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Silage review: Recent advances and future technologies for whole-plant and fractionated corn silage harvesting[1]

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ABSTRACT

Over the last 25 years, whole-plant corn silage has become an important and popular feedstuff for dairy production. Copious research has been dedicated to the development and evaluation of alternatives to enhance the nutritive value of whole-plant corn silage. These efforts have been aimed at manipulating the physical and chemical characteristics of whole-plant corn silage in an effort to maximize dairy profitability. Results from this review indicate that optimization of harvest maturity, kernel processing, theoretical length of cut, and cutting height improve or maintain the nutritive value and milk production of lactating dairy cows. Technological advancements have been developed and made available to dairy producers and corn growers desiring to enhance fiber and starch digestibility of whole-plant corn silage. Future research should be directed toward further assessment of new processors available in the market and the development of assessment methods for optimization of crop processor settings, harvest efficiency, and nutritional modeling.
Key words: corn silage, kernel processing, fractionated silage, silage harvest, forage analysis

INTRODUCTION

Whole-plant corn silage (**WPCS**) has become the predominant forage used in dairy cattle diets worldwide. Annually, 105 million Mg of fresh corn forage was harvested in the United States, on average, over the last 10 years (Table 1; USDA-NASS, 2017). Many factors contribute to the high adoption of WPCS by dairy farmers, including lower harvesting costs, minimized risks of production, elevated yield per area, and flexibility to harvest corn for forage or grain (Allen et al., 2003). Moreover, uniquely in comparison with other forages, WPCS offers dairy nutritionists the opportunity to provide high energy (mainly from starch in the kernel fraction) along with physically effective NDF (**peNDF**; provided by the stover fraction) concurrently.

Dairy farmers and corn growers are challenged to produce greater amounts of higher quality WPCS to meet the nutrient requirements of high-producing dairy cows (NRC, 2001). Despite continual improvements in total DM and kernel productivity of corn hybrids, advancements in nutritional quality of WPCS through hybrid selection programs were marginal in the last century (Lauer et al., 2001; Ferraretto and Shaver, 2015). Therefore, development of alternatives for enhancing the nutritive value of WPCS by manipulating its physical and chemical characteristics is crucial.

Harvest practices, such as proper maturity at harvest, kernel processing, theoretical length of cut (**TLOC**), and cutting height are well-established management tools for improving physical and chemical characteristics and hence nutrient digestibility of WPCS (Johnson et al., 1999; Allen et al., 2003; Buxton and O'Kiely, 2003; Ferraretto and Shaver, 2012b). However, nutritionists strive for greater consistency in the nutritive value of feedstuffs in the new era of precision feeding. Greater consistency allows for more optimal dietary formulation and feed bunk management. Thus, a greater understanding of how these various harvest practices interact with each other in combination with the development of new technologies are warranted to enhance the decision-making process for forage harvesting.

Recently, several technological advancements have been made available to dairy producers and corn growers desiring to enhance the nutritional value of forages. These advancements vary from data collection of spatial yield and nutrient characteristics at the time of harvest to processors and equipment modifications that allow for the production of silage of various whole- or fractionated-corn plant materials (i.e., shredlage,

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Table 1. Area harvested, yield, and production of corn for silage in the United States[1]

Year	Area harvested (1,000 ha)	Yield (Mg of fresh crop/ha)	Production (1,000 Mg of fresh crop)
2007	2,452	39.2	96,936
2008	2,414	41.9	101,259
2009	2,268	43.3	98,166
2010	2,253	43.3	97,354
2011	2,402	41.2	98,968
2012	2,986	34.5	102,920
2013	2,542	42.1	107,316
2014	2,578	45.1	116,163
2015	2,518	45.7	115,116
2016	2,503	45.5	114,006

[1]Adapted from USDA-NASS (2017).

snaplage, toplage). Although these developments have garnered a lot of interest by dairy farmers and corn growers, a review of research trials describing and summarizing these findings is unavailable.

Finally, continual improvements in on-farm methods to evaluate physical and chemical characteristics of forages enhance the likelihood of achieving greater consistency at harvest. Enhancement of these methods of analysis at the laboratory level would allow for potential improvements to the current models of diet formulation.

The objectives of this review are to (1) evaluate effects of selected practices and recent technological advancements for silage harvesting on physical and chemical characteristics of WPCS and their corresponding effects on lactation performance by dairy cows; and (2) discuss current procedures used for WPCS physical characterization and highlight areas where improvements are needed.

HARVEST PRACTICES

Kernel Processing

Although the use of self-propelled forage harvesters (**SPFH**) equipped with 2 counter-rotating rolls for corn processing was a common practice in Europe for many years, its US implementation came only in the 1990s (Johnson et al., 1999; Shinners, 2003). Adoption in the United States was possibly related to increasing grain prices, a trend toward longer TLOC, and rapid dry down of kernels due to climatic changes (Johnson et al., 1999).

The starch endosperm in corn kernels is protected by the pericarp, which, if intact, is highly resistant to microbial attachment and enzymatic digestion (McAllister et al., 1994); therefore, breakage of the seed coat is required for improved digestibility. Processing rolls are intended to break corn kernels down to a smaller particle size to ensure the starch endosperm is exposed, and thus, starch digestion and utilization by ruminant animals is enhanced. However, until the 1990s, the use of short TLOC settings (<10 mm) without processing rollers was a common harvest practice in the United States. Short TLOC settings allow for more kernel breakage by the cutting knives, and thus, the importance of kernel processing using a roller mill is tempered (Johnson et al., 1999; Ferraretto and Shaver, 2012b). With the establishment of peNDF as an index of chewing activity, ruminal pH, and milk fat content (Mertens, 1997), harvesting WPCS with longer TLOC settings became of greater interest, and thus, the importance of mechanical processing of kernels was established in the United States (Johnson et al., 1999; Allen et al., 2003). Shinners et al. (2000) reported that increasing TLOC settings from 9.5 to 19 mm without the addition of processing rolls reduced the proportion of broken and cracked kernels by 10 percentage units (61 vs. 51% of total kernel mass, respectively), on average, in whole-plant corn samples harvested between one-third and three-quarters kernel milk line. Conversely, when whole-plant corn was harvested with a harvester set for a 19-mm TLOC and equipped with processing rolls (roll gap set at 1 to 3 mm), broken and cracked kernels were >90% of total kernel mass (Shinners et al., 2000). Similar results were reported by others (Schurig and Rodel, 1993; Roberge et al., 1998). Ferraretto and Shaver (2012b), from a meta-analysis of WPCS trials with lactating dairy cows, reported 5.9- and 2.8-percentage-units greater total-tract starch digestibility (**TTSD**) when WPCS was processed using 1- to 3-mm roll gap settings compared with 4- to 8-mm processed or unprocessed WPCS. This was likely related to the extent of kernel breakage. Shinners et al. (2000) reported the fraction of broken and cracked kernels to be approximately 99, 96, and 88% of total kernel mass when roll gap settings were 1, 3, and 5 mm, respectively.

