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Abstract
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Keywords
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Article

Outdoor Storage Characteristics of Single-Pass Large Square Corn Stover Bales in Iowa

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Abstract: Year-round operation of biorefineries can be possible only if the continuous flow of cellulosic biomass is guaranteed. If corn (*Zea mays*) stover is the primary cellulosic biomass, it is essential to recognize that this feedstock has a short annual harvest window (≤1–2 months) and therefore cost effective storage techniques that preserve feedstock quality must be identified. This study evaluated two outdoor and one indoor storage strategies for corn stover bales in Iowa. High- and low-moisture stover bales were prepared in the fall of 2009, and stored either outdoors with two different types of cover (tarp and breathable film) or within a building for 3 or 9 months. Dry matter loss (DML), changes in moisture and biomass compositions (fiber and ultimate analyses) were determined. DML for bales stored outdoor with tarp and breathable film covers were in the ranges of 5–11 and 14–17%, respectively. More than half of the total DML occurred early during the storage. There were measurable differences in carbon, hydrogen, nitrogen, sulfur, oxygen, cellulose, hemi-cellulose and acid detergent lignin for the different storage treatments, but the changes were small and within a narrow range. For the bale storage treatments investigated, cellulose content increased by as much as 4%s from an initial level of ~41%, hemicellulose content changed by −2 to 1% from ~34%, and acid detergent lignin contents increased by as much as 3% from an initial value of ~5%. Tarp covered bales stored the best in this study, but other methods, such as tube-wrapping, and economics need further investigation.

Keywords: single-pass corn stover large square bales; dry matter loss (DML); outside storage characteristics

1. Introduction

Achievement of the target set by the Energy Independence and Security Act (EISA) of 2007 to produce 60 billion liters (16 billion gallons) of cellulosic biofuels annually in the United States by 2022 will require around 200 million tons (dry) of cellulosic feedstocks each year [1]. The fact that the cellulosic feedstocks are harvested within a short span of time, usually between 1–2 months, and are required by the biorefineries over the whole year necessitates their effective and efficient storage. Different types of cellulosic feedstocks, including agricultural residues, such as corn stover and soybean (*Glycine max* L. Merr.) straw, and energy crops, such as switchgrass (*Panicum virgatum*) and miscanthus (*Miscanthus* × *giganteus*), are being stored in different ways, such as bales, piles and silos, in different parts of the United States. Collection of cellulosic biomass as bales in a single-pass is one of the options for in-field biomass collection. The single-pass collection method is advantageous compared to the multi-pass method due to their reduced ash content, and the biomass collection as bales has advantage over bulk collection due to their enhanced bulk density. In addition to these notable advantages, single-pass bales have some disadvantages, primarily the inability to control moisture content prior to harvest. This may adversely affect the bale storage characteristics. Therefore, this study focuses on the storage characteristics of large square single-pass corn stover bales in Iowa, one of the principal, Midwestern corn growing states.

