New Perspectives on Fiber and Starch Digestibility of Corn Silage

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Introduction

Whole-plant corn silage (**WPCS**) is the predominant forage used in dairy cattle diets worldwide. On average, approximately 120 million tons of fresh corn forage per year is harvested in the United States. Besides providing energy for maintenance and lactation, coarser WPCS particles stimulate chewing and salivation, rumination, gut motility and health, regulate feed consumption and are the structural basis of the ruminal mat, which is crucial for ruminal digestion. Starch and fiber are the main sources of energy for dairy cows fed corn silage-based diets and therefore improvements in digestibility of these nutrients may increase milk production or reduce feed costs through enhanced feed efficiency. Greater digestibility of WPCS fiber and starch is desired for productivity, profitability and environmental reasons. The purpose of this paper is to review selected recent developments and strategies that may influence the nutritive value of WPCS.

Starch digestibility

An increase in starch digest may lead to better nutrient utilization and decreased feed costs. Starch digestion in the rumen and small intestine requires that starch granules be accessible for microbial or enzymatic degradation, but several layers within the corn kernel impedes the access. Kernels have a hard coat, the pericarp, which surrounds the endosperm and is highly resistant to microbial attachment (McAllister et al., 1993) and inhibits digestion of starch; therefore, the breakdown of the pericarp and correspondent exposure of the starch endosperm must be the primary objective at harvest to maximize energy availability. In addition, starch accessibility is dependent upon the intricate starch-protein matrices surrounding starch granules (Kotarski et al., 1992).

Storage length

Recently, prolonged storage has been featured an important tool to optimize starch digestibility in starchy feeds. Hoffman et al. (2011) observed a decrease in zein protein concentrations, as well as an increase in concentrations of soluble CP and ammonia-N, when HMC was ensiled for 240 d. These data suggested that proteases in the silo were responsible for degrading the zein protein matrix surrounding starch granules in corn kernels. Because the protein matrix is hydrophobic and represents a physicochemical barrier to rumen microorganisms, degradation of the matrix with prolonged storage was suggested to improve ruminal starch digestibility (Hoffman et al., 2011). Both, plant and microbial proteases in the silo are capable of degrading plant proteins to peptides and free amino acids. The subsequent deamination of amino acids by silage microbes results in an accumulation of ammonia-N. Experiments evaluating extended storage length in WPCS, earlage, and HMC consistently reported a gradual increase in ruminal in vitro or in situ starch digestibility (**ivSD** or **isSD**, respectively) as fermentation progressed. Studies evaluating these effects are summarized in Table 1. Briefly, all studies reported a gradual increase as fermentation progressed.

An increase in N fractions (i.e. soluble CP and ammonia-N) along with prolonged fermentation was also consistent across all studies. Positive linear relationships were observed between ivSD and ammonia-N or soluble CP in both HMC (Ferraretto et al., 2014) and WPCS (Ferraretto et al., 2015c). In addition, Ferraretto et al. (2014) observed negative linear relationships between pH and ammonia-N, soluble CP or ivSD in HMC samples. These results were not surprising because the two main mechanisms, solubilization and proteolysis, responsible for the disruption of the zein-proteins cross-linked to starch granules occur under acidic conditions. A study conducted by Junges et al. (2017) in reconstituted corn grain silage revealed that proteolytic activity in the silo was primarily from bacteria (60%), followed by kernel enzymes (30%), fungi (5%) and fermentation products (5%). The continuous decrease in pH and accumulation in acids along with fermentation favors the activity of plant proteases specific to the endosperm of cereal grains (Simpson, 2001), even though generally the activity of plant proteases is reduced under low pH. Furthermore, zein-proteins are soluble in acetic and lactic acids (Lawton, 2002), the two main fermentation end products of ensiling (Muck, 2010).

Despite CP not being a major nutrient in corn silage (usually within 5 to 9% of DM), increases in soluble CP and ammonia-N with prolonged storage was suggested to have potential implications in dietary formulation (Gerlach et al., 2018). To our knowledge, there are no published studies evaluating the effects of length of storage on lactation performance. However, if using the comparison between unfermented vs. fermented corn grain (i.e. dry ground corn vs. HMC, respectively) as a proxy for storage length effects, proteolysis of N fractions should not be of concern.

