CO-HARVEST AND ANAEROBIC CO-STORAGE OF CORN GRAIN AND STOVER AS BIOMASS FEEDSTOCKS

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HIGHLIGHTS

- Cutting height and harvest date were used to alter stover moisture content, yield, and composition.
- Anaerobic co-storage of grain and stover limited losses to less than 6% of dry matter.
- Extent of fermentation was greater for higher moisture stover than grain, but total acids were less than 5 g kg^{-1}.
- Reducing the harvester cutter head rotational speed resulted in a greater fraction of whole corn kernels.

ABSTRACT. *This research investigated the utility of co-harvesting and anaerobic co-storage of corn grain and stover to positively influence their physical and chemical characteristics as a biomass feedstock. Corn grain and stover were harvested in 2019 and 2020 with a self-propelled forage harvester. Stover yield, moisture content, and composition were altered by the harvest date, stubble height, and header configuration. Harvest date had the utility of varying the stover moisture content ($p < 0.001$) from 42.3% to 53.5% (w.b.) and 43.1% to 53.9% (w.b.) for the 2019 and 2020 harvest years, respectively. Stubble height was also utilized to vary stover moisture content. A negative linear relationship was established between stubble height and stover moisture content for the early ($R^2 = 0.76$) and late harvest ($R^2 = 0.91$) dates for both years. Stover yield also showed a negative linear relationship ($R^2 = 0.76$) with stubble height over both years. Regardless of the stubble height, the row-crop header collected more stover ($p < 0.001$) than the ear-snapper header. In 2020, harvested stover ranged from 5.0 to 10.5 Mg ha^{-1}, with ha^{-1} representing 41% to 85% of the total available stover. In both years, stover ash content was less than 64 g kg^{-1}. Material stored in pilot-scale silos (19 L) was well conserved during anaerobic storage, with average DM losses of 4.8% and 3.4% in 2019 and 2020, respectively. Grain moisture content averaged 23.6% (w.b.) at harvest, and 31.0% (w.b.) after storage as moisture migrated from the moist stover to the drier grain. Harvesting whole-plant corn with a forage harvester had the unwanted effect of reducing the particle size of the grain fraction, which would complicate downstream utilization. However, reducing the harvester cutterhead speed increased the fraction of intact kernels from 47% to 85% by mass. The studied system was a viable alternative to conventional corn grain and stover systems for producing feedstocks for biochemical conversion.*

Keywords. *Ash, Ensiling, Ethanol, Maize.*

Corn stover represents 70% of available crop residues that can be utilized for bioenergy and bioproducts (Langholtz et al., 2016). However, recent projections estimate that over 60% of corn stover in the Midwest would be collected at moisture levels that exceed 20% (w.b.) moisture content, resulting in poor conservation in conventional baled logistics systems (Oyedeji et al., 2017). Traditional stover harvest involving conventional hay harvest equipment and systems have been extensively investigated and found lacking. Field drying to baling moisture is difficult, baling productivity is slow, ash content is too great, bale density is too low for economical transport, and storage losses are often excessive. These issues have led to the conclusion that multi-pass bale-based corn stover feedstock systems are expensive and do not meet established quality targets (Cook and Shinners, 2011; Wendt et al., 2018; Davis et al., 2018).

An alternative to conventional systems has been explored, which involves a single-pass harvest of chopped corn, resulting in co-mingled bulk material or co-harvested, stored, and transported grain and stover. Unlike conventional corn silage harvested at roughly 65% (w.b.) moisture content, this harvest would occur well after senescence, when whole-plant moisture content would be approximately 30% to 50% (w.b.) It is envisioned that the co-mingled material is anaerobically stored, transported to a biorefinery together, and finally separated into starch and cellulosic fractions. This approach could reduce the intense logistics challenges typically associated with conventional stover systems and expand the harvest window. In small-scale proof-of-concept research, losses were less than 4% of dry matter (DM) for anaerobically stored grain and stover at 34% to 65%

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(w.b.) moisture content (Cook et al., 2014). This research expands on this earlier work by investigating the full-scale, co-mingled harvest of corn grain and stover.

While direct harvest of corn grain and stover has many potential advantages, the utility of the harvester to change the physical and chemical properties of the material has yet to be investigated. For example, we hypothesize that one can control whole-plant moisture by altering the cutting height, but what are the consequences for stover yield and composition, and how does varying the stover yield impact the amount of grain processed by the harvester? Here, we would posit that less yield would increase the amount of grain processed. The forage harvester is typically coupled with a whole-plant header, but our previous work in corn silage demonstrated that an ear snapper header could be modified to harvest the upper portion of the plant preferentially (Nigon et al., 2016; Walters et al., 2020). This portion of the plant is more digestible in ruminant diets and less recalcitrant to pretreatment and bioconversion (Duguid et al., 2009). However, this harvest method has yet to be investigated in mature corn, where the plant is drier and more fragile. Finally, how does the harvested composition of the high dry matter whole-plant corn affect its preservation through anaerobic storage?

