

# Aerobic and Anaerobic Storage of Single-pass, Chopped Corn Stover

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**Abstract** Corn stover has great potential as a biomass feedstock due its widespread availability. However, storage characteristics of moist corn stover harvested from single-pass harvesters have not been well quantified. In 2007, whole-plant corn stover at 19.1–40.3% (w.b.) moisture content was stored for 237 days in aerobic piles, one covered and one uncovered, as well an anaerobic silo bag. In 2008, two stover materials—whole plant and cob/husk from 31.7% to 58.1% (w.b.) moisture—were stored for 183 or 204 days in covered and uncovered anaerobic piles, ventilated bags, or anaerobic silo bags. Stover stored in uncovered piles was rehydrated by precipitation, which increased biological activity resulting in dry matter (DM) losses from 8.2% to 39.1% with an average of 21.5%. Stover in covered piles was successfully conserved when the average moisture was less than 25% (w.b.) with DM losses of 3.3%. Stover above 36% (w.b.) moisture and piled under a plastic cover had DM losses from 6.4% to 20.2% with an average of 11.9%. Localized heating occurred in the aerobic piles when moisture was above 45% (w.b.) which lead to temperatures where spontaneous combustion might be a concern (i.e., >70°C). Ambient air blown through a center tube in the ventilated storage bag dried stover near the tube to an average of 24.2% (w.b.), but the remainder of the bag averaged 46.8% (w.b.) at removal.

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Loss of DM ranged from 7.4% to 22.0% with an average of 11.8% with this storage method. Stover was most successfully conserved in the bags where anaerobic conditions were maintained. Under anaerobic conditions, DM losses ranged from 0.2% to 0.9%. When anaerobic conditions were not maintained in the silo bag, DM losses averaged 6.1% of DM. Anaerobic storage is the best solution for conserving the value of moist corn stover.

**Keywords** Biomass · Feedstock · Storage · Fermentation · Silage · Anaerobic · Aerobic · Stover · Corn

## Introduction

With approximately 32 million ha of corn (*Zea mays* L.) grown in the USA [22], the non-grain, above ground portion of the plant known as corn stover deserves attention as a possible biomass feedstock for cellulosic ethanol. Stover residue has value in limiting soil runoff and contributing to soil fertility and organic matter. However, a good fraction of stover can be removed without detrimental effects. Much of the available corn stover in the USA goes unused after the grain harvest [7]; so it is logical to pursue research assessing the value of this resource as a potential replacement for fossil-generated fuel. As competing uses for grains increase, corn stover may become economically attractive ruminant animal feed.

In the past, corn stover (stalk, leaf, cob, and husk) has been collected through various methods for on-farm use as animal bedding or as high-fiber feed for ruminant animals. One collection method involves a machine called a stacker wagon, which formed a moderately densified cube by flail chopping the stover into a wagon where it was compressed [3]. Although this was a workable two-pass harvesting

system, most producers abandoned this practice because the harvesting rate was too slow, stack density too low, and storage losses too high.

Another harvesting option involves shredding and then merging the material into a windrow. After the stover is sufficiently dry, the windrow is baled with a round or square baler. The bales would typically be stored outdoors or under a tarp. Another option is to chop the stover with a forage harvester and preserve the material by ensiling. Productivity was greater and storage losses lower with the chopped and ensiled system compared to storing round bales outdoors [18].

One of the major challenges limiting the utilization of corn stover and other biomass crops is the conservation of the feedstock during storage. The storage system must also fit efficiently between harvest and transportation to a biorefinery. Rigorous material specifications for successful storage, such as a narrow range of moisture or particle size, may complicate and delay harvest. Grain harvest is usually dependent on the grain moisture content, which is approximately half the moisture content of the stover [17]. Certain storage systems, such as dry bales stored outdoors, not only may have high storage losses, but may require long field wilting time, excessive handling, and extra processing before use as animal feed or as a biomass feedstock.

A major challenge with any storage option is the appropriate moisture for stable storage and the potential negative consequences of storing stover outside the proper moisture range. If sufficient moisture and air is available, microorganisms begin breaking down the feedstock leading to heating, mold growth, and undesirable product degradation. Mold is very undesirable in any feedstock. Corn silage with mold has been shown to lower DM intake and digestibility within beef cattle [24]. Similar results could be expected with moldy stover. Bioconversion facilities desire feedstocks free of mold because the molds may be lethal to microorganisms used in conversion processes. Microbial activity also may consume desirable components of the feedstock leaving a higher proportion of lignin, decreasing yields of end products such as ethanol. The objective of the research was to quantify the storage characteristics of moist corn stover (i.e., >25% w.b. moisture) as affected by initial moisture, stover fractions, and type of storage scheme.

## Materials and Methods

### Harvest and Storage—2007

Stover was harvested with a John Deere 9750 STS combine modified to harvest grain and whole-plant stover (stalk, leaf, cob and husk) in a single-pass [19, 20]. The theoretical-

length-of-cut (TLC) of the stover processor was 11 mm. Cut height was between the second and third nodes, and ground speed was about 3 km/h. The material was harvested at the University of Wisconsin Arlington Agricultural Research Station (AARS) using a single field of Renk 689 YGP corn hybrid. Harvesting was conducted on October 29–30 and November 3 and 11, 2007. Hand separation after harvest indicated an average of 4% of the harvested stover dry mass was grain. The mass of material harvested and placed into storage was determined to the nearest 2 kg with a weighed forage wagon. Random samples of material were taken throughout the filling process for later particle-size analysis using ABSAE Standard S424.1 [1, 2].

Three storage treatments were considered: (a) stored aerobically with cover, (b) stored aerobically without cover, and (c) stored anaerobically in a silo bag. The two aerobic treatments were not compacted, merely piled directly on the ground. The piles were roughly 3 m high, 5 m wide, and 15 m long. The piles averaged roughly 7,000 kg DM of stover. The covered pile was covered with a 200 µm plastic sheet and the sheet secured at the edges with weights. The three structures were placed on sod with a gentle slope for drainage. The 200 µm silo bag was 2.74 m diameter and was filled with a Kelly Ryan Centerline bagger. The silo bag was filled and sealed on October 29th while the piles were formed on the October 30th, and November 3rd and 11th.

As material was placed into all the structures, polypropylene mesh bags (55×80 cm with 7 mm mesh) were filled with the stover material and then placed throughout the structures to quantify storage performance. Between 1.5 and 2.0 kg DM of stover was placed in each bag and the weight determined to the nearest 5 g. Three replicate subsamples each for moisture and compositional analysis were collected from the mesh bags prior to weighing. Moisture samples were oven dried at 103°C for 24 h and composition samples at 60°C for 72 h [1]. Twelve mesh bags were placed into both aerobic piles. Four mesh bags were placed in the silo bag. These bags were buried as deeply into the bag as safely possible after the bagger had been removed. Material was recompacted around the mesh bags by weight of the material used to cover the bags. It was not possible to place mesh bags in the silo bag prior to this time because the baggers packing rotor would have destroyed the mesh sample bags.

### Removal Procedure—2007

Stover was removed on June 24, 2008. A front-end loader was used to remove material. The removed material was placed in trucks and the contents weighed to the nearest 10 kg on a truck scale. Care was taken to minimize spillage losses at removal. Mesh bags were collected by hand, and

the contents weighed and then sub-sampled for moisture and composition. Moisture and composition samples were oven dried as described above, except the moisture samples from the silo bag were dried at 60°C for 72 h [1].