Most related previous studies [2–8] were based on the storage of multi-pass bales formed with different types of biomass under different conditions and at different geographical locations. Blunk *et al.* [2] found the dry matter loss (DML) of large square rice straw bales stored under different indoor and outdoor storage treatments for a year to be in the range of 10 to 60%. Huhnke [3] found the DML of large round multi-pass wheat hay bales stored under different conditions (storage inside barn and several combinations of outdoor storage) for 10 months in Chickasha, Oklahoma to be in the range of 6.4 to 19.3%. Sanderson *et al.* [4] found the storage DML of large round bales of switchgrass stored either outdoor unprotected above grass sod or gravel pad, or indoor above concrete for 6 and 12 months in Stephenville, Texas to be in the range of 0 to 13%. Shinners [5] investigated the storage characteristics of large square alfalfa bales under treatments with propionic acid, bacterial inoculant and formation of 0.08 or 0.12 m diameter vent hole through the bale center, and found that the storage DML didn't significantly change under any treatment, when compared to the control bales. Shinners *et al.* [6] studied the wet and dry storage characteristics of corn stover bales stored for around 9 months, at the University of Wisconsin Arlington Agricultural Research Station. They found the storage DML for wet tube-wrapped, and dry indoor and outdoor stored bales to be 2.4, 3.3 and 18.1%, respectively. Shinners *et al.* [7] investigated the storage characteristics, including DML, of large round and square alfalfa bales stored as individually and tube-wrapped. They found that the average DML of bales with initial moisture in the ranges of 30 to 40 and 40 to 55%$_{wb}$ were 3.5 and 2.3%, respectively. Shinners *et al.* [8] studied the effects of wrap types and storage methods on the preservation of large round alfalfa bales stored for 5 to 11 months, and found the DML for outdoor stored bales with different wrap types to be between 7.2 and 19.5%. Additionally, they found the DML of outdoor stored plastic covered and indoor stored bales to be 4.5 and 1.9%, respectively.

All of the studies discussed so far were based on the storage of multi-pass bales, but to meet the biorefineries' quality demands, alternative methods for feedstock storage need to be evaluated. Single-pass bales have advantages over multi-pass bales in that they have significantly lower ash levels, but to date, storage characteristics of single-pass bales have not been determined. The objective of this study was to investigate the storage characteristics of low and high moisture, single-pass corn stover bales stored either outdoors on wooden pallets and under two different types of cover [tarp or a breathable film (brand name Tyvek) through which water vapor can pass, but which does not allow liquid water to penetrate], or on a concrete floor within a metal building for short (3 months) or long (9 months) durations. The DML, changes in moisture, biomass composition (as determined by fiber and ultimate analyses and heating values during storage were investigated.

2. Materials and Methods

2.1. Bales Used for Storage

Corn stover used in this study was harvested in the fall of 2009 with a John Deere Class 8 combine with a 12 row corn head, and was collected in a single-pass from the fields located in Iowa State University research farms in Story County. Collected stover was then baled using a single-pass AGCO baler configured to make square bales of dimensions 0.91 m high × 1.22 m wide × 2.44 m long. Bales were harvested at two moisture levels, designated as low and high, and were characterized with the typical values around 15–20 and 30–35$\%_{wb}$, respectively. High and low moisture level bales were harvested and stored between 4–6 November 2009 and 14–16 November 2009, respectively.

2.2. Storage of Bales

The low- and high-moisture bales were stored for short (~3 months) and long (~9 months) time periods in three different ways: (1) outdoors covered with a tarp, (2) outdoors covered with a breathable film, or (3) indoors in a metal building. This created seven different treatment combinations (TC) as briefly described in Table 1. For TC 1 through TC 4, tarps were used to restrain the flow of water across the bales. This technique is widely used to protect biomass during outdoor storage. For TC 5 and TC 6, a breathable film, which allows for the outflow of water vapor while restraining water inflow, was used to protect the bales. This material is widely used to protect buildings during construction. Finally, for TC 7, low moisture bales were stored on a concrete floor inside a non-insulated metal building. Bales were stored in stacks of 4 (2 wide × 2 high) and 6 (3 wide × 2 high) bales; but, some of the long term stored treatment bales could not be sampled for DML determination due to the technical difficulties (Table 1). However, all bales were sampled for moisture measurement.

Table 1. Summary of different bale storage treatments.

Storage Types	#Storage Moisture Content ($\%_{wb}$)	* Storage Durations	Treatment Combination ID	Total Stored Bales	Total Sampled Bales
Storage Type 1: Outside storage with tarp cover	Low	Short	TC 1	6 (1 stack)	6
		Long	TC 2	12 (2 stacks)	9
	High	Short	TC 3	6 (1 stack)	5
		Long	TC 4	6 (1 stack)	6
Storage Type 2: Outside storage with breathable film cover	Low	Short	TC 5	6 (1 stack)	6
		Long	TC 6	12 (2 stacks)	7
Storage Type 3: Inside storage within a metal building	Low	Long	TC 7	8 (2 stacks)	7

"Low" and "High" are characterized with ~15–20 and 30–35$\%_{wb}$ moisture contents, respectively.

