Effects of Chemical and Physical Characteristics of Corn on Starch Digestion

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Summary

Final Exam: Advanced Dairy Nutrition 504. Circle ALL correct answers.

1. The major source of net energy for lactation from corn grain is:
   a. Fiber
   b. Fat
   c. Protein
   d. Non-fiber carbohydrate
   e. Ash
   f. Water

2. The major source of net energy for lactation from corn silage is:
   a. Fiber
   b. Fat
   c. Protein
   d. Non-fiber carbohydrate
   e. Ash
   f. Water

3. On a dry matter (DM) basis, corn silage contains:
   a. Too much starch
   b. 15% starch
   c. 30% starch
   d. 45% starch

4. Typical diets fed to dairy cattle in the Midwest contain:
   a. 15 to 20% starch
   b. 20 to 25% starch
   c. 25 to 30% starch
   d. > 30% starch.

5. Compared with corn silage at 30% DM, corn silage at 35% DM has:
   a. No more starch
   b. 2% more starch
   c. More fiber
   d. 5% more starch

6. Compared with rolled grain, finely ground corn has:
   a. Less feeding value
   b. Greater digestibility
   c. Less acidosis potential

7. Starch digestibility of rolled or ground dry corn is most responsive to:
   a. Particle size
   b. Duration of storage
   c. Moisture content

8. Compared with finely ground dry corn grain, high moisture corn has:
   a. Lower digestibility
   b. Greater digestibility
   c. Less acidosis potential

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9. Starch digestibility of high moisture corn varies most greatly with:
   a. Particle size
   b. Duration of storage
   c. Moisture content.

10. Ideally, high moisture corn should contain:
    a. 15% moisture
    b. 24% moisture
    c. 30% moisture
    d. Moisture does not matter

11. Fermentation of high moisture corn:
    a. Is complete in 2 weeks
    b. Lasts a full month
    c. Can take 6 months or more

12. For dry rolled corn, what percentage of the starch is digested in the rumen?
    a. 25%
    b. 50%
    c. 80%
    d. 90%

13. Compared to the intestines, starch digestion in the rumen is preferred because:
    a. It generates microbial protein
    b. It can't be digested later
    c. Greater glucose yield

14. Compared to the rumen, starch digestion in the small intestine is preferred; it:
    a. reduces ruminal acidosis
    b. is more efficient energetically
    c. yields more microbial protein

15. Following grain processing, relative to small corn kernels, large corn kernels:
    a. Have equal feed value
    b. Have more fiber
    c. Have more feeding value

16. In the rumen, harder, more vitreous corn kernels, when fed as dry rolled grain:
    a. Are more fully digested
    b. Are fermented more rapidly
    c. Yield less acid

17. Compared to floury grain, when fermented or steam flaked, more vitreous kernels:
    a. Are equal in feeding value
    b. Have greater feeding value
    c. Have less value

18. Starch digestibility of steam rolled or steam flaked grain is related most closely to:
    a. Initial grain bushel weight
    b. Flaked bushel weight
    c. Flake thickness

19. Flaked corn decreases in feeding value when:
    a. Flakes get old
    b. Flakes are broken from mixing
    c. Flakes remain hot and moist

20. Corn kernels in manure are:
    a. Hollow and unimportant
    b. Incompletely digested
    c. Good bird food

21. Starch digestibility by lactating cows:
    a. Is complex to measure
    b. Can be estimated from analysis of feed and feces

22. Most starch availability measurements are estimates for digestion:
    a. In the rumen
    b. In the intestines
    c. In the total digestive tract

Reasoned (but not necessarily exclusive) answers: 1d, 2d, 3c, 4c, 5d, 6b, 7a, 8b, 9c, 10c, 11c, 12b, 13a, 14a+b, 15c, 16c, 17a, 18b+c, 19c, 20b+c, 21b, 22a.

Results and Discussion for Individual Questions

1 and 2. Non-fiber carbohydrate (**NFC**, mainly starch) is the primary source of net energy in both corn grain and corn silage (Table 1).

Corn grain contains over 70% starch, and NFC comprises over three-quarters of the DM and total digestible nutrients **(TDN)** in corn grain. Increasing the digestibility of dietary neutral detergent fiber **(NDF)** typically increases feed intake and production by high producing cows based on a series of elegant studies (Oba and Allen, 1999). But from an energy viewpoint, only about 1/3 of the truly digested energy from corn silage is derived from NDF. Once corn silage is harvested, NDF digestibility is difficult to improve except through long duration storage or inoculation with microbes that attack fiber. In contrast, processing of corn grain can markedly increase its starch digestibility. Processing adjustment factors from NRC (2001) indicate that the TDN for steam flaked and high moisture corn is 3.3% greater than for ground corn. And compared with ground corn, cracked corn has 4.1% less TDN (NRC, 2001). Note that digestibility of NFC is estimated at 98% according to the standard TDN formula (NRC, 2001). A greater reduction in starch digestibility for drier corn silage (particularly for unprocessed corn silage) is built into the Milk 2006 equations (Shaver et al., 2006).

3. Because corn grain DM has 70% starch, corn silage with 50% of its DM from grain will contain 35% starch. Starch content of corn silage from Dairyland (2009) and Dairy One (2009) for the past 7 years has averaged 29.2 and 31.4%, respectively, though this range (that should include 68% of all measured values) was 22 to 36% from Dairyland (2009) and 24 to 39% from Dairy One (2009). This indicates that grain as a percentage of silage DM varies from about 30 to 56%. If starch content of corn silage is greater than normal, the quantity of supplemental grain that needs to be fed to meet the cow's energy requirement for milk production will be reduced, so the value of starch in corn silage increases when grain prices are high. Though some nutritionists have expressed concern that corn silage high in grain is "too hot to feed," a condition that may be true for dry cows or growing heifers given free choice access to silage, diets for lactating cows in the US typically contain much more starch than is present in corn silage. Adjustments in the forage to grain ratio of the diet can compensate easily for corn silage that is rich in grain and starch content. If silage can be produced at the dairy, while grain often must be purchased and imported, the economics, convenience, and feed quality typically will favor production of silage hybrids with high grain content. More complex budgeting factors involved with corn silage production and utilization by dairy farms are included in a program called "Corn Picker®" developed by Allen (2006).