A potential use of length of storage as a management practice would be to mitigate the negative effects of factors well-known to impair starch digestibility, such as maturity at harvest and hybrid endosperm type. Increases in WPCS ammonia-N and soluble-CP contents were accompanied by increases in ivSD in response to increased time of ensiling. The effects of ensiling time and exogenous protease addition on fermentation profile, N fractions and ivSD in WPCS of various hybrids, maturities and chop lengths were evaluated by Ferraretto et al. (2015a). Extended time in storage increased ammonia-N, soluble CP and ivSD in WPCS of various hybrids, maturities and chop lengths. However, extended fermentation did not attenuate the negative effects of kernel vitreousness and maturity at harvest on ivSD. Exogenous protease attenuated but did not overcome negative effects of maturity on WPCS ivSD. A similar approach was used to evaluate the effects of prolonged storage in earlage harvested at either ½ of the kernel milk line or black layer stage (Ferraretto et al., 2016b; Ferraretto et al., 2018). Both studies highlighted that ivSD increases along with length of storage. However, differences in ivSD between maturities remained even after 240 days of fermentation.

In summary, research supports the use of inventory planning so a newly harvested crop would be fed only after four months in storage. Although prolonged storage of corn silage would be a valid management practice, several factors should be taken into consideration when implementing this practice. Prolonged storage requires proper silo management during filling, packing and covering to ensure beneficial fermentation patterns. Furthermore, storing silage for a longer period requires that more silage be harvested initially which, in turn, demands additional cropland and storage infrastructure (i.e. silos) on the farm.

Corn silage processing score

Although the breakdown of zein proteins allows for great exposure of starch granules to microbial fermentation and enzymatic digestion, perhaps a secondary effect may exacerbate this response at farm level. Disruption of the starch-protein matrix during ensiling may dissociate starch granules and thereby reduce mean particle size of kernels; smaller particles are more digestible. Ferraretto et al. (2015b) conducted two studies to evaluate the effect of ensiling and prolonged storage on CSPS. The first experiment reported a 10 percentage units greater corn silage processing score (**CSPS**) for silage fermented for 30 days compared with unfermented material (60.1% vs. 50.2%, respectively). These data suggest that the breakdown of zein proteins during fermentation (Hoffman et al., 2011) results in dissociation of starch granules and thereby reduces kernels particle size (measured as CSPS). The second experiment was designed to elucidate the effects of extended storage on CSPS of WPCS. A gradual increase in CSPS from 0 to 240 d of fermentation was observed, similarly to what commonly happens to starch digestibility, ammonia-N and soluble CP. These findings highlight the potential effects of extended fermentation not only in chemical but also physical characteristics of kernels. Interestingly, however, the extent of increase in CSPS in the second experiment was of lower magnitude than in the first experiment. Perhaps the magnitude of the change in CSPS as fermentation progresses is dependent upon the initial values of unfermented samples or other factors and more research is warranted.

Based on these findings, we hypothesized that ensiling would enhance CSPS to a greater extent in poorly (< 50% of starch passing through 4.75 mm sieve) compared with adequate or optimally (> 50% or 70% of starch passing through 4.75 mm sieve, respectively) processed silage. Thus, we designed a study to elucidate the effect of ensiling on CSPS of poorly processed silage (Agarussi et al., 2018); samples from eleven corn silage hybrids were ensiled for 0 or 120 d. Contrary to our hypothesis, CSPS was unaffected by ensiling and averaged 28.8% of starch passing through the 4.75 mm sieve. Further research is warranted across a wide range of CSPS values to elucidate under which conditions ensiling enhances this parameter.

It is crucial to highlight that prolonged storage length will not replace adequate processing at harvest. With the current available information, the best option may be to target for 60-65% CSPS entering the silo to have an optimal CSPS after fermentation.