* "Short" and "Long" term storage durations are characterized by ~3 and 9 months, respectively.

2.3. Measurements

Each bale was weighed before and after storage by placing it on a hayrack equipped with a weighing balance (Avery Weigh-Tronix, LLC, Fairmont, MN, USA). The capacity of the balance was 9000 kg with tolerance of 1 kg. Dry matter loss (DML) was determined as a percentage based on the difference of the initial and final dry matter weights. Bale densities were computed by dividing the dry weight by bale volume. Following the designated storage period, bales were sampled for moisture content and compositional analyses. Approximately 1 kg of bulk stover was collected before making each bale and dried to determine moisture content [9]. For compositional analyses, small sample was collected before each bale was made and mixed together to provide approximately 10 kg of sample, in total. After each storage period, bales were torn apart, and approximately 1 kg of sample from each bale was used to determine moisture content [9]. Another kg was collected from each test bale and mixed together to provide 6 to 9 kg of sample of each treatment combination.

Storage effects on feedstock properties were evaluated using: (1) short proximate analysis to yield total moisture, ash and sulfur [10–12], (2) ultimate analysis to yield carbon (C), hydrogen (H), nitrogen (N), total sulfur (S) and oxygen (O) (by difference) [13], and (3) chemical characterization to yield fractions of neutral detergent fiber (NDF), acid detergent fiber (ADF), and acid detergent lignin (ADL) [14,15]. The contents of cellulose and hemi-cellulose were then obtained from the values of NDF, ADF and ADL. The analyses were performed at Minnesota Valley Testing Laboratories, Inc., New Bismarck, ND. Higher heating values (*HHV*) of pre- and post-stored biomass were estimated from the results of ultimate analyses using Equation 1 [16]:

$$HHV = -1.3675 + 0.3137 \times C + 0.7009 \times H + 0.0318 \times O \quad (1)$$

where, *HHV* (MJ kg^{-1}) is the higher heating value of the biomass; *C*, *H* and *O* are respectively the percentages (dry basis) of carbon, hydrogen and oxygen in biomass, as determined by ultimate analysis of the samples.

2.4. Statistical Analysis

Statistical analysis was performed to determine the least significant differences between average DML and average change in moisture contents of different treatments at the 95% confidence interval. This analysis was done using "One-Way Analysis of Variance (ANOVA)" multiple comparison method in Minitab. Statistical analysis was not performed on compositional results as these tests were conducted and certified by an external lab, but were not replicated because of cost.

3. Results and Discussion

3.1. Physical Characteristics of Bales Stored under Different Treatment Combinations

3.1.1. Outdoor Storage of Bales with Tarp Cover

Low moisture bales stored outdoors for short- and long-term periods with tarp cover (*i.e.*, TCs 1 and 2) had an average DML of 6 and 11%, respectively (Table 2). Comparing the average DML for the two storage treatments indicates that most of the loss occurred early, as DML for the short term (3 months) treatment (TC 1) was more than half that measured with long term (9 months) storage (TC 2) even though the short term storage duration was only 33% of long term duration. High initial dry matter degradation was pre-dominantly due to initial respiration of stored biomass [17]. Variability in DML and biomass moisture, across the replicates of same treatment was uncontrollable during field storage experiments. Therefore, statistical multiple comparison results show that average DML values were not significantly different. However, the average change in moisture was negligible for TC 1, whereas it increased by around 9 percentage units for TC 2 bales.

Table 2. Summary of physical properties of bales stored under different treatment combinations.