Degree of kernel processing in WPCS, however, may be inhibited by other factors. The review by Allen et al. (2003) hypothesized potential greater benefits for processing rolls in scenarios with drier corn kernels, such as late-maturity WPCS or hybrids with delayed dry-down of stalks (i.e., hybrids with accentuated stay-green characteristics; Arriola et al., 2012a,b), but noted that data were not available. A meta-analysis of recent studies revealed the use of processing rolls increased TTSD for diets containing WPCS with 32 to 40% DM at feed-out, but not when WPCS was above 40% DM (Ferraretto and Shaver, 2012b; Figure 1). Kernel vitreous endosperm proportion increases with increased DM content of WPCS (Philippeau and Michalet-Doreau, 1997; Johnson et al., 1999); greater kernel hardness causes kernels in very dry WPCS to be less susceptible to breakage during kernel processing at harvest. Furthermore, Allen et al. (2003) suggested potential benefits of mechanically processing WPCS when longer TLOC is desired to enhance silage peNDF content. Harvesting silage with processing rolls increased diet TTSD when TLOC was set at 0.93 to 2.86 cm, but not when the TLOC setting was shorter or longer (Ferraretto and Shaver, 2012b). These results were thought to be related to greater kernel breakage by cutting knives at the lower TLOC (Johnson et al., 1999) or inhibition of kernel breakage during passage through the rollers by the stover portion at the longer TLOC. Johnson et al. (2003) reported that kernel processing lessened the amount of intact kernels when TLOC was 11.1 mm, but not when 27.8 or 39.7 mm. Although recent technology (i.e., shredding rolls, greater roll speed differential) has attempted to reduce issues with proper corn kernel processing when WPCS is harvested at longer TLOC settings, further technological improvement of processors is still warranted to allow for a consistent breakdown of kernels, especially with late-maturity WPCS.

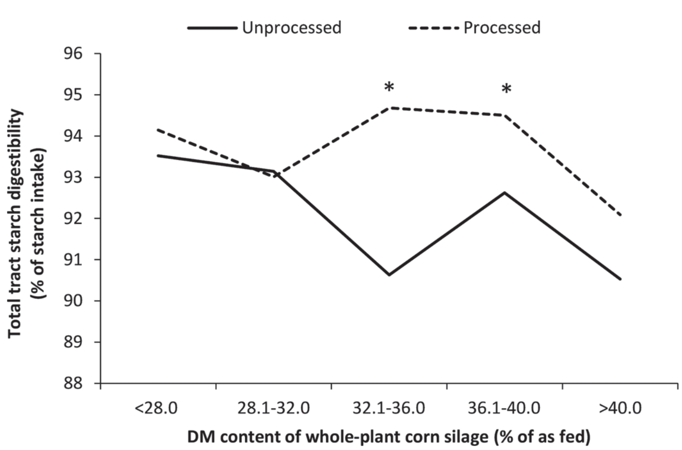

Figure 1. Interaction between kernel processing and DM content of whole-plant corn silage on total-tract digestibility of dietary starch (% of intake). $^{*}P < 0.01$. Adapted from Ferraretto and Shaver (2012b).

Particle size of whole-plant corn may be reduced by up to 40% with the use of a kernel processor at equal TLOC settings (Schurig and Rodel, 1993; Roberge et al., 1998; Shinners et al., 2000). The effects of mechanical processing on percentage of WPCS particles retained above the 18- or 19-mm sieves of particle separators are given in Table 2. At equal TLOC settings, processing reduced the percentage of particles retained above the 18- or 19-mm sieves by 20%, on average, across all studies. In addition, particle size of processed WPCS harvested with longer TLOC settings was similar to unprocessed silages in some (Dhiman et al., 2000, trial 2; Schwab et al., 2002; Cooke and Bernard, 2005) but not all (Bal et al., 2000a; Dhiman et al., 2000, trial 3; Weiss and Wyatt, 2000) studies. Moreover, the use of processing rolls eliminated intact cobs in the study by Shinners et al. (2000). According to Allen et al. (2003), crushing cobs is one of the greatest advantages of using processing rolls because it allows for greater TLOC without eliciting selective consumption of dietary fractions by cows. Although corn-stover tissue is sufficiently damaged by processing to increase ruminal fiber degradation (Johnson et al., 1999; Bal et al., 2000b), these effects are often inconsistent (Allen et al., 2003; Ferraretto and Shaver, 2012b). Perhaps insufficient ruminal retention time to allow for increased NDF digestibility (Allen, 1997) occurs due to reduced particle size of processed WPCS. In addition, increased ruminal digestibility of starch (Ferraretto and Shaver, 2012b) may attenuate effects on ruminal fiber degradation (Russell and Wilson, 1996).

Ferraretto and Shaver (2012b) reported no influence of kernel processing on DMI with a trend toward greater milk yield for WPCS processed at 1 to 3 mm or unprocessed compared with WPCS processed at 4 to 8 mm. No differences, however, were noted between WPCS processed at 1 to 3 mm and unprocessed WPCS. Although kernel processing reduces mean particle size of WPCS (Shinners, 2003), which in turn could be expected to increase DMI by attenuating ruminal retention time and fill (Allen, 1997), TLOC settings were shorter for unprocessed than processed WPCS treatments in most studies (Bal et al., 2000a; Dhiman et al., 2000; Weiss and Wyatt, 2000; Schwab et al., 2002; Ouellet et al., 2003; Cooke and Bernard, 2005). Alternatively, higher ruminal propionate concentrations for cows fed processed WPCS (Dhiman et al., 2000; Schwab et al., 2002; Johnson et al., 2003) may decrease meal size and thus DMI (Allen et al., 2009). Perhaps these opposing effects could explain the observed lack of effect of kernel processing on DMI, as suggested by Ferraretto and Shaver (2012b). Furthermore, Allen et al. (2003) reported effects of mechanical processing on animal performance and nutrient utilization were inconsistent.

Table 2. Effects of mechanical processing on percentage of whole-plant corn silage particles retained above the 18- or 19-mm sieves under similar or different theoretical length of cut (TLOC) settings

	Unprocessed		Processed	
Reference	TLOC (mm)	Particles (%)	TLOC (mm)	Particles (%)
Unequal TLOC				
Bal et al., 2000a	9.5	7.5	19.0	21.5
Dhiman et al., 2000, trial 2	9.5	15.6	19.5	15.9
Dhiman et al., 2000, trial 3	9.5	19.9	19.5	35.2
Weiss and Wyatt, 2000	9.5	3.0	19.0	21.9
Schwab et al., 2002	13.0	16.2	19.0	25.9
Schwab et al., 2002	19.0	32.7	32.0	34.1
Cooke and Bernard, 2005[1]	19.5	18.6	25.4	12.1
Equal TLOC				
Bal et al., 2000a	9.5	7.5	9.5	1.5
Schwab et al., 2002	19.0	32.7	19.0	25.9
Johnson et al., 2002a, trial 1	6.4	5.3	6.4	1.7
Johnson et al., 2002a, trial 1	6.4	5.9	6.4	2.4
Johnson et al., 2002a, trial 1	6.4	3.7	6.4	2.8
Johnson et al., 2002a, trial 2	12.7	33.5	12.7	27.1
Johnson et al., 2002a, trial 2	12.7	28.6	12.7	29.8
Johnson et al., 2002a, trial 2	12.7	27.7	12.7	31.5
Johnson et al., 2002a, trial 2	12.7	44.8	12.7	34.9
Johnson et al., 2002a, trial 2	12.7	41.7	12.7	38.6
Johnson et al., 2002a, trial 2	12.7	51.1	12.7	54.3
Johnson et al., 2003, trial 1	11.1	13.2	11.1	9.8
Johnson et al., 2003, trial 1	27.8	19.3	27.8	17.5
Johnson et al., 2003, trial 1	39.7	38.1	39.7	21.6
Johnson et al., 2003, trial 2	27.8	16.5	27.8	13.0
Johnson et al., 2003, trial 2	39.7	19.1	39.7	15.2
Ebling and Kung, 2004	19.5	14.0	19.5	8.0
Cooke and Bernard, 2005[1]	19.5	18.6	19.5	6.4

[1]Only processed treatments set for 2 mm of roll gap settings were used, not 8 mm.

