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Survey of mean particle length in whole-plant corn silage

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ABSTRACT

Theoretical length of cut (TLOC) settings on forage harvesters vary as dairy farmers attempt to increase the mean particle length (MPL) of whole-plant corn silage (WPCS). Our objective was to evaluate the MPL of WPCS using 2 methods of determination in whole-plant and stover-fraction samples. Eighty WPCS survey samples were collected and represented varied TLOC settings and processor types and settings. Particle size distributions for determining MPL were measured using either the Penn State Particle Size Separator (PSPS) or the Wisconsin Oscillating Particle Separator (WIOS). The MPL of WPCS samples determined by PSPS and WIOS, respectively, were 12.0 versus 11.8 mm and for the stover-fraction samples were 11.8 versus 8.1 mm. The TLOC, indicated verbally by surveyed dairy farmers or their custom operator, was unrelated to MPL regardless of particle-separation method ($P > 0.10$) for both whole-plant and stover-fraction samples. However, MPL measured by PSPS and WIOS were positively related in both as-fed whole-plant ($R^2 = 0.62$, $P = 0.001$) and dried stover-fraction samples ($R^2 = 0.60$, $P = 0.001$). The elimination of kernels through hydrodynamic separation did not improve the relationship between verbal TLOC and MPL. A relationship between MPL of as-fed whole-sample and MPL of the stover fraction was observed (PSPS, $P = 0.001$; WIOS, $P = 0.001$) but with poor R^2 values (PSPS, 0.25; WIOS, 0.18). The strong relationship between the 2 methods used to determine MPL in WPCS suggests that MPL may be measured adequately on farm by consultants using the PSPS.

Key words: corn silage, mean particle length, hydrodynamic separation

INTRODUCTION

Physically effective NDF, which is a combination of the physical and chemical characteristics of fiber, is positively associated with chewing activity, ruminal pH, and milk fat content in dairy cows (Mertens, 1997). Therefore, providing adequate physically effective NDF is necessary to maintain rumen and cow health, especially when highly fermentable diets are fed (Maulfair and Heinrichs, 2012; Zebeli et al., 2012). To harvest whole-plant corn silage (**WPCS**), greater theoretical length of cut (**TLOC**) settings (≥19 mm versus <10 mm) are used on forage harvesters that are equipped with kernel-processing rolls in an attempt to maintain or improve fiber effectiveness as the stover is also crushed by the rolls (Johnson et al., 2003). However, although TLOC is usually greater in kernel-processed WPCS with the aim of increasing mean particle length (**MPL)** to provide greater physically effective NDF, other factors can influence MPL in WPCS: kernel processing (Johnson et al., 1999; Mertens, 2005), processor roll-gap setting (Shinners et al., 2000), DM content (Shinners et al., 2000; Johnson et al., 2002), ratio of kernel to stover (Mertens, 2005), hybrid (Johnson et al., 2002), and knife sharpness and knife–to–shear bar clearance (Shinners, 2003). The TLOC is controlled by the peripheral speed of the feed rolls relative to the speed of the cutter head and the number of cutter head knives (Shinners, 2003), which also affects MPL.

The Penn State Particle Size Separator (**PSPS**) is the common forage or TMR particle separation technique used in the dairy industry primarily due to its ease of use on farm, but it requires manual manipulation of sieves that may induce human error (Maulfair and Heinrichs, 2012). Alternatively, the Wisconsin Oscillating Particle Separator (**WIOS**) is the standard method accepted by agricultural engineers for determination of the particle size distribution and MPL of chopped forages (S424.1; ASABE, 2007). Compared with PSPS, the WIOS is thought to have several advantages: it is mechanically operated, has a larger number of sieves, and has screens with greater surface area, which may limit human error (Maulfair and Heinrichs, 2012). However, the limited portability of the equipment due to the weight (>225 kg) and dimensions (102 × 64 × 145 cm, length × width × height) is a major disadvantage because it largely precludes use on farm (Maulfair and Heinrichs, 2012).

The study objectives were to (1) survey the MPL of WPCS samples from varied harvest conditions, (2) compare PSPS and WIOS methods of MPL determination, (3) evaluate hydrodynamic separation of WPCS kernel and

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stover fractions followed by determination of MPL in the stover fraction, and (4) evaluate the relationship of the TLOC indicated verbally by surveyed dairy farmers or their custom operator and the MPL of WPCS.

MATERIALS AND METHODS

Eighty WPCS samples from a field survey of commercial farms (Salvati et al., 2015) and 2 feeding trials (Ferraretto and Shaver, 2012; Vanderwerff et al., 2015) were collected and represented varied WPCS harvesting equipment, processor types, and TLOC and roll-gap settings. The TLOC and roll-gap settings, indicated verbally by surveyed dairy farmers or their custom operator, across samples ranged from 16 to 34 mm and 0.7 to 3.0 mm, respectively. Samples from Ferraretto and Shaver (2012; n = 2) and Vanderwerff et al. (2015; n = 2) were collected at the University of Wisconsin–Madison Arlington Blaine Dairy (Arlington, WI), whereas samples from Salvati et al. (2015; n = 76) were obtained from commercial dairy farms located in Illinois, Minnesota, and Wisconsin during farm visits.

