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Optimizing Starch Nutrition for Rhythmic Dairy Cattle: The Sustaining Economic and Environmental Challenges of Today's Industry

Review Article

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ABSTRACT

Starch makes up a considerable portion of dairy diets (up to >30%). Thus, starch utilization efficiency immensely affects rumen function, animal performance and health, farm economics, and environmental quality. It is crucial to take into account the ruminal digestion rhythms of different cereals when formulating diets for optimal dry matter intake (DMI), milk production, and animal health. Optimizing the physical processing of cereal grains is required for maximal microbial protein yield and minimal sub-acute rumen acidosis (SARA). Physical processing of barley and corn grains, as the two most popular cereals in dairy diets, needs more contemplation towards synchronizing rhythms of starch and protein fermentation in the rumen. Optimizing the dietary inclusion rates of cereal grains and starch has been a key missing part in improving nutrient efficiency and gastrointestinal health and integrity. Global guidelines need to be developed to precisely address optimal dietary inclusion rates of different cereal grains. Setting such guidelines becomes more important when high-starch corn silage is major forage in the diet. Monitoring circadian rhythms of rumen fermentation when differently processed cereal grains are fed will allow developing feeding strategies that minimize the occurrence of SARA. The minimized SARA will enable decreasing nutrient loss across portal drained viscera (PDV) and splanchnic tissues. An innovative global philosophy is being developed to rely more on oil seeds and less on starchy grains in feeding dairy cows. To practically prevent SARA, physical processing can be partly effective, but essentially the dietary inclusion rate of differently processed cereal grains needs to be optimized. Lessons are to be learnt from human nutrition. Although metabolism differs between ruminants and non-ruminants, carbohydrates especially sugars and starch are under scrutiny and need to be limited in human diets to minimize risks from obesity and diabetes. Education, education and education is the final frontier for success in improving rumen and animal health as far as starch nutrition is concerned. For now, it is recommended to feed dairy cows no more than 25-28% starch (DM based). Future research will focus on establishing optimal dietary inclusion rates of differently processed barley and corn/sorghum grains for cows of different production levels and lactation stages. Rumen fermentation circadian rhythmicity and environmental considerations including decreased methane production and urinary and fecal nitrogen excretion will be discussed.

KEY WORDS cereal, dairy cow, economics, environment, rhythm, starch.

INTRODUCTION

Starch is a significant portion of dairy diets (up to >30% of diet dry matter) and immensely affects rumen health and function and cow performance (NRC, 2001). Dietary starch is mainly supplied from cereals including corn, barley, wheat, oats, and sorghum grains as well as cereal forages namely corn silage and other cereal silages.

What makes starch nutrition challenging is differential rumen fermentation dynamics amongst differently processed grains and forages (Van Soest, 1994). Controversy exists as to the optimum site and rhythms of starch digestion (rumen vs. small intestine). Nonetheless, two facts are known. First, starchy grains must be optimally processed to maximize rumen microbial mass production while not increasing the risk of sub-acute rumen acidosis (SARA). Second, due to limited small intestinal capacity for starch assimilation and glucose transport, excessive escape of undigested or partially digested starch from the rumen fermentation must be avoided (Orskov, 1986; Huntington, 1997; Nikkhah, 2010). Notably, however, the key reason for starch malnutrition has been the suboptimal dietary inclusion rates of cereal grains in relation to dietary forage. Optimizing the dietary inclusion rate of cereal grains requires special attention in rhythmic starch nutrition management for dairy cows (Oba and Allen, 2003). The use of oil seeds and decreased dietary starch should allow mitigating methane production and decreased risk from SARA (Beauchemin *et al.* 2009). These dietary changes will result in improved production, health and profitability and decreased nutrient excretion via urine and feces that can potentially benefit the environment. Therefore, the main objective of this review was to describe how to optimize starch nutrition for rhythmic dairy cows to help overcome the sustaining economical and environmental challenges of today's industry. To meet this objective, rumen rhythms of differently processed grains and optimal dietary inclusion rates of cereal grains in relation to forage type will be discussed. In addition, circadian rhythms of rumen fermentation and hypothetically of portal-drained visceral and splanchnic tissues will be addressed. Moreover, lessons from human nutrition that are to be learned will be delineated to discuss how to reduce risks from SARA and other health disorders.

