Dietary Sugars for Optimizing Rumen Function and Dairy Cow Performance

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Introduction

Typical US lactating dairy rations without supplemental sugars contain about 1.5 to 3% sugar. The use of more fermented forages and processed feeds has resulted in the removal of many sugars that would otherwise naturally be in the dairy cow diet. Sugars are water-soluble and include monosaccharides (glucose and fructose) as well as disaccharides (sucrose and lactose). Adding supplemental dietary sugar often reduces rumen ammonia, suggesting that rapidly digestible sugars help the rumen microbes capture and use nitrogen. Fiber digestion, microbial protein synthesis, energy absorption and rumen pH can increase with additional dietary sugars when balanced appropriately with dietary starch to positively impact dairy cow performance. Dietary factors such as physically effective fiber, level of starch, starch digestion rate, degradable proteins, and unsaturated fatty acids may affect cow response to supplemental sugars. Level of milk production and DIM may also influence responses to added dietary sugars.

Rumen Ammonia and Microbial Protein Synthesis

For efficient rumen microbial growth, availability of carbohydrate and protein is essential (Nocek and Russell, 1988). Work with continuous cultures of rumen microbes showed that microbial yield decreased curvilinearly from 34.2 to 10.3 g bacterial nitrogen per kg DM digested as the nonstructural carbohydrate / rumen degradable crude protein ratio widened from 1.9 to 8.9 (Hoover, 1987, Stokes et al., 1991). Aldrich et al. (1993) found the highest microbial protein yield (262 g/d) when a rapidly digestible protein source was fed with a rapidly digestible starch source and the lowest microbial protein yield (214 g/d) when a slowly digestible protein source was fed with a rapidly digestible starch source.

Additional dietary sugar almost always reduces rumen ammonia (Hoover and Miller-Webster, 1998), suggesting that sugars help the microbes capture and use dietary nitrogen. Dietary sugar above 7% has reduced ammonia concentrations (Broderick et al., 2008; Chibisa et al., 2015; McCormick et al., 2001), indicating improved in N utilization. Added dietary sugar has been shown to increase microbial protein synthesis (Chamberlain et al., 1993; Khalili and Huhtanen, 1991; Piwonka and Firkins, 1993), however, not consistently (Broderick et al., 2008; Sannes et al., 2002). Hall (2017) speculated that microbial protein yield from sugar fermentation would be increased in the presence of true proteins and peptides in the rumen. When given glucose as a substrate, rumen microbes preferred to use amino acids and peptides rather than urea (Hristov et. al., 2005).

Rumen pH

Sub-clinical rumen acidosis (SARA) occurs when the pH of the cow's rumen drops below 5.8. Excessive production of rumen lactic acid, primarily from the fermentation of starch, reduces pH. At low rumen pH, hydrogen ions leak inside the microbes. To maintain near neutral pH within their cells, the microbes must expend energy to expel hydrogen ions, resulting in less energy available for growth (Strobel and Russell, 1986). Those microbes that ferment fiber are most negatively affected by rumen acidity (Russell and Dombrowski, 1980).

Supplemental sugars may improve rumen pH via a few different mechanisms. First, lower rumen propionate would be expected if sugar was substituted for dietary starch (Bannink et al., 2006). Second, if sugars improve efficiency of microbial protein production and are incorporated into the microbial mass, less rumen degraded OM would be converted into fermentation acids. Increasing microbial efficiency from 20 to 30 g microbial N per kg of rumen degraded OM should result in a 12.5% reduction in fermentation acids (Allen, 1997; Penner et al., 2009). Further, because sugars are rapidly available, they are more apt to be converted into the storage polysaccharide, glycogen, by rumen bacteria and protozoa (Hall, 2017), slowing fermentation to control rumen acidity.

Dietary sugar often increases the molar proportion of butyrate (Chibisa et al., 2015; DeFrain et al., 2004; Oba et al., 2015; Penner et al., 2011; Sun et al., 2015; Vallimont et al., 2004). Butyrate generates only one H^+ while propionate and acetate generate 2 H^+. Butyrate stimulates the rumen epithelial cells, increasing VFA absorption from the rumen (Oba et al., 2015). In continuous culture, Vallimont et al. (2004) linearly increased butyrate from 12.2 to 13.8, 13.7, and 14.2 mol/100 mol when 0, 2.5, 5.0, and 7.5% sucrose was supplemented. Higher rumen butyrate concentrations may improve both rumen epithelial absorption of acids and glucose transport, to moderate rumen pH (Oba et al., 2015; Penner et al., 2011).