4. If a dairy ration has a roughage:concentrate (DM) ratio of 55:45, if 60% of the roughage is corn silage, and if the corn silage contains 30% starch, then 10% of dietary DM (0.45*0.60*30) is starch from corn silage. A change in any of these factors alters the final value. How much starch is coming from added grain? As an example, with a 55:45 roughage:concentrate ratio, if 50% of concentrate DM is grain DM at 70% starch, the amount of starch from grain in dietary DM is 15.75% (0.55*0.50*70). This gives a total 25.75% starch in the total diet. Energy also is available from digestion of fat and fiber, so starch is not an essential component of the diet, but dairy diets that contain less than 22% starch are rare due to high diet bulkiness and limited local availability of ingredients low in starch that

can be fed at high levels; dairy diets containing over 30% starch also are rare due to management concerns about subacute ruminal acidosis.

5. Surprisingly, compared to corn silage at 30% DM, corn silage at 35% DM has 4 to 5% more starch (Figure 1). About 1/3 of this increase reflects conversion of sugar to starch; the remainder represents increased deposition of grain. Unlike forages that do not yield grain, the weight of NDF in the corn plant remains relatively constant or may decrease slightly during this grain deposition period and NDF digestibility does not decline markedly because the corn plant still is immature. With additional grain deposition, NDF as a percentage of silage DM decreases due to dilution. Although delaying harvest will increase starch content and decrease the NDF percentage of corn silage, hazards from late harvest include: a) increased difficulty in packing and air exclusion during ensiling and b) potential decreases in starch digestibility, especially with corn silage that has not been kernel processed adequately or has not been stored for a sufficient time to increase starch availability from corn kernels. Although silage DM content is the traditional index of plant maturity at corn silage harvest, DM content always is higher for grain than stover. Therefore, at a similar stage of stover maturity or moisture content, hybrids with a higher grain yield automatically have a higher DM content. Days after pollination, or preferably days after silking, provide a more precise index of stover maturity. However, compared with others, hybrids with the "stay green" trait maintain a higher ratio of stover moisture to grain moisture. Maturity of the grain traditionally has been judged by location of the milk line of kernels near the center of an ear; presence of black layer is used as an index of physiological maturity. These rapid and dramatic changes in both DM yield and composition with maturation of the corn plant markedly complicate field comparisons of silage hybrids. When harvested early (30% DM), hybrids with high grain content will not exhibit their full potential in terms of either DM yield or starch content. Even if 2 hybrids with the same relative maturity are harvested on the same date at the same silage DM content, the physiological stage of maturity of both the stover and the grain in these hybrids can differ. For comparison, corn silage hybrids should be harvested on multiple dates so that yield and composition changes can be plotted across time. Such plots can help producers select which hybrids should be harvested later to maximize the quality or quantity of silage available. For corn silage hybrids with high grain content that have been adequately kernel processed and inoculated to enhance fermentation and reduce aerobic deterioration, potential milk per ton and milk per acre (Shaver, 2006), as calculated from corn plant composition, generally are maximized at 37 to 38% DM. That is considerably drier than the average of samples assayed over the past 7 years in New York (34%; Dairy One, 2009) but not in Wisconsin (37.1%; Dairyland, 2009). It also is drier than most recommendations of the past, presumably reflecting the much higher grain yields of modern silage hybrids, improved late season plant health (less ear drop), and the widespread use of harvest equipment equipped with kernel processors.

6. Summaries of research trials with dairy cows indicate that compared with more coarsely rolled corn grain, extent of starch digestion from finely ground corn is 6 to 7% greater, both in the rumen (Figure 2) and in the total digestive tract (Figure 3). Unfortunately, if fine corn particles are present, cows often sort their feed, and cows selecting fine particles have an increased likelihood of subclinical acidosis. Acidosis is a multi-factor disorder often associated with imprecise cattle or bunk management (abrupt ration switches; separation

of fines in the bunk and feed sorting; inadequate amounts of effective forage; and water deprivation) as reviewed by Oetzel (2007). Some of these problems can be reduced or avoided by including more forage in the ration. Although starch is the primary source of fermentation acids generated in the rumen, feedlots diets typically contain over 50% starch (over 75% corn, often as steam flaked corn). Given adequate bunk and animal management and inclusion of an ionophore in the diet, signs characteristic of subclinical or clinical acidosis (fluctuating feed intake, depressed fiber digestion, diarrhea, depression, and physiological acidosis) among adapted feedlot cattle are rare, even though ruminal pH of such cattle typically falls below 5.5, the benchmark used as an index of subclinical acidosis in dairy cattle.

7. Total tract starch digestion from rolled or ground corn depends greatly on particle size of the processed grain (Figure 4). Grinding corn to a smaller particle size increases the extent of starch digestion, both in the rumen and the total digestive tract. Averaged across these 4 trials with lactating cows fed dry rolled grain, starch digestibility increased by 2.7 ($\pm$ 0.8) % ($P = 0.023$) for each decrease in mean particle diameter of 1000 microns. Spread in particle size, a factor that likely is more important than mean particle size alone, will be narrower if grain is ROLLED than if it is GROUND. During grinding, very fine, dusty particles are produced. Because drier, floury corn grain produces more dust than moist, vitreous corn, particle size of processed corn grain can change drastically from batch to batch. The concern about acidosis from fine starch particles has led many producers and consultants to prefer rolled over ground grain and to avoid grinding grains very finely. However, under excellent management conditions, when feed sorting and particle separation are avoided by including wet feeds in the ration and when sufficient roughage is fed to prevent acidosis, fine grinding will improve digestibility of starch. The finer the grind or the closer the roll setting, the greater the time and energy required to process grain. So grinding as fine as 600 microns, as is recommended for pigs, seldom is used with dairy diets. To prevent digestive problems, a geometric mean diameter of 1000 to 1200 microns (flour sifter size) often is recommended (Hutjens, 2008). With corn, even very fine grinding will not increase total tract starch digestibility to the degree achieved with more extensive corn grain processing (high moisture fermented grain or steam flaked grain; Figures 2 and 3) because physical factors (fiber and zeins) still physically inhibit digesting microbes and enzymes from reaching and attacking the vitreous starch granules of dry rolled grain. Besides particle size, other factors (grain vitreousness, pericarp thickness, and kernel size) can alter starch digestibility as reviewed by Hoffman and Shaver (2008).