Starch sources for dairy cattle: A global outlook

Cereal grains (Figure 1) are the main dynamic starch sources for dairy cattle. They vary in amylose and amylopectin content as well as in starch, protein, fiber, and fat percentage and vitamins and minerals (Figure 2). Starch comprises 55 (oats) to almost 75% (corn) of whole grains on a dry matter basis. Maize or corn is broadly grown across the world. Corn has the highest world production among all cereals with approximately 817 million tons per year (FAOSTAT, 2017). Corn is a vital principal food in many countries with wide usage in animal feed and other industries. The corn crop has remarkable genetic variability, enabling it to flourish in tropical, subtropical, and temperate climates. Wheat grain is the second most prevalent cereal in the world with an annual production of 755 million tons.

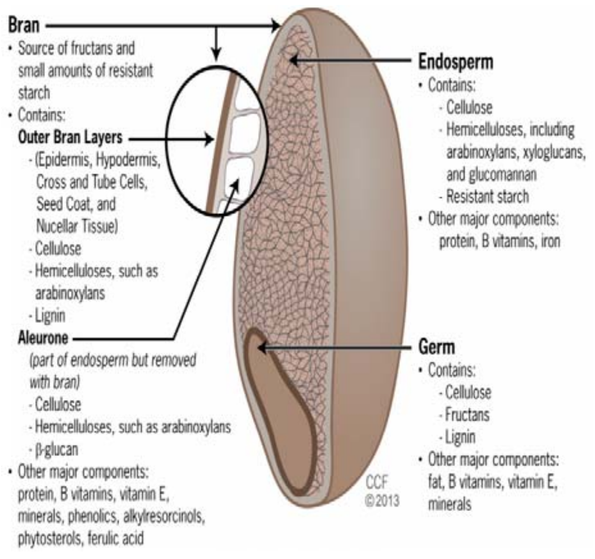

Figure 1 Specified cereal grain structure (Bernstein *et al.* 2013)

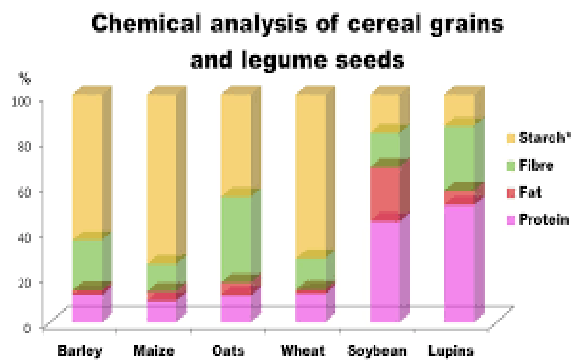

Figure 2 Starch, fiber, fat and protein fractions of cereal grains (McKevith, 2004)

The largest producers of wheat are China, India, Russia and United States. Because of its fast and extensive rumen fermentation, wheat grain may be used in dairy rations only in limited or moderate rates. Rice is a staple food for humankind throughout the world and a feed for animals. Rice as a staple food for more than half the human population of the world is the third largest produced cereal after maize with over 685 million tons production per year (FAOSTAT, 2017). The largest rice producers are China, India, Indonesia and Pakistan. The rice produced in Iran possesses unique taste that is distinct from the rice produced in other countries. Rice cultivation requires more water than other cereals and is more labor intensive. Where produced, rice can be considered as a dietary cereal choice in ruminant diets, but not in major amounts. Barley grain ranks fourth in the global cereal production, with an approximate world yield of 136 million tons per year (FAOSTAT, 2017). The barley crop requires a temperate climate with the major growing areas including Europe and Russia.