Theoretical Length of Cut

The forage component of lactating dairy cow diets is fed primarily to provide adequate peNDF. This is particularly desirable with increasing dietary concentrations of rapidly fermentable carbohydrates because peNDF is positively associated with chewing activity, ruminal pH, and milk fat content (Mertens, 1997). Under these circumstances, longer particle length would stimulate chewing and maintain short dietary fractions (i.e., concentrate feeds) entrapped in the rumen mat (Allen et al., 2003). Thus, reduction in particle size with the use of processing rolls (Table 2) suggests a need for longer TLOC when cows are fed processed WPCS. Bal et al. (2000a) compared unprocessed WPCS harvested at 9.5-mm TLOC with processed WPCS harvested at 9.5-, 14.5-, or 19.0-mm TLOC. The authors evaluated ascension time, the time necessary for a weight to ascend from the bottom of the rumen to the surface, as an indicator of ruminal mat consistency, and reported longer ascension times for unprocessed or 19.0-mm processed WPCS than for the other treatments.

Regardless of the benefits of achieving greater peNDF with forage particles of greater length, it may limit intake through reduced ruminal passage rate and increased fill (Mertens, 1987). Inconsistent effects of TLOC on nutrient digestibility and lactation performance by dairy cows were reported by Allen et al. (2003). Likewise, minimal effects of TLOC settings on lactation performance were observed by Ferraretto and Shaver (2012b). Despite the aforementioned interaction between TLOC and kernel processing on kernel damage and corresponding TTSD, no effect of TLOC on TTSD was observed in the meta-analysis report of Ferraretto and Shaver (2012b). These data underscore that the combined effect of TLOC and kernel processing is more important than TLOC alone with regard to TTSD. Digestibility of NDF was not altered by TLOC (Ferraretto and Shaver, 2012b). Greater ruminal pH and retention time is often reported for long particles (Allen, 1997), which could enhance NDF digestibility. In contrast, increased surface area for bacterial attachment when WPCS comprises short particles may also increase NDF digestibility despite its faster passage rate (Johnson et al., 1999). Perhaps the combination of these opposing factors for short and long forage particles may explain the lack of TLOC effects.

When feeding WPCS harvested at longer TLOC settings, it is important to monitor for selective consumption of particles because greater peNDF was previously reported to increase TMR sorting (Leonardi and Armentano, 2003) by dairy cattle. Kononoff et al. (2003b) reported that sorting behavior increased for dairy cows fed unprocessed WPCS harvested at 22.3 mm compared with a TLOC of 4.8 mm. However, this effect may be attenuated by adequate processing of WPCS and its effect on cob particle size (Shinners et al., 2000).

Maturity at Harvest

Maturity at harvest alters yield, nutrient composition, digestibility, and ensiling potential of crops (Buxton and O'Kiely, 2003). As the corn crop maturity progresses, most changes are associated with the extent of kernel development, which alters the proportion of DM contributed by its various fractions—typically, increased proportion of kernels and reduced proportions of stover (stalk, leaves, and husk; Buxton and O'Kiely, 2003). During maturation of the corn plant, sugars in kernels are converted to starch, and the DM content of kernels increases (Allen et al., 2003). Several reviews emphasize an increased concentration of starch and corresponding decline in CP, NDF, and ash concentrations with delayed WPCS harvest (Johnson et al., 1999; Allen et al., 2003; Buxton and O'Kiely, 2003). Thus, delayed maturity at harvest has been suggested as a management tool to increase DM and starch yields per hectare (Owens, 2014). Despite the effects on nutrient concentrations, delayed WPCS maturity at harvest impairs nutrient digestibility (Johnson et al., 1999; Allen et al., 2003; Ferraretto and Shaver, 2012b). As with other forage crops, cell wall digestibility of corn plants is diminished by advanced maturity (Johnson et al., 1999; Bal et al., 2000b; Buxton and O'Kiely, 2003). This is related to greater stover lignification during maturation of the corn plant (Table 3; Hunt et al., 1989; Cone and Engels, 1993). Therefore, targeting delayed maturity at harvest for greater concentrations of starch may come at the expense of stover digestibility (Allen et al., 2003). Surprisingly, however, Ferraretto and Shaver (2012b) reported greater NDF digestibility when WPCS was harvested above 40% DM in a meta-analysis of feeding trials. According to the authors, this could be related to less negative effects of greater ruminal starch digestibility on NDF digestibility for drier, more mature WPCS (Russell and Wilson, 1996). In contrast, Owens (2014) suggested that these results are related to the less obvious adverse effects of delayed harvest on fiber digestibility with modern hybrids. But the decline of ruminal in situ and in vitro NDF digestibility in mature corn stover continues to be reported (Figure 2; Lewis et al., 2004; Row et al., 2016) and further research is warranted. Along with negative effects on the stover fraction, delayed maturity at harvest also impairs the utilization of the kernel fraction. Reduced TTSD was observed in diets containing WPCS with >40% DM in the meta-analysis of Ferraretto and Shaver (2012b). This is likely related to an increase in the proportion of vitreous endosperm in the kernel associated with greater maturity (Figure 3). Increased proportion of vitreous endosperm in corn kernels is related to kernel hardness (Correa et al., 2002) and correspondingly may limit the percentage of fractured kernels during WPCS processing, as previously discussed. Furthermore, even the exposed endosperm is not fully digested due to existence of a starch-protein matrix formed in the chemical bonding of zein protein with starch granules (Kotarski et al., 1992). Lower ruminal in vitro starch digestibility reported by Ngonyamo-Majee et al. (2009) when corn kernels were harvested at intervals between one-half of milk line and black layer was related to increased proportion of vitreous endosperm in corn kernels with advanced maturity.

Table 3. Chemical composition of the stover fraction of whole-plant corn harvested at varied maturities[1]

Item	Stage of maturity[2]		
	1/3 ML	2/3 ML	BL
DM (% as fed)	25.9[c]	29.0[b]	33.1[a]
NDF (% of DM)	56.0[c]	60.8[b]	64.2[a]
ADF (% of DM)	35.0[c]	38.7[b]	41.3[a]
Hemicellulose (% of DM)	21.0[c]	22.2[b]	22.9[a]
Cellulose (% of DM)	28.2[c]	31.0[b]	33.4[a]
Lignin (% of DM)	3.48[c]	4.14[b]	4.63[a]
isDMD[3] (% of DM)	51.2[a]	47.1[b]	45.9[c]

[a–c]Means in the same row with different superscripts differ ($P \leq 0.05$).