Our primary objective was to investigate the feasibility of co-harvest and anaerobic co-storage of both grain and stover as an alternative biomass feedstock system. Toward this goal, we investigated the utility of harvester configuration (cutting height, header type) and harvest date (early, late) to control moisture content and composition of stover during harvest. Yield, composition, physical characteristics, and moisture content of both the grain and stover fractions, as well as the storage characteristics, were quantified.

MATERIALS AND METHODS

Corn grain and stover were harvested together using a modified John Deere (Moline, IL) model 6950 self-propelled forage harvester (SPFH) (fig. 1). Modifications were made to the header lift system so that a maximum cutting height of up to 100 cm could be attained, although drooped ear height typically limited header height to a maximum of 65 to 80 cm. Two 6-row John Deere headers were used: either a model 666R conventional row-crop (RC) header or a model 693 ear-snapper (ES) header (ASABE Standard S472, 2022; ASABE Standard S343.4, 2019). The ES header was modified to increase stover yield by adding disk cutting knives above the ear snapper rolls to cut the top portion of the stalk (Nigon et al., 2016; Walters et al., 2020). Locating the knives further forward on the header would cut the stalk lower and increase stover yield (Walters et al., 2020), so two knife configurations were used: the disk center was located either 16 or 32 cm from the rearmost part of the snapper rolls (RWK and FWK, respectively). The SPFH theoretical length of cut (TLOC) was 35 mm. The SPFH cutterhead speed was 1100 and 750 rpm in 2019 and 2020, respectively. In 2020, the lower cutterhead speed was used to reduce grain breakage.

In 2019, four header treatments were used: RC header operated at approximately 20 and 65 cm cut height (LC and HC, respectively), and ES header configured with four RWK and two FWK knives or two RWK and four FWK knives (ES1 and ES2, respectively). In 2020, four header treatments were used: an RC header operated at approximately 20, 40, and 65 cm cut height (LC, MC, and HC, respectively), and an ES header configured with four RWK and no knives on the remaining two rows (ES3). In both years, the ES header height was set so the front of the ear snapper rolls was approximately 60 cm from the ground. Corn grain and stover were harvested in two different periods. In 2019, the first and second harvests occurred on 23-25 October and 14-18 November from plots near Arlington, WI (43.30; 89.35) to provide an early and late harvest period. In 2020, the first and second harvest periods were 14 to 16 October and 2 to 4 November, respectively.

During each harvest period, the harvest experiments were carried out using a randomized block design with four replicated blocks. Machine configuration plots were randomly assigned within blocks; each plot was six rows wide (6 × 0.76 m) and 50 or 100 m long (2019 and 2020, respectively). Material harvested from each plot was collected in a forage wagon equipped with load cells to weigh the harvested material to the nearest 2 kg. Post-harvest stubble height was manually measured to the nearest 5 cm on one plant per row across all six rows in each plot. After harvest, two subsamples per plot were collected from the wagon to determine moisture content by oven drying at 105°C for 24 h (ASABE

Figure 1. Harvest of corn grain and stover illustrating weather independence of stover harvest. Note differences in amount of stalk harvested based on header treatment (left: row-crop header and right: ear-snapper header).

Standard S358.2, 2021). An additional two subsamples were oven dried at 60°C for 72 h and saved for later composition analysis.

Ten kg of material was collected from each plot, which was used to fill 19 L pilot-scale silos made of plastic containers lined with plastic bag liners, yielding four replicate silos for each treatment. The contents were compacted using a hydraulic cylinder and platen. A relief valve in the hydraulic circuit was set such that the pressure applied by the platen on the face of the material was 140 kPa. A locking lid with a neoprene gasket was used to tightly seal the container after filling and compaction. Because the containers were filled to the brim, the achieved density of 228 kg DM m^{-3} was maintained by the locking lid. The mass of each pilot-scale silo and its contents were weighed to the nearest 0.01 kg. The sealed containers were stored indoors at approximately 20°C until the contents were removed. Storage duration was 447 and 428 days (2019), and 264 and 245 days (2020) for the first and second harvests, respectively.

Upon removal from storage, the mass of each pilot-scale silo and its contents were first weighed to the nearest 0.01 kg to assess dry matter loss, and then the contents were removed and homogenized by hand mixing. The material was then processed in a vertical tube air separation device to separate the grain and stover fractions by differences in terminal velocity (Stubbe, 2015). Two subsamples of each the homogenized material, separated stover, and separated grain were oven dried at 60°C for 72 h to be used to determine moisture content and composition. Additional subsamples of the separated stover and grain were collected and frozen for later determination of fermentation products.