Penner et al. (2009) replaced cracked corn grain with sucrose to produce diets containing either 2.8 or 5.7% sugar. The high sugar diets resulted in a higher daily minimum rumen pH (5.61 vs. 5.42) as well as a higher mean rumen pH (6.30 vs. 6.17). Postpartum transition cows fed 8.4% vs. 4.7% dietary sugar tended to have higher nadir (5.62 vs. 5.42), mean (6.21 vs. 6.06) and maximum rumen pH (6.83 vs. 6.65) (Penner and Oba, 2009). Cows fed diets designed for milk fat depression (> 33% starch) had significantly higher rumen pH (5.87 vs. 5.73) when 5% of the diet DM from corn was replaced with molasses (Martel et al., 2011).

Milk Fat

A common effect of sugar supplementation is an increase in milk fat percentage and/or yield. This can be explained by a number of mechanisms. First, as previously discussed, sugars increase the molar proportion of butyrate and butyrate is used for milk fat synthesis. Second, if sugars moderate rumen pH as previously described, one would expect a positive relationship of rumen pH on milk fat percentage (Allen, 1997). Finally, sugars impact fatty acid biohydrogenation. When Sun et al. (2015) replaced corn starch with 3, 6, or 9% sucrose, *Butyrivibrio fibrisolvens* numbers increased. *Butyrivibrio fibrisolvens* produces both butyrate and CLA cis-9, trans-11 which is part of the normal fatty acid biohydrogenation pathway. At the same time, numbers of *Megasphaera elsdenii* were decreased thus inhibiting production of the trans-10 isomer of the 18:1 fatty acid implicated in milk fat depression.

When Broderick et al. (2008) replaced starch with 2.5, 5, and 7.5% sucrose, milk fat yield increased from 1.47 to 1.53, 1.65, and 1.62 kg/cow/day, respectively with the effect at 5% sucrose being statistically significant ($P<0.05$). Milk fat percentage changed from 3.81 to 3.80, 4.08, and 4.16%, with the positive effects at 5 and 7.5% sucrose being statistically significant ($P<0.05$). Postpartum transition cows fed 8.4% vs. 4.7% dietary sugar tended to have higher milk fat yield (1.44 vs. 1.35 kg/d) (Penner and Oba, 2009). Cows fed high starch diets (> 46% NFC) designed for milk fat depression responded with higher milk fat concentrations (3.01 vs. 2.61%), specifically from short- and medium-chain fatty acids, when 5% of the diet DM from corn was replaced with molasses (Martel et al., 2011).

Fiber Digestion

In a few studies, added dietary sugars have improved fiber digestion. Firkins (2011) suggested that sugar fermenting bacteria may provide growth factors and improve the environment for fluid-associated fiber-digesting bacteria in the rumen. Improvements in rumen pH as a result of sugar supplementation should also positively impact fiber digestion. Broderick et al. (2008) showed a positive quadratic effect on fiber digestion when they replaced corn starch with sugar (2.5, 5, and 7.5% sucrose) in a 60% forage diet. Both ADF and NDF digestion were highest with the addition of 5% sucrose (7.1% total dietary sugar). When Broderick and Radloff (2004, Trial 2) used liquid molasses to replace high moisture corn in a 60% forage diet to increase dietary sugar (2.6, 4.9, 7.4 and 10% of diet DM), fiber digestion was significantly higher with the 7.4% sugar diet.

Intake and Production

Supplemental sugars have generated variable intake and milk production results in published studies. Although Broderick et al. (2008) increased DM intake and yield of milk fat with added dietary sugar, effects on milk and fat-corrected milk yield were not significant. Postpartum transition cows fed 8.4% vs. 4.7% dietary sugar had higher DM intake (18.3 vs. 17.2 kg/d) but milk yield was not affected, averaging 33.7 kg/d (Penner and Oba, 2009). Adding a liquid molasses product to a TMR at a rate of 4.1% increased dietary sugar from 4 to 5.4% to reduce TMR sorting as well as improve DM intake (27.7 vs. 29.1 kg/d) and 4% FCM yield (39.7 vs. 42.8 kg/d) (DeVries and Gill, 2012).

When Broderick and Radloff (2004, Trial 1) incrementally replaced high-moisture corn with dried molasses (2.6, 4.2, 5.6 and 7.2% dietary sugar), there was a positive quadratic response in milk fat content, yield of fat, and FCM with maximum responses occurring at 4.2 to 5.6% dietary sugar. Dry matter intake increased by 1 kg/cow/d (26.3 vs. 25.3 kg/cow/d) with 5.6% vs. 2.6% dietary sugar.