[1]Adapted from Hunt et al. (1989) with permission.

[2]1/3 ML = one-third of kernel milk line, 2/3 ML = two-thirds of kernel milk line, and BL = black layer stage.

[3]Ruminal in situ DM digestibility (isDMD) at 24 h.

Overall, literature reviews have been consistent with regard to the effects of WPCS maturity at harvest on lactation performance by dairy cows. Johnson et al. (1999) described the relationship between WPCS maturity and nutritive value by estimating NE_L content with data from published feeding trials. The authors revealed that peak milk production was achieved when WPCS was harvested at approximately 35% DM or between one-half and two-thirds kernel milk line. Later, Allen et al. (2003) suggested the optimum harvest point for WPCS to be in the range of 32 to 35% DM, but noted that more research trials were warranted, particularly on the interactions among maturity at harvest, hybrid types, and diet formulation strategies. Recently, a meta-analysis of published trials (Ferraretto and Shaver, 2012b) reported a decline in actual and fat-corrected milk yields (2.0 and 2.7 kg/cow per day, on average, respectively), when WPCS was harvested

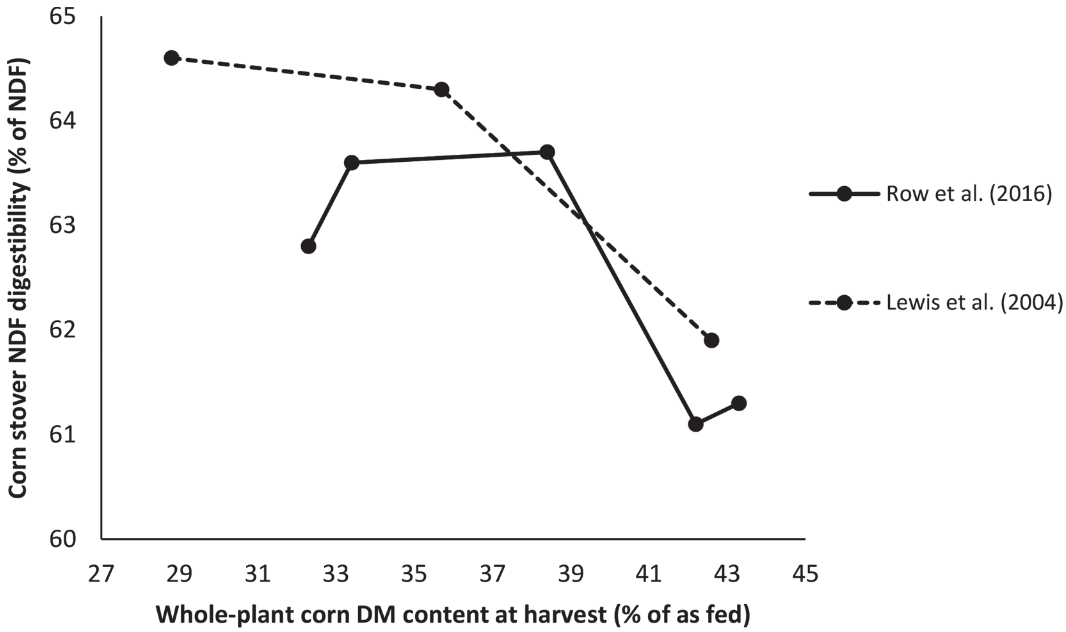

Figure 2. Relationship between whole-plant corn silage maturity at harvest (expressed as DM content) and ruminal in situ (at 28 h; adapted from Row et al., 2016) or in vitro (at 48 h; adapted from Lewis et al., 2004) NDF digestibility of corn stover.

above 40% DM. Therefore, targeting 35% DM at harvest is recommended for optimizing nutritive value of WPCS and lactation performance by dairy cows.

RECENT TECHNOLOGICAL ADVANCEMENTS FOR CORN SILAGE HARVEST

Yield Monitoring Sensors and On-Board Near-Infrared Spectrometers

Site-specific management of crops is of great interest to farmers. Focusing management on areas within a field rather than the entire field allows farmers to reduce inputs to production, focus those inputs on areas where they will be most utilized, and reduce environmental impact due to over-application. Data that provides feedback to a site-specific management of crops is spatial yield data collected at the time of harvest. A global navigation satellite system (**GNSS**) provides real-time location data to the SPFH, and sensors on the machine provide the yield data during harvest. Measurement of mass-flow on a forage harvester has been the subject of several research studies. Martel and Savoie (2000) investigated 2 sensors, an impact plate and feed-roll displacement, to measure mass-flow rate when harvesting corn with a pull-type forage harvester. Findings indicated the impact plate and feed-roll displacement sensor were both well correlated with mass-flow rate through the harvester in whole-plant corn. Ehlert (2002) studied the compression characteristics of multiple crops and crop conditions when passed between the feed-rolls on a forage harvester. Results produced an algorithm that utilizes crop type, pressure, DM content, and layer thickness to increase the accuracy of feed-roll displacement–based forage yield monitors. Yield monitoring sensors on current forage harvesting machines are based on feed-roll displacement and machine movement speed. These data in conjunction with the GNSS data provide a spatial representation of DM yield variation within a corn field. Future advancements in WPCS yield measurement and foreign object detection could be made with a range of sensing technologies. Recently, X-ray technology was implemented and proven effective at measuring DM yield and foreign object detection; however, safety concerns are a limiting factor (Wild et al., 2015).

Measurement of harvested crop quality parameters on board the forage harvester in real time provides information to the farmer or custom harvester that allows for maintenance of WPCS quality. Welle et al. (2003) implemented a diode array near-infrared spectrometer (**NIRS**), installed on a forage harvester, to determine DM, starch, soluble sugars, and in vitro digestibility of cellulose. Dry matter content of the harvested WPCS was well correlated with the output of the NIRS, and other parameters could be accurately assessed with calibration of the spectrometer. Digman and Shinners (2008) installed a diode array NIRS on a self-propelled forage harvester to assess the moisture content of harvested WPCS and alfalfa. Laboratory and in-field tests