Samples were collected from a pile that had been shaved from the exposed face of the horizontal silos (bunkers, piles, or bags) for feeding, frozen, stored at −20°C, and then thawed overnight before sample analysis. Each WPCS sample was placed in a bucket, homogenized manually, and divided into two 1-kg subsamples using a quartering technique; homogeneous samples were divided into 4 equal subsamples. Two subsamples allocated diagonally were rehomogenized and saved as 1 subsample, whereas the other 2 subsamples were rehomogenized and saved as the other subsample. On 1 of the subsamples, as-fed whole-plant samples were used for determination of particle size distribution and MPL using both PSPS and WIOS. The PSPS procedure was conducted manually using 3 sieves (19, 8, and 1.18 mm) and a pan according to the method of Kononoff et al. (2003). Samples measured with WIOS were sieved mechanically using 5 sieves (26.9, 18, 8.98, 5.61, and 1.65 mm) and a pan (ANSI, 2001). In addition, each sample was analyzed for corn silage processing score (**CSPS**; % of starch passing through a 4.75-mm sieve) in duplicate as described by Ferreira and Mertens (2005). This methodology is widely used in the dairy industry as the gold standard to estimate kernel breakage in WPCS and, thus, was used as an indicator of mechanical processing in the present study. The DM content was determined on WPCS samples by drying at 60°C for 48 h in a forced-air oven. Dried samples were ground to pass a 1-mm Wiley mill screen (Arthur H. Thomas, Swedesboro, NJ), and starch content was determined by near-infrared reflectance spectroscopy (**NIRS**; model 6500; Foss-NIR System, Silver Spring, MD). Each sample was packed into a cylindrical sample holder equipped with a quartz window (Part # 60013287; Foss-NIR System) and scanned, between 400 and 2,498 nm, as described by Mentink et al. (2006).

On the other subsample, kernel and stover fractions were separated by a hydrodynamic separation procedure (Savoie et al., 2004). This method is based on differences in buoyancy between the kernels and stover. Because all samples were fermented for at least 90 d, which is thought to make the separation process more difficult, all samples were dried in a forced-air oven set at 60°C for 48 h before immersion in water as recommended by Savoie et al. (2004). Each sample of approximately 400 g of DM was placed in a 10-L rectangular tub containing 7 L of water. Each dried sample was gently agitated manually for 2 min such that the entire sample was submerged in water. After 2 min, the stover fraction, which floats due to a lower density than water, was removed gently using a small 1.18-mm sieve (Savoie et al., 2004). After separation, the stover fraction was transferred to aluminum plates and redried at 60°C for 48 h in a forced-air oven. The dried stover-fraction samples were then used to determine MPL using the PSPS as previously described (Kononoff et al., 2003). Sequentially, stover samples were recombined and then sieved mechanically using the WIOS as previously described (ANSI, 2001). Stover samples were recombined once again and then ground to pass a 1-mm Wiley mill screen (Arthur H. Thomas), and CP, NDF, and starch concentrations were determined by NIRS as previously described. Prediction equations for determining nutrient composition were obtained from the NIRS Forage and Feed Test Consortium website (http://nirsconsortium.org/). These equations were calibrated for CP (methods 984.13, 988.05, and 990.03; AOAC International, 2012), amylase-treated NDF using α-amylase and sodium sulfite (method 2002.04; AOAC International, 2012), and starch (Bach Knudsen, 1997) using 754 (R^2 = 0.88), 1,193 (R^2 = 0.93) and 320 (R^2 = 0.97) fermented WPCS samples, respectively, from participating laboratories from across the United States and collected over more than 20 yr.

Regressions to determine linear and quadratic relationships between verbal TLOC, MPL, CSPS, and particle size distributions were performed using PROC REG of SAS (SAS Institute Inc., Cary, NC). Best-fit regression (linear or quadratic) was chosen using the highest coefficient of determination (R^2) and lowest root mean squared error as indicators. Although coefficient of determination is a reliable indicator of relationship, it does not evaluate the agreement among methods (Bland and Altman, 1986). Thus, Bland-Altman plots and Lin's concordance correlation coefficient (**CCC**) measurements were performed for regression analysis evaluating the relationship among methods but not for regression analysis determining mean particle size relationship to TLOC or CSPS. The Bland-Altman plot method determines the bias among methodologies by calculating the mean difference and the 95% CI (mean ± 1.96 SD) of the difference between 2 methods of measurement (Bland and Altman, 1986).The CCC is a common method of reproducibility and is calculated by multiplying the correlation coefficient by the bias correction (Lin, 1989). This coefficient may vary from 0 to 1, where 1 indicates perfect fit. Sixteen samples from the field survey did not have information on TLOC and roll-gap settings; thus, only 64 samples were used to evaluate the relationship between verbal TLOC and other parameters. All 80 samples were used in the other regression analyses. Statistical significance and trends were declared at $P \leq 0.05$ and $P > 0.05$ to $P \leq 0.10$, respectively.

RESULTS AND DISCUSSION

WPCS

The MPL of WPCS samples (Table 1) ranged from 10.0 to 15.4 mm and 8.6 to 14.8 mm for PSPS and WIOS, respectively. Extensive variation in MPL measurements is likely related to the verbal TLOC and roll-gap settings, which ranged from 16 to 34 mm and 0.7 to 3.0 mm, respectively. Average MPL for WPCS samples, independent of determination method, was 11.9 mm. The CSPS of WPCS samples averaged 66.2% and ranged from 49.5 to 82.6% (data not shown). Dry matter and starch contents of WPCS are in Table 1. As expected, based on the diversity of the sample set, all measured parameters varied greatly, likely in relationship to wide ranging environmental factors and harvest practices encountered across farms. The WPCS DM contents averaged 34.3%, ranging from 25.5 to 47.1%, and starch content averaged 33.6%, ranging from 17.1 to 42.6%. This likely reflects differences in the relative proportions of kernel and stover fractions among samples as affected by hybrid (Kennington et al., 2005) and growing conditions (Rooney and Pflugfelder, 1986; Philippeau and Michalet-Doreau, 1997). For the present study, 43.0% of the hybrids were reported as dual purpose, 26.4% as silage specific, 15.3% as brown midrib, and 15.3% as a combination of hybrid types.