However, barley is also a valuable and resilient crop in arid and semi-arid areas of Asia, the Middle East, and North Africa. It is primarily used as flour for human consumption, in animal feed, and as malt for beverage production. Due to its unique nature, barley grain is profoundly viewed as a treasure or tragedy in ruminant nutrition (Nikkhah, 2010). Sorghum is the fifth most significant cereal with an annual world production of over 55 million tons (FAOSTAT, 2017). Sorghum varieties are usually more heat and drought tolerant than other cereal crops. Thus, sorghum is an important crop in arid areas. Sorghum is a valuable food for humans as well in Africa, Central America, and South Asia. It is also used to produce beverages and biofuel. Millet is a communal word referring to various small-seeded annual grasses grown as grain crops, mainly on marginal lands in dry areas of temperate, subtropical and tropical regions. Millet is considered a subsistence grain cultivated for food and animal fodder.

The largest producers of millet are India and Nigeria with a total world production of 31 million tons per year (FAOSTAT, 2017). Traditionally, cereal grains have been compared in terms of major nutrients such as energy and protein. Less attention has been paid to their differences in minerals and vitamins while they vary considerably in this regard.

Optimizing dietary starch inclusion rate: The missing key

Much attention has long been paid to physical processing of cereal grains for optimal rumen and post-rumen starch utilization (Orskov, 1986; Huntington, 1997). However, optimizing the dietary inclusion rate of starch has received very inadequate thoughts.

Optimizing the dietary inclusion rate of starch is the key missing part of the whole starch story. Many dairy farmers feed more starch than recommended to their high-producing and to even low-producing lactating cows (farm observations). It is usually considered very risky to feed more than 25-28% starch (on a DM basis) to high-merit cows (Table 1). Assuming a minimum of 4-5% of total dietary starch coming from corn silage (presuming that 20% of diet DM is corn silage), about 20-25% starch is allowed to be supplied from grains. This calculation implies a maximum allowance of 26-34% corn in diet. Such a starch equivalent amount would be lower for barley grain since barley is fermented in the rumen with greater extent and rate than is corn grain. Nevertheless, it is often observed that farmers feed diets with 60-65% concentrate (DM basis), 60% of which is cereal grain that means feeding 36-42% cereal grain to dairy cows. Such high dietary cereal grain levels would be considered very risky (explosive in the rumen) given that an additional 5-10% starch is supplied from forages. At these starch inclusion rates, it is not surprising to observe high rates of SARA on many dairy farms (Humer *et al.* 2018). Public and farmer education must be enhanced to assist farmers to lower the risk of SARA occurrence. When we can prevent a problem or challenge from happening by practicing wisdom, why should we make it happen and then look for ways to overcome it?! Thus, the current concept and practice of excessive starch inclusion in the diet of dairy cows must be fundamentally challenged and refined for further improvement in dairy cow health and profitability.

Optimizing the physical processing of rhythmic starchy grains

Physical processing and damage to the whole cereal kernel is mandatory to make its endosperm accessible to microbial adherence and fermentation in the rumen. Different processing methods and technologies for starchy grains for dairy cows have previously been discussed (Ørskov, 1986; Huntington, 1997).

An innovative philosophy with regards to choosing optimal grain processing methods is based on the nature of endosperm in different cereals. For instance, barley grain is fermented in the rumen more rapidly and extensively than is corn grain. As a result, the entire philosophy of using steam-processing is different for barley *vs.* corn grain. Barley grain is already highly degradable and, hence, steam-processing is conducted to slow down its fermentation rate to better synchronize starch and protein degradation rates (Hall and Huntington, 2008).

Steam-rolling *vs.* grinding or dry-rolling produces larger barley particles that are more slowly degradable in the rumen, thereby minimizing SARA risks. In contrast, corn grain is slowly degradable in the rumen. Thus, steam-processing of corn grain aims to increase its degradation rate and extent in the rumen for increased nutrient synchrony and improved microbial mass production. In addition, the duration of steam exposure is shorter for rapidly fermentable grains (i.e., 5-10 minutes for barley and wheat) and longer for slowly degradable grains (i.e., 20-30 minutes for corn and sorghum grains). In addition to decreasing barley and wheat rumen degradation rate, steam-rolling decreases feed dusts and makes feed more palatable. These benefits hold especially true for early lactation cows when DMI is relatively low.

However, fundamentally, when dietary inclusion rates of barley and wheat grains are kept low to moderate (e.g., <10-20% of diet DM), steam-rolling would be expected to offer less advantage over grinding (Sadri *et al.* 2007; Soltani *et al.* 2009).