At a representative location in the aerobic piles, cross-sectional pictures and samples for moisture distribution were collected. A total of 15 moisture sub-samples were collected in a grid pattern. Samples for fermentation product analysis were taken from the silo bag at approximately 1-m intervals along the length of the bag. Samples were sealed in plastic bags and frozen. Additional samples were taken from random locations throughout the silo bag for particle size and moisture distribution analysis.

Dried compositional samples were ground in a hammermill using a 1-mm screen and then sent to Dairyland Laboratories Inc. (Arcadia, WI, USA) for analysis of neutral detergent fiber (NDF), acid detergent fiber (ADF), lignin (ADL), and ash using their standard wet laboratory techniques. Fermentation samples were also analyzed by Dairyland Laboratories for common fermentation products using high-performance liquid chromatography. Cellulose and hemicellulose content were estimated by differences between ADF and ADL and between NDF and ADF, respectively, and assuming that the C6 sugars were the cellulose content multiplied by 0.86 and the C5 sugars were the hemicellulose content multiplied by 0.71 [8]. Theoretical ethanol yield (TEY) was predicted using the NREL theoretical yield calculator [23]. Quantifying cellulose and hemicellulose by these differences were merely estimates of the stated cell wall components, intended for use in the TEY computation. Lorenz et al. [8] showed that these computations are valid to obtain relative differences among corn stover samples.

#### Harvest and Storage—2008

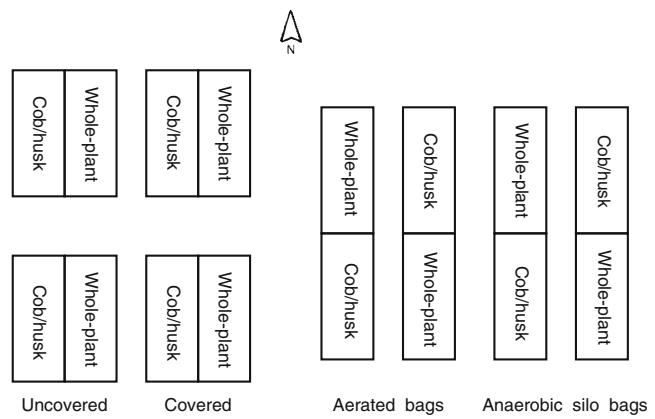
Stover storage structures were constructed at AARS in early fall of 2008. There were four major differences between the storage trials conducted in 2008 compared to 2007. First, actual structures were built to hold the aerobically stored material rather than relying on piles as used in 2007. The structures were meant to simulate a cross-section of a large pile. In 2008, two types of stover material were investigated: whole plant and cob/husk. Four storage treatments were considered: covered and uncovered aerobic piles, anaerobic silo bag, and a ventilated bag. The latter treatment is similar to that used to compost organic material [5]. Finally, two moisture ranges were targeted in 2008. Therefore, 16 different treatments were investigated: four storage schemes, two material types, and two moisture ranges.

Each aerobic structure measured 6 m square with a center wall splitting the structure into two halves. The structure was

constructed using fence posts and square mesh plastic fencing. The center wall was constructed with 2.5 m tall fence posts and the outside wall with 1.2 m posts. This allowed the stover to be heaped in the center simulating the slope of a pile. The mesh fencing was secured to the perimeter and center wall posts. Molded expanded polystyrene insulation (50 mm) was placed on the end walls of the structures prior to filling. One half of each structure was filled with whole plant or cob/husk stover, respectively. Four structures were built—two each for covered and uncovered stover at two moisture ranges (Fig. 1).

An Ag-Bag model CT-5 bagger was used to make the ventilated and anaerobic bags using 1.5 m diameter bag of 125 µm thickness. While forming the aerated bag, a 90-mm diameter perforated tube was placed at the bottom center along the full length of the bag. After filling, ventilation slits were cut into the bag every 5 m at the 2 and 10 o'clock positions. A centrifugal fan forced air through perforated tube. Within minutes after the fan was turned on, the bag was inflated and air could be felt exiting the ventilation slits. The CT-5 bagger also was used to form the silo bags. In this case, neither the perforated tube or ventilation slits were used. On a particular harvest date, about half the bag volume was filled first with one stover material and then the remaining volume was filled with the other so there were a total of four bags required for the eight-bagged treatments.

Whole-plant material was harvested by using the single-pass harvester described above configured with a whole-plant head from a forage harvester [20, 21]. The stover consisted of the stalk, leaf, cob, and husk. The stover processor TLC was 11 mm, the cut height between the second and third nodes, and ground speed was about 4 km/h. The cob/husk material was harvested with the same single-pass harvester, except the whole-plant head was replaced with an ear-snapper head, reducing stover capture to the cob and husk, with a small fraction of upper stalk and leaves.



**Fig. 1** Schematic representation of the storage site and treatment placement

The high moisture range material was harvested on October 27–31, 2008 using Pioneer 34A20 hybrid. The low-moisture range material was derived from the same hybrid, and was harvested on November 18–21, 2008 from the same field. Random samples of both stover materials were taken throughout the filling process for later particle size analysis using ASABE Standard S424.1 [1, 2].

A side-dumping forage wagon was used to fill one side of the split aerobic structures about half full. The material was leveled by hand and then ten mesh bags (described above) of material were buried throughout the structure. Bags were not placed within 1 m of the exposed side of the structure. The sampling and weighing techniques used with the mesh bags were similar to procedures used in 2007. Five probes with three thermocouples each spaced vertically 30 cm apart were randomly placed around the center of the structures. The thermocouples were attached to a multiplexer and data logger which recorded the temperatures at 1-h intervals. The second load of stover was placed in the structure and the top manipulated by hand to have roughly a 20° slope with a peak in the center (Fig. 1). The dimensions of the structure were measured to estimate the materials stored density. The covered structures were covered with the same material used in 2007 and restrained by weights.

The Ag-Bag CT-5 bagger used a telescoping hydraulic cylinder and large platen to compact material from the loading chamber into the bag rather than a compacting rotor used on conventional baggers. Although the compaction methods were different between the platen and rotor baggers, data presented later (Table 11) shows that the density in the bags compacted with the platen bagger was within the range of that created by rotor baggers. The platen bagger system allowed mesh bags to be placed throughout the ventilated and anaerobic bags, which was not possible with the rotor bagger. This was the motivating reason for switching to the platen bagger. Ten mesh bags of each of the two stover materials were placed in each bagged treatment. Thermocouple probes similar to those described above were placed into the material at the ventilation slits of the ventilated bags. Individual thermocouples were forced into the anaerobic bag at random locations and then the holes sealed with tape and silicone sealant. A total of 15 thermocouples were distributed throughout both material types for each of the four bag structures. The cross-sectional dimensions of the bags were measured to determine material density.

In the ventilated bags, a fan forcing air through the perforated tubes was operated continuously from the time of bag formation until December 6 in an attempt to dry the stover for preservation. After this time, the fan was operated for most of the winter and spring months by turning the fan on for 12 h during the night for two

consecutive nights each week. After May 2, the fan was operated continuously until the material was removed on May 20.

Heating degree days (HDD) were calculated as the summation of the daily increment by which the temperature of an individual thermocouple was greater than 35°C. An accumulated HDD value was calculated for each thermocouple location and then an average for each storage treatment was calculated.

#### Removal Procedure—2008

The material was removed from storage on May 20 and 21, 2009. The procedures for removing material, collecting the mesh bags and sampling for moisture, constituents and fermentation products were the same as used in 2007. Roughly halfway through removing a particular treatment, a vertical face was created. Samples were collected in a grid pattern across this face to estimate the cross-sectional moisture distribution. The ten sub-samples collected were oven dried using the same procedures used in 2007. Several individuals rated the removed material for evidence of mold based on a score of one (no mold visible, no mold odor) to four (high degree of mold visible, strong mold odor).