Replacing corn grain with sugar to reduce dietary starch from 32 to 27% and increase dietary sugar from 4.5 to 9% resulted in higher DM intake (27.5 vs. 26.2 kg/d), higher ECM (39.6 vs. 38 kg/d) and higher milk CP yield (1.31 vs. 1.26 kg/d) (Gao and Oba, 2016).

Predicting Dairy Cattle Response to Added Dietary Sugars

The impact of supplemental dietary sugar on dairy cow responses was determined using an 85 observation dataset from published research, while accounting for the effects of other diet nutrients and cow factors including DIM and production level (de Ondarza et al., 2017). Sugar sources included molasses, whey, and dry sugar (sucrose or lactose). Dietary forage NDF was 17.4 to 29.5%, typical of commercial US dairy diets. Diet nutrient profiles were determined by entering diet and feed analysis data from each experiment into an advanced nutrition model (CNCPS 6.1 with NDS platform, RUM&N Sas, Italy). Mixed model linear regression analysis was conducted using the Fit Model function of JMP statistical software (SAS Inst. Inc, Cary, NC). The model fit used treatment category (control, 1.5-3%, 3-5%, vs. 5-7% added dietary sugar (% of diet DM)), DIM category (< 150 or > 150 DIM) within treatment, control milk yield category (> 33 or < 33 kg/d) within treatment, and the following nutrient variables (% of diet DM) as continuous variables: starch, soluble fiber, forage NDF, ammonia, RDP, and protein B_2 (insoluble in boiling neutral detergent but soluble in boiling acid detergent solution). Number of cows per treatment was included as a weighting factor and experiment was included as a random effect. A description of the dataset including number of treatment means reported for each study, number of cows per treatment, mean DIM, and control 3.5% FCM (kg/d) for each study is presented in Table 1. Mean performance and diet characteristics are reported in Table 2. Days in milk ranged from 14 to 252. Fat-corrected milk yield in control cows ranged from 18 to 45 kg/cow/d.

Table 1. Published research studies used to determine the effect of additional dietary sugar on dairy cattle performance (adapted from de Ondarza et al., 2017).

Experiment	Number of Treatment Means	Number of Cows per Treatment	Mean DIM	Control 3.5% FCM, kg/cow/d
Baurhoo and Mustafa, 2014	3	12	129	38
Broderick et al., 2008	3	12	112	41
Broderick & Radloff, 2004 #1	3	12	167	41
Broderick & Radloff, 2004 #2	4	12	120	45
Cherney et al., 2003	4	20	98	38
Chibisa, 2013	4	8	165	41
De Frain et al., 2004	3	12	252	25
De Vries and Gill, 2012	2	12	109	43
Eastridge et al., 2011 #1	4	5	219	35
Eastridge et al., 2011 #2	4	12	109	41
Firkins et al., 2008 #1	4	10	81	36
Firkins et al., 2008 #2	5	10	81	34
Firkins et al., 2008 #3	4	12	112	38
Golombeski et al., 2006	4	12	173	30
Hall et al., 2010	4	18	114	40
Hindrichsen et al., 2006	3	6	223	18
Maiga et al., 1995	3	10	74	35
McCormick et al., 2001	4	8	100	38
Nombekela & Murphy, 1995	2	16	42	28
Oelker et al., 2009	5	7	202	36
Penner et al., 2009	4	8	205	24
Penner and Oba, 2009	2	25	14	37
Sannes et al., 2002	4	16	149	36
Siverson et al., 2014	4	40	238	31
Vargas-Rodriguez et al., 2014	2	48	157	35

Additional dietary sugar increased yield of milk, 3.5% FCM, and milk true protein (P<0.05) (Table 3). Milk yield was 31.91 kg/cow/d with no added sugar and increased (P=0.03) to 33.33 and 33.02 kg/cow/d with 3-5% and 5-7% added dietary sugar (% of diet DM), respectively. Likewise, 3.5% FCM increased (P=0.04) from 32.35 to 33.80 kg/cow/d with 5-7% added dietary sugar (% of diet DM). Milk true protein yield increased (P=0.05) from 0.98 kg/cow/d without supplemental sugar to 1.05 kg/cow/d with 5-7% added dietary sugar (% of diet DM). Increased milk true protein yield suggests a possible increase in rumen microbial protein synthesis with dietary sugar addition as observed by Chamberlain et al. (1993) and Khalili and Huhtanen (1991). Unlike the results of others (Broderick et al., 2008; Firkins et al., 2008), DM intake and milk fat percentage were not significantly increased (P>0.20) with additional sugar across these studies. Milk urea nitrogen was numerically lower with increasing supplemental sugar but this change was not statistically significant (P>0.20). Feed efficiency was not significantly impacted by sugar addition (P=0.13).