Fiber digestibility

Lignin is the key obstacle to fiber digestion as it obstructs the enzyme access to the digestible fiber fractions, cellulose and hemicellulose. In addition, rumen microorganisms cannot breakdown lignin. Due to its importance to animal performance, this association between lignin and other fibrous fractions (i.e. cellulose and hemicellulose) is considered in many diet formulation models. This undigested or indigestible NDF fraction is estimated using either lignin or quantified as the proportion of NDF remaining after in vitro or in situ ruminal incubations (i.e. 240 h uNDF). Thus, the reduction of lignin or indigestible NDF fractions in forages improves fiber digestibility.

Storage length

Although allowing an extended storage may be beneficial for increasing starch digestibility, research does not support the same fate for NDF digestibility. Overall, data from several sites across the U.S. demonstrate that extended storage does not change or slightly reduces NDF digestibility in corn silage (Kung et al., 2018). In addition, a recent study by Gerlach et al. (2018) evaluated in vitro gas production of the NDF fraction in WPCS stored from 0 to 120 d. Fiber digestibility was unaffected by prolonged storage.

Chop height

A harvesting management option to reduce lignin concentration is chop height. With enhanced chop height more lignin is left with the portion that remains in the field, and thus, digestibility of the harvested material is greater. Results from a recent industry-university collaborative study from our group is in Table 2 (Ferraretto et al., 2017). Although our study compared 6 vs. 24 inches, these results are similar to other trials comparing 6 vs. 18 inches of chop height. Briefly, DM yield is reduced as the row-crop head is raised. This is consistent across several studies conducted across the United States. However, decreased DM yields are offset by an increase in the milk per ton estimates at the higher chop height. Greater milk estimate is a response to the greater fiber digestibility and starch concentration of the harvested material. In addition, most studies reported that estimated milk per acre is reduced by only 1 to 3% with high-chop. Also, increased quantities of high-chop silage could be included in the diet, rather than corn grain being added to the diet, providing an economic benefit to implementing increased chop heights.

As a follow-up study, we conducted a meta-analysis to evaluate the effects of chop height on nutrient composition and yield of WPCS (Paula et al., 2019). Yield of DM was reduced by 0.05 ton/ac for each inch of increased chop height. However, for each inch of increase in chop height there was an increase of 0.23, 0.20, and 0.20%-units in DM, starch, and ruminal in vitro NDF digestibility, respectively. A negative linear effect was observed for NDF, with a 0.25%-unit decrease per inch of increase in chop height. Using these responses, we calculated the effect of increasing chop height from 6 to 24 inches, these results are reported in Table 2. Briefly, we used Ferraretto et al. (2017) 6 inches treatments as baseline and simulated what the response would be for 24 inches. Overall, responses were similar to the observed. Our next goal is to validate these equations. Perhaps in the future these equations could be used in team discussions among farmers, nutritionists and crop consultants to determine individual farm priorities for maximum yield versus higher quality prior to the establishment of new chop height guidelines.

Plant population

Plant population could be used to increase yield per area without compromising nutritive value of WPCS. Thus, the combination of greater plant population with increased chop height could be of interest to maintain yield while increasing silage of WPCS. In our study (Ferraretto et al., 2017), we compared 2 chop heights (6 vs. 24 inches) and 4 plant populations (26,000, 32,000, 38,000 and 44,000 plants per acre). This experiment was conducted in Wisconsin. As aforementioned, increased chop height improved the nutritive value of whole-plant corn forage at the expense of yield. In contrast, plant population affected yield but not quality of whole-plant corn forage. No interactions were observed. However, effects of plant population may be affected by location and season. Diepersloot et al. (2019) aimed to evaluate the effect of plant population on yield, nutrient composition and ruminal in vitro NDF digestibility at 30 of whole-plant corn forage grown in Florida during the summer of 2016 and spring of 2017. Plant population effects on nutrient composition were inconsistent across seasons. In the spring, increasing plant population increase DM yield. However, DM yield of the summer crop was not affected by plant population.