#### Statistical Analysis

Statistical analysis was performed using SAS [16]. Significance differences between treatments was determined through single factor analysis of variance (ANOVA) based on variability among replicated nylon mesh bag samples within a storage treatment. Least significant difference was used to describe significant statistical differences between means of different treatments. Statistical analysis was done on initial compositional samples to determine if there were differences in composition between materials at the time of harvest, and on the changes in a compositional parameter (i.e., final–initial expressed as a percent of the final) to determine the effect of storage treatment on the material composition.

## Results

#### Particle Size and Density—2007

The average particle size of material placed into storage was 27 mm, more than twice that of the TLC of the processor. The particle size of material recovered from the silo bag after storage was 18 mm, showing the additional size reduction caused by the packing rotor of the bagger. The density of the piles and silo bag was 75 and 140 kg DM/m<sup>3</sup>, respectively.

## Moisture Content—2007

High ambient temperatures and low humidity in 2007 caused the standing corn plants to dry at a much faster rate than is typically experienced in south-central Wisconsin. These conditions also produced a wide range of stover moisture in the field and into the storage treatments (Table 1). There was no significant change in the moisture during storage of material in the mesh bags stored in the silo bag or covered pile. Since the material in these two structures was not exposed to precipitation, significant increases in moisture would have been evidence of respiration losses [13]. The material in the mesh bags in the uncovered pile had a significant change in moisture content during the storage period with average moisture content above 70% (w.b.) at removal. The total precipitation during the storage period was 660 mm, which is 230 mm more than the 25-year average for the storage site. Although a crust or thatch formed on this pile shortly after storage, the high aggregate final moisture shows that this crust did not prevent precipitation from entering the pile. Large fissures opened on the top of the pile during the spring and summer months, allowing precipitation easy access to interior of the pile.

The cross-sectional moisture distribution of the two piles showed that outer areas of the uncovered pile had greater moisture than the core (Table 1). The covered pile had more uniform moisture than the uncovered pile. The range of

moisture from the anaerobic silo bag at removal was similar to that when stored.

## Composition—2007

The material placed into the uncovered pile had slightly greater NDF, ADF, and ash than the stover used in the other two treatments, so the material had a slightly greater TEY into storage, although the difference was less than 4% (Table 2). There was only one statistically significant change of the compositional parameters measured from the mesh bag samples stored in the silo bag or covered pile (Table 2). There were several significant changes in composition of the material in the uncovered pile. There was a slight loss of NDF, but significant apparent gains in ADF, ADL, and ash, which indicated a loss of carbohydrates. These changes led to a significant loss in TEY. Coupled with the loss of DM (Table 3), the potential ethanol yield from 1 Mg of DM placed into storage in the uncovered pile was significantly less than for the other two treatments (Table 3).

## Storage Losses

Loss of DM during storage was quantified in two ways: by changes in dry mass of the material in the replicated mesh bags and by loss of mass in the entire storage treatment. There was very good agreement between the two methods,

**Table 1** Moisture content (% w.b.) of whole-plant corn stover placed into storage in the fall of 2007 as affected by three different storage methods

Storage method	Into storage <sup>a</sup>			At removal <sup>a</sup>		
	Max	Min	Average	Max	Min	Average
Covered pile	31.3	17.9	22.9	43.3	17.7	22.2
Uncovered pile	30.7	19.6	23.8	83.8	48.5	71.1
Silo bag	40.3	19.1	29.8	38.8	19.9	28.7
Material in mesh bags						
Into		At		Distribution at removal <sup>a</sup>		
Storage <sup>a</sup>		Removal <sup>a</sup>		Difference <sup>b</sup>	Top <sup>c</sup>	Side <sup>c</sup>
Covered pile	21.1	19.5 a	1.6 b	20.7	25.5	18.5
Uncovered pile	20.9	73.4 b	52.5 a*	59.7	68.6	48.5
Silo bag	19.5	22.5 a	3.1 b	—	—	—
LSD <sup>e</sup>	2.5	13.6	13.0			
P <sup>f</sup>	0.47	<0.0001	<0.0001			

<sup>a</sup> Stover stored on October 27, 30 and November 3, 11 2007 and removed on June 24, 2008

<sup>b</sup> Final–initial moisture content

<sup>c</sup> Average of three samples collected from the top and side of pile, respectively

<sup>d</sup> Average of four samples collected from the core of pile

<sup>e</sup> Mean values followed by different letters in the same column are significantly different at 95% confidence

<sup>f</sup> Results of ANOVA tests, effect is significant if P<0.05

\*P=0.05, statistically significant change in moisture during storage period

**Table 2** Composition (% of DM) of whole-plant corn stover into placed into storage in the fall of 2007 and the percent change in composition as affected by three different storage methods

Storage method	Into storage <sup>a</sup>				
	NDF	ADF	ADL	Ash	TEY <sup>b</sup>
Covered pile	79.4 a	50.9 a	6.0	4.5 ab	410 a
Uncovered pile	81.8 b	53.0 b	5.7	5.2 b	426 b
Silo bag	79.7 ab	51.1 ab	5.9	4.2 a	412 a
LSD <sup>c</sup>	2.4	1.9	0.4	1.0	13
P <sup>d</sup>	0.03	0.02	0.38	0.07	0.008
Percent change during storage <sup>e</sup>					
Storage method	NDF	ADF	ADL	Ash	TEY
Covered pile	3.5 b	5.4 ab*	0.9 b	-4.2 a	-0.3 a
Uncovered pile	-1.6 a	9.1 b*	140.7 c*	44.6 b*	-15.1 b*
Silo bag	3.2 b	3.0 a	-10.9 a	-4.0 a	0.0 a
LSD <sup>c</sup>	3.5	3.9	42.6	16.5	5.5
P <sup>d</sup>	0.02	0.05	<0.0001	<0.0001	<0.0001

<sup>a</sup> Stover stored on October 27, 30 and November 3, 11 2007 and removed on June 24, 2008<sup>b</sup> Theoretical ethanol yield, L/Mg DM into storage<sup>c</sup> Different markers within the column group are statistically different at P=0.05<sup>d</sup> Results of ANOVA tests—effect is significant if P<0.05<sup>e</sup> Percent Change = (Final – Initial)\*100/Initial

\*P=0.05, indicates a statistically significant change in constituent during storage

showing that the mesh bag method is a good surrogate for estimated DM loss in the entire treatment (Table 3).