Table 2. Mean performance characteristics and diet nutrient parameters of published research studies used to determine the effect of additional dietary sugar on dairy cattle performance (adapted from de Ondarza et al., 2017).

	Mean	SD
DIM	142	58
DMI, kg	23.48	2.83
Milk, kg	35.30	5.79
Milk true protein, %	3.06	0.25
Milk true protein, kg	1.07	0.16
Milk fat, %	3.61	0.37
Milk fat, kg	1.27	0.22
3.5% FCM, kg	35.83	5.80
MUN, mg/dl	14.06	2.80
% Forage	50.85	6.45
CP, %DM	17.36	1.28
Ammonia, %DM	0.75	0.58
Protein B_2, %DM[a]	1.41	0.48
RDP, %DM	10.74	1.11
NDF, %DM	32.16	3.93
Forage NDF, %DM	22.89	2.85
Sugar, %DM	5.57	2.04
Starch, %DM	23.68	4.99
Soluble Fiber, %DM	6.44	1.93

[a] Protein that is insoluble in boiling neutral detergent but soluble in boiling acid detergent solution

Cows producing > 33 kg milk/d had greater responses to added dietary sugar ($P<0.0001$). Cows producing > 33 kg/d of milk produced 2.14 kg/d more 3.5% FCM with 5-7% added dietary sugar (% of diet DM) (37.78 vs. 39.92 kg/d). However, cows producing < 33 kg/d only responded with 0.77 kg/d more 3.5% FCM (26.91 vs. 27.68 kg/d) (Figure 1). Similar differences were observed with milk true protein yield ($P<0.0001$), increasing by 0.09 vs. 0.05 kg/cow/d with 5-7% added dietary sugar (% of diet DM) for higher vs. lower producing cows (Figure 2).

Ruminal VFA concentrations were impacted by dietary sugar addition (Table 3). Level of added dietary sugar tended ($P<0.10$) to affect rumen butyrate concentrations, increasing with 5-7% added dietary sugar (Table 3). Acetate and propionate (mM) decreased ($P<0.05$) with added dietary sugar.

Table 3. The effect of additional dietary sugar category (control, 1.5-3%, 3-5%, vs. 5-7% added dietary sugar) on DMI, milk yield, 3.5% FCM, milk components, feed efficiency, and ruminal VFA concentrations (adapted from de Ondarza et al., 2017).

	Added Dietary Sugar (%DM)								
	Control		1.5-3%		3-5%		5-7%		*P*-Value
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	
DMI, kg/d	22.16	0.52	22.40	0.51	21.99	0.57	22.92	0.82	0.22
Milk, kg/d	31.91	0.65	32.90	0.65	33.33	0.73	33.02	1.11	0.03
FCM, kg/d	32.35	0.56	33.37	0.57	33.72	0.66	33.80	1.11	0.04
TP, %	3.14	0.04	3.11	0.04	3.13	0.05	3.16	0.07	0.42
TP, kg	0.98	0.02	1.01	0.02	1.04	0.02	1.05	0.04	0.05
MF, %	3.64	0.08	3.61	0.08	3.56	0.08	3.55	0.12	0.65
MF, kg	1.14	0.02	1.18	0.02	1.19	0.03	1.20	0.05	0.16
MUN mg/dl	14.19	0.43	13.80	0.45	13.56	0.52	12.58	0.88	0.27
FE[a]	1.46	0.03	1.48	0.03	1.52	0.03	1.46	0.05	0.13
Ac, mM	68.65	3.37	64.90	3.25	60.35	3.48	60.17	4.17	0.02
Pr, mM	22.92	1.04	22.22	1.03	21.28	1.17	17.86	1.50	0.03
Bu, mM	12.81	0.65	11.79	0.66	11.68	0.77	13.19	0.99	0.06