Table 1 Carbohydrate recommendations for high-merit lactating dairy cows (Sniffen, 2004)

Fraction	Amount
Total neutral detergent fiber (NDF), % of DM	28-32
Physically effective neutral detergent fiber (PeNDF), % of NDF	20-24
Forage NDF, % of DM	18-23
Fermentable NDF, % of NDF	> 35.0
Nonfiber carbohydrate (NFC), % of DM	30-43
Soluble fiber, % of DM	4-10
Starch, % of DM	23-28
Fermentable starch, % of starch	83-86
Sugars, % of DM	4-8
Sugar: soluble protein ratio	1.5:1
Fermentable total carbohydrates, % of DM	42-44
Total volatile fatty acids (VFA), % of DM	0-5

Thus, the dietary inclusion rate is more important than processing method in optimizing barley starch use, whereas, for corn grain, processing method would seem more important than dietary inclusion rate.

Optimizng rhythms of cereal silage and forage feeding in relation to grain choice

Forage type chosen for ensilage affects how efficiently dietary starch is utilized in the rumen and post-rumen. When corn silage (and thus corn starch) is fed to dairy cows, it would be more efficient to include barley grain in the diet to improve nutrient synchrony (Figure 3; Kowsar *et al.* 2008).

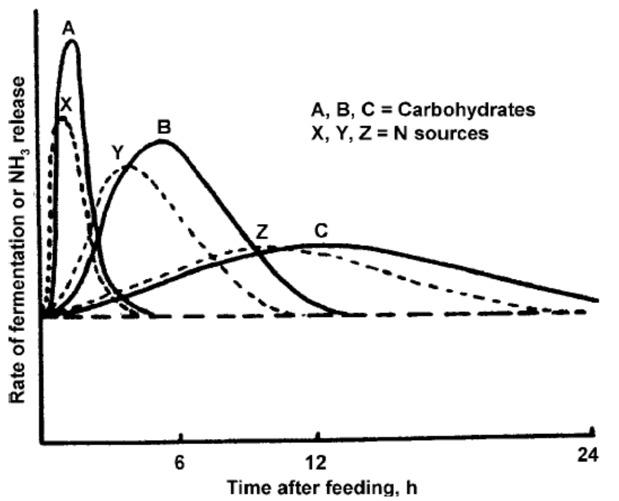

Figure 3 Ruminal rhythms and dynamics of rapidly (A and X), moderately (B and Y) and slowly (C and Z) fermentable starch and protein (Hall and Huntington, 2008)
For optimal rumen microbial yield and health, it is recommended to have various types of differently processed cereal grains that can supply all three portions of starch and protein for a fruitful rhythmic metabolism

Since small intestinal capacity to assimilate starch and glucose is limited in ruminants (Huntington, 1997), including much corn grain in rations based on corn silage may not lead to optimal starch utilization. However, when low-grain and high-fiber corn silage or barley silage are fed, diets may accommodate higher inclusion rates of corn grain, but this should rather be fed alongside barley grain to be optimally utilized in the rumen and post-rumen. When alfalfa hay or silage is fed as main dietary forage, there would be ample opportunities for corn starch (either as grain or silage) to be effectively utilized by the dairy cow. Specifically and globally, it would be advisable to include combined legume and cereal forages alongside corn (or sorghum) and barley (or wheat and oats) grains to provide healthier nutrient synchrony.

In terms of ration particle size, when total mixed rations (TMR) are offered, forage hay or silage are mixed with the concentrate in chopped and smaller particles, and as a result, adequately long physically effective fiber may not be provided to fresh and high-producing cows. Hence, it would be recommendable to supply top-dress long forages to these cows.

This trend would follow the ruminant nature and holds true particularly when barley grain is fed, since barley grain based diets would require greater physically effective fiber than would corn grain based diets (Beauchemin and Rode, 1997).

Basically, when feeding ensiled forages, adequate rapidly fermentable starch (e.g., ground and steam-rolled barley, and steam-flaked corn or sorghum) should be provided to enable capturing fast-release non-protein nitrogen of silage into microbial proteins (Figure 3). This would avoid substantial nitrogen losses in urine. The interactive effects of grain and forage sources on periparturient cow performance and health require future studies. Sadri *et al.* (2009) found that grain source (barley *vs.* corn) affects periparturient cow response to chromium-methionine supplementation, such that cows on barley, but not corn, based diets increased peripartal DMI.