Loss of DM was very low for the silo bag despite the low initial moisture (Table 3). The pH of this material at removal was 6.7, and lactic, acetic, and total acids were 0.2%, 0.3%, and 0.5% of total DM, respectively, indicating very little fermentation took place. Despite this, DM losses

were very low because anaerobic storage conditions were maintained until removal. These results were consistent with those reported by Shinners et al. [18–20]. Losses of DM would be expected to be quite high for whole-plant corn silage ensiled in the range of stover moisture experienced here [12, 13]. Whole-plant corn silage also exhibited low levels of fermentation products when ensiled

**Table 3** DM loss of whole-plant stover stored in the fall of 2007 as measured by replicated mesh bag technique or change in dry mass of entire contents of storage treatment and estimated mold score

Storage method	Moisture into storage (% w.b.)	DM Loss (% of total)			
		Mesh Bags	Whole Structure	Mold Score <sup>b</sup>	TEY loss <sup>c</sup>
Covered pile	22.9	3.3 a	3.7	1	-17 a
Uncovered pile	23.8	39.1 b	33.3	4	49 b*
Silo bag	29.8	0.2 a	0.1	1	-18 a
LSD <sup>d</sup>		12.6			32
P <sup>e</sup>		<0.0001			<0.0001

<sup>a</sup> Stover stored on October 27, 30 and November 3, 11 2007 and removed on June 24, 2008<sup>b</sup> 1, little or no mold present, no mold odor; 2 mold present in some locations, some mold odor; 3, mold visible throughout, heavy mold odor; 4, high degree of mold, very strong mold odor<sup>c</sup> TEY loss = initial TEY – ((1 – DM loss)\*removal TEY; L/Mg DM into storage<sup>d</sup> Different markers in the same column group are statistically different (P=0.05)<sup>e</sup> Results of ANOVA tests, effect is significant if P<0.05

\*P=0.05, indicates a statistically significant change in TEY during storage

**Table 4** Physical properties of whole-plant and cob and husk stover harvested and placed into storage at two different periods in the fall of 2008

Storage method	Harvested October 27–31			Harvested November 18–21		
	Moisture (% w.b.)	Density <sup>a</sup> (kg DM/m <sup>3</sup> )	GMPS <sup>b</sup> (mm)	Moisture (% w.b.)	Density (kg Dm/m <sup>3</sup> )	GMPS <sup>a</sup> (mm)
Whole-plant stover						
Covered	57.0	70	41	35.7	73	55
Uncovered	58.1	74	38	48.3	63	57
Compost bag	57.6	96	48	36.2	86	65
Silo bag	54.1	176	49	44.4	88	—
Cob and husk stover						
Covered	45.8	111	47	37.2	90	59
Uncovered	47.1	106	59	35.2	93	60
Compost bag	46.6	166	55	37.8	129	59
Silo bag	44.7	169	62	31.7	160	92

<sup>a</sup> Density of stover in respective storage structure

<sup>b</sup> Geometric mean particle size as determined by ASABE Standard S424.1

at low moisture content [6, 9]. The difference here is that stover was removed in 1 day whereas ensiled animal feed would be removed daily from bunker or bag silos in relatively small quantities. In this research, the entire silo bag contents were removed in a single day. Pitt and Muck [14] modeled DM loss due to aerobic deterioration at feed out as inversely proportional to the feed out rate. DM losses due to aerobic deterioration of whole-plant corn silage at 35% DM decreased dramatically at feed out rates greater than 10 cm/day.

Losses of DM were also low for the covered pile (Table 3). The average initial moisture of the material was below 23% (w.b.; Table 1). Round bales of stover stored under cover in this moisture range had DM loss from 1.1% to 4.9% [18]. There was very little evidence of mold at removal, although there was some slight mold at the interface between the stover and the plastic cover, likely due to moisture condensation and higher levels of oxygen. Losses of DM in the uncovered pile were very high (Table 3). Since there was no barrier to prevent precipitation from entering the pile, high moisture in the pile caused considerable biological degradation. The material was observed to have a great deal of mold at removal. It was observed that the volume of the pile started to decrease within a few weeks of storage; and by the end of the storage period, the pile was less than half its original volume.

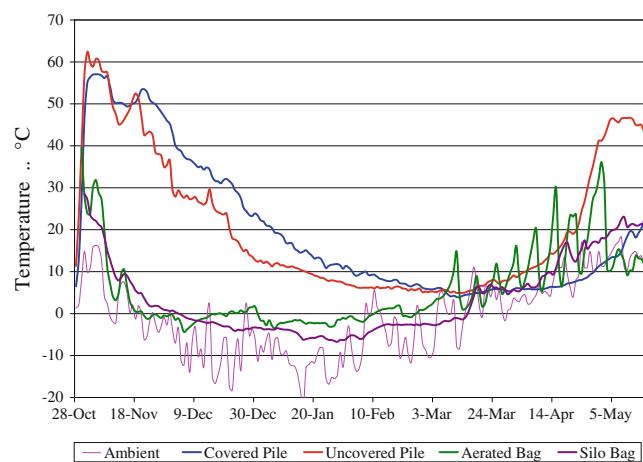
#### Particle Size, Density, Temperature—2008

The mean particle size for the early harvested stover was 44 and 56 mm for the whole-plant and cob/husk stover, respectively (Table 4). The mean particle size was 59 and 67 mm for whole-plant and cob/husk stover, respectively, for the later harvest (Table 4). The densities did not decrease remarkably in the later harvest as might be expected with lower moisture content and increased particle size.

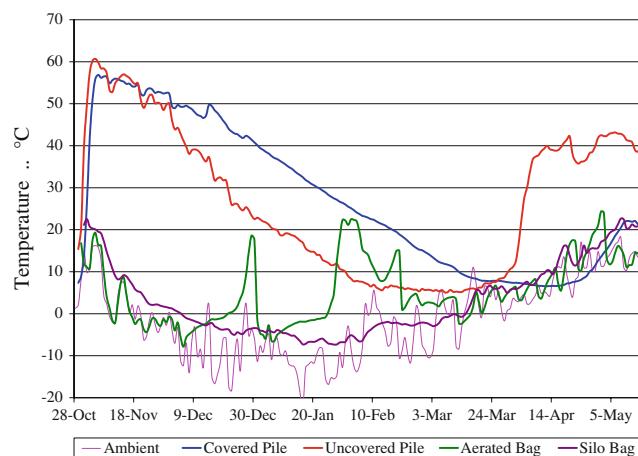
Grain moisture was 33% (w.b.) when harvested in late October, which was unusually high for south-central Wisconsin. The average stover moisture was 57% and 46% w.b. for the whole-plant and cob/husk stover, respectively. By November 18, the grain moisture had decreased to 25% (w.b.) while the stover moisture was 41% and 35% (w.b.), respectively.

The covered and uncovered aerobic pile treatments harvested in late October heated immediately for both stover materials (Figs. 2 and 3). Peak temperatures reached 72°C, which were sustained for several days in some locations. Temperatures above 35°C were maintained for long periods of time with both stover materials (Table 5). The uncovered piles of both stover materials began to heat again after the spring thaw when precipitation entered the pile and restarted biological activity.

The silo bag formed in late October with both stover materials followed the ambient temperature closely for the



**Fig. 2** Average stover temperatures for whole-plant stover harvested on October 27–31, 2008 and stored using four different storage methods. Average stover moisture was 57.7% (w.b.)



**Fig. 3** Average stover temperatures for cob/husk stover fraction harvested on October 27–31, 2008 and stored using four different storage methods. Average stover moisture was 46.1% (w.b.)

duration of the storage period. Temperatures rose quickly during the aerobic phase, and then temperatures declined and were very stable throughout storage (Figs. 2 and 3). Independent of stover material, this treatment had the lowest levels of heating as quantified by HDD (Table 5).

There was an initial temperature spike with the aerated bag, but internal temperatures dropped quickly following ventilation and followed ambient trends for most of the winter months. As ambient temperatures consistently exceeded 0°C, temperatures within the ventilated bag also started to rise. Operating the fan for 12 h over each of two consecutive nights temporarily reduced stover temperature, but prevented heating for only a few days. The level of heating was significantly less with this treatment compared to the other aerobic storage treatments (Table 5).

Compared to the earlier harvest date, there was less initial heating of the aerobic piles of stover harvested in mid-November, possibly because all the stover entered storage at or near-freezing temperatures (Figs. 4 and 5). The heating in the ventilated bag generally followed the same pattern as with the earlier harvest date. The level of heating in each storage treatment also was less for the later harvest date compared to the earlier harvest date (Table 5).