One 300 g subsample per pilot-scale silo of the separated grain was fractionated by mechanical sieving (Model Ro-Tap RS-29, W.S. Tyler, Mentor, OH). The sieve shaker was configured with eight screens (9.53, 6.35, 4.75, 3.35, 2.36, 1.70, 1.19, and 0.59 mm) and a bottom pan. After operating the shaker for 2 min, the contents of each screen and the pan were weighed to the nearest 0.001 g, and the kernel geometric mean particle size (GMPS) was determined per ASABE Standard S319.4 (2022). The grain was further separated by hand into three fractions: whole, split (kernel split into two pieces), or broken (broken into more than two pieces). The GMPS of the broken fraction was then calculated. One subsample of separated stover from each pilot-scale silo was fractionated by size using a cascade of screens (19.0, 12.7, 6.3, and 4.0 mm) that oscillated in a horizontal plane for 2 min following ASABE Standard S424.1 (2022) and the GMPS calculated.

The dried pre- and post-storage compositional samples were first ground in a knife mill equipped with a 1 mm screen. Constituent analysis was performed using wet chemistry by the University of Wisconsin Soil and Forage Lab (Marshfield, WI) for neutral detergent fiber (NDF), acid-detergent fiber (ADF), acid detergent lignin (ADL), and ash (Peters, 2022).

Post-storage grain and stover were analyzed separately for fermentation products. Fermentation analysis was conducted on four divisions independent of header treatment: the grain and stover fractions for the first and second harvests. Prior to analysis, samples were homogenized by processing for 1 minute in an industrial twin-blade food processor (Robot-Coupe model R2B, Robot-Coupe, Ridgeland, MS). Analysis was subsequently performed by Rock Rover Laboratories (Watertown, WI) using their standard wet laboratory techniques.

On 4 November 2020, a separate study was conducted to determine the impact of SPFH cutterhead speed on kernel damage. The SPFH was equipped with the RC head set at a cut-height of 40 cm. The cutterhead was operated at 750, 900, 1100, and 1250 rpm. Three plots were harvested in random order for each cutterhead speed. Stover and kernels were separated using the air separation technique described above.

A statistical analysis of these experiments was completed using the Standard Least Squares option in the Fit Model platform of JMP Pro (ver. 15, SAS Institute Inc., Cary, NC). Where appropriate, data were analyzed using one-way or two-way ANOVAs with the least square means compared using Tukey's test or the Student's t-test.

RESULTS AND DISCUSSION

The duration between harvest periods was approximately three weeks, during which time the grain moisture decreased by 8.4 and 8.7 percentage points in 2019 and 2020, respectively (table 1). Based on grain moisture content, the corn harvest would have been considered early for the first harvest period in both years (Parvej et al., 2020). Despite the early harvest, grain yield was not significantly different ($p > 0.450$) between harvest dates in either 2019 or 2020. Due to ear declination, the maximum header height was limited to approximately 65 cm to ensure the ends of the drooped ears were not severed by the cutoff knives of the RC header. The second harvest in 2019 occurred with snow on the ground, demonstrating the relative weather independence of this harvest system.

Stover moisture content was linearly related to stubble height (fig. 2). The slope of the line was greater for the second harvest period because the top half of the stalk typically dries more quickly than the bottom half (Shinners and Binversie, 2007). Across all harvest dates and header configurations, average stover moisture content at harvest was approximately 21 to 27 percentage points greater than average grain moisture.

Table 1. Harvest date and crop information for 2019 and 2020 harvests.

Year and Harvest [a, b]	Date	Days After Planting	Average Grain Moisture (% w.b.)	Lowest Ear Droop Height[c] (cm)
2019				
First	23-25 Oct.	155	29.3	90
Second	14-18 Nov.	176	20.9	85
2020				
First	14-16 Oct.	164	20.2	110
Second	2-4 Nov.	182	17.8	110

[a] Corn hybrid in 2019 was LG Seeds LG5499STX with comparative relative maturity (CRM) of 100 days planted on 23 May.

[b] Corn hybrid in 2020 was Dairyland DS-4018AMXT with CRM of 101 days planted on 4 May.

[c] Distance from ground to ear connection point on stalk or lowest point of the drooped ear, measured to nearest 5 cm.