Circadian rhythmicity of rumen fermentation and starch nutrition

Rumen fermentation possesses circadian rhythmicity (Nikkhah, 2013). This rhythmicity stems partly from diurnal patterns of feed intake (Nikkhah *et al.* 2008; Nikkhah *et al.* 2010). Ruminants in nature have developed a specialized grazing behavior to eat/graze mostly during sunrise and sunset and ruminate mostly overnight. As a result, the rumen experiences increased fermentation overnight (Robinson *et al.* 1997). Recent studies suggested that dairy cows fed once daily in the evening vs. morning had more extensive rumen fermentation shortly post-feeding and increased total tract nutrient and fiber digestibility (Nikkhah *et al.* 2008; Nikkhah *et al.* 2010). Accordingly, the evening-fed cows consumed more feed during 3-h after feeding than did the morning-fed cows. As a result, rumen fluid from the evening-fed cows exhibited lower pH and greater concentrations of acetate and total volatile fatty acids (VFAs) shortly post-feeding than that from the morning-fed cows (Figure 5). Consequently, the evening-fed cows experienced higher concentrations of blood beta-hydroxy butyric acid (BHBA) and lactate after feeding. Finally, the evening-fed cows produced milk with greater percentage and yield of fat and energy, compared to the morning-fed cows (Nikkhah *et al.* 2008; Nikkhah *et al.* 2010).

These data challenge the traditional thought and conventional wisdom that greater diurnal fluctuations in the rumen fermentation may necessarily be undesirable. The evening-fed cows had more fluctuations in their circadian rhythms of rumen acidity and fermentation products, but were still healthy and were able to produce greater daily milk fat, when compared to the morning-fed cows. Importantly, despite greater diurnal fluctuations, the nadir in rumen pH was above 5.5 that means only none or modestly (if any) compromised rumen fiber digestion. This finding was supported by the increased total tract apparent fiber digestibility by evening vs. morning feeding (Nikkhah *et al.* 2010).

Ruminant and non-ruminant chronophysiology is a rising science. Chronophysiology relates to how internal metabolism is altered by altering external cues such as feeding timing and photoperiod. The increased rumen volume overnight (by evening instead of morning feeding) suggests increased VFA absorption capacity. This would imply decreased exposure to acidotic conditions overnight. The chrono-provision of various starch sources has recently been postulated to ease transition from pregnancy to lactation in dairy cows. Offering more fermentable ration components (e.g., barley-based concentrate) during afternoon and evening hours may provide healthier rumen conditions overnight when rumination prevails. The increased rumen buffering capacity overnight may reduce duration of SARA and prevent milk fat depression. This "school of thought" will need to be substantiated in future studies.

Feeding systems and strategies: Different cereal processing choices

Feeding management for dairy cows is a highly dynamic phenomenon that is in close relation with dietary properties such as dietary starch inclusion rate and cereal grain processing method (Robinson, 1989; Shabi *et al.* 1999). Feeding management includes feeding systems and feeding strategies. Feeding system is concerned with how rations are prepared (i.e., totally mixed ration (TMR), partially mixed ration (PMR), or component feeding (CF)). Feeding strategies are attributed to feeding frequency (FF), feeding sequence (FS), and feeding timing (FT). Altering feeding systems and strategies would alter starch digestion site and nutrient efficiency (Nocek and Tamminga, 1991). Although it is believed that more frequent feeding may decrease diurnal variations in nutrient intake and rumen fermentation, and thus, may improve milk solids yield. Under uncompetitive environments, feeding less frequently (1 *vs.* 4 times daily) increased DMI and altered feeding behavior of lactating dairy cows. This finding would place FF at the interface of tradition and modernity in dairy production. Principally, when feeding rapidly fermentable starch sources (e.g., barley, wheat, and oats), it would be recommended to feed TMR instead of PMR or CF. In contrast, when the main dietary grains are corn and sorghum, PMR and CF systems may also lead to desirable health and production outcomes. Accordingly, barley-based rations need to be fed more frequently than corn-based rations just to ensure that rumen fermentation would not face dramatic alterations unfavorable for fiber digestion. As for FS, the data are scarce and inconclusive.