The silo bag formed at the later harvest date began heating after about 1 month in storage. At that time, it was observed that the seal around the thermocouples in this bag had become compromised. The tape and silicone sealant used to seal the holes were stiff due to low temperatures when the thermocouples were placed in the bag. This

**Table 5** Heating characteristics during storage of whole-plant and cob and husk stover harvested and placed into storage at two different periods in the fall of 2008

Storage method	Whole plant			Cob and husk		
	Max temp. <sup>b</sup> °C	No. of days <sup>c</sup> >35°C	HDD <sup>d</sup>	Max temp. <sup>b</sup> °C	No. of days <sup>c</sup> >35°C	HDD <sup>d</sup>
Harvested October 27–31 <sup>a</sup>						
Covered pile	69	30b	554b	70	45b	784b
Uncovered pile	72	37b	687b	67	64c	1108c
Aerated bag	62	2a	38a	66	5a	51a
Silo bag	34	0a	0a	25	0a	0a
LSD <sup>e</sup>		14	203		8	240
P <sup>f</sup>		<0.0001	<0.0001		<0.0001	<0.0001
Harvested November 18–21 <sup>a</sup>						
Covered pile	39	9b	100b	62	7b	92b
Uncovered pile	63	0a	10a	66	10b	103b
Aerated bag	33	0a	0a	30	0a	0a
Silo bag	60	29c	335c	62	26c	390c
LSD <sup>e</sup>		3	38		3	49
P <sup>f</sup>		<0.0001	<0.0001		<0.0001	<0.0001

<sup>a</sup> Stover removed from storage on May 20 and 21, 2009

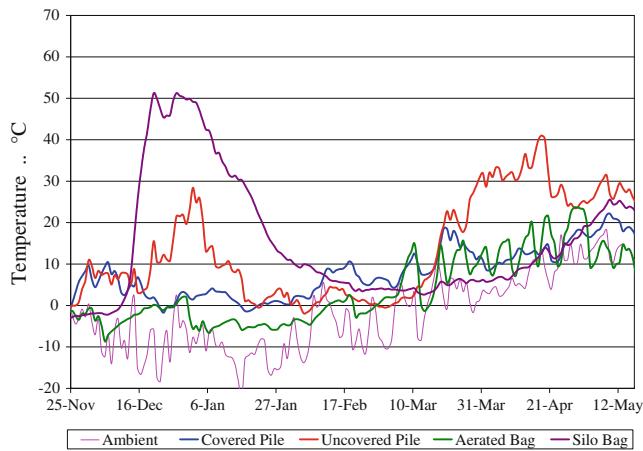
<sup>b</sup> Maximum temperature recorded in a given storage treatment during the storage period

<sup>c</sup> Average number of days for the storage treatment in which a temperature measurement location resided above 35°C

<sup>d</sup> Heating degree days—summation of the daily increment by which a temperature measurement location was greater than 35°C

<sup>e</sup> Different markers in the same column group are statistically different ( $P=0.05$ )

<sup>f</sup> Results of ANOVA tests, effect is significant if  $P<0.05$



**Fig. 4** Average stover temperatures for whole-plant stover harvested on November 18–21, 2008 and stored using four different storage methods. Average stover moisture was 41.2% (w.b.)

problem became worse with time as the stiff thermocouple wires were moved by the wind, snow and ice. Attempts were made to reseal the holes with additional silicone sealant and silo bag repair tape, but the low temperatures made these repairs ineffective and anaerobic conditions could not be maintained. Compounding this problem was the fact that the density of the whole-plant section of the silo bag was one half that obtained in the earlier harvest date (Table 4). The high porosity of this section of the bag created further difficulty maintaining an anaerobic environment.

The covered piles had the least amount of heating, except for a brief spike early in the storage of the cob/husk material (Fig. 5). Heating occurred again after the spring thaw in the uncovered treatments when precipitation increased moisture in the piles.

#### Moisture Content

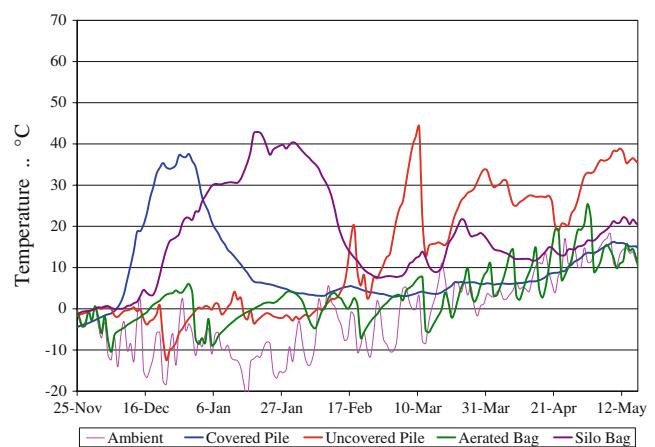
At the time of harvest, there was no significant difference in moisture concentrations between materials placed in the four storage treatments for either stover material harvested in October (Table 6). There were significant differences in moisture between treatments for stover harvested in November, but these were attributed to field variations. There was a significant loss of moisture during storage for both materials stored in the covered piles. This was attributed to the considerable heating causing evaporation of water. For instance, on cold days, water vapor could be seen exhausting from under the cover. Whole-plant stover stored in piles without cover gained moisture, although difference in moisture during storage was not significant. Uncovered piles of cob/husk had a significant loss of moisture during storage, again attributed to heating. The cob/husk stover also formed a better thatch or crust than the whole-plant stover, which may have helped reduce the

amount of precipitation entering the pile. Three of the four aerated bag treatments produced a significant loss of moisture. Since the aerated bags heated less than the other two aerobic treatments, the forced air ventilation probably helped dry the material. There was no significant difference in moisture in the silo bag where anaerobic conditions were maintained. There was a loss of moisture in the silo bag where anaerobic conditions were not maintained

Samples collected from a single cross-section near the top, sides, and core of the structures at removal showed moisture was generally greater near the top of all storage treatments (Table 7). This was attributed to precipitation in the uncovered treatment and water vapor condensation in the remaining treatments. The pile's core tended to have the lowest moisture of all the treatments. Individual thermocouples located in the core of the treatment had the greatest temperature rise. The silo bag where anaerobic conditions were maintained had the most uniform moisture distribution. Uniform composition is an important attribute for feedstocks that will be converted to bioproducts. Uniform moisture facilitates feeding bioreactors with the correct amount of DM and insures a more uniform treatment from chemical or biological amendments.

#### Storage Losses

All storage treatments except the anaerobic silo bag had greater than 10% loss of DM during storage for the material harvested on October 27–31 when the stover moisture content was 57.7% and 46.1% for the whole-plant and cob/husk materials, respectively (Table 8). Losses were greater for the whole-plant material because this material had greater moisture. The temperature history for aerobic piles showed a prolonged period of heating due to microbial metabolism which resulted in the large DM losses.



**Fig. 5** Average stover temperatures for cob/husk stover fraction harvested on November 18–21, 2008 and stored using four different storage methods. Average stover moisture was 35.5% (w.b.)