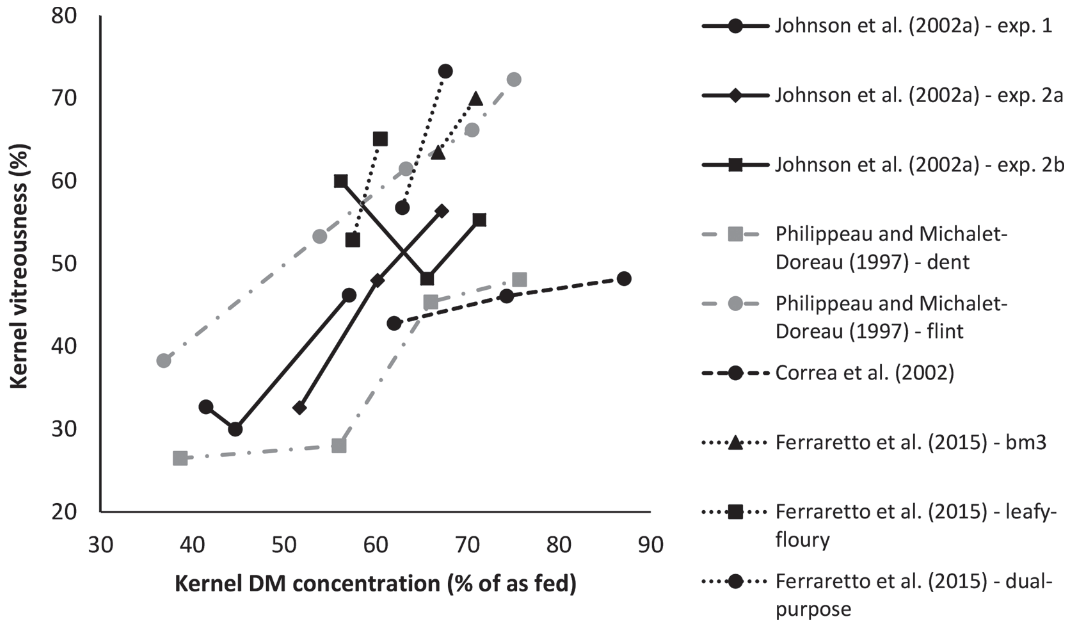

Figure 3. Relationship between DM concentration and vitreousness in corn kernels. Adapted from Philippeau and Michalet-Doreau (1997), Correa et al. (2002), Johnson et al. (2002a), and Ferraretto et al. (2015a).

showed the capability to predict moisture content of the harvested crops, but moisture content at different harvest locations (e.g., Wisconsin versus Arizona) were not well predicted, indicating the need for local calibration of the NIRS sensor. Crop quality sensors can also be paired with GNSS data to provide a spatial representation of variations in crop quality over the harvested field. Utilizing NIRS technology to measure crop moisture has also advanced the capabilities of machine control. Forage harvesters use the moisture information provided by the NIRS sensor to adjust the TLOC in real-time during harvest. Drier or more mature corn at harvest requires a shorter TLOC to provide better packing and storage characteristics in bunker silos (Allen et al., 2003; Shinners, 2003; Deere and Co., 2010).

Cutting Height

Harvesting WPCS at different cutting heights influences its nutritive value. Lewis et al. (2004) studied differing hybrids, maturities, and cutting heights of WPCS and assessed the yield and quality of the silage produced. Decreased DM yields due to increased cutting heights from 15 to 46 cm were offset by an increase in milk yield at the higher cutting height. Recommendations from this study were to increase cutting height on leafy hybrids of corn for corn silage quality improvement, but brown midrib (**BMR**) hybrids showed no benefit to increased cutting heights. Neylon and Kung (2003) increased cutting height from 12.7 to 45.7 cm in leafy WPCS hybrids to assess effects on yield and nutritive value. Dry matter yield was decreased at the greater cutting height, but milk yield per ton of DM calculated from measured nutrient parameters was greater for the high-cut WPCS harvested at 34% DM. In contrast, lactation performance of mid-lactation cows was not improved when cutting height was increased from 10.2 to 30.5 cm in the study by Bernard et al. (2004). The authors suggested that issues related to typical environmental conditions of the southeastern United States might inhibit the potential benefits observed in other areas. Wu and Roth (2003) reviewed 11 studies that evaluated WPCS cutting height. The cutting heights in these studies ranged from 17.2 ± 6.4 to 49.0 ± 7.1 cm. Dry matter yield decreases were usually offset by increased silage quality at the high cutting height. A similar summary of recent studies is in Table 4. Also, increased quantities of high-cut WPCS forage could be included in the TMR, rather than corn grain being added to the diet, providing an economic benefit to implementing increased cutting heights.

From a machinery operation perspective, altering the harvest parameters from conventional WPCS to increased cutting height, earlage or snaplage with an ear-snapping header, or the new toplage will reduce the total amount of material passing through the machine at similar cutting widths and speeds. Operators will be able to maintain the ton per hour of DM harvested by the machine by increasing ground speed. Increased ground speed during harvest will have a positive effect

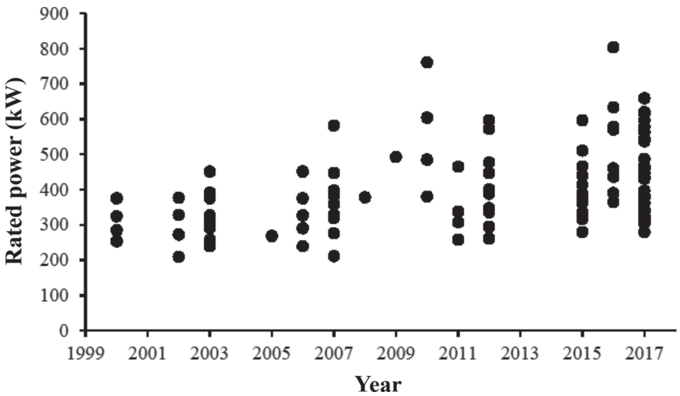

Figure 4. Rated engine power (kW) versus terminal year of manufacture of self-propelled forage harvesters from 2000 to 2017. All models produced by 4 major self-propelled forage harvester companies are included in this data (IRON Solutions Inc., 2017).

on harvest efficiency (i.e., time required to harvest) while maintaining feed quality. The SPFH rated engine power has increased over recent years (IRON Solutions Inc., 2017). Increasing demands for harvest efficiency gains from increased operating speeds, increased header widths, and increased throughput capacity has driven this trend. Figure 4 shows the rated power of all models of SPFH from 4 major manufacturers versus the terminal year of manufacture of each model. The general trend of rated engine power for SPFH is increasing, with large gains in maximum power of the largest machines over the past 17 years, the largest of which was rated greater than 800 kW.

Snaplage

Harvesting corn snaplage is a viable alternative to rolled high-moisture shelled corn (**RHMC**). Snaplage generally contains the ear (cob and grain), husk, and shank and is harvested using a SPFH equipped with a snapper head and an on-board kernel processor. This allows for an earlier corn harvest, which proceeds more rapidly, with kernel processing done in the harvester rather than at the silo as done with RHMC. However, snaplage has different nutritional qualities and harvest management considerations than RHMC. Considerations include moisture content, forage harvester set-up, storage capacity, and potential impacts of starch digestibility on milk production.

A feeding trial compared the effects of feeding snaplage to RHMC in diets for lactating dairy cows (Akins and Shaver, 2014). Snaplage and RHMC were harvested from the same field with the same hybrid on 2 dates to achieve desired moisture levels (kernel moisture targeted at 28–30% for RHMC and product moisture at 32–35% for snaplage) and stored in 3-m-diameter silo bags. Moisture concentrations at feed-out were 21.8% for RHMC and 31.5% for snaplage. Both were drier than targeted due to fast dry down and a brief delay of the custom operator for snaplage harvest.