Starch nutrition and sub-acute rumen acidosis: Practical and immune revelations

Sub-acute rumen acidosis is one of the main challenges of today's dairy industry with increased research interests (Figure 6; Plaizier *et al.* 2009; Humer *et al.* 2018). Sub-acute rumen acidosis may occur when rumen pH decrease below 5.8 for more than 5-6 h per day (Zebeli *et al.* 2012). Humer *et al.* (2018) suggested that when dietary starch concentration increases to 22-26%, physically effective NDF > 8 requirements increase to above 18% that may limit DMI. This warns against feeding excessive amount of starch to dairy cows. Realistically, often dairy farmers feed more than 22-26% starch to their high-producing lactating cows. There are many farmers that feed up to 35% starch that along with dietary (unavoidable) sugars would seriously threaten rumen and cow health.

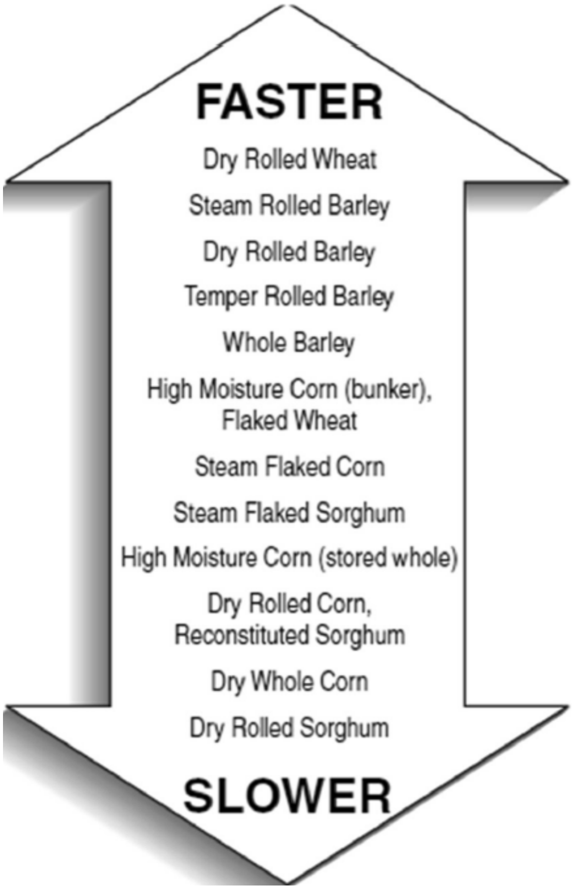

Figure 4 Rumen fermentation rates of differently processed cereal grains (Nikkhah, 2010)

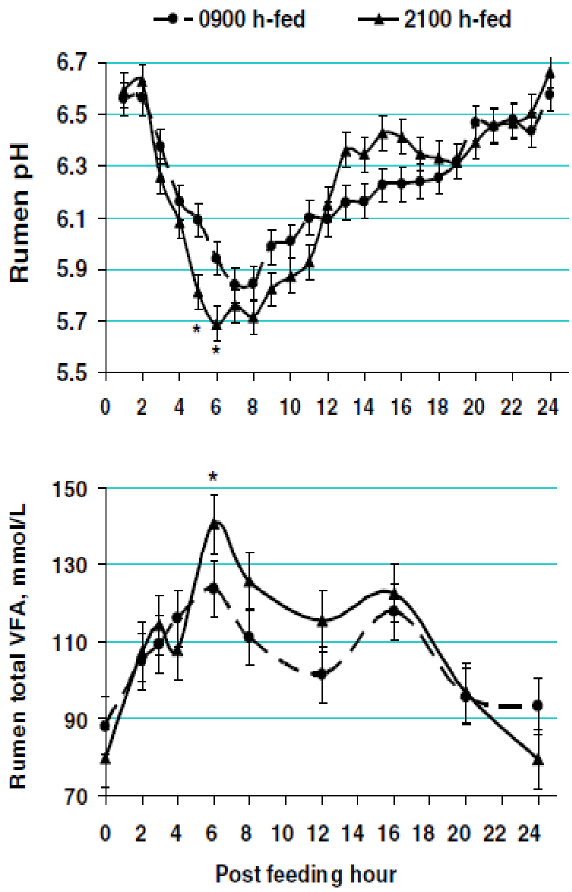

Figure 5 Circadian rhythms of rumen pH and volatile fatty acids concentrations in evening (9 pm) and morning (9 am) fed lactating dairy cows (Nikkhah, 2010)
* (P<0.05)