**Table 6** Aggregate moisture content (% w.b.) from the material in the mesh bags used to quantify DM loss filled with two different stover materials harvested at two different periods and stored using four different storage treatments

Storage method	Whole plant			Cob and husk		
	Into Storage	At Removal <sup>a</sup>	Difference <sup>b</sup>	Into Storage	At Removal <sup>a</sup>	Difference <sup>b</sup>
Harvested October 27–31, 2008						
Covered pile	57.0	33.7 a	-23.3 b*	45.8	24.6 a	-21.2 b*
Uncovered pile	58.1	62.8 b	4.7 a	47.1	25.3 a	-21.8 b*
Aerated bag	57.6	53.2 b	-4.4 a	46.6	24.5 a	-22.1 b*
Silo bag	54.1	57.4 b	3.3 a	44.7	44.1 b	-0.6 a
LSD <sup>c</sup>	3.6	13.7	14.8	3.1	4.3	5.4
P <sup>d</sup>	0.13	0.0008	0.001	0.43	<0.0001	<0.0001
Harvested November 18–21, 2008						
Covered pile	35.7 a	24.2 a	-11.5 b*	37.2 bc	24.2 ab	-13.0*
Uncovered pile	48.3 c	50.5 b	2.2 a	35.2 b	24.7 ab	-10.5*
Aerated bag	36.2 a	25.8 a	-10.4 b*	37.8 c	27.4 b	-10.4*
Silo bag	44.5 b	22.9 a	-21.5 c*	31.7 a	22.5 a	-9.2*
LSD <sup>c</sup>	3.7	8.2	8.2	2.2	3.4	3.9
P <sup>d</sup>	<0.0001	<0.0001	<0.0001	<0.0001	0.048	0.25

<sup>a</sup> Stover removed from storage structures on May 20 and 21, 2009

<sup>b</sup> Final—initial moisture content

<sup>c</sup> Mean values followed by different letters in the same column are significantly different at 95% confidence

<sup>d</sup> Results of ANOVA tests, effect is significant if  $P < 0.05$

\* $P = 0.05$ , indicates a statistically significant change from initial to final moisture

Although the temperature history did not show as much heating in the aerated bag, DM losses of both materials was similar to the aerobic piles. The DM losses combined with the chemical changes in storage caused a large loss of TEY. All the aerobic treatments were observed to have significant visual evidence of molds at removal.

The DM losses were numerically less for most treatments placed into storage at the later harvest date because

**Table 7** Aggregate moisture content (% w.b.) of samples collected at removal (stover removed from storage on May 20 and 21, 2009) from three locations at a single cross-section for two different stover materials harvested at two different periods and stored using four different storage treatments

Storage method	Whole-plant			Cob and husk		
	Top <sup>a</sup>	Side <sup>b</sup>	Core <sup>c</sup>	Top <sup>a</sup>	Side <sup>b</sup>	Core <sup>c</sup>
Harvested October 27–31, 2008						
Covered pile	62.9	41.7	27.6	49.7	42.4	25.7
Uncovered pile	84.8	84.4	71.6	76.5	80.2	39.0
Aerated bag	58.4	49.3	30.9	45.9	30.5	21.0
Silo bag	59.1	55.1	51.0	51.5	44.7	46.4
Harvested November 18–21, 2008						
Covered pile	45.6	40.4	24.1	44.2	30.8	25.1
Uncovered pile	74.4	86.1	48.4	72.5	79.1	37.3
Aerated bag	59.1	47.6	23.6	31.6	26.5	21.1
Silo bag	66.8	37.0	27.2	52.4	31.8	20.2

<sup>a</sup> Average of three samples collected from the top portion of pile or bag structures

<sup>b</sup> Average of three samples collected from the side of pile or sides of the bag.

<sup>c</sup> Average of four samples collected from the core or center area of pile or bags structures

the low temperatures delayed heating and average moisture of the whole-plant and cob/husk material was less (41.2% and 35.5%, respectively). The temperature history indicated long periods of heating in the aerobic treatments, corresponding to the DM losses that averaged 9.9% for the three aerobic treatments. Mold was evident in all treatments when removed from storage. The losses in the silo bag were similar to most of the other treatments because anaerobic conditions were not maintained in the bag. The temperature history indicated long periods of heating in this structure, leading to the unexpectedly high DM losses.

The silo bag with the late harvested material did not ensile properly because it was not kept anaerobic. Fermentation products were below detectable levels in these materials. The pH of the whole plant and cob and husk materials were 8.2 and 7.4, respectively, which are much higher than would be expected from similar material where anaerobic conditions were maintained. For the silo bag where anaerobic conditions were maintained, the pH levels were 4.7 and 4.8 and the fermentation products were 4.3% and 0.9% of DM for the whole plant and cob and husk materials, respectively. The fermentation products were almost entirely made up of lactic and acetic acids. The total acid production and pH were consistent with ensiled stover reported previously [18–20].

#### Composition

There were almost no statistical differences in measured constituents between materials placed into the four storage structures at harvest (Tables 9 and 10). The NDF, ADF, ADL, and ash content averaged across treatment and harvest date was 80.6% and 82.7%, 49.3% and 45.6%,

**Table 8** Loss of stover DM during storage (stover removed from storage on May 20 and 21, 2009) using replicated mesh bag technique; loss of theoretical ethanol yield (TEY); and estimated mold content for

two different stover materials harvested at two different periods and stored in four different structures

Storage method	Whole plant			Cob and husk		
	DM loss (% of DM)	TEY loss <sup>a</sup> (L/Mg DM)	Mold Score <sup>b</sup>	DM loss (% of DM)	TEY loss <sup>a</sup> (L/Mg DM)	Mold Score <sup>b</sup>
Harvested October 27–31, 2008						
Covered pile	20.2 b	92	3	13.2 b	56	3
Uncovered pile	24.5 b	110	4	12.4 b	57	3
Aerated bag	22.0 b	118	3	10.3 b	57	3
Silo bag	0.9 a	11	1	0.7 a	-3	1
LSD <sup>c</sup>	7.2			3.9		
P <sup>d</sup>	<0.0001			<0.0001		
Harvested November 18–21, 2008						
Covered pile	7.9 a	11	2	6.4	-3	2
Uncovered pile	23.3 b	88	4	8.2	11	3
Aerated bag	7.4 a	9	3	7.4	6	3
Silo bag	6.4 a	4	3	5.8	-4	3
LSD <sup>c</sup>	6.6			3.5		
P <sup>d</sup>	<0.0001			0.51		

<sup>a</sup> TEY loss = harvest TEY – ((1 – DM loss)\*removal TEY)

<sup>b</sup> 1—Little or no mold present, no mold odor 2—Mold present in some locations, some mold odor 3—Mold visible throughout, heavy mold odor 4—High degree of mold, decomposed stover

<sup>c</sup> Mean values followed by different letters in the same column are significantly different at 95% confidence

<sup>d</sup> Results of ANOVA tests, effect is significant if  $P < 0.05$

4.7% and 4.6%, and 5.5% and 3.7%; for the whole-plant and cob/husk stover, respectively. The greater NDF and lower ADF values for the cob/husk materials are consistent with that found by others [8].

Most of the compositional changes in storage resulted in an apparent gain in NDF, ADF, ADL, and ash as a result of DM loss from biological respiration. Many of these changes were statistically significant. For most constituents, there was significantly less change in chemical composition in the anaerobically stored stover harvested on October 27–31 compared to the other three storage treatments (Table 9). None of the remaining storage treatments revealed consistent trends in compositional changes.

Hemicellulose as estimated by NDF–ADF generally decreased for all early harvest treatments except the silo bag. Breaking down hemicellulose into monosaccharides can be an indication that respiration and hydrolysis occurred [4, 10]. The indigestible fraction of the hemicellulose remains and can lower NDF concentration [12]. Break down of hemicellulose and DM loss also occur on a smaller scale in normal anaerobic storage [11]. The remaining indigestible fraction after loss of soluble carbohydrates usually increases the fiber concentration [15], which may explain the general increase of ADL in treatments with high DM losses.