8. Total tract starch digestion is greater for high moisture corn than for dry rolled or ground corn grain, primarily due to increased starch digestion in the rumen. Heat processing (e.g., flaking, popping, or extruding grain) gelatinizes or explodes starch granules; in contrast, the fermentation process softens proteins surrounding vitreous starch to increase the accessibility of starch granules for digestion. Surprisingly, flaking does not increase extent of starch digestion in the rumen as much as it increases intestinal starch digestion (Figure 2), perhaps because proteins melted during the flaking process smear and coat fine starch particles.

9. For efficient packing and fermentation, an adequate amount of moisture must be present with high moisture corn. For packing and fermentation, rolling or grinding high moisture corn grain before storage is recommended

unless the material is stored in an oxygen limiting structure. A longer duration of storage increases the rate and extent of starch digestion, both with high moisture corn (Benton et al., 2005) and corn silage (Hallada et al., 2008).

10. For adequate fermentation to increase its feeding value, high moisture corn should contain more than 26% moisture. Adding water to dry or semi-moist ground corn grain prior to ensiling yields high moisture corn with a net energy advantage over dry corn similar to that seen with grain harvested at the higher moisture content. In the range of 20 to 24% moisture, corn grain often has a *lower* feeding value than grain that is either wetter or drier! Harvesting grain with more than 32% moisture usually reduces grain yield. For maximum grain yield, harvest of high moisture corn should be delayed until grain reaches physiological maturity (presence of kernel black layer). If the cob is harvested with high moisture corn grain to produce high moisture ear corn silage, recommended harvest moisture levels will be 3 to 5% greater than with high moisture corn grain because the cob contains more moisture than the grain.

11. Fermentation of high moisture corn can continue for more than 6 months as judged by continuing increases in ruminal starch digestion and solubility of the corn protein (Benton et al., 2005). Because starch availability of high moisture corn grain increases during storage, a diet containing high moisture corn that is 9 months old is considerably more likely to cause acidosis than a similar diet containing high moisture corn that has been stored for only 1 to 3 months. Diet reformulation based on duration of fermentation can help avoid this "spring acidosis" condition. Likewise, starch digestibility of corn silage also increases with longer storage time. To maximize feeding value of corn silage, some dairy producers purposely delay feeding of corn silage until it has fermented for several months.

12. Surprisingly, only about half of the starch from dry rolled corn is fermented in the rumen, leaving half to flow to the small intestine (Figure 5). In nearly 30% of the digestion site studies with lactating cows fed dry rolled corn, more starch disappeared PAST the rumen than WITHIN the rumen (Owens, 2005). Compared with feedlot steers, lactating cows often have a greater postruminal supply of starch (weight and percentage of dietary starch), probably because of their high feed intakes of diets rich in NDF. These two factors decrease the time that starch particles spend in the rumen to be digested by microbes. In sharp contrast with dry rolled or ground corn, with high moisture corn the extent of ruminal digestion of dietary starch often exceeds 80% (Figure 5). Compared with diets based on rolled or ground dry grain, high moisture corn diets have much more extensive ruminal starch digestion, leaving less starch to be digested or fermented in the intestines.

13. With fermentation in the rumen, about 190 g microbial protein can be generated for every kilogram of organic matter fermented. This means that replacing 1 kg of dry rolled corn by high moisture corn will increase microbial protein supply by over 50 g, slightly over 1% of the typical supply. This increases the amount of ammonia that will be used in the rumen, but ruminal degradation of corn protein also is greater for high moisture than dry rolled corn. Is an increase in postruminal starch useful for ruminants? How much starch is digested in the small intestine, how much of this starch becomes available as glucose or is converted to fat at the site of absorption, and relative energetic efficiencies of ruminal and intestinal digestion currently are being debated (Huntington et al., 2006; McLeod et al., 2006). Energetically, carbohydrate digested in the small intestine

provides over 20% more energy for the animal because when carbohydrate is fermented in the rumen, energy is loss as methane and heat. Although fermentation of starch in the large intestine will recover energy as fermentation acids, fermentation in the large intestine is inefficient energetically for the animal because microbial mass generated in the large intestine is excreted in feces. In terms of energetic efficiency, the rank order for digested carbohydrate is: 1) small intestine, 2) rumen, and 3) large intestine. The relative value of digestion in the rumen versus the small intestine depends primarily on the animal's ability to digest starch within the small intestine. For small intestinal digestion to have an energetic advantage over ruminal fermentation, the digestibility of carbohydrate reaching the small intestine must exceed 73%. Based on the mean values from Figure 5, increasing ruminal bypass of starch from either dry corn (60% small intestinal digestion) or high moisture corn (70% small intestinal digestion) will reduce energetic efficiency as compared with fermenting the starch in the rumen. In contrast, numerous measurements with growing steers indicate that small intestinal digestion would be advantageous energetically (78% small intestinal digestion of starch from dry rolled and over 98% small intestinal digestion from steam flaked and high moisture corn). Reasons for this discrepancy between lactating cows and finishing steers in digestive efficiency are not yet clear.

