn and 50% coarse ground corn, and SRC = steam rolled corn.

[L,Q,NS]First letter designates linear or quadratic effect of particle size of ground corn, the second letter designates linear or quadratic effect of level of steam rolled corn, and NS = not significant.

## ■ Dietary Formulation of Carbohydrates

A maximum amount of rapidly fermentable carbohydrates (i.e., NFC) and a minimum amount of slowly degradable carbohydrates (i.e., NDF) must be provided when formulating diets and the ratio between these carbohydrate fractions is important. The historical index for adequate structural carbohydrates has been forage concentration (or forage:concentrate ratio); however, this provides neither consideration for quality of the forage (level of fiber) nor recognizes fiber from nonforage sources. Hence, minimum levels of fiber have been established (Table 3). The minimum concentrations of NDF and ADF and the proportion of the NDF that should be provided from forage take into consideration forage quality: as forage quality increases (NDF decreases), more of the forage must be fed to meet minimum fiber levels. As forage quality decreases (NDF increases), the level of forage in the diet should be decreased. High NDF diets can reduce DMI, thus high concentrations of NDF, especially FNDF, need to be avoided.

**Table 3. Dietary factors for balancing carbohydrates in diets for lactating dairy cows.**

| Dietary Component[1,2] | General Guideline | Comments |
|---|---|---|
| Forage, % of DM | 40 to 60 | Not a good indicator because forage quality, total NDF, NFC degradability, and particle sizes are unknown |
| NDF, % of DM | 26 to 28 minimum | Source of NDF unknown |
| eNDF, % of NDF | 65 to 85 | Actual value varies with particle size and association with other dietary ingredients |
| peNDF, % of DM | 20 to 22 minimum | Lack of research to establish relationships between effects on animals and measurement with 1.18 mm screen |
| ADF, % of DM | 19 to 21 minimum | Excludes hemicellulose, which varies among forage species |
| FNDF, % of DM | 16 to 21 minimum (25 maximum) | Good indicator of effective fiber (exceeding this concentration increases risk of rumen fill) |
| NFC, % of DM | 35 (minimum) to 42 (maximum) | Variation occurs in methods of calculations |
| Starch, % of DM | 25 (minimum) to 35 (maximum) | Often unavailable |
| FNDF/NFC | 0.45 to 0.50 | Evaluative index for balance of carbohydrates to maintain rumen function |
| Sugar, % of DM | 4 to 5 | Limited research; molasses is often the supplemental source |

[1]DM = Dry matter, NDF = neutral detergent fiber, eNDF = effective NDF, peNDF = physically effective NDF, ADF = acid detergent fiber, FNDF = forage NDF, and NFC = nonfiber carbohydrates.

[2]Particle size of forage, grain, and TMR also must be evaluated.

Use of ADF instead of NDF as the index for minimum dietary fiber results in different minimum levels of forage because of the different ratios of NDF to ADF among forage species. However, ADF is more reflective of effective fiber when a major portion of the total fiber in a ration is being contributed from nonforage sources. Some people desire to express dietary NDF recommendations as percentages of body weight, which has some merit because of the relationship between rumen size and body weight; however, the overall meaningfulness of this approach is limited.

A maximum dietary level of 42 to 44% NFC has been suggested, but this concentration depends on concentration of FNDF in the diet and the rate and extent of ruminal digestibility of the NFC fraction as discussed previously. A minimum concentration of starch or NFC is most likely necessary to optimize microbial protein synthesis. Maintaining a stable rumen fermentation by providing a minimum level of fiber and not exceeding a maximum level of NFC must be complemented by the feeding system. A consistent flow of substrates to the rumen provides for an efficient and stable fermentation. Yet, particle sizes for the forage, starch source, and use of a total-mixed ration (TMR) are very important for providing effective fiber (larger size), regulating rate of carbohydrate fermentation, stimulating saliva production (larger size), and for minimizing sorting by cows (smaller size). Using the Penn State Particle Size Separator (Heinrichs, 1997), the TMR should have a distribution of 10, 45, and 45% in the top (> 19 mm), middle (8 to 19 mm), and pan (< 8 mm) with typical diets, respectively. The distribution of particles in a TMR consisting of nonforage fiber sources and low forage may be 5, 50, and 45%, respectively. Because the quality of haycrop forage fed to dairy cows has increased (lower NDF) in recent years as less hay and more haylage is being fed on farms, and because corn silage often consists of a greater proportion of the TMR than previously, small amounts of straw, usually 2 to 5% of the ration, are fed on some farms as a source of peNDF (Eastridge, 2004).