A relationship between MPL of WPCS samples measured by PSPS and WIOS was observed ($R^2 = 0.62$, $P = 0.001$, CCC = 0.74, Figure 1a). Results support the suitability of the PSPS method in WPCS for MPL measurements at the farm level. It is important to note, however, that measurements differed in MPL, difference ranged from −1.53 to 1.93 mm (mean ± 1.96 SD; Figure 1b). Murphy and Zhu (1997) compared 9 different methods to determine particle size distributions of feeds, including WPCS, and observed a 9-fold variation in MPL among the methods. However, PSPS and WIOS were not included in that study. Lammers et al. (1996) reported no difference between PSPS and WIOS for predicting proportions of WPCS particles retained on the 19-mm and 8-mm sieves.

Verbal TLOC was unrelated to MPL of as-fed whole samples measured by either PSPS ($P = 0.23$, Figure 2a) or WIOS ($P = 0.58$, Figure 2b). Factors other than TLOC can influence the MPL in WPCS, such as kernel processing (Johnson et al., 1999), processor roll-gap setting (Shinners et al., 2000), DM content (Shinners et al., 2000), ratio of kernel to stover (Mertens, 2005), hybrid (Johnson et al., 2002), knife sharpness and knife–to–shear bar clearance (Shinners, 2003), and use of a silage bagger (L. Kung, 2017, University of Delaware, Newark, personal communication). All of these factors may have influenced the relationship between TLOC and MPL in the present study as demonstrated by the range in roll-gap settings, starch (used as a proxy for kernel:stover ratio), DM content (Table 1), and hybrid types. Poor inverse relationships among CSPS and MPL measured by PSPS (R^2 =

Table 1. Descriptive statistics of DM, starch composition, and MPL[1] (PSPS[2] and WIOS[3]) in whole-plant corn silage and hydrodynamically separated stover-fraction nutrient composition

Item	Mean	SD	Minimum	Maximum
Whole-plant corn silage				
DM, % of as fed	34.3	3.9	25.5	47.1
Starch, % of DM	33.6	5.6	17.1	42.6
Stover fraction				
CP, % of DM	8.9	0.7	7.2	10.5
ADF, % of DM	33.4	2.6	27.0	40.1
NDF, % of DM	57.0	3.7	49.2	67.0
Starch, % of DM	16.6	3.8	8.0	26.4
Whole-plant corn silage MPL, mm				
PSPS	12.0	1.1	10.0	15.4
WIOS	11.8	1.4	8.6	14.8
Stover fraction MPL, mm				
PSPS	11.8	1.3	8.9	16.9
WIOS	8.1	0.9	5.9	10.5

[1]MPL = mean particle length.

[2]PSPS = Penn State Particle Size Separator.

[3]WIOS = Wisconsin Oscillating Particle Separator.

0.12, $P = 0.01$, data not shown), MPL measured by WIOS ($R^2 = 0.29$, $P = 0.001$, data not shown), and percentage of WPCS retained above the 8-mm sieve of PSPS ($R^2 = 0.33$, $P = 0.001$, data not shown) were observed but not between CSPS and the percentage of WPCS retained on the 19-mm screen of PSPS ($P = 0.50$; data not shown). These poor relationships support our premise that several factors interfere with MPL besides TLOC and mechanical processing. In addition, the field survey TLOC values were only obtained verbally from farmers and or custom harvesters during the farm visit. Verbal TLOC was not related to CSPS ($P = 0.39$; data not shown).

Kernel processing with pull-type forage harvesters reduced MPL by 19 or 29% when the TLOC was set at 19 mm in the studies of Schwab et al. (2002) and Bal et al. (2000), respectively. Shinners et al. (2000) reported similar particle size between WPCS harvested at 19 mm of TLOC and processed at 1-mm roll-gap or unprocessed WPCS harvested at 9.5 mm of TLOC. In the same study (Shinners et al., 2000), a reduction of the roll-gap settings from 3 to 1 mm increased the fraction of cracked and broken kernels to near 100% but reduced the average WPCS MPL by about 2 mm. In the present study, processors of different makes and models were used. Furthermore, Shinners et al. (2000) observed small differences in WPCS physical characteristics when harvested between one-third (31% DM) and one-half (37% DM) kernel milk line. However, when WPCS was harvested at three-fourths (40% DM) kernel milk line, WPCS particle size was reduced compared with the more immature material. Recent availability of new processors requires future research. Research should be focused on evaluating the effects of these processors and their settings on WPCS physical characteristics within a wide range of maturities, hybrids, and silo types.

Percentage of WPCS retained above the 8-mm sieve of PSPS was poorly related to verbal TLOC ($P = 0.001$, $R^2 = 0.16$, Figure 3a). A similar poor relationship was ob-

