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Anaerobic Storage Characteristics of Whole-Ear Corn and Stover

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Abstract: Whole-plant corn has been previously investigated as a biomass feedstock. Current approaches are analogous to harvesting whole-plant corn for livestock feed or biogas production. They include utilizing a self-propelled forage harvester to harvest the plant as a bulk material and storing it anaerobically. This process leads to grain damage, reducing the marketability of the grain after fractionation. This work investigated a process that included harvesting and anaerobically storing whole-ear corn with corn stover as an alternative. Over two harvest seasons, dry matter losses, moisture content changes, and grain damage were assessed after anaerobic storage. Less than 3% grain damage was observed across all treatments. Stover moisture decreased by 3% to 7% wet basis. Depending on the harvest year ($p < 0.001$), grain moisture content increased by 7 to 10 percentage points wet basis ($p = 0.012$). Cob moisture increased by about four percentage points wet basis regardless of harvest year ($p = 0.49$). Dry matter losses for the overall treatment were less than 3% across both harvest seasons, but high variability was observed when reviewing the losses in the ear and stover fractions. Based on this work, whole ear storage should be considered where subsequent grain fractionation and the marketability of the grain fraction are a concern.

Keywords: biomass; feedstock; whole-plant corn; ethanol; biofuel; zea mays

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1. Introduction

A novel biomass feedstock system has been proposed to harvest and store corn stover as a whole-plant material [1]. This system offers cost advantages over traditional corn stover and grain feedstock systems, including reduced harvest, transport, and storage costs, and better control over feedstock quality. While comparable to whole-plant corn utilized for animal feed, the whole-plant corn here is stored at a high dry matter (i.e., >40% dry matter). Anaerobic storage at high dry matter minimizes carbohydrates utilized during fermentation and transportation of non-value-added water. However, the storage density and aerobic stability are reduced.

While the whole-plant feedstock system offers many advantages, current biorefining processes necessitate the separation of the lignocellulose (stover) and starch-based (grain) anatomical fractions. The separation of grain and stover has been achieved at high product yields, but the system is complicated by the amount of grain damaged during the harvest process [2]. An alternative harvest system that minimizes grain damage would facilitate grain separation yield.

The seed corn industry has achieved a high yield of corn grain by harvesting and transporting the grain in a whole-ear format. The ears are then transported, dried, threshed, and separated before sizing, coating, and distributing as seed. The whole-ear format reduces grain damage, ensuring maximum seed germination [3]. This process could be beneficial in harvesting and storing corn grain and stover as whole-plant corn. Storing whole ears would also facilitate fractionation. The large, heavy ear portions could be easily classified from the stover, and subsequently separated into the cob, grain, and husk fractions using conventional threshing and separating technology.

Recently, Ref. [2] studied a single-pass, whole-plant bale system for producing corn stover feedstock. According to the abstract, bales were evaluated using anaerobic and aerobic storage. Ref. [4] evaluated the storage of chopped whole-plant corn from 35 to 66% dry matter, where dry matter losses were observed to be less than 6%. Anaerobic fermentation acids were limited to 2% of dry matter. While they did observe a similar starch mass fraction in the grain, they did not isolate the changes in grain dry mass relative to the stover. Still, recent work has been reported on aerobically storing ear corn as a source of corn cobs for biochemical conversion [5], and anaerobically storing high-moisture corn, ground high-moisture corn, and snaplage for livestock feed. The need for year-round availability of a corn cob feedstock for biochemical conversion has been noted, and ear corn systems have been explored to meet this need. Information on how to properly store high-moisture corn grain, ground ear corn, and snaplage in an anaerobic environment has also been explored [6]. Proper moisture parameters for storing ground high-moisture ear corn, which was between 32% and 36% w.b., and any moisture larger than 40% w.b., would create undesirable fermentation due to the creation of ethanol, resulting in poor acceptance by animals as feed.

This work aims to combine the anaerobic storage of whole-ear corn with chopped stover. To our knowledge, this has yet to be investigated previously. We hypothesize this approach will have similar benefits to the chopped high dry matter whole-plant corn systems proposed by [4], but will result in an easier to fractionate whole-ear fraction and result in more intact corn grain kernels, which will improve downstream handling, storage, and utilization.

The goals of this study were to determine if ear corn and stover could be preserved in an anaerobic environment, to determine the dry matter losses associated with a co-storage, and to determine the damage to the grain fraction after the shelling of high-moisture, fermented corn ears.

2. Materials and Methods

The storage study occurred over two harvest seasons, 2020 and 2021. Harvests were conducted on two dates in each season. In 2020, the two dates were 20 October and 6 November. In 2021, the two dates were 12 October and 3 November. In both years, the harvests were spaced to allow for a variation in the whole-plant moisture content. The harvest on 20 October 2020 consisted of three treatments with four replicates of each treatment (Table 1). The packaging treatments were varied to determine if there was an optimal packing situation for this material. The treatments included whole-ear with the husk on the ear layered with stover, whole-ear with the husks off layered with stover, and a shelled-grain treatment where the grain was shelled and mixed in with the stover. In the second year, the treatments were adjusted to reflect the experience gained from year one. The remaining harvest of 2020 and the two harvests of 2021 consisted of four treatments of three replicates each. The treatments consisted of a whole ear with husk layered with stover, a whole ear without husk layered with stover, a whole ear with husk mixed with stover, and a whole ear without husk mixed with stover. In the treatments where the husk was removed, the husk was size reduced and mixed in with the stover (Table 1).