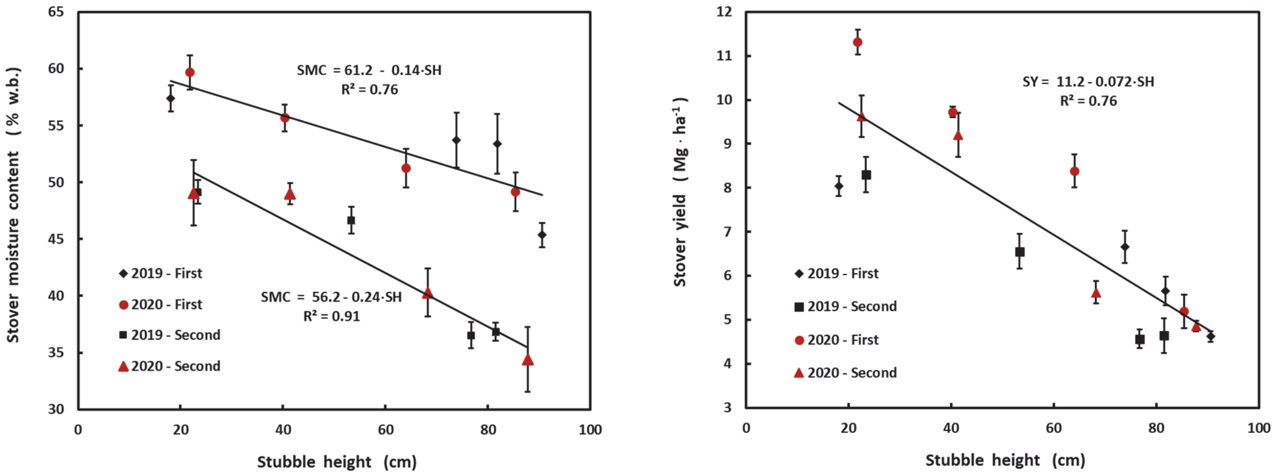

Figure 2. Stover moisture content (SMC) versus stubble height (SH) for both harvest years and first or second harvest periods (left). Stover dry basis yield (SY) versus stubble height (SH) for both harvest years and first and second harvest periods (right). Error bars represent standard error of mean.

Significant differences in stover dry basis yield were observed between header treatments during both years, but grain yields were consistent (table 2). In 2019, both the ES1 and ES2 treatments produced similar stover yields, with LC and HC being significantly different from the ES treatments and each other. The most significant difference in stover yield was found between LC and ES2, with a difference of 3.6 Mg ha^{-1}. In 2020, the ES and HC treatments had significantly different stover yield compared to all others, while the LC and MC treatments had similar stover yields. The most significant difference in stover yield was found between LC and ES3, with a difference of 5.5 Mg ha^{-1}. In 2020, between 41% and 85% of the available stover was captured. Stover dry basis yield was linearly related to stubble height, with

Table 2. Yield and moisture content from field plot study conducted in 2019 and 2020.

Year	Harvester Header Treatment[a,b]	Harvest [c, d]	Post-Harvest Stubble Height (cm)	Moisture Content: Grain and Stover [e, f] (% w.b.)	Moisture Content: Stover (% w.b.)	Dry Basis Yield: Grain (Mg ha^{-1})	Dry Basis Yield: Stover (Mg ha^{-1})	Fraction of Available Stover[g] (%)
2019	LC		21c	41.4a	53.2a	10.5	8.2a	
	HC		64b	37.6b	50.2a	11.1	6.6b	
	ES1		82a	33.8c	45.1ab	12.0	5.2c	
	ES2		84a	33.3c	41.0b	11.9	4.6c	
SEM[h]			1.2	0.98	2.2	0.50	0.33	
p-value			< 0.001	< 0.001	0.003	0.149	< 0.001	
LSD[h]			5.0	3.6	9.0	2.0	1.4	
2019		First	66a	40.6a	52.5a	11.2	6.2a	
		Second	59b	32.4b	42.3b	11.5	6.0a	
SEM[h]			0.80	0.70	1.6	0.35	0.23	
p-value			< 0.001	< 0.001	< 0.001	0.503	0.502	
LSD[h]			3.0	2.8	6.4	1.5	1.0	
2020	LC		22d	46.1a	54.4a	11.4	10.5a	85a
	MC		41c	43.4a	52.3ab	11.2	9.5a	77a
	HC		66b	38.0b	45.7bc	11.2	7.0b	57b
	ES3		87a	36.4b	41.8c	12.4	5.0c	41c
SEM[h]			1.4	0.83	1.9	0.38	0.36	2.6
p-value			< 0.001	< 0.001	< 0.001	0.125	0.001	< 0.001
LSD[h]			6.0	3.3	7.7	1.6	1.5	11
2020		First	53	45.3a	53.9a	11.4	8.7a	68
		Second	55	36.7b	43.1b	11.7	7.3b	63
SEM[h]			1.0	0.59	1.3	0.27	0.25	1.8
p-value			0.147	< 0.001	< 0.001	0.468	< 0.001	0.073
LSD[h]			4.0	2.4	5.5	1.1	0.53	8.0

[a] 2019: Row-crop header operated at 20 and 65 cm (low cut (LC) and high cut (HC), respectively), and ear-snapper (ES) header configured with four forward and two rearward knives or two forward knives and four rearward knives (ES1 and ES2, respectively).

[b] 2020: Row-crop header operated at 20, 40, and 65 cm (LC, MC, and HC, respectively), and ear-snapper (ES3) header configured with four rearward knives and no knives on the remaining two rows.

[c] 2019: First and second harvests occurred from 23 to 25 October and 14 to 18 November, respectively.

[d] 2020: First and second harvests occurred from 14 to 16 October and 2 to 4 November, respectively.