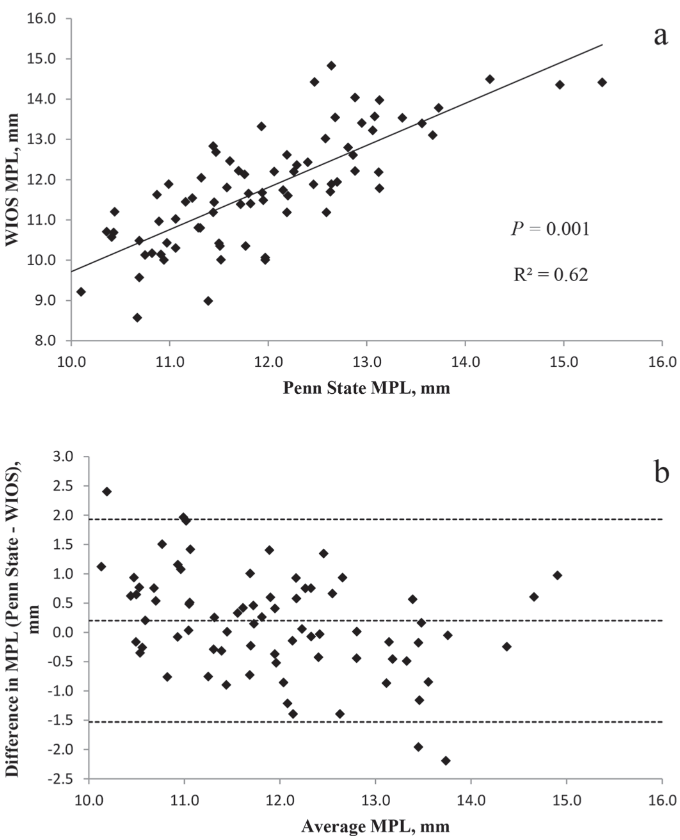

Figure 1. Relationship between whole-sample geometric mean particle length (MPL; mm) measured by the Penn State Particle Size Separator and whole-sample geometric MPL (mm) measured by the Wisconsin Oscillating Particle Separator (WIOS). Prediction equation: y = −0.73 (±1.13) + 1.05x (±0.09); n = 80, root mean squared error = 0.89, $R^2 = 0.62$, $P = 0.001$, concordance correlation coefficient = 0.74 (panel a). Bland-Altman plot (panel b). The x-axis presents the average whole-sample geometric mean length between Penn State and WIOS, and the y-axis presents the difference in whole-sample geometric mean length between Penn State and WIOS (Penn State − WIOS). Central, upper, and lower horizontal lines correspond to the mean (0.20) and higher (1.93) and lower (−1.53) 95% limits of agreement (mean ±1.96 SD), respectively, SD = 0.89.

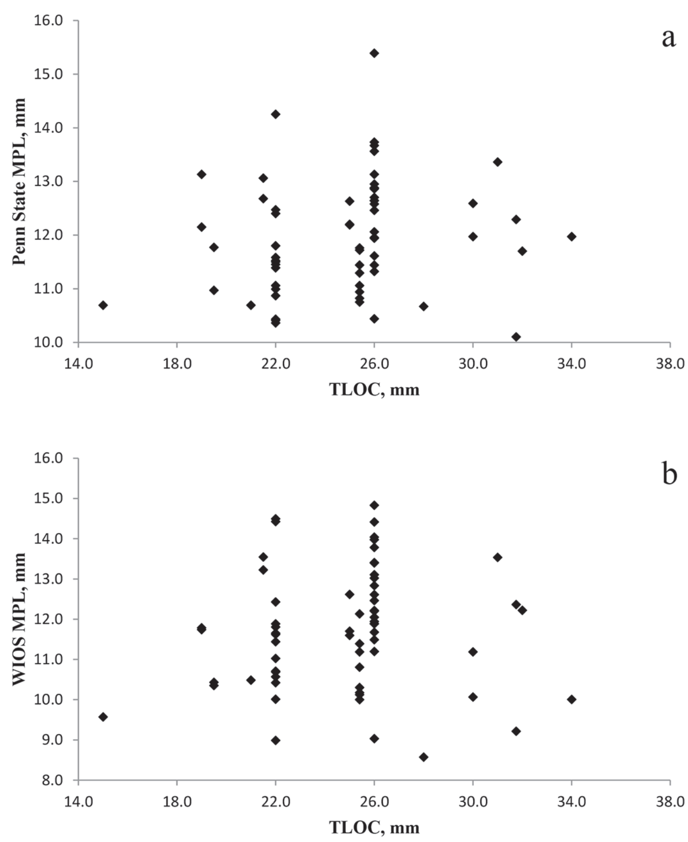

Figure 2. Distribution plots of verbal theoretical length of cut (TLOC) settings (mm) and geometric mean particle length (MPL; mm) measured by the Penn State Particle Size Separator (panel a) or Wisconsin Oscillating Particle Separator (WIOS; panel b). Prediction equation of panel a: y = 10.77 (±0.98) + 0.05x (±0.04); n = 64, root mean squared error = 1.07, $R^2 = 0.02$, $P = 0.23$. Prediction equation of panel b: y = 10.98 (±1.36) + 0.03x (±0.05); n = 64, root mean squared error = 1.48, $R^2 = 0.01$, $P = 0.58$.

served for verbal TLOC and the percentage of WPCS retained on the 19-mm screen of PSPS ($P = 0.01$, $R^2 = 0.10$, Figure 3b). Lammers et al. (1996) reported that the percentage of particles in a TMR that are larger than some critical value (e.g., 19 or 25 mm) may be more useful than MPL. Johnson et al. (2003) evaluated 3 TLOC settings (11.1, 27.8, and 39.7 mm) for WPCS harvested in 2 trials. Increasing TLOC increased average MPL and tended to increase the percentage of particles retained on the 19-mm sieve of PSPS. Johnson et al. (2003) evaluated the effect of ensiling on MPL and reported an increase in MPL with ensiling. It was suggested that compaction of the forage in the silo may have altered the physical characteristics of the forage (flattened some of the particles), making it difficult for some particles to pass through the screens in the particle separator. Andrae et al. (2001) observed that physical processing decreased large particles (>19 mm) and increased mid-size (8 to 19 mm) and small (<8 mm) particles. Visual observation of the material remaining on each screen indicated that these trends were likely the result of increased fracture of the cobs and kernels. Rollers disrupt kernel, cob, and stover portions of corn plants harvested for silage and as a consequence reduce MPL (Johnson et al., 1999). Although the forage chopper is set to specific TLOC, particle distribution is variable, and the subsequent handling and processing may further reduce particle size (Lammers et al., 1996).

