Optimizing the Role of Starch as an Energy Source for Dairy Cows

Luiz F. Ferraretto[1]
Department of Animal Sciences
University of Florida

Summary

Although starch is not considered a required nutrient, it is often a topic of discussion, primarily due to its high concentration in corn grain and silage. The objectives of this article are to present and discuss: 1) the effects of dietary starch concentration throughout the lactation, and 2) potential strategies to optimize digestibility of starch in feedstuffs and its utilization by lactating dairy cows. Potential negative effects on either milk yield or feed efficiency when reducing dietary starch exist and underscores that monitoring income over feed costs is recommended rather than price per unit of diet dry matter (**DM**) when corn prices are high to fully assess economic benefits of reduced-starch diets. Many factors alter starch digestibility of feedstuffs; mean particle is the most important factor in corn silage, corn grain, and high-moisture corn. However, on farm assessment is advised.

Introduction

Compared with other nutrients, starch was the most under evaluated research topic in dairy nutrition for many years. Consequently, starch recommendations for dairy cows were not established by the NRC (2001). Recently, improvements in the use of starch by lactating dairy cows garnered much interest by dairy farmers and their nutritionists; particularly over the past decade with the 2-fold rise in corn prices. Although starch is still not considered a required nutrient, it was highlighted as a very important factor for diet formulation during the 28th ADSA Discovery Conference – Starch. But despite not being considered a required nutrient, starch is often a topic of discussion, primarily due to its high concentration in corn grain (approximately 70% on a DM basis). Although other carbohydrates can be fed to dairy cows to supply and meet energy demands, carbohydrate sources differ in fermentation end-products produced by rumen microorganisms. Starch is rapidly fermented by rumen microorganisms into propionate. Propionate is absorbed into the bloodstream and transported to the liver, and later, it is used as a precursor for glucose. If not digested in the rumen, starch reaches the small intestine and is digested by pancreatic amylase directly into glucose. Thus, despite starch not having established requirements, its supplementation directly affects glucose supply and thereby, lactation performance of dairy cows. Consequently, starch utilization by lactating dairy cows became an important research topic. Thus, the objectives of the present article are to present and discuss: 1) the effects of dietary starch concentration throughout the lactation, and 2) potential strategies to optimize digestibility of starch in feedstuffs and its utilization by lactating dairy cows.

[1]Contact at: 2250 Shealy Drive, 202B Animal Sciences Bldg., Gainesville, FL 32611, (352) 294-1005, Email: lferraretto@ufl.edu

Starch Concentration in the Diet

Although starch can be used throughout the entire lactation, its concentration or potential replacement viability is dependent of the stage of lactation. These effects are related to energy demand and metabolism during each stage. The most controversial period is the early lactation; few studies were conducted with fresh cows compared with the abundant available data for mid-lactation cows. During early lactation, cows require a diet balanced to support the extreme metabolic adaptations they undergo through calving. Briefly, there is a major limitation in feed consumption which severely reduces the energy available to meet the requirements of high-producing animals. Thus, it would be coherent to increase dietary starch concentration to minimize the period by which dairy cows remain in negative energy balance. However, in several herds, cows are fed controlled-energy close-up diets, which if combined with a fresh cow diet of high-starch concentration may negatively affect rumen health and metabolism. Based on 3 studies conducted in the northeast of the United States, McCarthy et al. (2015) suggested that perhaps the difference in starch levels between pre- and post-partum diets may be more important than specific dietary starch levels fed to fresh cows. In addition, it is important to formulate lower starch diets during the early lactation period with digestible carbohydrates so they do not limit intake because of gut fill or through the hepatic oxidation pathway (Allen et al., 2009).

As dairy cows reach the peak of their milk production and continue throughout their mid-lactation, energy requirements are still high, but the metabolic constraints of feed consumption are no longer a concern. Unless limited by gut fill, cows would adjust their consumption levels to attend to their energy demands. For example, a reduction in feed consumption and milk production were observed when corn silage partially replaced dry ground corn in the diet (26 vs. 32% of dietary starch, respectively) which is indicative of increased gut fill (Weiss et al., 2011). In contrast, studies replacing dry ground corn with soy hulls revealed similar milk production but greater intake for cows fed the reduced-starch diets; this is indicative of adjusted consumption to achieve the required energy intake.