Education must receive adequate attention at least as does the interest for higher milk production. Farmers need to realize that they ought to strive for maximal nutrient efficiency and minimal SARA incidence. Increased starch intake above 25% may increase milk production during certain periods of time, but it may eventually compromise cow health and longevity and may result in major economic losses to the whole enterprise.

Lessons from human chrono-nutrition and chrono-physiology

Bridging human physiology and nutrition to animal agriculture could help overcome both sides' challenges more effectively. There is an ongoing debate among human nutritionists on optimal dietary regimens for healthier lifestyle. It has been suggested to rely on low-carbohydrate (i.e., low sugar and starch) high-fat high-fiber ketogenic diets (Aude *et al.* 2004; Ludwig and Ebbeling, 2018). Feeding low-sugar, low-starch diets is recommended to decrease risks from diabetes because of obesity and insulin resistance (Ludwig and Ebbeling, 2018).

Despite the vast differences in gastrointestinal physiology and intermediary metabolism between ruminants and humans, feeding lower-starch diets should be contemplated in light of the production and health challenges of SARA in dairy cows. Oil seeds should be well utilized in high-yielding and fresh dairy cow diets to mitigate methane production, improve milk quality for human health, and indeed to decrease requirements for dietary starch. Adding one unit of fat from oil seeds will replace almost 2 units of starch and sugars in the diet to supply the same level of energy. In addition, oil seeds supply essential long chain fatty acids and fat-soluble vitamins that can improve fertility and milk quality. Cottonseed, canola seed, flax seed, linseed, sunflower, and soybean are the distinct oil seeds that can be fed to dairy cows (Arieli, 1998; Beauchemin *et al.* 2009). What make whole cottonseed unique are the physically effective fibers that along with fat, protein and vitamins-minerals provide a complete nutritional package to lactating cows (Arieli, 1998).