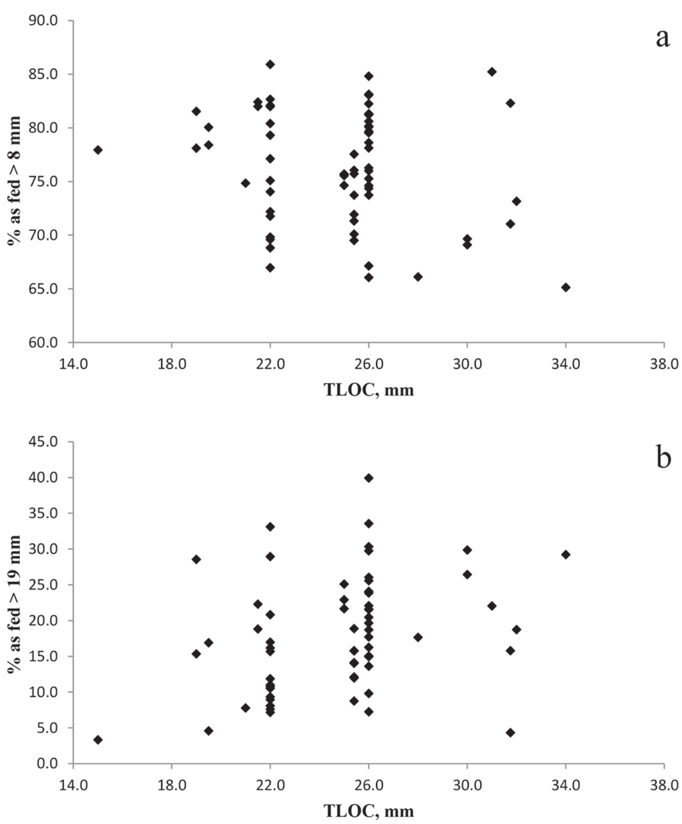

Figure 3. Distribution plot of varied theoretical length of cut (TLOC) settings (mm) and percentage of as-fed whole-plant corn silage retained above the 8-mm (panel a) or 19-mm (panel b) sieve of the Penn State Particle Size Separator. Prediction equation of panel a: y = 0.84 (±0.08) − 0.01x (±0.003); n = 64, root mean squared error = 0.08, $R^2 = 0.16$, $P = 0.001$. Prediction equation of panel b: y = −0.0008 (±0.07) + 0.007x (±0.003); n = 64, root mean squared error = 0.08, $R^2 = 0.10$, $P = 0.01$.

Stover Fraction

The composition of the stover fraction is in Table 1. Unexpectedly, starch content was highly variable (ranged from 8.0 to 26.4% and averaging 16.0% of DM). Savoie et al. (2004) tested 1 versus 8 water separations and reported that the starch content of the stover fraction ranged from 9.5 to 16.7% of DM. These authors also reported that the soak effluent averaged 26% starch (DM basis), which is indicative of a greater proportion of kernel than stover fractions in the soak effluent. The high content of starch

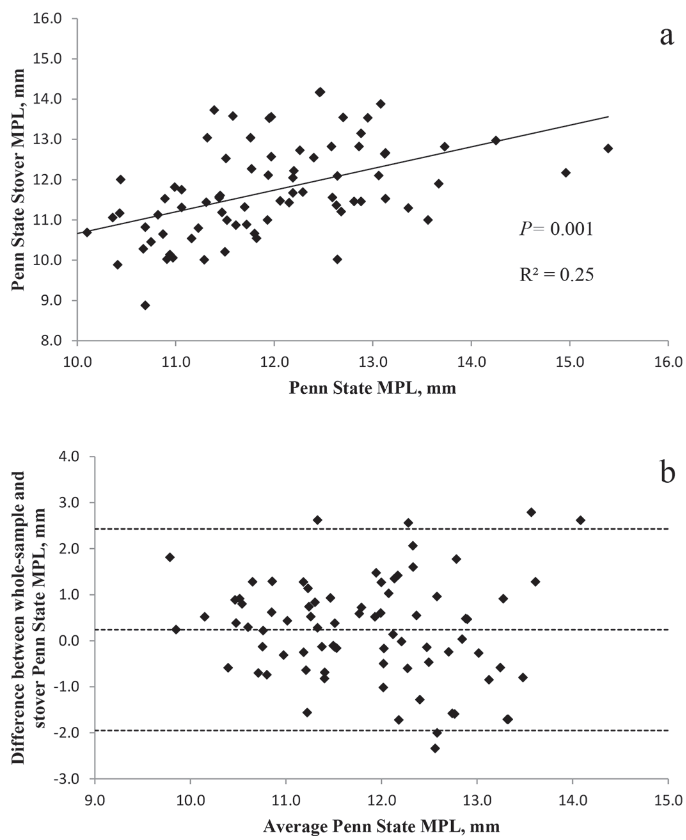

Figure 4. Relationship between whole-sample geometric mean particle length (MPL; mm) and stover geometric mean length (mm) measured by Penn State Particle Separator. Prediction equation: y = 5.29 (±1.29) + 0.54x (±0.11); n = 80, root mean squared error = 1.01, $R^2 = 0.25$, $P = 0.001$, concordance correlation coefficient = 0.48 (panel a). Bland-Altman plot (panel b). The x-axis presents the average geometric mean length between whole-sample and stover measured by the Penn State Particle Separator, and the y-axis presents the difference in geometric mean length between whole-sample and stover measured by Penn State Particle Separator (whole − stover). Central, upper, and lower horizontal lines correspond to the mean (0.24) and higher (2.43) and lower (−1.95) 95% limits of agreement (mean ±1.96 SD), respectively, SD = 1.12.

in soak-effluent DM is likely due to the presence of small pieces of kernel and insoluble starch, because industrial cornstarch (99% starch, less than 0.25% protein) has very low water solubility (Zinn and Owens, 1986). Lynch et al. (2012) studied the effects of hybrid and harvest date on the composition of stover, cob, and whole plant. The starch content of the stover fraction ranged from 0.2 to 3.0% of DM. Savoie et al. (2004) reported that the grain, stalk, husk, cob, and leaf fractions contained 42.5, 0.4, 1.3, 0.1, and 1.3% of starch, respectively, or a total of 3.1% starch in the stover fraction (DM basis). It is unlikely that this starch is from stover synthesis, because starch content in this fraction is low due to synthesis in chloroplasts for temporary storage as one of the stable end-products of photosynthesis. For long-term storage, starch is synthesized in the amyloplasts of the nonphotosynthetic parts of plants, such as seeds, roots, and tubers (Nelson et al., 2008). Stover NDF content ranged from 49.2 to 67% of DM. Savoie et al. (2004) observed a similar variation from 50.9 to 61.5% in the hydrodynamically separated stover fraction of WPCS. Lynch et al. (2012) reported a range in stover NDF content from 68.1 to 75.9% in Irish hybrids. Although broad ranges exist for NDF, ADF, and lignin of stover within and between maize populations (Frey et al., 2004), the contents of starch and NDF in the stover fraction in the present study are mainly related to the contamination with small starch particles from effluent water.