After the treatments were determined, harvesting could occur (Figure 1). Plants were hand-harvested above the first visible node. The ears were removed, and the remaining parts of the plant were size reduced using a stationary chopper (Model 770, New Holland Agriculture, New Holland, PA, USA) with a theoretical length of cut of 15 mm. For the first harvest date in 2020, only 30 ears and stalks were utilized, but the second harvest date in 2020 had 36 ears and stalks. Both harvests in 2021 had 36 ears and stalks per treatment.

Table 1. Independent variables evaluated for this study.

Year	Harvest	Packing Procedure	Husk
2020	1st	Layered	On
		Layered	Off, discarded
		Shelled [a]	Off, discarded
	2nd	Layered	On
		Mixed	On
		Layered	Off, size reduced, mixed with stover
		Mixed	Off, size reduced, mixed with stover
2021	1st	Layered	On
		Mixed	On
		Layered	Off, size reduced, mixed with stover
		Mixed	Off, size reduced, mixed with stover
	2nd	Layered	On
		Mixed	On
		Layered	Off, size reduced, mixed with stover
		Mixed	Off, size reduced, mixed with stover

[a] Ears were shelled prior to packing. The cobs were size reduced in the same stationary chopper. The cob, grain, and stover fraction were mixed at packing.

Figure 1. The process to assess the potential of anaerobic storage of ear corn. Starting at the left: chopping the stover with a stationary chopper, placing chopped stover and ears into a plastic-lined barrel, compressing with a hydraulic press to achieve the desired packing density, removing from storage, and shelling the ears with an ear sheller to determine grain damage.

In 2020, four grain samples of approximately 500 g were taken to define the grain moisture content. A stover sample of approximately 500 g was also taken for each barrel. The moisture samples were dried in a forced-air oven at 103 °C for 24 h. According to [7,8]. In 2021, a grain, stover, and cob moisture sample was taken from each barrel. The grain and cob portions were collected from a representative ear from a corn plant that was to be packed into the barrel. The ear was shelled, and the grain and cob portions were put in separate bags for drying. The samples were approximately 175 g and 50 g for the grain and cob fraction, respectively. The stover sample was randomly selected from the chopped corn stalks and typically weighed between 500 and 600 g.

The material was packed in 72-L barrels lined with a plastic bag. The ear and stover fractions were each weighed before filling the barrel. Nominally, 20 kg of material was added to each barrel to achieve a target density of 225 kg DM/m^3. For all treatments, half of the material was loaded into the barrel lined with a plastic bag, compressed with a hydraulic press to simulate a traditional silage pile, and compacted by a tractor. The remaining material was placed in the barrel, and the barrel was compressed again. The barrel liners were tied off, sealed with a lid, weighed, and stored indoors at approximately 20 °C until unpacking. At the first harvest in 2020, one treatment consisted of a shelled grain treatment. Here, the ears were shelled before being packed into the barrels to determine if the damage would be similar between ears shelled before or after storage. Similar sampling and packing procedures were utilized for these treatments.

The barrels packed in 2020 were unpacked on 18 and 19 May and then in 2021, after 210 days in storage (for the material packed at the October date) and 193 days in storage (for the material at the November date). The barrels packed in 2021 were unpacked on 19 January 2022. Barrels from both harvests were unpacked in the following manner. The barrel was weighed to the nearest 0.1 kg before it was opened. Once opened, any spoiled material was removed from the top of the barrel. The barrel was separated into ear and stover fractions. Each of those fractions was weighed separately. The ears were shelled using an ear sheller (Model ECS, Almaco, Nevada, IA, USA) with a tip speed of 900 rpm and a concave clearance of about 30 mm, mimicking the tip speed and concave clearance of a conventional combine harvester, meaning the ears could be threshed on a larger scale by a machine with similar characteristics. This assumes that the rotor shaft diameter would be about 0.61 m and the rotor shaft speed would be about 450 rpm.

Individual grain, stover, and cob samples were collected to determine their moisture content. These samples were randomly selected from the aggregate grain, cob, and stover samples from each barrel. The moisture samples typically weighed 350, 600, and 200 g for the stover, grain, and cob fractions. Moisture samples were dried in a forced-air oven at 103 °C for 24 h. According to [7,8], the DM from each fraction and the overall barrel was determined using the moisture content samples collected at barrel packing and unpacking for the stover, grain, and cob. Since moisture information on the ear fraction was split into the grain and cob sub-fractions, it was necessary to determine the grain:cob ratio. The moisture samples collected at barrel packing consisted of one ear and one cob per barrel. These samples served as the basis for determining the grain:cob ratio of the ears in the barrel.