[e] 2019: Average grain moisture content was 29.3% and 20.9% (w.b.) for the first and second harvest, respectively.

[f] 2020: Average grain moisture content was 20.2% and 17.8% (w.b.) for the first and second harvest, respectively.

[g] Fraction of available stover harvested based on hand-sampled material before each harvest. Data not available for 2019.

[h] Standard error of the mean (SEM), least square difference (LSD) p = 0.05. Within each column, lowercase markers indicate significant differences at $p < 0.05$ using Tukey's comparisons or Student's t-test.

every 10 cm increase in stubble height resulting in a decrease in stover yield of approximately 7% (fig. 2).

Conservation of stover and grain during anerobic storage was very good, with an average DM loss of 4.8% in 2019 and 3.3% in 2020 (table 3). Dry matter loss did not vary significantly between header treatments in both 2019 and 2020. The only significant difference in DM loss was observed between the two harvest dates in 2020, with an increase of 1.7 percentage points from the first harvest to the second harvest. During storage, moisture migrated from the moist stover to the drier grain, but the moisture content did not equalize between the two fractions. Grain moisture content increased from harvest to removal from storage by 5.4 and 6.6 percentage points (first harvest) and by 8.6 and 8.7 percentage points (second harvest) for 2019 and 2020, respectively. Stover moisture content decreased by 7.1 and 7.7 percentage points in 2019 and by 5.1 and 4.3 percentage points in 2020 for the first and second harvests, respectively.

In both years, we observed that most of the grain had been dislodged from the cob during harvest. In 2019 and 2020, the mass fraction of whole kernels was significantly less for the ES treatment(s) compared to when the RC header was used (LC, MC, and HC treatments) (table 4). The ES header configurations harvested less stover (table 2), likely exposing the kernels to greater mechanical damage by the SPFH cutterhead. The cutterhead speed was reduced from 1100 rpm (2019) to 750 rpm (2020). This change resulted in approximately a 50% reduction in knife impact energy, which resulted in a greater mass fraction of whole kernels in 2020.

Table 3. Post-storage moisture content and dry matter loss for material harvested in 2019 and 2020 stored in pilot-scale silos.

Harvest Date	Header Treatment[a,b]	Moisture Content (%w.b.)			Dry Matter Loss[c,d]
		Grain and Stover	Grain	Stover	
2019	LC	42.5a	34.9a	45.6a	3.8a
	HC	39.9a	32.2b	41.1b	6.2a
	ES1	35.2b	30.5b	37.9bc	5.2a
	ES2	33.5b	30.6b	35.6c	4.0a
SEM[e]		0.81	0.69	0.99	0.92
p-value		< 0.001	< 0.001	< 0.001	0.236
LSD[e]		3.3	2.8	4.0	3.8
23-25 Oct 2019		42.0a	34.7a	45.4a	4.4a
14-18 Nov 2019		33.5b	29.5b	34.6b	5.2a
SEM[e]		0.57	0.49	0.70	0.65
p-value		< 0.001	< 0.001	< 0.001	0.378
LSD[e]		2.3	2.0	2.8	2.7
2020	LC	46.6a	33.4a	49.7a	3.6a
	MC	41.7b	29.9b	44.4b	3.6a
	HC	38.6c	28.9b	42.2c	3.9a
	ES3	35.8d	27.1c	38.9d	2.2a
SEM[e]		0.56	0.33	0.29	0.60
p-value		< 0.001	< 0.001	< 0.001	0.212
LSD[e]		2.2	1.3	1.6	2.5
14-16 Oct 2020		44.8a	33.1a	48.8a	2.5b
02-04 Nov 2020		36.6b	26.5b	38.8b	4.2a
SEM[e]		0.39	0.23	0.41	0.42
p-value		< 0.001	< 0.001	< 0.001	0.011
LSD[e]		1.6	0.9	1.2	1.6

[a] 2019: Row-crop header operated at 20 and 65 cm (LC and HC, respectively), and ear-snapper header configured with four forward and two rearward knives or two forward knives and four rearward knives (ES1 and ES2, respectively).

[b] 2020: Row-crop header operated at 20, 40, and 65 cm (LC, MC, and HC, respectively), and ear-snapper (ES3) header configured with four rearward knives and no knives on the remaining two rows.

[c] 2019: Change in dry mass during storage. Material stored in pilot-scale silos for 447 and 428 days for first and second harvest, respectively.

[d] 2020: Change in dry mass during storage. Material stored in pilot-scale silos for 264 and 245 days for first and second harvest, respectively.

[e] Standard error of mean (SEM), least square difference (LSD) $p = 0.05$. Within each column, lowercase markers indicate significant differences at $p < 0.05$ using Tukey's comparisons or Student's t-test.