A relationship between MPL of as-fed whole-sample and MPL of the stover fraction was observed (PSPS, R^2 = 0.25, P = 0.001, CCC = 0.48; WIOS, R^2 = 0.18, P = 0.001, CCC = 0.07, Figures 4a and 5a) but with low R^2 and CCC. A relationship between PSPS and WIOS was observed when stover MPL was evaluated (R^2 = 0.60, P = 0.001, CCC = 0.1,0 Figure 6a), suggesting accuracy of PSPS in comparison with the WIOS. But as noted for whole-samples, difference in stover MPL between PSPS

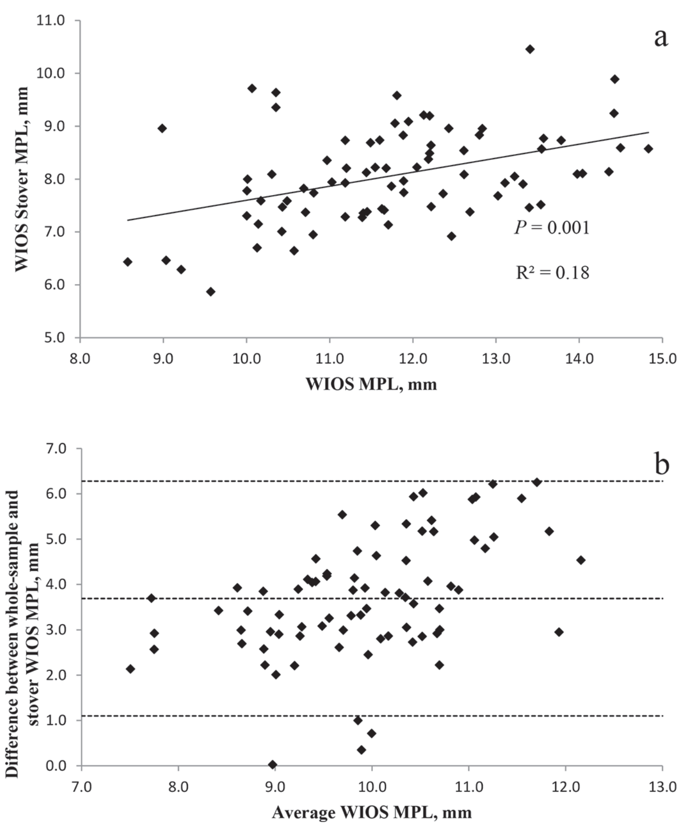

Figure 5. Relationship between whole-sample geometric mean particle length (MPL; mm) and stover geometric MPL (mm) measured by Wisconsin Oscillating Particle Separator (WIOS). Prediction equation: y = 4.95 (±0.76) + 0.27x (±0.06); n = 80, root mean squared error = 0.81, R^2 = 0.18, P = 0.001, concordance correlation coefficient = 0.07 (panel a). Bland-Altman plot (panel b). The x-axis presents the average geometric MPL between whole-sample and stover measured by the WIOS, and the y-axis presents the difference in geometric MPL between whole-sample and stover measured by the WIOS (whole − stover). Central, upper, and lower horizontal lines correspond to the mean (3.69) and higher (6.28) and lower (1.10) 95% limits of agreement (mean ±1.96 SD), respectively, SD = 1.32.

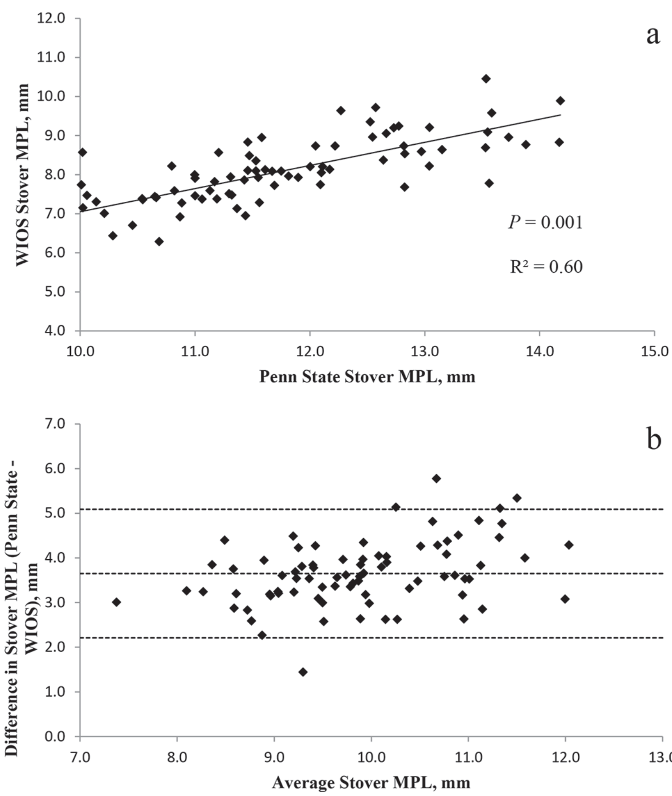

Figure 6. Relationship between stover geometric mean particle length (MPL; mm) measured by the Penn State Particle Size Separator and stover geometric MPL (mm) measured by the Wisconsin Oscillating Particle Separator (WIOS). Prediction equation: y = 1.13 (±0.65) + 0.59x (±0.06); n = 80, root mean squared error = 0.57, R^2 = 0.60, P = 0.001, concordance correlation coefficient = 0.10 (panel a). Bland-Altman plot (panel b). The x-axis presents the average stover geometric mean length between the Penn State and WIOS, and the y-axis presents the difference in stover geometric mean length between the Penn State and WIOS (Penn State − WIOS). Central, upper, and lower horizontal lines correspond to the mean (3.65) and higher (5.09) and lower (2.21) 95% limits of agreement (mean ±1.96 SD), respectively, SD = 0.73.