14. Bypassing more starch reduces acid production in the rumen and thereby reduces the likelihood of ruminal acidosis. In Europe, where lactating cows often are fed diets based on wheat and barley, both of which are rapidly and extensively fermented within the rumen, increasing ruminal bypass of starch through feeding more slowly fermented corn types (coarsely ground corn grain from flint rather than floury, or finely ground dent corn grain) often has increased productivity.

15. The larger a sphere, the lower its surface area to volume ratio. Consequently, larger kernels have less surface (pericarp) area per unit weight (kernel). Because the pericarp is nearly 90% NDF, barring differences in pericarp thickness, hybrids with a larger mean kernel size or weight will have a lower percentage of NDF. Because NDF is less digestible than cell contents, larger kernels have more net energy as noted in steer feeding trials by Jaeger et al. (2004). In addition, large kernels are more likely to be damaged during grain processing (rolling or grinding); while small kernels often escape processing and consequently are poorly digested. For rapid and efficient grinding to avoid flour and dust, a uniform kernel size is preferred; addition of moisture with or without a surfactant for a short time prior to grinding can reduce dustiness of ground corn.

16. Dent corn grain is the product of an ancient cross between floury and flinty grain parents. Hence, dent corn contains both floury endosperm (loosely packed starch that forms flour when ground) and a densely packed more crystalline endosperm encased in a starch matrix (proteins including the zeins). This fraction is considered to be flinty, vitreous, horny, or hard. The ratio of floury to vitreous starch differs with plant genetics and maturity of the grain, typically increasing as grain matures to black layer. Small, floury particles are rapidly and extensively digested in the rumen. Consequently, extent of ruminal digestion and acid production from dry ground grain is greater for corn grain with a higher percentage of floury endosperm as nicely outlined by Shaver (2003). Though the relationship is not perfect, grain samples with lower bushel weight often have a higher percentage of floury endosperm and would be preferred to maximize extent of

ruminal digestion of starch from dry ground grain. The range in vitreousness of highly productive dent corn hybrids commercially produced in the US is quite small (54 to 65%) when compared with the wide range (0% for floury to >80% for flints) that has been tested in feeding trials. Considering that hybrids with a higher proportion of floury starch in the endosperm generally have reduced cold tolerance for germination, decreased grain yields, increased damage during grain handling, and have failed to improve feed efficiency by growing pigs (Moore et al., 2008), it seems unlikely that the slight increase in total tract starch digestibility by cattle noted with grain that has been dry rolled or ground will be sufficient to justify commercial production of grain hybrids that have a more floury texture.

17. The lower ruminal and total tract digestion with dry grain that is associated with greater kernel vitreousness (Hoffman and Shaver, 2008) disappears when corn grain is either steam flaked (Corona et al., 2006) or when grain is fermented to produce either high moisture corn grain (Szasz et al., 2007) or corn silage (Jensen et al., 2005).

18. The thinner the flake and the lower the bulk density of flaked corn grain, the higher the rate and extent of starch digestion. Bulk density (pounds per bushel) is the standard index of flake quality typically used by operators of steam flakers. Thinner flakes generally have a higher percentage of the starch gelatinized and readily accessible for enzymatic digestion. Because additional factors (flake temperature, packing, and drying) can influence flake density, analytical procedures to evaluate starch availability (gas production rate and release of glucose during incubation with enzymes) have been developed and are available from some commercial laboratories. Not yet verified in cattle trials except for flaked grain, these tests are being used to appraise relative availability of starch from dry and high moisture corn and from corn silage. For corn silage, a Kernel Processing Score that measures the fraction of total dietary starch remaining on a coarse screen (> 4.75 mm) also has been used as a predictor of starch digestibility based on studies by Ferreira and Mertens (2005). The greater the cost of the grain, the greater the value of extensive processing. Although many feedlots own and operate flakers, few dairy farms handle a sufficient volume of grain to justify the high purchase and operating cost of equipment to steam flake grain. However, some feed mills in areas that serve multiple large dairy farms have installed steam flakers. Dairy farms that arrange to trade home-grown dry corn for a flaked, dried product generally have appreciated the convenience, improved feed consistency, and higher energy value (up to 15% greater net energy) obtained from feeding grain that has been steam flaked. Economics of this process could be improved markedly if the flaked grain could be fed immediately (as at commercial feedlots) in order to avoid the cost of drying flakes to conserve them.

19. Large and flat with few fines, picturesque corn flakes preferably are fed to feedlot cattle while still warm and moist. Research results indicate that: a) aged flakes have equal feeding value as fresh flakes and b) digestibility of flakes is not reduced by the extensive mixing that reduces size of the flakes. However, enzymatic availability of starch from flakes decreases when flakes remain very hot and moist for more than an hour following flaking, probably due to starch retrogradation (hardening). Retrogradation appears to reduce digestibility or at least shift more starch from the rumen to the intestines for digestion.

20 and 21. When separated and assayed, whole corn kernels from manure contain as much

starch as kernels that have never been consumed; they represent incompletely digested grain. Whole kernels are not detected in feces when grain is ground, but the mere absence of whole kernels (as when ground grain is being fed) does not mean that starch digestibility has been increased. Small kernel fragments are difficult to spot. For estimating starch digestibility, one must assay feces for starch. Greater fecal starch concentrations reflect lower starch digestibility. With feedlot steers fed diets based on adequately processed steam flaked corn, fecal starch concentrations generally fall below 5% of DM. For lactating cows fed well processed corn, starch content of feces ideally should be less than 10% of DM. By comparing the starch concentration of feces with the concentration of some other constituent of feed and feces that either is indigestible (e.g., lignin or insoluble ash) or has a known digestibility (e.g., protein), one can calculate starch digestibility. To be certain that a fecal sample represents an average for the herd, samples from several animals should be obtained and mixed for analysis. Intakes of starch from grain and corn silage can be readily calculated as discussed previously (Answer 4), but one cannot readily determine whether starch in feces is coming from silage or supplemented grain unless the 2 starch sources in both feed and feces can be distinguished physically (particle size) or chemically.