In 2019, a greater mass fraction was broken than was split, but the opposite occurred in 2020. Harvest date did not significantly affect grain properties in 2019. In 2020, there was significantly greater grain damage in the second harvest, possibly because grain moisture content was the driest of all the four harvest dates. There were differences in grain GMPS in both years, but the differences were typically very small (< 1 mm) and may not have practical significance. Broken grain GMPS was consistent across treatments and averaged approximately 3 mm.

In 2019, the GMPS of the stover fraction was significantly lower for the ES2 treatment compared to the other three treatments, and the average GMPS in the second harvest was less than the first harvest (table 4). There were no significant differences in stover GMPS in 2020. In both years, the stover GMPS was less than the TLOC of 35 mm. Typically, GMPS would be greater than TLOC as a portion of the crop is not cut perpendicular to the cutterhead. However, whole-plant corn harvested for animal feed is typically chopped at approximately 65% (w.b.) moisture content. In this research, harvest occurred between 32% and 41% (w.b.) moisture content. It is possible that harvesting at lower moisture contents caused shattering of leaves and cob, resulting in the GMPS being less than the TLOC.

Header type and configuration, as well as pre- or post-storage, significantly affected stover composition (table 5). In 2019, stover NDF, ADF, and ADL showed significant differences between the LC, HC, and ES treatments but no significant difference between the two ES treatments. A reduction in stubble height was accompanied by greater fiber and lignin content. This was true in 2020 as well, but the differences between treatments were less. Changes in NDF, ADF, and ADL concentrations during storage were significant, as was DM loss, and the creation of fermentation acids increased the concentration of these components. Changes in fibrous structural components in forages have been reported after ensiling as readily soluble nutrients are converted to fermentation acids (Kung et al., 2018).

Fermentation analysis was conducted independent of header treatment: the grain and stover fractions for first and second harvest. For each harvest period, stover had statistically greater lactic, acetic, and total acid levels than the grain (table 6). This result was likely due to the greater moisture content of the stover at each harvest period and year. Cook et al. (2014) reported that stover had greater lactic and acetic acids than the grain when whole-plant corn was ensiled at similar moisture contents. Average moisture content was 7.8 percentage points greater for the first harvest period than the second, so pH and lactic acid of the grain and stover fractions were statistically greater for the first compared to the second harvest. In 2019, the first harvest acetic acid was significantly greater than the second harvest for the stover fraction but not for the grain fraction.

Grain pH increased and lactic acid decreased as grain moisture decreased, similar to trends reported by Goodrich

Table 4. Kernel and stover properties for material harvested in 2019 and 2020 and stored in pilot-scale silos.

Harvest Date	Header Treatment[a,b]	Grain to Stover Dry Mass Ratio	Fraction (%) of Grain Dry Mass[c]			Geometric Mean Particle-Size (mm)		
			Whole	Split	Broken	All Grain[d]	Broken Grain[d]	Stover[e]
2019	LC	1.3b	55a	15b	30b	5.5a	2.9a	23ab
	HC	1.7b	56a	16b	28b	5.5a	2.9a	29a
	ES1	2.4a	38b	17b	45a	4.6b	2.8a	21ab
	ES2	2.6a	38b	19a	43a	4.7b	2.8a	18b
SEM[f]		0.16	2.60	0.7	2.6	0.14	0.04	2.1
p-value		< 0.001	< 0.001	0.002	< 0.001	< 0.001	0.237	0.013
LSD[f]		0.6	11	3	11	0.6	0.2	9
23-25 Oct 2019		2.1a	48a	16a	36a	5.1a	2.8a	26a
14-18 Nov 2019		1.9a	46a	17a	38a	5.0a	2.8a	19b
SEM[f]		0.12	1.8	0.5	1.8	0.10	0.05	1.5
p-value		0.235	0.363	0.328	0.523	0.590	0.937	0.001
LSD[f]		0.5	8	2	7	0.4	0.2	6
2020	LC	1.1c	84b	9b	6ab	7.1bc	3.3a	27a
	MC	1.2c	86ab	9bc	5bc	7.2ab	3.3a	26a
	HC	1.8b	88a	8c	4c	7.3a	3.2a	31a
	ES3	2.4a	81c	11a	7s	7.0c	3.4a	28a
SEM[f]		0.07	0.8	0.3	0.5	0.04	0.06	1.4
p-value		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.517	0.148
LSD[f]		0.3	3	1	2	0.2	0.3	6
14-16 Oct 2020		1.5b	87a	8b	5b	7.2a	3.3a	27a
02-04 Nov 2020		1.8a	83b	10a	7a	7.0b	3.4a	29a
SEM[f]		0.05	0.5	0.2	0.3	0.02	0.04	1.0
p-value		< 0.001	< 0.001	< 0.001	< 0.001	0.001	0.076	0.246
LSD[f]		0.2	2	1	1	0.1	0.2	4

[a] 2019: Row-crop header operated at 20 and 65 cm (LC and HC, respectively), and ear-snapper header configured with four forward and two rearward knives or two forward knives and four rearward knives (ES1 and ES2, respectively).