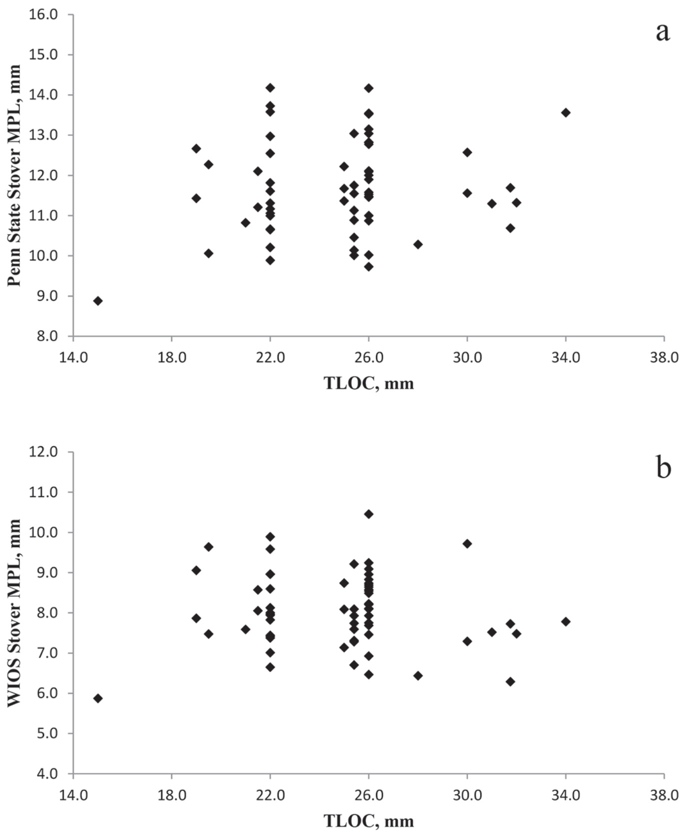

Figure 7. Distribution plot of varied theoretical length of cut (TLOC) settings (mm) and fiber geometric mean particle length (MPL; mm) measured by the Penn State Particle Size Separator (panel a) or Wisconsin Oscillating Particle Separator (WIOS; panel b). Prediction equation of panel a: y = 10.25 (±1.08) + 0.06x (±0.04); n = 64, root mean squared error = 1.18, R^2 = 0.03, P = 0.17. Prediction equation of panel b: y = 8.40 (±0.85) − 0.01x (±0.03); n = 64, root mean squared error = 0.92, R^2 = 0.003, P = 0.68.

and WIOS existed (Figure 6b). Despite this relationship, there was a reduction in MPL for the stover fraction compared with WPCS for both methods (Table 1; Figures 4b and 5b), which explains the low CCC values observed for these comparisons. This reduction appeared greater for WIOS than PSPS, which might reflect the intensity of the WIOS procedure compared with PSPS. Furthermore, difference increased along with MPL (Figures 4b, 5b, and 6b), which is likely related to fragility of coarse fiber particles. Moreover, drying procedures after hydrodynamic separation likely shattered particles and further reduced particle size throughout the sieving process. Kononoff et al. (2003) reported that drying forage samples increases fragility and, thereby, particle breakage during the separation process. In addition, DM content of samples increases variation in the WIOS procedure (ASABE, 2007). The MPL of the stover fraction was not related to verbal TLOC (PSPS, $P = 0.17$; WI-OS, $P = 0.68$, Figures 7a and 7b).

IMPLICATIONS

Average MPL of as-fed WPCS samples from varied harvest conditions, independent of method, was 11.9 mm. A strong relationship between 2 different procedures to determine MPL in WPCS was observed, suggesting that MPL can be measured adequately on farm with the PSPS. Verbal TLOC was not related to MPL of WPCS. In addition, the elimination of the kernel fraction through hydrodynamic separation did not improve this relationship. Perhaps specific TLOC guidelines are warranted for different DM contents and kernel processor types and settings to achieve desired MPL and physically effective fiber. In addition, measurement of particle size at harvest and feed out is an important nutrition practice to account for WPCS particle size differences.

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LITERATURE CITED

ANSI (American National Standards Institute). 2001. American National Standards Institute, Method of Determining and Expressing Particle Size of Chopped Forage Materials by Sieving, Standards. Am. Soc. Agric. Eng., St. Joseph, MI.

Andrae, J. G., C. W. Hunt, G. T. Pritchard, L. R. Kennington, J. H. Harrison, W. Kezar, and W. Mahanna. 2001. Effect of hybrid, maturity, and mechanical processing of corn silage on intake and digestibility by beef cattle. J. Anim. Sci. 79:2268–2275.

AOAC International. 2012. Official Methods of Analysis. 19th ed. AOAC Int., Arlington, VA.

ASABE (American Society of Agricultural and Biological Engineers). 2007. Method of determining and expressing particle size of chopped forage materials by screening. ANSI/ASAE S424.1:663–665.

Bach Knudsen, K. E. 1997. Carbohydrate and lignin contents of plant materials used in animal feeding. Anim. Feed Sci. Technol. 67:319–338.

Bal, M. A., R. D. Shaver, A. G. Jirovec, K. J. Shinners, and J. G. Coors. 2000. Crop processing and chop length of corn silage: Effects on intake, digestion, and milk production by dairy cows. J. Dairy Sci. 83:1264–1273.

Bland, J. M., and D. G. Altman. 1986. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1:307–310.