## Discussion

The corn crop dried more rapidly than expected in 2007. By the time stover was harvested, the stover moisture content was generally less than 30% (w.b.). The whole-plant stover stored in the covered aerobic pile and anaerobic silo bag for over 8 months conserved the stover quite well with small DM losses, minimal changes to the chemical composition and little or no mold growth. The uncovered aerobic pile was subject to considerable rehydration from precipitation which promoted biological activity so DM losses were high and extensive mold growth was evident. Although there were a few low moisture locations in the uncovered pile at removal, mold was evident in these locations as well. Stover in the aerobic covered pile was well conserved because the initial moisture content averaged below 25% (w.b.) and the plastic cover kept precipitation from rehydrating the stover, limiting biological activity. The material in the silo bag was maintained under anaerobic conditions throughout the storage period, so preservation was excellent, despite the low initial moisture.

By the last week in October 2008, the corn grain had only dried to 33% (w.b.), which is considerably greater moisture than typical for south-central Wisconsin [17]. However, delaying grain harvest for further field drying of

**Table 9** Chemical composition (% of DM) into storage and percent change in composition for two different stover materials harvested October 27–31, 2008 and stored using four different storage treatments. Stover removed from storage on May 20 and 21, 2009

Storage method	NDF	ADF	Lignin	Ash	TEY <sup>b</sup>
Whole-plant stover into storage					
Covered pile	80.5	48.8	4.2	7.2	423
Uncovered pile	77.3	49.4	4.6	6.5	407
Aerated bag	80.4	49.3	4.1	6.1	424
Silo bag	78.3	48.6	5.0	6.0	407
LSD <sup>c</sup>	8.0	3.2	2.1	2.3	47
P <sup>d</sup>	0.64	0.87	0.68	0.55	0.63
Percent change during storage <sup>d</sup>					
Covered pile	0.5 a	24.1 b*	104.7 b*	5.2 a	-2.1 b
Uncovered pile	-0.4 a	23.5 b*	101.9 b*	61.5 b*	-3.4 a*
Aerated bag	-3.6 a*	12.7 a*	105.5 b*	38.8 b*	-7.5 a*
Silo bag	3.5 c*	8.1 a*	25.8 a*	7.4 a	2.6 c
LSD <sup>c</sup>	2.4	5.0	27.4	27.8	2.6
P <sup>d</sup>	0.0002	<0.0001	<0.0001	0.002	<0.0001
Cob and husk stover into storage					
Covered pile	80.6	43.8	3.2	4.1	423
Uncovered pile	82.7	45.2	3.5	3.4	432
Aerated bag	83.1	45.5	3.3	3.8	436
Silo bag	80.2	44.6	5.7	4.3	406
LSD <sup>c</sup>	5.3	2.0	5.7	2.2	52.6
P <sup>d</sup>	0.44	0.25	0.61	0.71	0.49
Percent change during storage <sup>d</sup>					
Covered pile	2.0	22.2 d*	112.0 b*	36.2 b*	-0.1 ab
Uncovered pile	0.4	19.3 c*	86.2 b*	48.7 b*	-1.0 b
Aerated bag	-0.2	13.1 b*	103.6 b*	1.9 a	-3.1 a
Silo bag	1.4	6.9 a*	1.6 a	-10.7 a	2.4 b
LSD <sup>c</sup>	3.0	2.8	27.9	21.6	3.3
P <sup>d</sup>	0.48	<0.0001	<0.0001	<0.0001	0.02

<sup>a</sup> L/Mg DM

<sup>b</sup> Mean values followed by different letters in the same column are significantly different at 95% confidence

<sup>c</sup> Results of ANOVA tests, effect is significant if  $P<0.05$

<sup>d</sup> Percent Change =  $(\text{Final} - \text{Initial}) * 100 / \text{Initial}$

\* $P=0.05$  indicates a statistically significant change in constituent during storage

the grain would not be an option because of the risk of snowfall. The stover moisture was at 57% and 46% (w.b.) for whole-plant and cob/husk materials, respectively. Stover at this range of moisture has been successfully conserved in anaerobic conditions [18–20] but no previous research was found to suggest successful preservation at this moisture range under aerobic conditions.

As expected, the silo bag where anaerobic conditions were maintained preserved the material very well. None of the aerobic storage methods preserved the stover DM and there was considerable mold growth throughout all three aerobic structures. The heating in the covered and uncovered piles was prolonged and reached temperatures where spontaneous combustion was a concern, as peak temperatures of 73°C were measured in the piles. The whole plant, uncovered pile was in the worst condition with precipitation penetrating deep into the pile because there was no visible thatch or crust to help shed moisture. The cob/husk uncovered pile was observed to have formed a better crust or thatch and was able to keep some precipitation from the

interior of the pile, but losses and material decomposition were still very high.

Ideally, forcing ambient temperature air through the stover in an enclosed bag would have dried the stover, helping with preservation. Drying did occur near the ventilation tube, but at removal from storage moisture away from the tube was still well above 30% (w.b.) in most cases. Although the material around the ventilation tube was dry and generally free of mold, the rest of the aerated bag was poorly preserved with considerable evidence of mold.

The second harvest occurred in the third week of November when ambient temperatures were near freezing but the grain was 25% (w.b.), still well above typical [17]. This harvest date would be quite late for south central Wisconsin due to concerns with snowfall. Despite the late harvest date, whole-plant and cob/husk moisture was 41% and 35% (w.b.), respectively, so that successful preservation under aerobic conditions was still difficult. There was less heating and generally lower losses than when stover

**Table 10** Chemical composition (% of DM) into storage and percent change in composition for two different stover materials harvested November 18–21, 2008 and stored using four different storage treatments. Stover removed from storage on May 20 and 21, 2009

Storage method	NDF	ADF	Lignin	Ash	TEY <sup>b</sup>
Whole-plant stover into storage					
Covered pile	84.5	49.0	4.1 a	4.7 b	442
Uncovered pile	79.2	49.8	5.4 b	4.9 b	411
Aerated bag	83.8	48.7	4.7 ab	4.0 a	436
Silo bag	81.1	50.9	5.2 ab	4.5 ab	423
LSD <sup>c</sup>	5.3	2.5	1.2	0.5	30
P <sup>d</sup>	0.14	0.22	0.12	0.04	0.14
Percent change during storage <sup>d</sup>					
Covered pile	7.5 b*	12.8 a*	49.9 ab*	15.9 a	5.9
Uncovered pile	4.7 a*	23.9 b*	73.7 b*	68.3 c*	2.5
Aerated bag	6.5 b*	12.4 a*	32.0 a*	62.6 bc*	5.8
Silo bag	7.2 b*	14.1 a*	41.3 ab*	17.7 ab	5.8
LSD <sup>c</sup>	1.7	3.7	31.7	47.1	7.2
P <sup>d</sup>	0.04	<0.0001	0.12	0.02	0.62
Cob and husk stover into storage					
Covered pile	84.0	47.3	5.3	3.8	431
Uncovered pile	84.4	46.6	5.3	3.4	432
Aerated bag	83.2	46.0	5.3	3.2	425
Silo bag	83.1	46.0	5.1	3.4	426
LSD <sup>c</sup>	7.2	2.2	2.3	1.6	35
P <sup>d</sup>	0.95	0.38	0.99	0.76	0.94
Percent change during storage <sup>d</sup>					
Covered pile	7.6*	10.7 ab*	14.1	-10.3 a	7.6*
Uncovered pile	5.6*	14.1 c*	15.5	12.7 b*	6.1*
Aerated bag	6.6*	8.7 a*	12.4	26.6 b*	6.5*
Silo bag	7.1*	12.3 bc*	16.7	25.1 b*	7.2*
LSD <sup>c</sup>	2.9	2.7	18.9	19.4	3.3
P <sup>d</sup>	0.54	0.005	0.97	0.004	0.78

<sup>a</sup> L/Mg DM

<sup>b</sup> Mean values followed by different letters in the same column are significantly different at 95% confidence

<sup>c</sup> Results of ANOVA tests, effect is significant if  $P<0.05$

<sup>d</sup> Percent Change =  $(\text{Final} - \text{Initial}) * 100 / \text{Initial}$

\* $P=0.05$  indicates a statistically significant change in constituent during storage

moisture was greater, but DM losses for all aerobic treatments still approached 10% and there was evidence of mold throughout each of the treatments.