Sixty Holstein cows at approximately 100 DIM were used. Cows were fed 1 of 3 diets with either (1) RHMC at 21.5% of DM, (2) snaplage at 29% of diet DM (**SNAP**), or (3) snaplage at 20% of diet DM plus dry ground shelled corn at 9% of diet DM (**SPDC**). All diets included corn silage at 22% of DM and alfalfa silage at 33% of DM. The RHMC diet included soyhulls at 9% of DM to have similar NDF content to SNAP and SPDC. Cows were fed diets in 30 electronic gate feeders to measure individual intakes. Cows were fed a 50:50 mix of RHMC and SNAP for a 2-wk adjustment period followed by an 8-wk treatment period when cows were fed their treatment diets.

Greater DMI for cows fed RHMC (27.1 kg/d) than for SNAP (24.9 kg/d) and SPDC (24.2 kg/d) was likely due to greater starch digestibility for the snaplage. Milk yields were similar, averaging 39.4 kg/d. Component-corrected milk yields were also similar, resulting in higher feed efficiency (kg of milk/kg of DMI) for both SNAP (1.57) and SPDC (1.62) compared with RHMC (1.46). Reduced milk fat percentage, by 0.27 percentage units, for SNAP compared with RHMC was likely due to greater starch digestibility for SNAP. Partial replacement of snaplage with dry ground shelled corn alleviated the depression in milk fat percentage with SPDC being 0.12 percentage units higher than SNAP, but still 0.15 percentage units lower than RHMC.

The snaplage containing diets (SNAP and SPDC) contained 26 to 27% starch, whereas RHMC contained 24% starch (DM basis), which could also contribute to the reduced milk fat content. Milk fat yield, milk protein concentration, and milk protein yield were unaffected by the treatments. Results suggest that well-fermented snaplage may have a high starch digestibility, and diets may need a source of starch with lower

Table 4. Effect of cutting height (low or high) on whole-plant corn silage nutrient composition, digestibility, and yield[1]

Item	Low	High
Cutting height (cm)	16.9 ± 6.9	52.3 ± 14.7
NDF (% of DM)	40.1 ± 5.2	37.2 ± 6.5
Starch (% of DM)	31.5 ± 8.5	34.5 ± 10.0
ivNDFD[2] (% of NDF)	52.3 ± 7.4	55.4 ± 7.4
Yield[3] (Mg of DM/ha)	17.3 ± 5.4	15.3 ± 4.5
Milk (kg/Mg)	1,642 ± 337	1,707 ± 279
Milk (kg/ha)	23,926 ± 3,484	22,261 ± 4,151

[1]Summary of 7 studies: Neylon and Kung (2003), Bernard et al. (2004), Lewis et al. (2004), Kung et al. (2008), Aoki et al. (2013), Nigon et al. (2016), Ferraretto et al. (2017). Not all studies reported all parameters.

[2]Ruminal in vitro NDF digestibility.

digestibility such as dry corn to maintain normal milk fat concentrations.

Toplage

Nigon et al. (2016) modified a conventional ear-snapping corn header with cut-off knives in an effort to collect more of the upper stalk and leaf portion of the corn plant. The goal was to produce a silage product that fell between high-cut WPCS and snaplage (Seglar and Shaver, 2014) and was referred to as toplage. Yields of DM were 72 to 77% of the yield produced by WPCS harvest, but starch concentration was greater for toplage than for WPCS (43.0 vs. 33.9% of DM). Furthermore, this novel design has specific wheel space configurations that allow a second operation to collect the remaining stalks. Cook et al. (2016) suggested this fractionation of corn plants at harvest could be used as a tool in ration formulation; for example, by separating and feeding the less digestible fraction, the stalks, to animals of lower energetic demand (i.e., heifers, far-off dry cows). A comparison of yield and nutrient composition for WPCS, high-cut WPCS, snaplage, and toplage is in Table 5.

To our knowledge, experiments evaluating the effects of replacing WPCS or high-cut WPCS with toplage in dairy cattle diets are unavailable in the literature. However, a recent study by Cook et al. (2016) fractionated corn plants at harvest as toplage and stalklage and treated the lower plant fraction with calcium oxide to enhance fiber digestibility. The authors evaluated (1) the effects of alkali-treated stalklage in combination with toplage on lactation performance by dairy cows in relation to negative (conventional WPCS hybrid) and positive (BMR WPCS hybrid) controls; and (2) the effects of alkali-treating WPCS. Overall, alkali-treatment of WPCS and fractionated WPCS were successful at improving intake and milk production by dairy cows similarly to the well-established effects of BMR WPCS. These results are likely related to improved total-tract NDF digestibility for alkali-treated WPCS. Further research is warranted to evaluate the prospective benefits of fractionated WPCS in ration formulation.

Shredding Rollers

Crop processing is now an integral part of corn silage production. Particle size reduction of the kernel fraction of the corn plant has been shown to improve feeding and storage characteristics along with milk production (Shinners et al., 2000; Johnson et al., 2002a,b; Cooke and Bernard, 2005; Shinners and Holmes, 2013). Zhang et al. (2003) developed a shredding and flail chopping forage harvester. This study showed that large plant particles could be maintained while the kernel fraction particle size was reduced due to the speed differential of the shredding rolls. Current trends in crop processing include maximizing the size reduction of the kernel fraction by (1) minimizing the gap between conventional processing rolls (1 mm), and (2) manufacturers providing the capability to increase the roll speed differential from the typical 20% difference to 40 to 50% speed differential to maximize the shearing action of the crop processor.

Corn Shredlage

A new method of harvesting WPCS, termed corn shredlage (**SHRD**), has received much interest by dairy producers and nutritionists. The SHRD was harvested with a commercially available SPFH fitted with after-market cross-grooved crop-processing rolls set for 2 to 3 mm of roll gap and approximately 20% greater roll speed differential than had typically been used previously. Moreover, the developer of this processor recommended that the SPFH be set for a longer (26–30 mm) TLOC than had typically been used previously (19 mm). Thus, compared with conventional-processed

Table 5. Dry matter yield and nutrient composition of whole-plant corn harvested with various methods[1]

Item	Whole-plant corn silage	High-cut corn silage	Snaplage	Toplage
Cutting height (cm)	25.0	100.0	130.0	115.0
DM (% of as fed)	37.7[c]	40.6[b]	55.3[a]	42.2[b]
CP (% of DM)	8.2[b]	8.9[a]	8.8[a]	8.9[a]
NDF (% of DM)	40.3[a]	34.5[b]	19.5[c]	32.1[b]
Lignin (% of DM)	4.0[a]	3.4[b]	2.2[d]	3.1[c]
Starch (% of DM)	33.9[d]	38.8[c]	58.6[a]	43.0[b]
Ash (% of DM)	3.7[a]	3.4[ab]	1.7[c]	3.1[b]
Yield[2] (Mg of DM/ha)	23.0[a]	20.5[b]	12.5[d]	17.6[c]

[a–d]Means in the same row with different superscripts differ ($P \leq 0.05$).

[1]Adapted from Nigon et al. (2016) with permission.

[2]Yield calculations did not account for extra biomass from stalklage following snaplage or toplage harvesting.