[a] kg 3.5% FCM/kg DMI

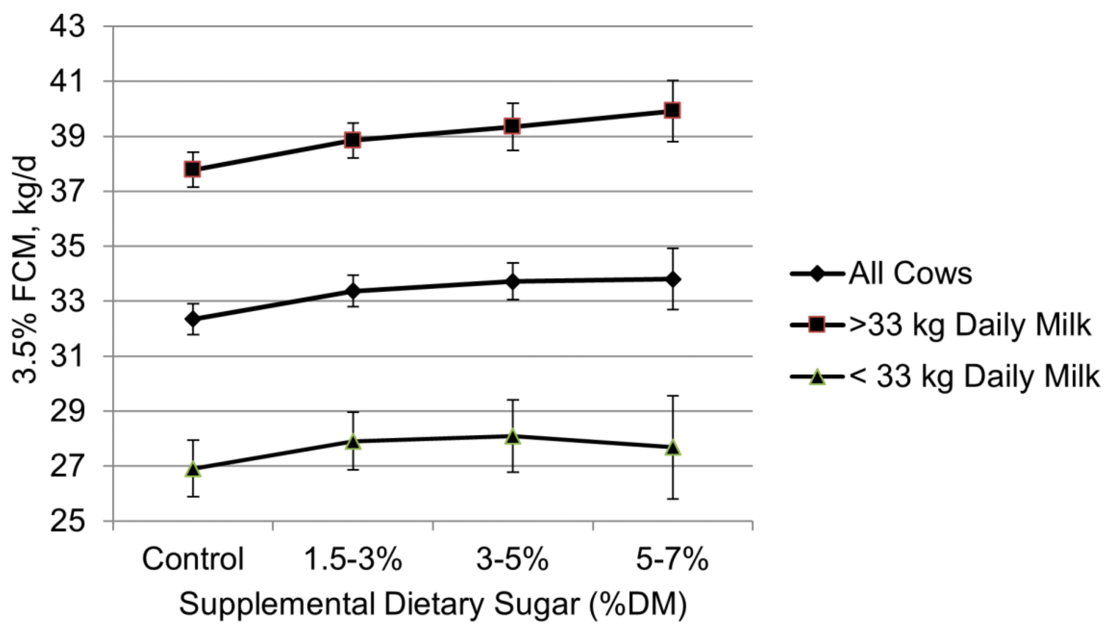

Figure 1. Effect of additional dietary sugar on 3.5% FCM by production level in published research studies (all cows vs. > 33 kg (high yield cows) vs. < 33 kg (low yield cows) (adapted from de Ondarza et al., 2017).

Table 4. Nutrient parameter estimates for variables tending (P<0.10) to effect milk and milk component production in published research studies used to determine the effect of additional dietary sugar on dairy cattle performance (adapted from de Ondarza et al., 2017).

	Milk, kg	Milk TP, %	Milk TP, kg	Milk fat, %	Milk fat, kg	MUN, mg/dl
Starch, %DM	+0.31	---	+0.02	-0.02	+0.01	-0.20
Soluble Fiber, %DM	---	---	---	---	+0.02	-0.67
RDP, %DM	---	---	---	---	---	+1.30
Protein B_2, %DM[a]	+1.78	---	---	---	---	+1.78

[a] Protein that is insoluble in boiling neutral detergent but soluble in boiling acid detergent solution

Nutrient parameters that tended (P<0.10) to affect milk and milk component production are recorded in Table 4. As expected, increased dietary starch improved milk and milk true protein yield while tending to decrease milk fat percentage and MUN (mg/dl). Soluble fiber reduced MUN (mg/dl). Increases in RDP increased MUN (mg/dl) while increases in protein B_2 tended to increase milk yield and MUN (mg/dl).

Non-linear analysis indicated that to optimize 3.5% FCM yield response when feeding additional sugars, a low to moderate starch diet should be fed (22 to 27% of diet DM) in combination with a moderate to high soluble fiber content (6 to 8.5% of diet DM) while 6.75 to 8% DM of dietary sugar was ideal (de Ondarza et al., 2017).