+ Treatment Combination ID	‡ Range of dry matter stored (kg)	#,‡ Initial dry densities of stored bales (kg m^{-3})	#,‡ Moisture Content (%$_{wb}$)			#,‡,† DML (%)
			Initial	Final	*,† Change	
TC 1	373–424	134(6)	18(4)	18(1)	−0(4) abc	6(2) a
TC 2	400–463	141(8)	15(4)	24(11)	9(14) c	11(4) ab
TC 3	369–468	134(9)	33(3)	24(1)	−10(2) ab	5(3) a
TC 4	384–437	129(7)	31(5)	17(1)	−14(5) a	8(5) ab
TC 5	392–466	137(10)	22(3)	22(3)	1(4) bc	14(7) bc
TC 6	414–574	146(9)	19(5)	29(11)	11(12) c	17(5) c
TC 7	365–458	135(9)	19(6)	16(2)	−3(6) ab	8(4) ab

+ Descriptions of different treatment IDs included in Table 1; ‡ All values are rounded to the nearest whole number; # Values are the average over all the replications, with standard deviation in parentheses; * Positive values signify increase in moisture content of bales during storage; † Means followed by dissimilar letters are significantly different ($p < 0.05$).

High moisture bales stored under tarp cover for either short or long periods, (*i.e.*, TCs 3 and 4), had an average DML of around 5 and 8% respectively (Table 2). Statistically, these changes were not different from TC 1 and TC 2 bales. More than half the DML for high moisture, tarped bales also occurred during the first 3 months of storage. Furthermore, in contrast to low initial moisture tarped bales, high initial moisture tarped bales lost water during storage (10 and 14 percentage units, respectively), probably due to a higher rate of heating. The final moisture content of all bales stored within TCs 1–4 were in the range of 17 to 24%$_{wb}$, suggesting that for this region, that may be equilibrium moisture content for bales stored outdoors under tarp.

3.1.2. Outdoor Storage of Bales with Breathable Film Cover

Low moisture bales stored for short and long terms with breathable film cover (*i.e.*, TCs 5 and 6) had an average DML of 14 and 17%, respectively (Table 2). Like TCs 1–4, comparisons of average DML for TC 5 and 6 indicate that most dry matter degradation occurred early during storage. Average DML for low initial moisture breathable film covered bales was significantly higher than tarp covered low moisture bales stored for same storage duration. Furthermore, average changes in bale moisture for TCs 5 and 6 were similar to TC 1 and 2. Average change in bale moisture during short term storage was negligible for TC 5, whereas it increased by around 11 percentage units for TC 6 bales. Interestingly, for both TCs 5 and 6, the final bale moisture was in the range of 22 to 29%$_{wb}$, which was close to the range observed for TCs 1–4 bales.

3.1.3. Indoor Storage of Bales within Metal Building

Low initial moisture bales stored indoors for 9 months (TC 7) had an average DML of 8%, which was numerically lower than for bales with similar initial moisture content when stored outdoors under tarp or breathable film cover for same duration (TCs 2 and 6). Statistically, average DML for TC 2 and TC 7 bales was not different, but average DML for indoor storage may have been slightly lower due to enhanced protection from ambient conditions. During storage, moisture content for TC 7 bales decreased by around 3 percentage units. Furthermore, bales stored indoors had a final moisture content of 16%$_{wb}$.

3.2. Chemical Characteristics of Bales Stored under Different Treatment Combinations

Ultimate and fiber analyses based chemical properties of bales stored under different treatment combinations are summarized in Table 3. It should be noted that chemical characterization tests were performed only on different long term stored samples, and ash contents of stored biomass were not determined. However, for quantifying oxygen content in stored biomass, their ash contents were assumed to be equal to that of original biomass. Ash contents of low and high initial moisture single-pass bales were 3.1 and 2.7 wt.% (dry basis), respectively (Table 3), which are lower than ash content of multi-pass bales. Ash content of multi-pass bales can be more than 11 wt.% (dry basis) [18].