22. To predict starch availability, samples are incubated with enzymes or ruminal bacteria (with or without sample drying and with or without sample grinding) for several hours and the amount of starch degraded or is used to generate gas (Sapienza, 2004; Blasel et al., 2006) is measured. Sampling preparation procedures are not standardized and grind size can markedly alter results. Such tests generally appraise immediately accessible starch; thereby, they may reflect rate of ruminal digestion and serve as an index of the potential for acidosis. Prediction of total tract digestibility from starch availability relies either on the concept that ruminal and total tract digestion are closely correlated or physical addition of an analytical step in which residues remaining after ruminal digestion are incubated with starch-digesting enzymes. Based on published values from trials where ruminal and total tract starch digestion have been measured with feedlot or lactating cattle (Owens, 2005), the correlation of ruminal and total tract starch disappearance is reasonably high for samples of high moisture corn grain and steam flaked corn ($R^2 = 0.92$ and 0.72, respectively) but surprisingly low for dry rolled corn ($R^2 = 0.01$). If only 1% of the variation in total tract starch digestion can be attributed to differences in ruminal starch digestion by cattle, extrapolation from ruminal to total tract starch digestion is useless. Further research to develop or improve animal-relevant assay procedures and near infrared prediction equations to quantify both site and extent of digestion of grain components will increase our capacity to evaluate individual corn grain samples and corn hybrids and to quantify responses to grain processing. These, in turn, should lead to grains with improved nutritive value and energy availability and grain processing methods that can further enhance rate and efficiency of production by ruminants.

References and Additional Readings

Allen, M. 2006. CornPicker® for silage: A partial budget approach. Michigan Dairy Review, January 2006. https://www.msu.edu/~mdr/cornpicker1.05.xls

Benton, J.R., T.J. Klopfenstein, and G.E. Erickson. 2005. Effects of corn moisture and length of ensiling on dry matter digestibility and rumen degradable protein. Nebraska Beef Report pp. 31-33. http://beef.unl.edu/beefreports/2005.pdf

Blasel, H.M., P.C. Hoffman, and R.D. Shaver. 2006. Degree of starch access: An enzymatic method to determine starch degradation potential of corn grain and corn silage. Anim. Sci. Feed Tech. 128:96-107.

Corona, L., F. N. Owens, and R. A. Zinn. 2006. Impact of corn vitreousness and processing on site and extent of digestion by feedlot cattle. J. Anim. Sci. 84:3020-3031.

Dairy One Cooperative, Inc. 2009. Forage Laboratory Services, Statistical summary guidelines. Nutrient composition of corn silage from 5/01/2000 to 4/30/2008. http://www.dairyone.com/Forage/FeedComp/default.asp. accessed 3/12/2009.

Dairyland Laboratories, Inc. 2009. Forage summaries from 2002 to 2008. http://www.dairylandlabs.com/pages/interpretations/summaries.php. Accessed 3/12/2009.

Ferreira, G., and D.R. Mertens. 2005. Chemical and physical characteristics of corn silages and their effects on in vitro disappearance. J. Dairy Sci. 88:4414-4425.

Firkins, J.L, M.L. Eastridge, N.R. St-Pierre, and S.M. Noftsger. 2001. Effects of grain variability and processing on starch utilization by lactating dairy cattle. J. Anim. Sci. 79:E218-238.

Hallada, C.M, D.A. Sapienza, and D. Taysom. 2008. Effect of length of time ensiled on dry matter, starch and fiber digestibility in whole plant corn silage. J. Dairy Sci. 91(Suppl. 1):30. (Abstr.)

Hoffman, P.C., and R.D. Shaver. 2008. Corn biochemistry: Employing cereal chemistry techniques in grain and corn silage analysis. 2008 Penn State Dairy Cattle Nutrition Workshop. Available at: http://www.das.psu.edu/dairy/nutrition/pdf-dairy-nutrition/hoffman-corn-grain-silage-analysis.pdf. Accessed 3/12/2009.

Huntington, G.B. 1997. Starch utilization by ruminants: From basics to the bunk. J. Anim. Sci. 75:852-867.

Huntington, G.B., D.L. Harmon, and C.J. Richards. 2006. Sites, rates, and limits of starch digestion and glucose metabolism in growing cattle. J. Anim. Sci. 84(Suppl. E):E14-E24.

Hutjens, M. 2008. Dairy strategies with expensive grain. The Cattle Site. http://www.thecattlesite.com/articles/1731/dairy-strategies-with-expensive-corn. Accessed 3/12/2009.

Jaeger, S.L., C.N. Macken, G..E. Erickson, T.J. Klopfenstein, W.A. Fithian, and D.S. Jackson. 2004. The influence of corn kernel traits on feedlot cattle performance. 2005 Beef Cattle Report, pp. 54-57. http://beef.unl.edu/beefreports/2004.pdf

Jensen, C., M.R. Weisbjerg, P. Nørgaard, and T. Hvelplund. 2005. Effect of maize silage maturity on site of starch and NDF digestion in lactating dairy cows. Anim. Feed Sci. Tech. 118:279-294.

McLeod, K., R.L. Baldwin, V.I., S.W. El-Kadi, and D.L. Harmon. 2006. Site of starch digestion: Impact on energetic efficiency and glucose metabolism in beef and dairy cattle. pp. 130-137. In Cattle Grain Processing Symposium, Oklahoma State Univ., MP-177.

Moore, S.M., K.J. Stalder, D.C. Beitz, C.H. Stahl, W.A. Fithian, and K. Bregendahl. 2008. The correlation of chemical and physical corn kernel traits with growth performance and carcass characteristics in pigs. J. Anim. Sci. 86:592-601.

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

NRC. 2001. Nutrient Requirements of Dairy Cattle. 7th Rev. Ed. National Academy Press, Washington, DC.

Oba, M., and M.S. Allen. 1999. Evaluation of the importance of the digestibility of neutral detergent fiber from forage: Effects on dry matter intake and milk yield of dairy cows. J. Dairy Sci. 82:589-596.