[b] 2020: Row-crop header operated at 20, 40, and 65 cm (LC, MC, and HC, respectively), and ear-snapper (ES3) header configured with four rearward knives and no knives on the remaining two rows.

[c] Split: fraction of dry kernel mass split into two pieces. Broken: fraction of dry kernel mass broken into more than two pieces.

[d] Geometric-mean particle-size of kernel fraction based on screening following ASABE Standard S319.4 (2022).

[e] Geometric-mean particle size based on screening following ASABE Standard S424.1 (2022).

[f] Standard error of mean (SEM), least square difference (LSD) $p = 0.05$. Within each column, lowercase markers indicate significant differences at $p < 0.05$ using Tukey's comparisons or Student's t-test.

et al. (1975) for fermented shelled corn. Grain pH was 4.49 and lactic acid was 13.3 g kg^{-1} when the grain moisture content was 31.9% (w.b.) (table 6). Goodrich et al. reported that shelled corn at 33% (w.b.) moisture content had a pH of 4.3 and lactic acid of 10.5 g kg^{-1}. Grain acetic acid was consistent at approximately 4.3 g kg^{-1}, slightly greater than the estimate of Goodrich et al. of 2.5 g kg^{-1}.

Stover pH increased and lactic acid decreased as stover moisture decreased, similar to trends reported by Shinners et al. (2011) for fermented stover. They reported stover pH increased from 4.1 to 4.5, lactic acid decreased from 37 to 7 g kg^{-1}, and acetic acid decreased from 10 to 5 g kg^{-1}, as moisture content decreased from 55% to 34% (w.b.). Wendt et al. (2018) reported that ensiled stover at 47% (w.b.) moisture content had a pH of 4.62, and lactic and acetic acid levels of 31 and 9 g kg^{-1}, respectively, similar to the values reported here.

Our results show that, on a given harvest day, the moisture content of the feedstock was manipulated by an average of approximately 9 percentage points by altering the cut height or header configuration. Harvest control of moisture is important because moisture content impacts material conservation during storage, transportation economics, and downstream processing techniques.

Manipulating cut height also significantly affected stover DM yield, with a decrease in stover yield of approximately 8% for every 10 cm increase in stubble height. As cut height increased, stubble height also increased, indicating more stalk was left behind, and the lower portion of the stalk had the greatest moisture content (Shinners and Binversie, 2007). On average, a decrease in stover DM yield of 1.0 Mg ha^{-1} lowered the moisture content by 1.6 and 2.8 percentage points for the first and second harvests, respectively.

Capturing more of the stalk when harvesting whole-plant corn for ruminant animal feed increases the NDF, ADF, and lignin content (Neylon and Kung, 2003; Nigon et al., 2016). With the exception of NDF in 2020, similar results were found here. Based on 2019 results, every 10 cm increase in stubble height resulted in a 10, 12, and 2 g kg^{-1} decrease in the NDF, ADF, and ADL, respectively, of the aggregate stover.

The high ash content of typical baled corn stover negatively influences pretreatment and disposal costs for the conversion facility (Shah and Darr, 2016). The ash content for baled stover ranged from 115 to 282 g kg^{-1} depending on the baling scenario (Bonner et al., 2014), more than twice the ash content reported here. The ash content of the lower stalk was greater than the upper stalk by an average of 4 g kg^{-1} (Lizotte et al., 2015). Control over ash content was significant and generally followed stubble height. The ash content was found to be linearly related to stubble height ($R^2 = 0.84$) with a decrease in ash content of about 2 g kg^{-1} for every 10 cm increase in stubble height. These results were consistent with those reported by Shinners et al. (2009).

This system is intended to use a downstream fractionation process to separate the grain and stover fractions before use. As a result, it is preferable to recover a clean grain fraction with minimal losses to the stover fraction. As planned, the grain fraction would be used to produce ethanol or as ruminant animal feed. Feeding moist, fermented grain to ruminant animals is common, but grain removed from anaerobic storage as used here has very different physical properties than the corn grain typically used for ethanol production. For instance, in 2020, the grain removed from storage had a 27% to 33% (w.b.) moisture content, split or broken grain accounted for 13% to 17% of the total grain dry mass, and 1% to 2% of the DM consisted of fermentation acids. Although ethanol plants can relatively easily use broken corn (Hurburgh, 2008), ethanol plants typically expect delivered grain to have less than 18% moisture content and no more than 10% damage (Hardy and Holz-Clause, 2006). It remains to be determined if moist, fermented grain with greater than 10% damage can be economically integrated into typical ethanol production systems or if the harvest system can be altered to reduce grain damage.

Table 5. Composition of the stover fraction as determined by wet laboratory techniques for the 2019 and 2020 harvests. Data analyzed by header treatment independent of harvest date.