The difference in drying rate of the standing crop between the 2 years of this study demonstrates year-to-year variations can cause the moisture of single-pass stover to vary considerably. What is needed are robust harvest and storage schemes that ensure excellent preservation no matter what the stover moisture. Successful stover conservation is quantified by low DM losses, minimal compositional changes and almost no mold growth. Only two storage methods met these criteria: stover stored in covered aerobic piles when stover moisture was less than 25% (w.b.) or stover stored anaerobically. The former system will likely not work for single-pass stover harvest except in those areas where the stover moisture can be expected to consistently reach 25% (w.b.) well before the winter weather ends the harvest season. In most of the US Corn Belt, this would not be the case, so a two-pass harvest system would be required where stover would be field wilted to the desired moisture prior to harvest. Anaerobic storage is the most robust method

because it has been shown to produce excellent conservation over a wide variety of stover moisture. This is the only system that will provide the maximum flexibility with respect to weather and crop moisture. If single-pass stover harvest systems are used, preservation by anaerobic storage would be required.

A summary of previous research where stover was stored anaerobically shows DM loss averaged 3.3% across a wide range of moisture and ambient conditions (Table 11). Fermentation products and pH were well correlated with initial stover moisture. Pitt [13] suggested that bacteria will be suppressed when the silage enters the stable phase when the ensiled animal feed reaches 3.8–5.0 pH. Lactic and acetic acid are the most common acids formed during fermentation and the acidity ( $\text{pK}_a$ ) of these acids is 3.85 and 4.75, respectively, which limits the pH of most ensiled stover to 4.0–4.5 no matter the quantity of fermentation products. Conversion of cell wall contents to fermentation acids would be considered a loss if these acids could not be converted to useful products at the biorefinery, so it would be appropriate to achieve the desired pH for stability while

**Table 11** Summary (after Shinners et al. [18–20]) of storage characteristics of whole-plant and cob/husk stover stored 7–9 months in anaerobic silo bags

Year into storage	Material type <sup>a</sup>	Into storage moisture (% w.b.)	DM loss (% of total)	pH	Total acids <sup>b</sup> basis (% DM)	Density.. (kg/m <sup>3</sup> )	
						wet basis	dry basis
2003	WP	41.7	1.4	4.1	5.0	227	131
2003	WP	55.4	3.8	4.1	4.2	275	122
2004	WP	42.2	6.0	4.8	2.4	170	96
2004	WP	42.8	4.2	4.8	3.6	224	128
2005	WP	51.3	4.1	4.2	5.9	390	194
2005	WP	50.1	3.5	4.2	5.3	245	120
2006	WP/CH	34.5	4.4	4.6	2.0	243	157
2007	WP	26.7	3.5	6.3	0.5	192	141
2008	WP	54.1	0.9	4.7	4.8	383	176
2008	CH	44.7	0.7	4.3	0.9	306	169

<sup>a</sup>Type of stover—WP whole-plant stover, CH cob/husk stover

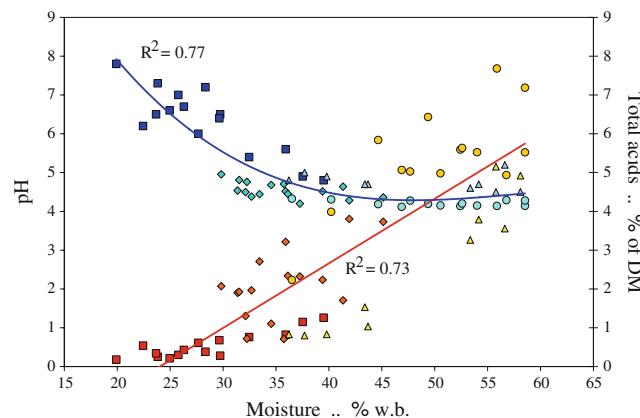
<sup>b</sup>Fermentation products consisted mainly of lactic and acetic acid

limiting the quantity of fermentation products. Individual samples of ensiled stover from silo bags stored in 2005 through 2008 were analyzed for pH and total fermentation acids and the data plotted versus wet basis moisture (Fig. 6). If the goal is to achieve a pH of 4.0–4.5 but not excessively convert carbohydrates to fermentation products, this plot indicates the desired harvest and storage moisture would be in the range of 35–45% (w.b.). This moisture requires considerably less water to be shipped compared to stover in the range of 45–60% (w.b.). For instance, if legal weight limits can be achieved, 44% more DM can be shipped when stover moisture is 35% (w.b.) compared to when it is 55% (w.b.). Low levels of fermentation products

in ensiled animal feed would create concerns with aerobic stability at feed out, but feed out rate of biomass destined for a biorefinery would be comparatively much faster. Nonetheless, aerobic stability of ensiled biomass with low levels of fermentation products merits further research.

## Summary

- Storage characteristics of two types of stover were investigated: whole-plant consisted of stalk, leaf, cob, and husk (2007 and 2008) and cob/husk consisted of cob, husk and some top stalk (2008). Both materials were harvested using a single-pass harvester.
- In all cases, stover stored in uncovered piles was rehydrated from precipitation, which increased biological activity and produced DM losses from 8.2% to 39.1% with an average of 21.5%. When moisture content was greater than 46% (w.b.), temperatures in the structure averaged greater than 35°C for prolonged periods.
- Stover in covered piles was successfully conserved when the average moisture was less than 25% (w.b.) with DM losses of 3.3% (2007). Stover above 36% (w.b.) and piled under a plastic cover heated during storage and had losses of DM from 6.4% to 20.2% with an average of 11.9%.
- An aerated bag was investigated as a method to use ambient air forced through the stover with a fan and perforated tube to dry the stover. Stover near the tube did dry, but the remainder of the bag did not. Loss of DM ranged from 7.4% to 22.0% with an average of 11.8%.



**Fig. 6** pH (upper curve) and total fermentation acids (lower line) as a function of moisture for whole-plant stover stored at least 7 months in anaerobic silo bags. Individual samples collected from silo bags at removal. Stover stored in 2005 (filled circle), 2006 (filled diamond), 2007 (filled square) and 2008 (filled triangle). After Shinners et al. [18–20]

- Mold was evident throughout most the aerobic structures at removal and the stover moisture varied spatially in the structures. The exception was the material under the covered pile stored at less than 25% (w.b.) moisture.
- Stover was most successfully conserved in the anaerobic silo bag. In two of the three bags formed, anaerobic conditions were maintained and DM losses ranged from 0.2% to 0.9%. In one case, holes where thermocouples were placed through the plastic bags were poorly sealed so anaerobic conditions were not maintained, and little fermentation took place, so DM losses averaged 6.1% of DM.

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