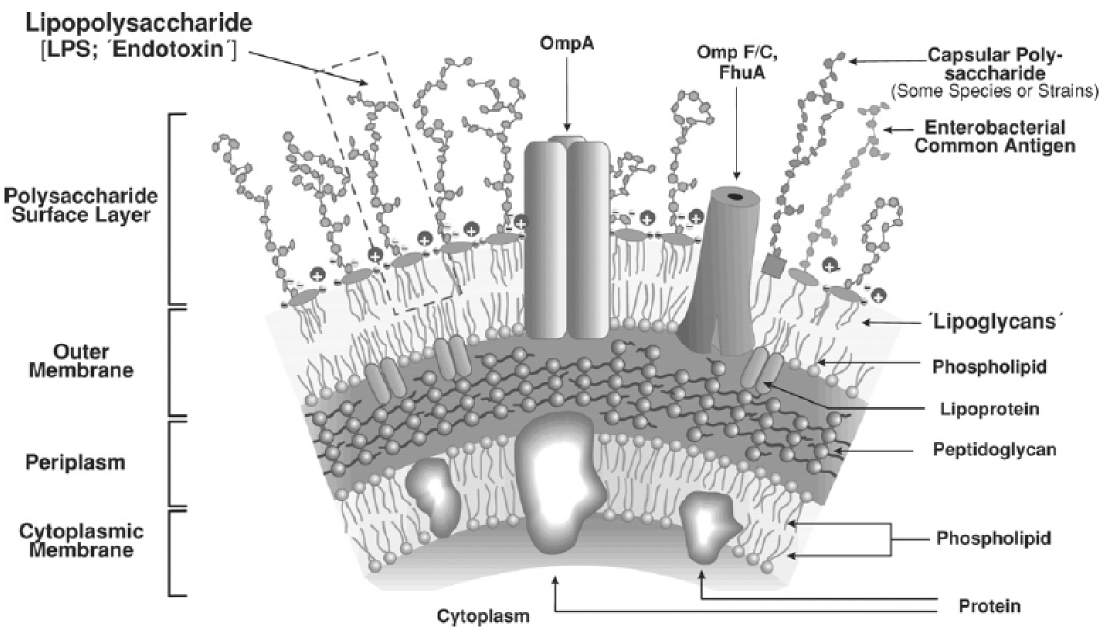

Figure 6 A diagram of gram-negative bacteria cell wall structure (Alexander and Rietschel, 2001)
The LPS considered as endotoxins can elicit immune response in the host dairy cows when they experience sub-acute rumen acidosis

Nutritional lessons are, hence, to be learned from human studies that are applicable to animal agriculture.

Also to note, glucose tolerance in human decreases as day ends and evening begins (La Fleur *et al.* 1999; La Fleur *et al.* 2001). The evening insulin resistance would suggest avoiding large evening meals to decrease obesity and diabetes. Accordingly, to improve insulin action and glucose tolerance, morning eating and evening exercise have been recommended. Such evening glucose intolerance has not yet been reported in ruminants. However, ruminants ruminate mostly overnight when they eat no or little feed. As a result, they are expected to encounter increased rumen volume and fermentation capacity during night. Feeding lactating cows at 2100 h instead of 0900 h has altered periprandial rhythms of blood glucose, such that the evening-fed cows experienced decreased blood glucose shortly prefeeding that rose to normal concentrations shortly postfeeding (Nikkhah, 2013). This information suggests that circadian rhythms of nutrient intake and metabolism are orchestrated by feeding timing in ruminants as well. Future studies are required to enlighten how dairy cow circadian glucose and insulin dynamics are mediated and entrained by external factors such as feeding timing and photoperiod.

Industrial and environmental obligations: Future research

The foremost obligation for the global dairy industry is "education" and "science edification". Without thorough education of our science philosophies to the public (e.g., dairy farmers), limited progress towards profitable production and clean environment may be realized.

Maximal adaptation to healthy starch assimilation is a life-time process that should start from younger ages as calves and heifers. Heifers need to be carefully managed to be able to develop efficient microbial (rumen and hindgut) and endocrinological (small intestine) mechanisms to digest and assimilate starch and transfer glucose across portal-drained viscera. This physiological development in the gastrointestinal capacity to bioprocess starch is prerequisite for minimized nutrient losses across splanchnic tissues (Reynolds, 2002). Targeting for healthy rumen should be a priority in constructing future strategies to optimize starch utilization in dairy cows.

Limit milk program is another strategy that decreases starch requirement in the diet to meet nutrient demands for increased milk production during the peak of lactation curve. Planning for smoother lactation curve with lower peak can practically decrease the need to feed too much starch and can considerably reduce SARA risks. However, lowering the peak may result in reduced milk yield per lactation. These areas warrant future studies. Exploring the optimal inclusion rates and processing methods of different cereal grains would be another promising field of research (Karam-Babaei *et al.* 2018). Finally, clear-cut guidelines as to optimal dietary inclusion rates of differently processed cereal grains will need to be developed for on-farm practice. Until then, it is mandatory to keep the dietary starch at logically moderate levels (<25-28%) and do not raise it to lower the risk of SARA incidence and milk fat depression amongst many other environmental and economical challenges.

CONCLUSION

Practical and rhythmic feeding of starch has received very inadequate research and education. This missing key part is a main reason for the high incidence of SARA in large dairy farms across the world. Farmer education and science edification are the final frontiers in improving rhythmic rumen and dairy cow health and longevity. It is recommended to feed rations with no more than 25-28% starch (DM based) under any circumstances. Relying relatively more on oil seeds and less on starchy grains is a philosophy that should be taken into consideration in planning for improved environmental quality and economical viability of future dairy enterprises. However, attention must be paid to not over-feed oil seeds too to avoid challenges such as milk fat depression. Future research should establish a rhythmic approach for optimizing daily and postprandial patterns of rumen fermentation and post-rumen host metabolism.

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