Oetzel, G.R. 2007. Subacute ruminal acidosis in dairy herds: Physiology, pathophysiology, milk fat responses, and nutritional management. Amer. Assn. Bovine Practitioners 40th Annual Conf. Available at: http://www.vetmed.wisc.edu/dms/fapm/fapmtools/2nutr/sara1aabp.pdf. (Sourced 3/12/2009)

Owens, F.N. 2005. Corn grain processing and digestion. Minnesota Nutrition Conference. pp. 113-133. http://www.ddgs.umn.edu/articles-proc-storage-quality/2005-Owens%20(MNC)%20Corn%20grain%20proc.pdf

Owens, F.N., and R.A. Zinn. 2005. Corn grain for cattle: Influence of processing on site and extent of digestion. pp. 78-85. Southwest Nutr. Conf., Univ. of Arizona. http://animal.cals.arizona.edu/swnmc/2005/index.htm

Owens, F.N., R.A. Zinn, and Y.K. Kim. 1986. Limits to starch digestion in the ruminant small intestine. J. Anim. Sci. 63:1634-1648.

Sapienza, D.A. 2004. Pioneer tripartite method: Linking nutrient content to availability. Cornell Nutr. Conf. pp. 27-40.

Shaver, R.D. 2003. Impact of vitreousness, processing, and chop length on the utilization of corn silage by dairy cows. Florida Ruminant Nutrition Symposium, Gainesville. Pp. 1-9. http://www.wisc.edu/dysci/uwex/nutritn/pubs/flnutrconf103.pdf

Shaver, R. 2006. Corn silage evaluation: MILK2000 challenges and opportunities with MILK2006. http://www.wisc.edu/dysci/uwex/nutritn/pubs/milk2006weblinktext.pdf

Szasz, J.I., C.W. Hunt, P.A. Szasz, R.A. Weber, F.N. Owens, W. Kezar, and O.A. Turgeon. 2007. Influence of endosperm vitreousness and kernel moisture at harvest on site and extent of digestion of high-moisture corn by feedlot steers. J. Anim. Sci. 85:2214-2221.

Table 1. Contributions to total digestible nutrients (TDN) (NRC, 2001).

Component	Corn grain (% of DM)	Corn grain (% of TDN)	Corn silage (% of DM)	Corn silage (% of TDN)
NFC[1]	76.1	77.5	40.8	50.3
Protein	9.4	9.6	8.3	9.5
Fat	4.2	7.5	3.3	7.2
NDF	9.5	5.4	44.6	33.3

[1]NFC = Non-fiber carbohydrates.

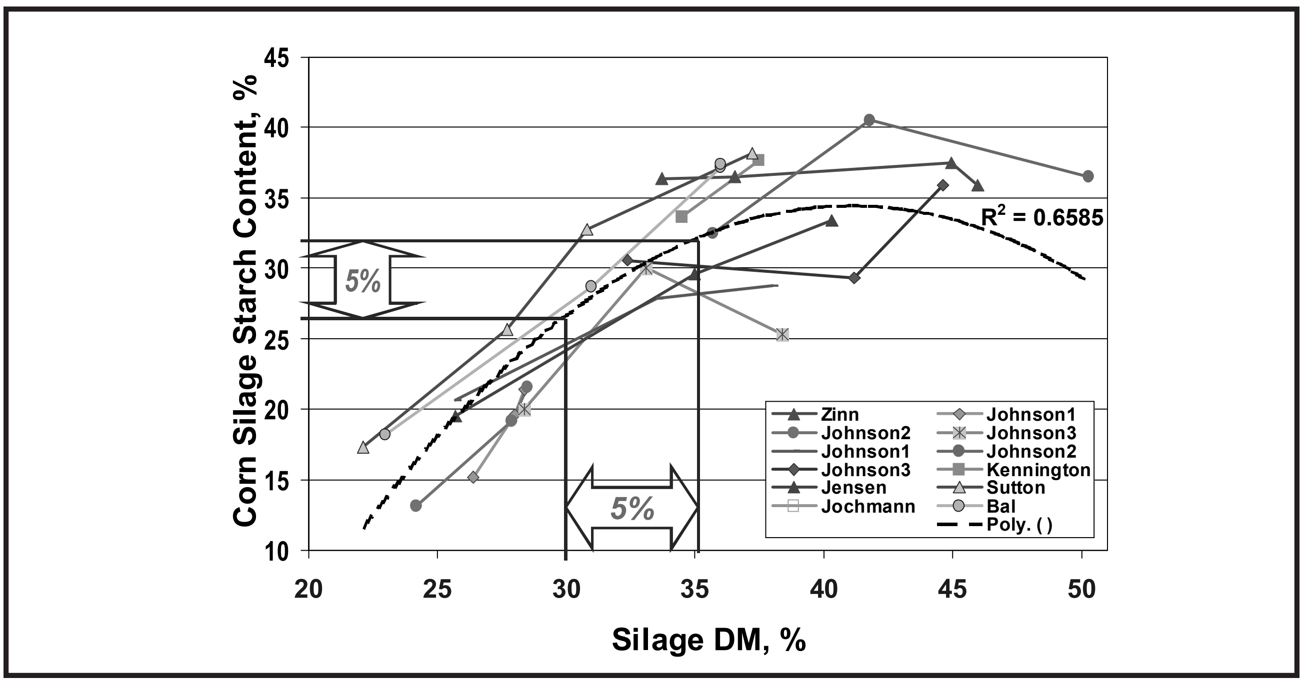

Figure 1. Influence of corn silage DM content on starch content of corn silage.