Ferraretto, L. F., and R. D. Shaver. 2012. Effect of corn shredlage on lactation performance and total tract starch digestibility by dairy cows. Prof. Anim. Sci. 28:639–647.

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.

Frey, T. J., J. G. Coors, R. D. Shaver, J. G. Lauer, D. T. Eilert, and P. J. Flannery. 2004. Selection for silage quality in the Wisconsin quality synthetic and related maize populations. Crop Sci. 44:1200–1208.

Johnson, L., J. H. Harrison, C. Hunt, K. Shinners, C. G. Doggett, and D. Sapienza. 1999. Nutritive value of corn silage as affected by maturity and mechanical processing: A contemporary review. J. Dairy Sci. 82:2813–2825.

Johnson, L. M., J. H. Harrison, D. Davidson, W. C. Mahanna, and K. Shinners. 2003. Corn silage management: Effects of hybrid, chop length, and mechanical processing on digestion and energy content. J. Dairy Sci. 86:208–231.

Johnson, L. M., J. H. Harrison, D. Davidson, J. L. Robutti, M. Swift, W. C. Mahanna, and K. Shinners. 2002. Corn silage management I: Effects of hybrid, maturity, and mechanical processing on chemical and physical characteristics. J. Dairy Sci. 85:833–853.

Kennington, L. R., C. W. Hunt, J. I. Szasz, A. V. Grove, and W. Kezar. 2005. Effect of cutting height and genetics on composition, intake, and digestibility of corn silage by beef heifers. J. Anim. Sci. 83:1445–1454.

Kononoff, P. J., A. J. Heinrichs, and D. R. Buckmaster. 2003. Modification of the Penn State forage and total mixed ration particle separator and the effects of moisture content on its measurements. J. Dairy Sci. 86:1858–1863.

Lammers, B. P., D. R. Buckmaster, and A. J. Heinrichs. 1996. A simplified method for the analysis of particle sizes of forage and total mixed rations. J. Dairy Sci. 79:922–928.

Lin, L. I. 1989. A concordance correlation coefficient to evaluate reproducibility. Biometrics 45:255–268.

Lynch, J. P., P. O'Kiely, and E. M. Doyle. 2012. Yield, quality and ensilage characteristics of whole-crop maize and of the cob and stover components: Harvest date and hybrid effects. Grass Forage Sci. 67:472–487.

Maulfair, D. D., and A. J. Heinrichs. 2012. Review: Methods to measure forage and diet particle size in the dairy cow. Prof. Anim. Sci. 28:489–493.

Mentink, R. L., P. C. Hoffman, and L. M. Bauman. 2006. Utility of near-infrared reflectance spectroscopy to predict nutrient composition and in vitro digestibility of total mixed rations. J. Dairy Sci. 89:2320–2326.

Mertens, D. R. 1997. Creating a system for meeting the fiber requirements of dairy cows. J. Dairy Sci. 80:1463–1481.

Mertens, D. R. 2005. Particle size, fragmentation index, and effective fiber: Tools for evaluating the physical attributes of corn silages. Pages 211–220 in Proc. Four-State Dairy Nutr. Mgmt. Conf. MWPS-4SD18, Dubuque, IA. Iowa State Univ., Dubuque, IA.

Murphy, M. R., and J. S. Zhu. 1997. A comparison of methods to analyze particle size as applied to alfalfa haylage, corn silage, and concentrate mix. J. Dairy Sci. 80:2932–2938.

Nelson, D. L., A. L. Lehninger, and M. M. Cox. 2008. Lehninger Principles of Biochemistry. Macmillan, London, UK.

Philippeau, C., and B. Michalet-Doreau. 1997. Influence of genotype and stage of maturity of maize on rate of ruminal starch degradation. Anim. Feed Sci. Technol. 68:25–35.

Rooney, L. W., and R. L. Pflugfelder. 1986. Factors affecting starch digestibility with special emphasis on sorghum and corn. J. Anim. Sci. 63:1607–1623.

Salvati, G. S. S., R. D. Shaver, M. Lippert, E. Ronk, and C. Wacek-Driver. 2015. Corn Silage Processing: Dairy Farm Survey. Accessed Feb. 16, 2016. https://shaverlab.dysci.wisc.edu/wp-content/uploads/sites/87/2015/04/cornsilageprocessingsurveysummaryreport.pdf.

Savoie, P., K. J. Shinners, and B. N. Binversie. 2004. Hydrodynamic separation of grain and stover components in corn silage. Appl. Biochem. Biotechnol. 113:41–54.

Schwab, E. C., R. D. Shaver, K. J. Shinners, J. G. Lauer, and J. G. Coors. 2002. Processing and chop length effects in brown-midrib corn silage on intake, digestion, and milk production by dairy cows. J. Dairy Sci. 85:613–623.

Shinners, K. J. 2003. Engineering principles of silage harvesting equipment. Pages 361–403 in Silage Science e Technology. Agron. Monogr. 42. Am. Soc. Agron., Crop Sci. Soc. Am., and Soil Sci. Soc. Am., Madison, WI.

Shinners, K. J., A. G. Jirovec, R. D. Shaver, and M. Bal. 2000. Processing whole-plant corn silage with crop processing rolls on a pull-type forage harvester. Appl. Eng. Agric. 16:323–331.

Vanderwerff, L. M., L. F. Ferraretto, and R. D. Shaver. 2015. Brown midrib corn shredlage in diets for high-producing dairy cows. J. Dairy Sci. 98:5642–5652.

Zebeli, Q., J. R. Aschenbach, M. Tafaj, J. Boguhn, B. N. Ametaj, and W. Drochner. 2012. Invited review: Role of physically effective fiber and estimation of dietary fiber adequacy in high-producing dairy cattle. J. Dairy Sci. 95:1041–1056.

Zinn, R. A., and F. N. Owens. 1986. A rapid procedure for purine measurements and its use for estimating net ruminal protein synthesis. Can. J. Anim. Sci. 66:157–166.