Percentage of C, H, N, S and O in originally stored low and high initial moisture bales were almost same, and were around 46, 5.8, 0.5, 0.06 and 44.7 wt.%, respectively (Table 3). For bales stored under different treatment combinations, changes in different ultimate analytes were almost the same. For different treatment combinations, changes in C, H, N, S and O were 3.3–3.7% (decrease), 0.3–0.4% (increase), 0.1–0.4% (increase), 0.06% (decrease), and 2.7–3.2% (increase).

Table 3. Summary of chemical properties of bales stored under different treatment combinations.

Storage Type	Storage Phase	* Ultimate Analysis Results (wt.%)						* HHV (MJ kg^{-1})	* Fiber Analysis Results (wt.%)		
		Ash Content	C	H	N	S	$^{\Delta}$O		Cellulose	Hemi-Cellulose	Lignin
Originally stored, Low moisture biomass	Before	3.1	45.8	5.8	0.5	0.06	44.7	18.5	41.9	35.1	3.7
Originally stored, High moisture biomass	Before	2.7	46.4	5.8	0.5	0.06	44.6	18.7	41.5	32.9	5.3
Tarp-covered, low moisture, long term stored	After	† ND	42.2	6.2	0.7	0.00	47.8	17.7	41.3	35.9	5.3
	$^{\#}$ Change	-	−3.7	0.4	0.2	−0.06	3.1	−0.8	−0.5	0.8	1.5
Tarp-covered, high moisture, long term stored	After	ND	42.8	6.1	0.7	0.00	47.6	17.8	45.4	32.7	6.9
	$^{\#}$ Change	-	−3.6	0.3	0.1	−0.06	3.1	−0.9	3.9	−0.1	1.6
Breathable film-covered, low moisture, long term stored	After	ND	42.1	6.1	0.8	0.00	47.8	17.6	42.3	33.7	6.5
	$^{\#}$ Change	-	−3.7	0.3	0.4	−0.06	3.2	−0.9	0.4	−1.4	2.8
Indoor storage, low moisture, long term stored	After	ND	42.5	6.2	0.8	0.00	47.4	17.8	42.1	35.1	5.3
	$^{\#}$ Change	-	−3.3	0.4	0.3	−0.06	2.7	−0.7	0.3	0.0	1.6

* All values are in dry basis; $^{\#}$ "Negative" sign indicates decrease in respective values and *vice versa*; † "ND" refers to "Not Determined"; $^{\Delta}$ Although ash content was not determined for stored bales, for the estimation of oxygen content by difference in post storage biomass, ash content of stored biomass was taken same as the original biomass.

Furthermore, the initial HHVs for low and high initial moisture bales were 18.5 and 18.7 MJ kg^{-1}, respectively (Table 3). For bales stored under different treatment combinations, cellulose increased by around 4 wt.% for high initial moisture bales whereas changed negligibly for low moisture bales. Hemicellulose content changed in either direction, and ranged between increase by 0.8 wt.% to decrease by 1.4 wt.%. For different storage treatments, ADL content increased by 1.5–2.8 wt.%, probably due to their higher resistance to biological degradation. HHV of stored biomass decreased by 0.7–0.9 MJ kg^{-1}.

4. Conclusions

Interactions between initial moisture content, and type and duration of storage on physical and chemical characteristics of corn stover bales were investigated. Covering with tarp preserved bales better than breathable film during outdoor storage in Iowa. For investigated storage treatments, more than half of total dry matter degradation occurred early in the storage. Additionally, changes in biomass compositions (ultimate and fiber analyses) were within a narrow range for different storage treatments. Although tarp preserved bales stored well in this study, other methods for outdoor bale storage, such as tube-wrapping, should be investigated. Furthermore, for the overall success of baled corn stover supply chain, economic feasibility of different storage methods should be evaluated.

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