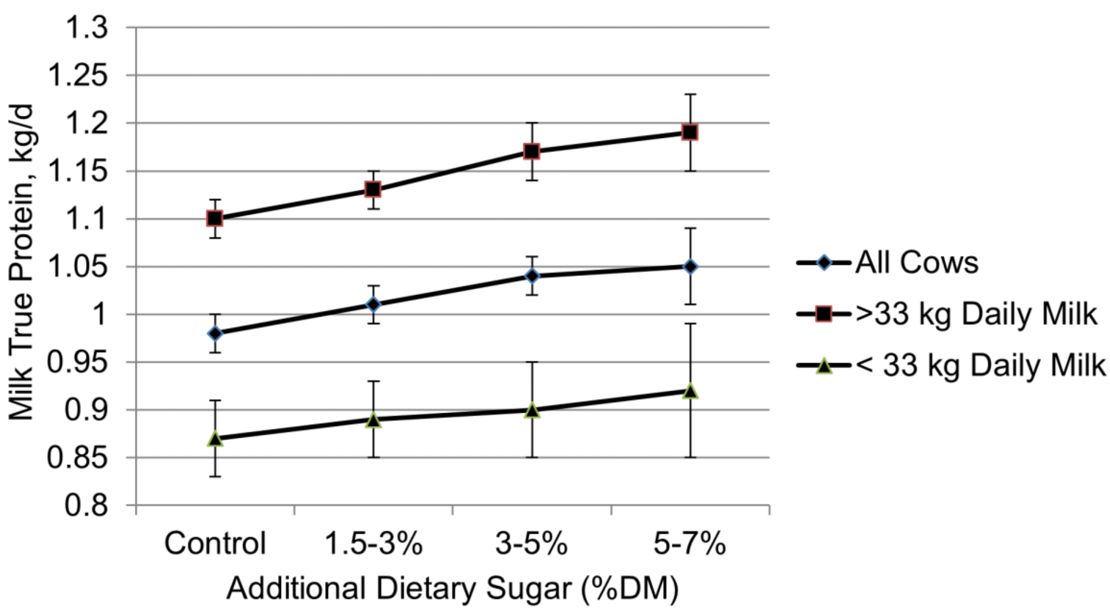

Figure 2. Effect of additional dietary sugar on milk true protein yield (kg/d) by production level in published research studies (all cows vs. > 33 kg (high yield cows) vs. < 33 kg (low yield cows) (adapted from de Ondarza et al., 2017).

Practical Applications

Consider supplementing sugar in lactating dairy diets to achieve 6 to 8% diet sugar for optimum rumen function and performance. Generally, 0.7 to 1.0 kg/cow/d of supplemental sugar would be needed to achieve 6 to 8% total sugar in typical US diets. Higher producing cows would be expected to have more positive responses to added dietary sugar. Liquid sugar sources have the added benefit of reducing TMR sorting.

Recognize the interactions between sugar, starch, soluble fiber, and rumen degradable protein. Research and field experience suggest the following optimal nutrient ranges (%DM): starch at 22 to 27%, soluble fiber at 6 to 8%, and RDP at 10 to 11%. Further, consider the impact of starch and protein degradation rates on responses to supplemental sugars. Sugars would be expected to have a more positive effect with a diet containing a lower percentage of rapidly digestible starch. Consider increasing soluble protein, using milk urea nitrogen (MUN) levels as a guide.

Future research to characterize and understand the effects of dietary sugars by type (glucose, sucrose, fructose, lactose, etc.) as well as to define multiple starch pools based on digestion rate and understand their impact on dietary sugar optimization would be helpful.

References

Aldrich, J.M., L.D. Muller, G.A. Varga, and L.C. Griel, Jr. 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. 1997. Relationship between fermentation acid production in the rumen and the requirement for physically effective fiber. J. Dairy Sci. 80:1447-1462.

Bannink, A., J. Kogut, J. Dijkstra, J. France, E. Kebreab, A.M. Van Vuuren, and S. Tamminga. 2006. Estimation of the stoichiometry of volatile fatty acid production in the rumen of lactating cows. J. Theor. Biol. 238:36-51.

Baurhoo, B. and A. Mustafa. 2014. *Short communication:* Effects of molasses supplementation on performance of lactating cows fed high-alfalfa silage diets. J. Dairy Sci. 97:1072-1076.

Broderick, G.A., N.D. Luchini, S.M. Reynolds, G.A. Varga, and V.A. Ishler. 2008. Effect on production of replacing dietary starch with sucrose in lactating dairy cows. J. Dairy Sci. 91:4801-4810.

Broderick, G.A. and W.J. Radloff. 2004. Effect of molasses supplementation on the production of lactating dairy cows fed diets based on alfalfa and corn silage. J. Dairy Sci. 87:2997-3009.

Chamberlain, D.G., S. Robertson, and J. Choung. 1993. Sugars versus starch as supplements to grass silage: Effects on ruminal fermentation and the supply of microbial protein to the small intestine, estimated from the urinary excretion of purine derivatives, in sheep. J. Sci. Food Agric. 63:189-194.