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Table 1. Effects of ensiling time on ruminal in vitro and in situ starch digestibility in whole-plant corn silage, earlage and high-moisture corn

Item	Days Ensiled													
	0	30	45	60	70	90	120	140	150	180	240	270	360	*P*-value
Whole-plant corn silage	- - - - - - - - - - - - - - - - % of starch - - - - - - - - - - - - - - - -													
Der Bedrosian et al., 2012[1]	69	---	75	---	---	77	---	---	---	79	---	82	82	0.01
Windle et al., 2014[1]	54	---	59	---	---	63	---	---	68	---	---	---	---	0.01
Young et al., 2012[1]	66	---	76	---	---	---	---	---	79	---	---	---	---	0.01
Ferraretto et al., 2015a[2]	56	59	---	61	---	---	63	---	---	---	67	---	---	0.01
Ferraretto et al., 2015b[2]	62	72	---	---	---	---	79	---	---	---	84	---	---	0.01
Ferraretto et al., 2016a – exp. 1[2]	61	69	---	---	---	---	72	---	---	---	---	---	---	0.05
Ferraretto et al., 2016a – exp. 2[2]	54	62	---	---	---	---	67	---	---	---	---	---	---	0.04
Saylor et al., 2019[3]	74	80	---	82	---	86	88	---	---	---	---	---	---	0.001
Earlage	- - - - - - - - - - - - - - - - % of starch - - - - - - - - - - - - - - - -													
Ferraretto et al., 2016b[2]	---	58	---	61	---	---	66	---	---	---	74	---	---	0.001
Ferraretto et al., 2018[2]	---	58	---	60	---	---	68	---	---	---	70	---	---	0.001
High-moisture corn	- - - - - - - - - - - - - - - - % of starch - - - - - - - - - - - - - - - -													
Kung Jr. et al., 2014[1]	46	---	---	---	54	---	---	62	---	---	---	---	---	0.01

[1]Ruminal in vitro starch digestibility at 7 h on samples ground through a 3-mm screen.
[2]Ruminal in vitro starch digestibility at 7 h on samples ground through a 4-mm screen.
[3]Ruminal in situ starch digestibility at 7 h on samples ground through a 6-mm screen.

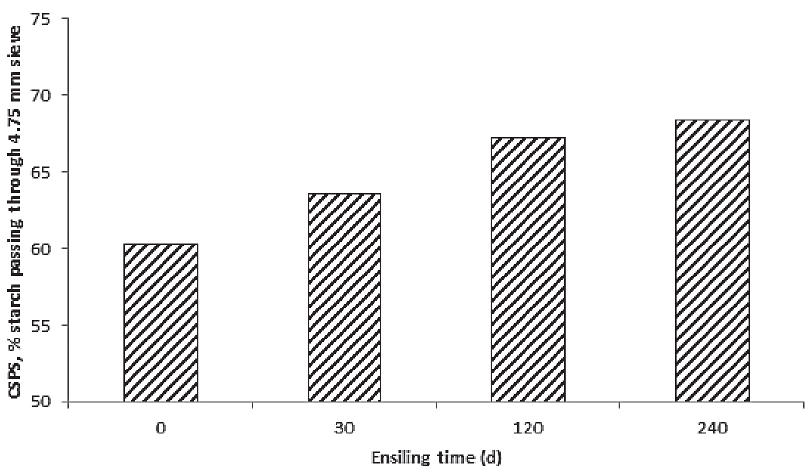

Figure 1. Effect of length of storage on corn silage processing score (CSPS) of whole-plant corn silage; n = 3, SEM = 2.0, $P = 0.08$. Adapted from Ferraretto et al. (2015b)

Table 2. Effect of cutting height on whole-plant corn silage nutrient composition, digestibility and yield[1]

Item	Low	High	Simulation[2]
Cutting height, inches	6	24	24
NDF, % of DM	37.7	33.8	33.2
Starch, % of DM	37.5	41.7	41.1
ivNDFD[3], % of NDF	49.6	52.7	53.2
Yield, ton/acre	8.9	8.1	8.0
Milk, lb/ton	2224	2378	---
Milk, lb/acre	24009	23498	---

[1]Adapted from Ferraretto et al. (2017).
[2]Predicted using equations from Paula et al. (2019).
[3]Ruminal in vitro NDF digestibility at 30 h.