Sugar concentration in feeds varies and these carbohydrates are rapidly fermented in the rumen. Sugar supplementation to diets for lactating cows has received limited attention in controlled studies (although often practiced in the field) and has resulted in mixed responses. Optimization of ruminal fermentation may occur when the diet contains 4 to 5% sugars.

## ▪ Efficiency of Animal Production

As stated previously, the NFC fraction is very important for optimizing microbial protein synthesis in the rumen and supplying energy to the cow. The fibrous fraction is important for maintaining rumen health and also for supplying energy. Therefore, balancing these fractions is critical for optimizing DMI and milk yield (1 kg additional DM intake should result in about 2 kg additional milk). Excessive amounts of either NFC or NDF will decrease DMI and thus decrease milk yield. However, within the margins of safety, there is opportunity to focus on maximizing efficiency of animal performance. One of the long-term problems with looking at efficiency is that there are several approaches to describe efficiency. Efficiency can be defined as a measure of output generated per unit of an input. The beef cattle industry has monitored feed efficiency (FE; kg gain/kg DMI) for years; however, the dairy industry was slow in adopting this monitor until recently. Some of the slowness in adoption is justified because FE is more variable with dairy cattle than finishing beef cattle. Dairy cattle are fed more diverse diets and milk yield and composition vary with stage of lactation which contributes to this variation. So using feed efficiency requires an understanding of additional information, including those already mentioned and whether milk or fat-corrected milk (FCM) are used as the output, to explain the difference between actual and target levels. Although the target level is 1.4 to 1.6 for 3.5% FCM/DMI, fresh cows should have about a 0.2 unit higher efficiency because they are mobilizing body fat to support milk yield. First lactation cows may have about a 0.2 unit lower FE because of nutrients required for continued growth, with second lactation cows having a 0.1 unit lower FE than the expected average. Cows in hot months of the year will likely have at least a 0.1 unit lower FE than cows in cool months (Britt et al., 2003).

Feed efficiency is somewhat reflective of utilization of carbohydrate sources. Using data from 13 herds, Britt et al. (2003) observed a negative correlation with FE and either forage or NDF intake. Increasing digestibility (ruminal and/or total tract) of starch by processing grain sources generally increases FE, especially when comparing within a grain source, and tends to reduce milk fat/milk protein (Table 4). Therefore, feeding management needs to focus on improving FE while also maintaining rumen health.

**Table 4. Animal responses to processing of grain sources.[1]**

| Grain source[2] | DMI (kg/day) | Milk (kg/day) | Milk fat (%) | FE | MF/MP |
|---|---|---|---|---|---|
| Corn, steam-rolled | 26.5 | 35.8 | 3.11 | 1.27 | 1.04 |
| Corn, steam-flaked | 26.5 | 38.0 | 2.98 | 1.31 | 0.97 |
| Sorghum, dry-rolled | 25.6 | 35.6 | 3.20 | 1.32 | 1.08 |
| Sorghum, steam-flaked | 25.1 | 37.4 | 3.03 | 1.38 | 1.00 |
| | | | | | |
| Corn, dry cracked/rolled | 22.5 | 30.9 | 3.59 | 1.39 | 1.16 |
| Corn, dry ground | 23.1 | 31.5 | 3.53 | 1.37 | 1.11 |
| Corn, dry ground finely | 21.9 | 32.4 | 3.49 | 1.48 | 1.16 |
| Corn, steam-rolled | 22.1 | 31.9 | 34.9 | 1.44 | 1.13 |
| Corn, steam-flaked | 22.8 | 32.5 | 3.36 | 1.39 | 1.08 |
| Corn, HM rolled | 22.7 | 32.5 | 3.54 | 1.44 | 1.12 |
| Corn, HM ground | 23.1 | 33.9 | 3.37 | 1.44 | 1.06 |
| Sorghum, dry rolled/gr | 23.4 | 31.5 | 3.50 | 1.35 | 1.17 |
| Sorghum, steam-flaked | 23.0 | 32.7 | 3.41 | 1.40 | 1.10 |
| Barley, dry or steam roll | 20.5 | 33.1 | 3.44 | 1.60 | 1.11 |
| Barley, steam roll hull-less | 20.9 | 31.9 | 3.53 | 1.53 | 1.16 |

[1]DMI = Dry matter intake, feed efficiency (FE) = 3.5% fat-corrected milk/DMI, MF/MP = milk fat/milk protein, and HM = high moisture.
[2]First four observations taken from Theurer et al. (1999) and the remainder from Firkins et al. (2001).

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