Table 6. Effects of shredlage processor on whole-plant corn silage particle size, corn silage processing score (means ± SD), and ruminal in situ digestibility

Item	Ferraretto and Shaver, 2012a		Vanderwerff et al., 2015	
	Conventional	Shredlage	Conventional	Shredlage
Corn silage processing score[1]				
Starch passing 4,750-μm sieve (%)	60.3 ± 1.9	75.0 ± 1.9	67.6 ± 6.5	72.4 ± 3.6
Particle size[2] (% of as-fed retained)				
19.0 mm	5.6 ± 2.0	31.5 ± 5.7	7.1 ± 2.8	18.3 ± 6.4
8.0 mm	75.6 ± 2.6	41.5 ± 3.9	68.1 ± 3.5	54.5 ± 4.4
1.18 mm	18.4 ± 1.6	26.2 ± 2.0	22.3 ± 3.5	24.8 ± 3.2
Ruminal in situ digestibility[3]				
Starch	64.2[b]	80.8[a]	76.0[b]	88.3[a]

[a,b]Means within trials with different superscripts differ ($P \leq 0.05$).

[1]Processing score was measured as described by Ferreira and Mertens (2005).

[2]Particle size was measured using the Penn State Particle Separator as described by Kononoff et al. (2003a).

[3]Ruminal in situ starch digestibility (%) measured at 12 h on undried and unground samples.

WPCS (**CPCS**), the most obvious visual difference for SHRD was the greater proportion of long stover particles in SHRD (Table 6). When fed in rations for lactating dairy cows, this can increase the peNDF content of the ration, which is important for proper rumen function, cow health, and milk fat content (Mertens, 1997). As noted previously, however, longer TLOC may impair kernel breakage even when SPFH are fitted with processing rolls (Ferraretto and Shaver, 2012b). Nevertheless, this new method allowed WPCS to be harvested at a longer TLOC while maintaining or improving the degree of kernel processing (Table 6).

The initial feeding trial conducted with SHRD (Ferraretto and Shaver, 2012a) used a SPFH equipped with the new shredlage processing rolls set for a 30-mm TLOC by removing half of the knives and the processor roll gap set at 2.5 mm. Harvest of the CPCS was done using a SPFH set for a 19-mm TLOC and equipped with conventional processing rolls set at 3-mm roll gap. Removing knives when harvesting WPCS can add stress and wear to the SPFH kernel processor due to large cob pieces. Therefore, in practice, a 22- to 26-mm TLOC setting is most common for SHRD so that knife removal is not required. In a follow-up feeding trial, harvest of SHRD was done with the SHRD processor set at a 2-mm roll gap and 32% roll speed differential with the SPFH set for a 26-mm TLOC (Vanderwerff et al., 2015). The conventional processor was set for a 2-mm roll gap and 40% roll speed differential with the SPFH set at a 19-mm TLOC for harvest of the CPCS.

Despite the greater amount of coarse particles for SHRD than CPCS, measurements of weigh-backs during both trials indicated minimal sorting and no differences in sorting among treatments. Greater lactation performance was observed for SHRD compared with CPCS either when using a conventional (1.0 kg/d per cow greater 3.5% FCM; Ferraretto and Shaver, 2012a) or a BMR (1.5 kg/d per cow greater milk yield; Vanderwerff et al., 2015) corn hybrid. Furthermore, SHRD increased ruminal in situ starch digestibility (Table 6) and TTSD in both trials. This response was likely related to greater kernel breakage during passage through rolls and the corresponding increased surface area allowing for enhanced bacterial attachment and digestion. These results suggest that feeding SHRD offers dairy producers and their nutritionists an opportunity to feed WPCS containing a greater proportion of coarse particles without compromising kernel breakage, energy availability, and sorting behavior. There is no evidence, however, that the use of SHRD processor attenuates or overcomes the negative effects of maturity on starch digestibility, and further research is warranted. Despite the greater TLOC, improved milk fat content and rumination activity were not observed in feeding trials. Further research is warranted to evaluate ruminal fermentation patterns and in vivo digestion kinetics to better understand the effect of adding SHRD in diets for high-producing dairy cows. In addition, more data are needed regarding NDF digestibility for SHRD and the relative peNDF for SHRD compared with hay-crop silage, whole cottonseed, and chopped hay or straw, to allow for better decisions on the optimum scenarios to utilize SHRD in dairy cattle diets.

Optimal kernel processing can be achieved regardless of the type of chopper or processor used. Thus, benefits of using shredlage processors may not be as pronounced in the field as in the reviewed feeding trials. Other factors, such as proper processor maintenance from wear, frequent quality control monitoring of kernel breakage during harvest, and adequate TLOC and roll-gap settings for the chopper and processor used are also crucial for obtaining optimal kernel processing. Furthermore, some SPFH were adapted to allow for greater roll-speed differential, and new intermeshing disc rolls were released after these feeding trials were concluded. To our knowledge, trial reports evaluating these new developments are unavailable and future research is warranted.

PROCEDURES TO EVALUATE PHYSICAL CHARACTERISTICS OF SILAGE

Assessment of whole-plant corn physical properties during harvest provides farmers, nutritionists, and custom harvesters the ability to check the forage harvester settings to ensure high silage quality is achieved and consistency is maintained. Furthermore, assessment of these properties in WPCS at feed-out is critical to implementing an optimal TMR when fed to lactating dairy cows.

Kernel Fraction

As mentioned, the efficacy of kernel processing in WPCS is variable and can be influenced by several factors; thus, methods to evaluate the adequacy of kernel processing in WPCS are critical. Visual evaluation of kernel breakage at harvest is drastically improved by the absence of the stover fraction. Savoie et al. (2004) developed a method for partial separation of the kernel from the stover fraction in chopped and processed WPCS. Hydrodynamic separation involves mixing WPCS in water to allow the less buoyant kernel particles to sink, while the more buoyant plant particles float. This method was effective at separating grain from stover in fresh WPCS, but drying the WPCS samples before water separation yielded a more complete separation. A guide for on-farm implementation of this hydrodynamic separation method was developed by Shinners and Holmes (2013) and its adoption by dairy farmers, nutritionists, and custom harvesters is advised. Furthermore, recent research has shown image analysis can be effectively used to quantify the particle size distribution of particulate materials (Mora et al., 1998; Fernlund et al., 2007; Igathinathane and Leslie, 2007; Igathinathane et al., 2008a,b, 2009). Therefore, utilizing image analysis techniques for determination of particle size distribution of the kernel portion of WPCS in-field during harvest could provide information about the performance of the crop-processing rolls. An image-processing algorithm has been developed to assess the particle size distribution of kernels contained within chopped and processed WPCS (kernel fraction index determination via image analysis techniques; B. D. Luck, unpublished data, 2017). Results from initial development tests show the algorithm is capable of distinguishing different mean particle sizes from samples collected at different kernel processor settings (2-, 3-, 4-, and 5-mm processor gap clearance; Table 7).

Table 7. Image analysis based mean particle size (MPS) determination of chopped, processed, and dried corn kernels and multiple processor roll gap settings[1]

Crop processor gap setting (mm)	MPS from image analysis algorithm (mm)	SE of the estimate (mm)
2	0.8[a]	0.06
3	1.3[b]	0.06
4	2.2[c]	0.06
5	2.4[d]	0.06

[a–d]Means with different superscripts differ ($P \leq 0.0001$).

[1]ANOVA performed with mixed models in SAS 9.4 (SAS Institute Inc., Cary, NC) and means separated by Fisher's LSD (Saxton, 1998).