A recent review used a meta-analysis approach to evaluate the effect of dietary starch on lactation performance by dairy cows (Ferraretto et al., 2013). Dietary starch values were considered for this study but not the specific type of carbohydrate used to replace starch. Starch concentration in the diet did not affect intake and this was thought to be related to 2 opposing effects: rumen fill limitation (Mertens, 1987) and increased ruminal propionate concentrations with corresponding decreased meal size (Allen et al., 2009) when corn grain was partially replaced by forage and non-forage fiber sources, respectively. Although milk yield increased 0.08 kg/day per %-unit increase in dietary starch content, feed conversion was unaffected by dietary starch. In addition, increased dietary starch concentration enhanced milk protein content. Reduced milk protein content for cows fed reduced-starch diets are related to lower starch intake reducing ruminal microbial protein production (Oba and Allen, 2003). Alternatively, lower amount of starch reaches the small intestine mediating milk protein content through alterations in arterial insulin concentrations (Rius et al., 2010). Conversely, however, milk fat content decreased as dietary starch content increased. Milk fat depression in high-starch diets is likely related to greater starch and lower NDF intakes (Jenkins and McGuire, 2006). The MUN concentration was also reduced by increasing dietary starch concentrations. Overall, these data suggest better ruminal nitrogen utilization (NRC, 2001) as starch in the diet increases.

Another result of interest highlighted by the meta-analysis of Ferraretto et al. (2013) is the effect of dietary starch concentration on in vivo NDF digestibility. The digestibility of dietary NDF decreased 0.61%-units ruminally and 0.48%-units total-tract per %-unit increase in dietary starch content. Similarly to milk fat depression, decreased fiber digestibility may be partially explained by a decrease in rumen pH as a consequence of greater amounts of starch being digested in the rumen as starch intake increases. Low rumen pH is known to affect microbial growth and bacterial adherence and thereby fiber digestion. Also, the inherently high fiber digestibility of non-forage fibrous by-products used to partially replace corn grain in reduced-starch diets may be partly responsible. A meta-analysis by de Souza et al. (2018) used individual animal data instead of treatment means and observed a similar reduction of 0.59%-units in total tract NDF digestibility for each 1%-unit change in dietary starch. An exercise presented by Weiss (unpublished) during the 28th ADSA Discovery Conference on Starch for Ruminants calculated the effects of a 0.5%-unit change in total tract NDF digestibility for each 1%-unit change in dietary starch content on dietary energy values. In the Weiss exercise, a 5%-unit increase in dietary starch content (e.g., 30 vs. 25%) would increase diet NE_L content by 6.5% without accounting for adverse effects of dietary starch on total tract NDF digestibility. However, it was revealed that the reduction of 2.5-% units (46.5 to 44.0%) in total tract NDF digestibility would alter this scenario to a 5.3% increase in diet NE_L content. Further incorporation of these effects on models are warranted. However, other factors should also be considered to enhance future predictive equations. For example, grass inclusion in the diet and intake (expressed as percentage of BW) altered total tract NDF digestibility in the study by de Souza et al. (2018). White et al. (2017) observed greater effects of intake than starch concentration on total tract NDF digestibility and suggested that the potential negative effects of starch on consumption may attenuate its effect on NDF digestibility when gut fill is not a constraint.

Perhaps to separate the specific feed ingredients used to replace starch in dairy cattle diets could be an important step. Reduced-starch diets could be formulated by partially replacing cereals grains with high-fiber, low-starch byproduct feedstuffs (e.g., soy hulls, citrus pulp, whole cottonseed, beet pulp, cottonseed hulls, wheat middlings, etc.), high starch forages (i.e. whole-plant corn silage), or high-sugar ingredients (i.e. molasses, whey, sucrose). However, although these varied carbohydrate sources can be used for energy, their ruminal fermentation by microorganisms yields different fermentation end-products than starch, which in turn alter metabolism and performance by dairy cows. Fredin (2015) conducted a meta-analysis to identify which of these feeding strategies could mitigate potential negative effects of feeding reduced-starch diets to lactating dairy cows. Milk yield was decreased when starch was replaced by either non-forage fiber sources (0.16 kg/day per %-unit decrease in dietary starch) or forage (0.32 kg/day per %-unit decrease in dietary starch). Reduced intake and ruminal degradation of forage NDF compared to non-forage NDF (Allen, 1997) were thought to induce greater reduction in milk yield when dietary starch was replaced by forage in the study by Fredin (2015). However, Fredin (2015) highlighted that 24 out of 61 treatment means for milk yield were greater for reduced-starch compared to high-starch diets, suggesting that positive lactation performance can be achieved when feeding reduced-starch diets. Milk component yields were also reduced when dietary starch was replaced.

Potential negative effects on either milk yield or feed efficiency underscores that monitoring income over feed costs is recommended rather than price per unit of diet DM to fully assess economic benefits of reduced-starch diets. Based on these meta-analysis reviews of literature (Ferraretto et al., 2013; Fredin, 2015) to reduce dietary starch for peak and mid-lactation dairy cows may not be feasible and individual scenarios for each farm must be carefully evaluated.