Cherney, D.J.R., J.H. Cherney, and L.E. Chase. 2003. Influence of dietary nonfiber carbohydrate concentration and supplementation of sucrose on lactation performance of cows fed fescue silage. J. Dairy Sci. 86:3983-3991.

Chibisa, G.E. 2013. Optimizing the efficiency of nutrient utilization in dairy cows. Ph.D. Thesis, Univ. Saskatchewan, Saskatoon

Chibisa, G.E., P. Gorka, G.B. Penner, R. Berthiaume and T. Mutsvangwa. 2015. Effects of partial replacement of dietary starch from barley or corn with lactose on rumen function, short chain fatty acid absorption, nitrogen utilization and production performance of dairy cows. J. Dairy Sci. 98:2627-2640.

DeFrain, J.M., A.R. Hippen, K.F. Kalscheur, and D.J. Schingoethe. 2004. Feeding lactose increases ruminal butyrate and plasma β-hydroxybutyrate in lactating dairy cows. J. Dairy Sci. 87:2486-2494.

de Ondarza, M.B., S.M. Emanuele, and C.J. Sniffen. 2017. Effect of increased dietary sugar on dairy cow performance as influenced by diet nutrient components and level of milk production. Prof. Anim. Sci. 33:700-707.

DeVries, T.J. and R.M. Gill. 2012. Adding liquid feed to a total mixed ration reduces feed sorting behavior and improves productivity of lactating dairy cows. J. Dairy Sci. 95:2648-2655.

Eastridge, M.L., A.H. Lefeld, A.M. Eilenfeld, P.N. Gott, W.S. Bowen, and J.L. Firkins. 2011. Corn grain and liquid feed as nonfiber carbohydrate sources in diets for lactating dairy cows. J. Dairy Sci. 94:3045-3053.

Firkins, J.L., B.S. Oldick, J. Pantoja, C. Reveneau, L.E. Gilligan, and L. Carver. 2008. Efficacy of liquid feeds varying in concentration and composition of fat, non-protein nitrogen, and nonfiber carbohydrates for lactating dairy cows. J. Dairy Sci. 91:1969-1984.

Firkins, J.L. 2011. Liquid feeds and sugars in diets for dairy cattle. Proc. Florida Ruminant Nutrition Symposium, Gainesville, p. 62.

Gao, X. and M. Oba. 2016. Effect of increasing dietary nonfiber carbohydrate with starch, sucrose, or lactose on rumen fermentation and productivity of lactating dairy cows. J. Dairy Sci. 99:291-300.

Golombeski, G.L., K.F. Kalscheur, A.R. Hippen, and D.J. Schingoethe. 2006. Slow-release urea and highly fermentable sugars in diets fed to lactating dairy cows. J. Dairy Sci. 89:4395-4403.

Hall, M.B., C.C. Larson, and C.J. Wilcox. 2010. Carbohydrate source and protein degradability alter lactation, ruminal, and blood measures. J. Dairy Sci. 93:311-322.

Hall, M.B. 2017. Sugars in Dairy Cattle Rations. Proceedings of the 26th Tri-State Dairy Nutrition Conference. April 17-19, 2017. Pp. 135-146.

Hindrichsen, I.K., H.-R. Wettstein, A. Machmuller, K.E. Bach Knudsen, J. Madsen, and M. Kreuzer. 2006. Digestive and metabolic utilization of dairy cows supplemented with concentrates characterized by different carbohydrates. Anim. Feed Sci. Technol. 126:43-61.

Hoover, W.H. 1987. Potential for managing rumen fermentation. Page 53 in Proc. Cornell Nutr. Conf. Feed Manuf., Syracuse, New York.

Hoover, W.H. and T.K. Miller-Webster. 1998. Role of sugars and starch in ruminal fermentation. Page 1 in Proc. Tri-State Nutrition Conference, Fort Wayne, Indiana.

Hristov, A. N., J.K. Ropp, K.L. Grandeen, S.Abedi, R.P. Etter, A. Melgar and A.E. Foley. 2005. Effect of carbohydrate source on ammonia utilization in lactating dairy cows. J. Anim. Sci. 83:408-421.

Khalili, H. and P. Huhtanen. 1991. Sucrose supplements in cattle given grass silage-based diet. 1. Digestion of organic matter and nitrogen. Anim. Feed Sci. Tech. 33:247-261.

Maiga, H.A., D.J. Schingoethe, and F.C. Ludens. 1995. Evaluation of diets containing supplemental fat with different sources of carbohydrates for lactating dairy cows. J. Dairy Sci. 78:1122-1130.