Implementing this method in a usable format, such as a smartphone application, would provide the capability of crop processor performance assessment in-field without the need for sieve analysis. By using these real-time techniques, any errors in the crop processing roll adjustment could be corrected during harvest to maintain feed quality and harvest efficiency.

Ferreira and Mertens (2005) defined a corn silage fragmentation index (corn silage processing score; **CSPS**) that provides producers and nutritionists a metric for determining the effectiveness of crop processing rolls during harvest. This methodology is widely used in the dairy industry and utilizes sieves to separate the corn kernels from the plant material in a vertical shaker. Fragmented corn kernels passing through a sieve with square apertures of 4.75 mm are analyzed for starch; thus, the CSPS is expressed as a percentage of starch passing through the 4.75-mm sieve. Ferreira and Mertens (2005) suggested that CSPS represents the proportion of kernels that are broken into at least one-fourth of a kernel. Guidelines commonly used for CSPS suggest a sample with greater than 70% being optimal processing, 50 to 69% being sufficient processing, and below 50% being suboptimal processing (Shinners and Holmes, 2013). However, across 2 experiments, ensiling was reported to increase CSPS (% of starch passing through a 4.75-mm sieve) by 7 to 10 percentage units in WPCS ensiled in vacuum-sealed plastic bags for at least 30 d and up to 240 d (Ferraretto et al., 2015b). These data suggest that CSPS determinations performed on fermented samples obtained from silos before feeding may be more accurate than those performed on samples obtained before ensiling. Additional evaluation of this issue is warranted. The use of a single sieve to determine degree of kernel processing leads to the assumption that all particles passing through this sieve are equal. Nevertheless, it is well established that kernel particles of varied sizes have different starch digestibility (Dias Junior et al., 2016). Consequently, the utilization of a single sieve to determine kernel breakage and its potential digestibility in WPCS may be too inaccurate for use in ruminant nutrition models to estimate the nutritive value of WPCS. Dias Junior et al. (2016) proposed a novel laboratory procedure to measure kernel fragmentation based on the hydrodynamic separation method of Savoie et al. (2004) in combination with dry-sieving and geometric mean particle size calculation (ASABE, 2007).

Stover Fraction

Manipulation of TLOC at harvest is a common practice in an attempt to improve peNDF of WPCS. Particle size distribution of chopped and processed WPCS is traditionally determined by passing the subject through progressively smaller sieves (ASABE, 2012). The mass of the WPCS remaining on the individual sieves is used to determine the mean particle length (**MPL**) of the sample. But the stover fraction is also crushed and MPL reduced when forage harvesters are equipped with processing rolls (Table 2; Johnson et al., 2003), particularly under tighter roll-gap settings (Shinners et al., 2000). Variation in MPL may also be influenced by knife sharpness and knife to shear bar clearance (Shinners, 2003), ratio of kernel to stover (Mertens, 2005), and maturity at harvest (Shinners et al., 2000; Johnson et al., 2002a). Salvati et al. (2015) performed a survey of WPCS harvesting practices and compared the relationship between verbal (i.e., reported but not measured) TLOC and MPL of WPCS samples. Not surprisingly, no relationship between verbal TLOC and MPL of WPCS samples from varied harvest conditions was reported. The same authors also attempted to evaluate MPL after removal of the kernel fraction through an adaptation of the hydrodynamic separation method of Savoie et al. (2004), but no relationship with verbal TLOC was observed either. Therefore, MPL assessment at harvest is crucial to achieve desired levels of peNDF.

Due to its ease of use on-farm, the Penn State Forage and TMR Particle Separator (**PSPS**; Lammers et al., 1996) is the most frequently used particle separation technique in the dairy industry. Kononoff et al. (2003a) modified this method and assessed the effect of moisture content of the TMR when analyzed. An additional sieve was added to the device with an aperture size of 1.18 mm along with the existing 19.0- and 8.0-mm sieves. Results showed that a shaking frequency of 1.1 Hz or greater and a 17-cm stroke length provides sufficient force and frequency for separation. Moisture content of the samples had little effect on particle size distribution results except when the moisture content of the sample was almost completely dry. Recently, the 1.18-mm sieve was replaced with a 4-mm sieve (Heinrichs, 2013). Heinrichs (2013) suggested this novel sieve retains small forage particles with potential high fiber concentration and is representative of particles typically entrapped in the ruminal mat but could be easily digested. Because the PSPS requires manual manipulation of sieves, some could argue it may induce human error (Maulfair and Heinrichs, 2012). Alternatively, the standard method accepted by agricultural engineers for determination of MPL of chopped forages is the Wisconsin Oscillating Particle Separator (WI-OS; S424.1, ASABE, 2007). This particle separator is mechanically operated, has a larger number of sieves (26.9-, 18-, 8.98-, 5.61-, and 1.65-mm diagonal apertures), and has screens with greater surface area. Although this method may limit human error, it requires a heavy (>225 kg) and large (102 × 64 × 145 cm, length × width × height) piece of equipment, which precludes its use on-farm (Maulfair and Heinrichs, 2012). A strong relationship (R^2 = 0.62) between the PSPS and the WI-OS procedures to determine MPL in WPCS was observed by Salvati et al. (2015), suggesting that MPL can be measured adequately on-farm with the PSPS.

Savoie et al. (2014) measured particle size and other parameters of chopped forages. Results indicated that traditional sieving analysis underestimated particle length by 31% compared with image analysis. Furthermore, the authors combined image analysis with precision weighing to estimate thickness and particle outer surface area. Incorporation of outer surface area measurements in chopped forage may enhance the understanding of fiber digestibility and "effectiveness" in dairy cattle diets and further research is warranted. In addition, further application of this technology for real-time assessment could eliminate sieving analysis and enhance the process of silage harvesting.

CONCLUSIONS

Whole-plant corn silage has been shown to be an effective feed for dairy cattle. Research conducted over the past several years has focused on manipulation of the physical and chemical characteristics of WPCS in an effort to improve its nutritive value and maximize milk production. Maturity at harvest remains an important factor in silage production, because negative effects of late maturity on nutrient digestibility are not offset by modern hybrids. Adjustments to harvest practices, such as increasing the cutting height, have been shown to improve feeding value of the WPCS. Reductions in yield were offset by increases in feeding value. Perhaps the use of increased cutting height in years of greater yields or in combination with greater plant population may exacerbate these benefits and future research is warranted. It is well established that processing the WPCS during harvest with counter-rotating rolls reduces the particle size of the kernel fraction contained within. Breaking the corn kernels increases digestibility and available starch, which in turn improve milk production and feed efficiency by dairy cows. Multiple types of processing rolls exist, and roll surface geometry and machine settings change the physical characteristics of the WPCS. Future research should focus on evaluating the effects of new processors available in the market and their settings on WPCS physical characteristics and lactation performance by dairy cows. Although longer TLOC of the plant portion of the WPCS provides benefit to rumen health in dairy cows, benefits on lactation performance are minimal. Future technological advancements in characterizing the physical properties of WPCS at harvest will provide dairy farmers and custom harvesters the ability to maintain feed quality throughout the harvest process. In addition, improvements of current laboratory methods may enhance modeling of starch digestibility and peNDF in WPCS and further research is warranted.

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