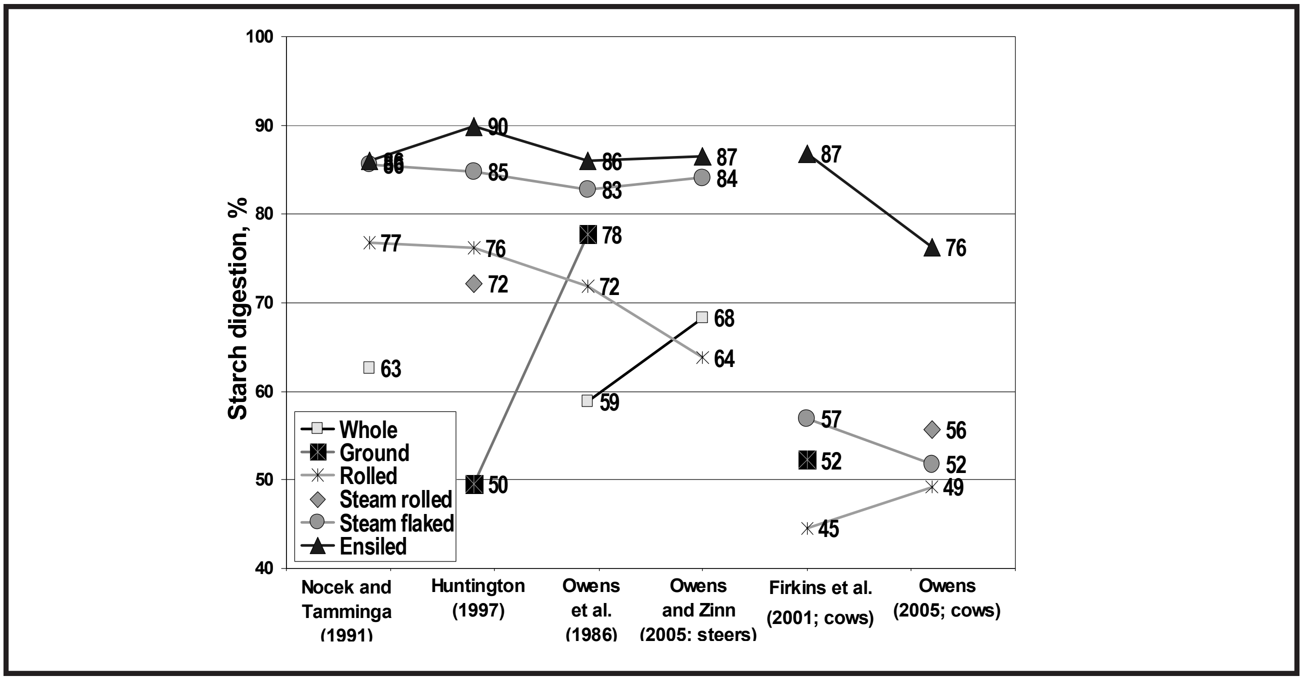

Figure 2. Digestion of starch in the rumen of cattle as a fraction of starch from corn grain that was fed with grain processed by various methods.

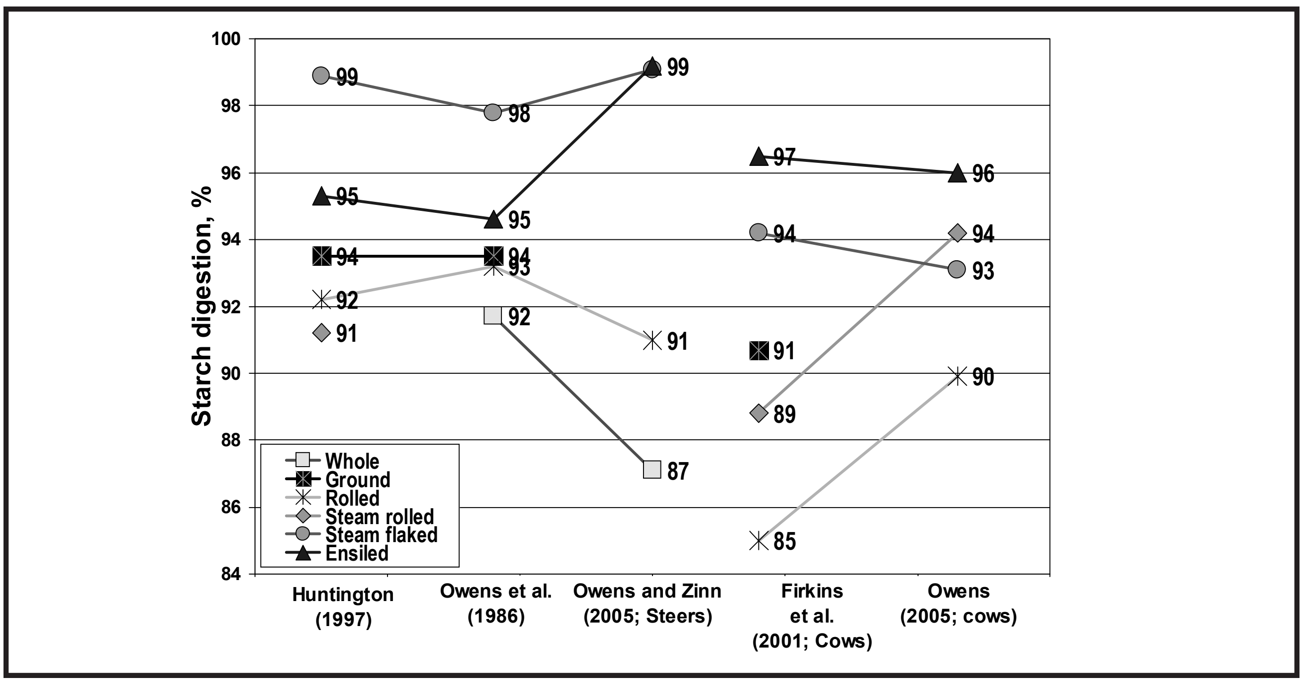

Figure 3. Mean values for total tract digestion by cattle of starch from corn grain processed by various methods based on literature reviews by various authors.