Starch Digestibility in Corn Grain and Silages

Starch represents approximately 50 and 75%, respectively, of the energy value of corn silage and corn grain (calculated from NRC, 2001). Compared with other starch sources (i.e., barley and wheat), corn has lower ruminal and total tract starch digestibility (**TTSD**; Ferraretto et al., 2013).

A better understanding of factors affecting starch availability and digestion could lead to the formulation of more efficient and cheaper rations with lower starch levels and aid to prevent ruminal acidosis, which is typical in high-starch diets. In addition, focus on ruminal starch digestibility is desired as it alters efficiency of energy usage and increases ruminal microbial synthesis when dietary ruminal degradable protein levels are adequate (Firkins et al., 2006). Greater microbial protein synthesis explains the greater milk protein concentration per unit of rumen-digestible starch concentration (Ferraretto et al., 2013). An increase in starch digestion may lead to better nutrient utilization and decreased feed costs. Detailed descriptions about factors influencing starch utilization in corn silage and grain will be discussed in this section.

Starch digestibility of whole-plant corn silage (**WPCS**), high-moisture corn (**HMC**), and dry ground corn (**DGC**) may be affected by several factors. First, the starch endosperm is protected by the pericarp which, if intact, is highly resistant to microbial attachment (McAllister et al., 1994), thereby breakage of the seed coat is obligatory. Diets containing HMC with mean particle size (**MPS**) below 2 mm had greater total TTSD compared with HMC with MPS greater than 2 mm (95.2 to 89.5%; Ferraretto et al., 2013). Likewise, increased MPS reduced TTSD in DGC-based diets (77.7 to 93.3% for 4 mm and 1 mm respectively; Ferraretto et al., 2013). This is related to the increased surface area exposed for bacterial and enzymatic digestion with finer particles (Huntington, 1997). Greater starch digestibility and corresponding milk production by dairy cows is achieved when corn silage is harvested using a kernel processor with roll gap settings between 1 to 3 mm (Ferraretto and Shaver, 2012).

Reduced kernel particle size improves starch digestibility by increasing the surface area exposed to ruminal microbes. However, even the exposed endosperm is not fully digestible due to existence of a starch-protein matrix formed by the chemical bonds of zein proteins with starch granules (Kotarski et al., 1992; McAllister et al., 1993). Thus, the next step would be to liberate starch from its protein matrices. As corn matures, starch not only becomes more vitreous but more bonds are formed with zein proteins. This starch-protein matrix reduces starch digestibility. Ruminal in vitro starch digestibility was greater when HMC was harvested at lower DM content (Ferraretto et al., 2014). Furthermore, reduced TTSD were observed in diets containing WPCS above 40% DM in the meta-analysis review by Ferraretto and Shaver (2012). This may be related to an increase in the proportion of vitreous endosperm in the kernel associated with greater maturity (Correa et al., 2002; Ngonyamo-Majee et al., 2009). Alternatively, a reduction in the extent of fermentation for drier WPCS (Der Bedrosian et al., 2012) may attenuate the breakdown of zein proteins during fermentation (Hoffman et al., 2011). Goodrich et al. (1975) harvested HMC with 67% DM and oven-dried corn to 73 and 79% DM to study the effects of moisture content on fermentation of HMC and observed a decrease in acetate and lactate concentrations and a corresponding increase in pH as DM content of HMC increased. Lower lactate and acetate concentrations are likely related to a reduced bacterial growth due to limited water availability (Muck, 1988). Goodrich et al. (1975) also observed reduced ruminal in vitro gas production as DM content increased, suggesting reduced starch digestibility for HMC at greater DM contents. Combining these results suggest that proper maturity at harvest is required to maximize starch digestibility in WPCS and HMC.

Research trials on the effects of storage length on ruminal in vitro starch digestibility (**ivSD**) of WPCS were summarized by Kung et al. (2018). Interestingly, all the summarized trials had a spike in ivSD after 30 to 45 days of storage followed by a gradual increase in ivSD after additional storage time. These results indicate that perhaps ivSD continuously increases during storage. Proteolytic activity, either from microbial or plant proteases, occurs more extensively during the anaerobic fermentation process (Baron et al., 1986). The anaerobic phase is characterized by a drastic decrease in pH (Muck, 2010), which favors the activity of plant proteases specific to the endosperm of cereal grains (Simpson, 2001), even though the activity of plant proteases is typically reduced under low pH (Muck, 1988). Junges et al. (2015) evaluated the contribution of proteolytic sources on protein solubilization in rehydrated corn ensiled for 90 days. These authors reported that bacterial proteases are responsible for 60% of the increase in soluble CP concentration, followed by kernel enzymes (30%), and fungi and fermentation end-products (5% each).