Martel, C.A., E.C. Titgemeyer, L.K. Mamedova, and B.J. Bradford. 2011. Dietary molasses increases ruminal pH and enhances ruminal biohydrogenation during milk fat depression. J. Dairy Sci. 94:3995-4004.

McCormick, M.E., D.D. Redfearn, J.D. Ward, and D.C. Blouin. 2001. Effect of protein source and soluble carbohydrate addition on rumen fermentation and lactation performance of Holstein cows. J. Dairy Sci. 84:1686-1697.

Nocek, J.E. and J.B. Russell. 1988. Protein and energy as an integrated system. Relationship of ruminal protein and carbohydrate availability to microbial synthesis and milk production. J. Dairy Sci. 71:2070-2107.

Nombekela, S.W. and M.R. Murphy. 1995. Sucrose supplementation and feed intake of dairy cows in early lactation. J. Dairy Sci. 78:880-885.

Oelker, E.R., C. Reveneau, and J.L. Firkins. 2009. Interaction of molasses and monensin in alfalfa hay- or corn silage-based diets on rumen fermentation, total tract digestibility, and milk production by Holstein cows. J. Dairy Sci. 92:270-285.

Oba, M., J.L. Mewis, and Z. Zhining. 2015. Effects of ruminal doses of sucrose, lactose, and corn starch on ruminal fermentation and expression of genes in rumen epithelial cells. J. Dairy Sci. 98:586-594.

Penner, G.B., L.L. Guan, and M. Oba. 2009. Effects of feeding Fermenten on ruminal fermentation in lactating Holstein cows fed two dietary sugar concentrations. J. Dairy Sci. 92:1725-1733.

Penner, G.B. and M. Oba. 2009. Increasing dietary sugar concentration may improve dry matter intake, ruminal fermentation, and productivity of dairy cows in the postpartum phase of the transition period. J. Dairy Sci. 92:3341-3353.

Penner, G.B., M.A. Steele, J.R. Aschenbach, and B.W. McBride. 2011. Molecular adaptation of ruminal epithelia to highly fermentable diets. J. Anim. Sci. 89:1108-1119.

Piwonka, E.J. and J.L. Firkins. 1993. Rumen and total tract digestion, or forage based diets with starch or dextrose supplements fed to Holstein heifers. Dept. of Dairy Science Research Highlights, 1993. The Ohio State University pg. 9.

Russell, J.B. and D.B. Dombrowski. 1980. Effect of pH on the efficiency of growth by pure cultures of rumen bacteria in continuous culture. Applied and Environmental Microbiology. 39:604-610.

Sannes, R.A., M.A. Messman, and D.B. Vagnoni. 2002. Form of rumen-degradable carbohydrate and nitrogen on microbial protein synthesis and protein efficiency of dairy cows. J. Dairy Sci. 85:900-908.

Siverson, A., C.F. Vargas-Rodriguez, and B.J. Bradford. 2014. *Short communication:* Effects of molasses products on productivity and milk fatty acid profile of cows fed diets high in dried distillers grains with soluble. J. Dairy Sci. 97:3860-3865.

Stokes, S.R., W.H. Hoover, T.K. Miller, and R.P. Manski. 1991. Impact of carbohydrate and protein levels on bacterial metabolism in continuous culture. J. Dairy Sci. 74:860-870.

Strobel, H.J. and J.B. Russell. 1986. Effect of pH and energy spilling on bacterial protein synthesis by carbohydrate-limited cultures of mixed rumen bacteria. J. Dairy Sci. 69:2941-2947.

Sun, X., Y. Wang, B. Chen, and X. Zhao. 2015. Partially replacing cornstarch in a high-concentrate diet with sucrose inhibited the ruminal trans-10 biohydrogenation pathway in vitro by changing populations of specific bacteria. J. Anim. Sci. Biotech. 6:57.

Vallimont, J.E., F. Bargo, T.W. Cassidy, N.D. Luchini, G.A. Broderick, and G.A. Varga. 2004. Effects of replacing dietary starch with sucrose on ruminal fermentation and nitrogen metabolism in continuous culture. J. Dairy Sci. 87:4221-4229.

Vargas-Rodriguez, C.F., M. Engstrom, E. Azem, and B.J. Bradford. 2014. Effects of dietary amylase and sucrose on productivity of cows fed low-starch diets. J. Dairy Sci. 97:4464-4470.