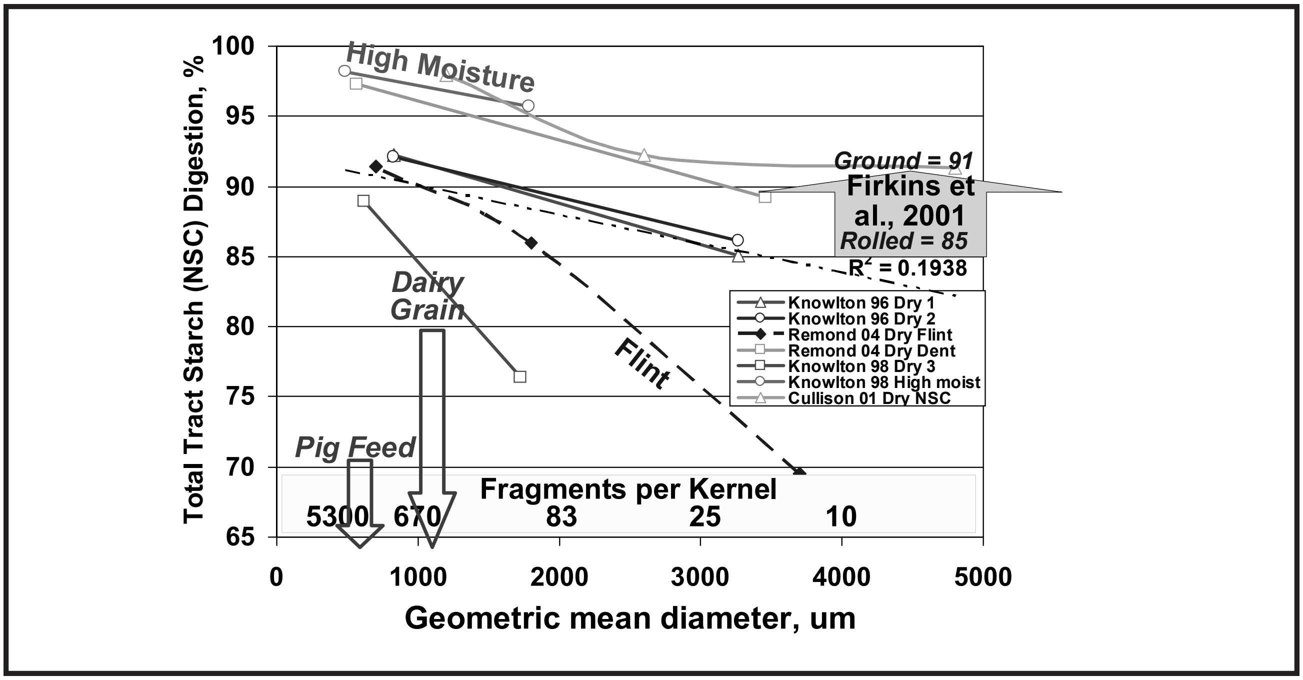

Figure 4. Influence of particle size on starch or non-structural carbohydrate digestion by lactating cows.

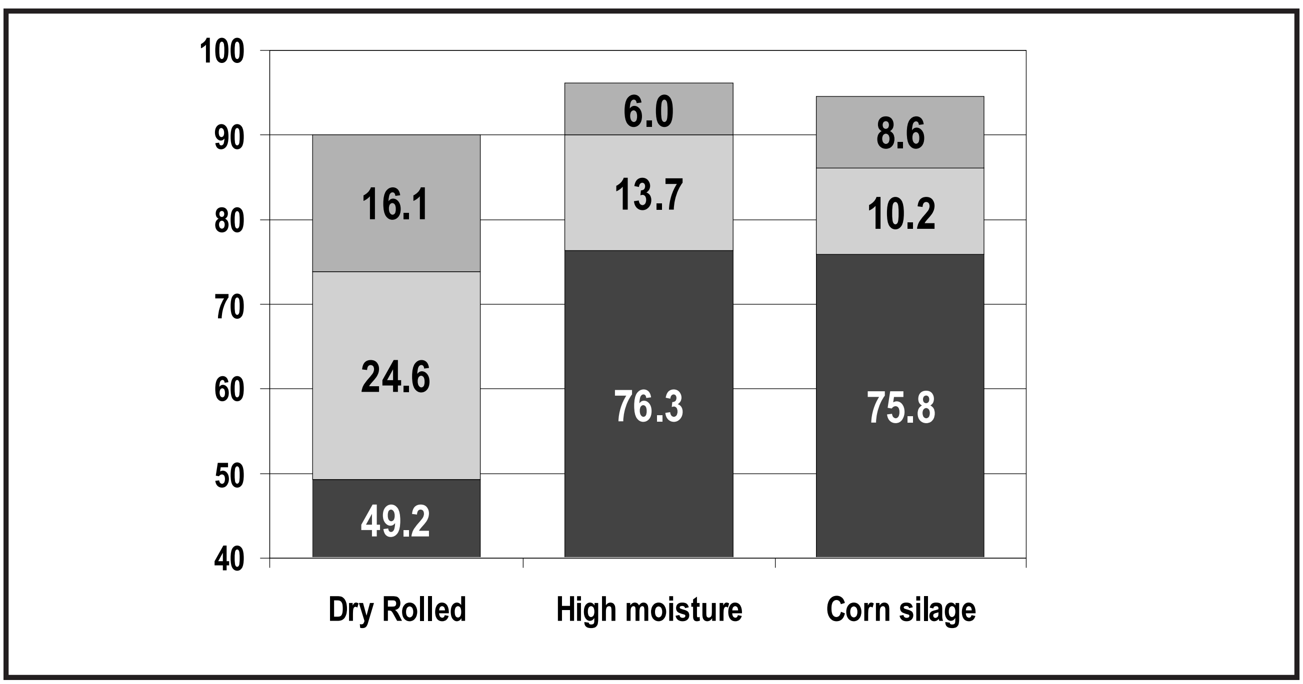

Figure 5. Site of starch disappearance (% of dietary starch) from corn grain and corn silage fed to cows. The lower section represents digestion in the rumen, the midsection represents digestion in the small intestine, and the top section represents fermentation in the large intestine.