This variance in starch digestibility within and among feeds suggests that the assessment of starch digestibility is essential for adequate diet formulation. Although the incubation of feeds in ruminal fluid for 7 hours is the standard assay used in the United States (either in vitro or in situ) to rank feedstuffs, more accurate predictions of starch digestibility would benefit various industry sectors. Perhaps a similar approach to the various pools of NDF digestion used by the Cornell Net Carbohydrate Protein System (**CNCPS**) model could be an option. Recently, Fernandes et al. (2018) analyzed rapidly and slowly degradable fractions and rate of disappearance of starch in several starchy feedstuffs. Fraction A ranged from 13.4 to 96.1% of starch, whereas rate of disappearance varied from 2.1 to 11.5% per hour. Although the validation was only performed for mature corn grain, Fernandes et al. (2018) suggested that 0, 3 (or 6), and 48 hours of incubation could be feasible to evaluate digestibility and rank feedstuffs. Perhaps in combination with laboratory assays, the on-farm assessment of starch digestibility may be a great option.

Fredin et al. (2014) reported a strong relationship between fecal starch measurements and TTSD. These results suggest that additional measurements, such as starch content of the diet or marker concentrations of the feces or diet, are unnecessary. Furthermore, Fredin et al. (2014) reported high accuracy of near infrared reflectance spectroscopy to predict fecal starch, which allows for more rapid and inexpensive analysis. Although benefits of greater starch digestibility on milk production is well known, it is very difficult to reliably estimate its economic impact. The exercise presented and discussed in this article is an attempt to provide some numbers to dairy producers and their nutritionists as a starting point.

To accomplish our goal, a hypothetical scenario was created and 5 values of fecal starch were arbitrarily chosen and used to predict TTSD using the equation of Fredin et al. (2014; Table 1). Subsequently, the amount of corn that would need to be supplemented in order to obtain the same amount of digestible starch as if TTSD was 100% was estimated using the following assumptions: dietary starch was 25% of DM and consumption of DM was 25 kg/day. Consequently, it was assumed that cows were eating 6.25 kg/day of starch. Based on TTSD, values of starch loss in the manure was calculated and ranged from 0 to 1.56 kg. If one consider that corn grain has 70% starch and 70% ruminal in vitro starch digestibility, for each kg of corn supplemented only 0.49 kg of digestible starch is provided. Thus, by dividing starch loss by 0.49, we reached the amount of corn necessary to fulfill for undigested starch. Last, US$130/ton (US$0.13/kg) was used to calculate corn grain costs. Values used in the present exercise is not representative of the entire American dairy industry, but it is a good indication of potential economic loss related to low starch digestibility. Thus, it is recommended that dairy farmers and their nutritionists perform similar calculations based on their own scenarios and goals.

Fecal starch does not indicate digestibility of specific feedstuffs but of total diets, and it can be used as a valuable tool to monitor specific groups over time by collecting samples from at least 10% of animals in the group. If fecal starch levels are above 3%, it is advised the evaluation of specific starchy feedstuffs to elucidate the problem. In addition, re-evaluation of fecal starch values are recommended after 2 or 3 weeks of dietary or management adjustments.

Conclusions

- Starch digestibility affects milk and milk components production;
- Several strategies may increase starch digestibility of individual ingredients; particularly mean particle size, maturity at harvest, and hybrid endosperm type;
- Reduction in dietary starch reduces price per unit of DM but analysis of income over feed cost is advised; and
- Combine fecal starch and milk analysis to optimize nutritional management.

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Table 1. Economic estimates of corn supplemented to fulfill undigested starch.

Fecal starch, % of DM	0	5	10	15	20
TTSD[1], % of starch	100	93.75	87.50	81.25	75.00
Starch intake[2], kg/cow/day	6.25	6.25	6.25	6.25	6.25
Starch loss[3], kg/cow/day	0	0.39	0.78	1.17	1.56
Corn grain supplementation[4], kg/cow/day	0	0.80	1.59	2.39	3.18
Corn grain cost[5], US$/cow/day	0.00	0.10	0.21	0.31	0.41

[1]Predicted from equation of Fredin et al. (2014); TTSD = 100 – (1.25 x fecal starch).
[2]Starch intake = (25 kg DMI x 25% starch) / 100
[3]Starch loss = starch intake – [(starch intake x TTSD) / 100]
[4]Corn grain supplementation = starch loss / 0.49
[5]Corn grain cost = corn grain supplementation x 0.13. Corn grain cost obtained from values reported by FeedVal 2012 on March, 2018.