Harvester Header Treatment[a,b]	Pre- or Post-Storage[c,d]	Stover Composition (g kg DM^{-1}) NDF[e]	ADF[e]	ADL[e]	Ash
2019					
LC		624a	398a	36a	60a
HC		639a	384a	29b	56ab
ES1		558b	322b	22c	50b
ES2		558b	326b	21c	50b
SEM[f]		13.6	8.7	1.8	1.6
p-value		< 0.001	< 0.001	< 0.001	< 0.001
LSD[f]		54	33	7	6
	Pre-storage	581b	355b	18b	53a
	Post-storage	609a	380a	36a	54a
SEM[f]		9.6	6.1	1.2	1.1
p-value		0.044	< 0.001	< 0.001	0.606
LSD[f]		27	24	4	4
2020					
LC		681b	454a	37a	64a
MC		691ab	452a	37a	58b
ES3		699a	433b	31b	52c
SEM[f]		4.3	4.2	1.3	1.2
p-value		0.038	0.002	0.017	<0.001
LSD[f]		17	17	5	5
	Pre-storage	665b	418b	32b	56b
	Post-storage	715a	471a	38a	59a
SEM[f]		3.1	2.9	0.9	0.8
p-value		< 0.001	< 0.001	< 0.001	< 0.001
LSD[f]		12	12	4	3

[a] 2019: Row-crop header operated at 20 and 65 cm (LC and HC, respectively) and ear-snapper header configured with four forward and two rearward knives or two forward knives and four rearward knives (ES1 and ES2, respectively).

[b] 2020: Row-crop header operated at 20, 40, and 65 cm (LC, MC, and HC, respectively) and ear-snapper (ES3) header configured with four rearward knives and no knives on the remaining two rows.

[c] 2019: Material stored in pilot-scale silos for 447 and 428 days for first and second harvest, respectively.

[d] 2020: Material stored in pilot-scale silos for 264 and 245 days for first and second harvest, respectively.

[e] Neutral detergent fiber (NDF), acid detergent fiber (ADF) and acid detergent lignin (ADL).

[f] Standard error of mean (SEM), least square difference (LSD) $p = 0.05$. Within each column, lowercase markers indicate significant differences at $p < 0.05$ using Tukey's comparisons or Student's t-test.

CONCLUSIONS

This research demonstrated that co-harvesting by chopping and anaerobic co-storage of corn grain and stover is a viable alternative to conventional dry bale stover systems. Moisture content, yield, and composition were significantly altered through the manipulation of header type, cutting height, and harvest date. With this system, harvest could start earlier than typical, and stover harvest could occur in weather conditions that would have prevented stover baling. The harvested stover had a much lower ash content than conventional stover baling systems. Harvesting by chopping caused grain damage, but as much as 87% of the kernels remained intact when the harvester cutterhead speed was reduced. The conservation of both fractions in terms of dry matter recovery was very good during anaerobic storage. Still, the grain and stover fractions were fermented, which may affect some conversion techniques. These results show that the studied system can be an alternative to conventional corn grain and stover systems. Future work should focus on grain marketability and recovery from the stover.

Table 6. Fermentation profile of the grain and stover fractions after anerobic storage in pilot-scale silos. Data analyzed by material fraction independent of header treatments.

	Harvest[a,b]	Material Fraction	Moisture Content (% w.b.)	pH	Stover Composition (g kg DM^{-1}) Lactic	Acetic	Total[c]
2019	23-25 Oct 2019	Grain	37.6b	4.16b	19.0b	4.2b	26.1b
		Stover	46.5a	4.19b	32.4a	7.5a	45.0a
	14-18 Nov 2019	Grain	31.9c	4.49a	13.3c	4.2b	19.7c
		Stover	36.7b	4.52a	18.2b	5.0b	25.7b
	SEM[d]		0.28	0.009	0.67	0.43	1.29
	p-value		< 0.001	0.788	< 0.001	0.010	< 0.001
	LSD[d]		1.3	0.04	2.9	1.9	5.7
2020	14 to 16 Oct 2020	Grain	36.0c	4.40d	14.0b	4.6b	19.4c
		Stover	52.8a	4.46c	35.9a	9.5a	48.2a
	02 to 04 Nov 2020	Grain	30.1d	4.90a	3.3c	4.0b	7.8d
		Stover	46.1b	4.85b	13.5b	8.3a	25.2b
	SEM[d]		0.53	0.003	0.55	0.41	1.16
	p-value		< 0.001	< 0.001	< 0.001	0.488	< 0.001
	LSD[d]		2.3	0.001	2.4	1.8	5.0

[a] 2019: Material stored in pilot-scale silos for 447 and 428 days for first and second harvest, respectively.

[b] 2020: Material stored in pilot-scale silos for 264 and 245 days for first and second harvest, respectively.

[c] Butyric, propionic, succinic acids averaged less than 2 g kg-1 DM and there were no significant differences between treatments.

[d] Standard error of mean (SEM), least square difference (LSD), $p = 0.05$. Within each column, lowercase markers indicate significant differences at $p < 0.05$ using Tukey's comparisons.

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