A particle sizing method was used to assess the amount of grain damage in the shelled grain sample [9]. The third screen in the separator had a small enough opening size to retain the whole grain but allow the broken grain to fall through. Therefore, the whole grain would reside solely on the third screen, and all mass below would be assumed to be broken grain. In 2020, the sample size was typically 2000 g, while in 2021, the sample size was increased to 4000 g. The initial mass was recorded, and the total mass on each tray was recorded. A percentage of the total mass was calculated for each screen.

Data were analyzed using statistical software (JMP Pro15, SAS, Cary, NC, USA). Outliers were removed using a center and scale technique with three different calculated centers, Huber, Cauchy, and Quartile. The number of spreads, K, was set to a value of 1 to ensure no data extremely far from the center were removed. From the clean data, a full factorial statistical analysis was conducted. Factors considered were year (2020, 2021), harvest date (early, late), packing method (layer, mixed) and husk status (on, off), and responses included dry-matter loss and moisture content changes in the stover, ear, and whole-plant material fractions. Statistical significance was recognized for $p < 0.05$.

3. Results & Discussion

The into-storage moisture for the aggregate material was 44 and 33% w.b. in 2020, and 48 and 39% w.b in 2021. The into-storage density for the aggregate material was 178 kg DM m^{-3} in 2020 and 193 kg DM m^{-3} in 2021. When analyzing the 2020 data, discrepancies were found in the dry matter loss data, including what appeared to be dry matter gains during storage (Table 2). This was believed to be due to errors with moisture sampling at packing, and the scale's precision of 0.1 kg. Due to the small sample size of three barrels per treatment, it was determined that treatments within each harvest needed to be combined. The combinations were based on whether the husk remained on the ear, creating a treatment size of six for each harvest date for the second harvest in 2020 and both harvests in 2021. The first harvest in 2020 had a sample size of four; no recombination was possible.

Table 2. Descriptive statistics for dry matter loss of ear, stover, and whole plant biomass. Averages were reported after cleaning outliers from the data.

Year	Harvest	Fraction	Husk on?	Average DM Loss (%)	Median DM Loss (%)	Std. Deviation	Outliers Removed
2021	1	Ear	Yes	0.25	0.31	0.197	3
2021	2	Ear	Yes	−1.93	−2.02	0.891	2
2021	1	Stover	Yes	3.04	3.32	1.191	3
2021	2	Stover	Yes	7.39	6.78	3.489	2
2021	1	Overall	Yes	0.80	0.30	1.337	2
2021	2	Overall	Yes	0.16	0.18	0.835	2
2021	1	Ear	No	2.72	2.83	0.529	3
2021	2	Ear	No	−0.78	−0.79	0.238	3
2021	1	Stover	No	9.59	9.20	5.430	2
2021	2	Stover	No	16.62	16.58	3.983	2
2021	1	Overall	No	4.79	4.89	2.593	2
2021	2	Overall	No	5.51	5.51	0.305	2
2020	1	Ear	Yes	1.71	1.71	0.057	2
2020	2	Ear	Yes	−1.90	−1.87	0.282	2
2020	1	Stover	Yes	19.78	19.78	5.288	2
2020	2	Stover	Yes	22.30	21.27	2.182	3
2020	1	Overall	Yes	5.85	5.85	1.460	2
2020	2	Overall	Yes	0.146	−0.067	1.615	2
2020	1	Ear	No	1.28	1.28	0.667	1
2020	2	Ear	No	2.168	2.148	2.895	2
2020	1	Stover	No	2.78	2.78	0.899	2
2020	2	Stover	No	−2.14	−2.09	3.477	2
2020	1	Overall	No	0.70	1.03	1.377	1
2020	2	Overall	No	−3.58	−3.67	1.374	4

Ear fraction DM losses were impacted by whether the husk remained on or removed from the ear (p = 0.001), as well as by harvest date (p = 0.001), but were not impacted by the harvest year (p = 0.262). Ear DM losses were reported at −0.63 and 1.35% for the treatments where the husk remained on or removed from the ear, respectively, and 1.33 and −0.61% for the first and second harvest, respectively (Table 3). An interaction between these variables (husk x year x harvest) was also observed (p = 0.021).

Table 3. Measured dry matter losses for stover, ear, and the overall treatment.

Variable	Stover Dry Matter Loss (%)	Ear Dry Matter Loss (%)	Overall Dry Matter Loss (%)
Harvest year			
2020	10.68 a	0.66 a	0.78 a
2021	9.16 a	0.06 a	2.81 b
p-value	0.33	0.26	0.002
Harvest date			
1st [a]	8.80 b	1.33 b	3.03 c
2nd [b]	11.04 b	−0.61 c	0.56 d
p-value	0.16	0.0014	<0.001
Husk location			
On	13.13 c	−0.63 d	1.74 e
Off	6.71 d	1.35 e	1.85 e
p-value	<0.001	0.0012	0.84

[a] 20 October 2020, 12 October 2021, [b] 6 November 2020, 3 November 2021. Values in the same column and not separated by a header row followed by different letters are significantly different at the 95% confidence level.

From these results, the husk provided additional protection for the ear fraction from spoilage treatment differences ($p = 0.001$). With negative DM losses reported for these treatments, it is possible that very little DM was lost during storage, and any error is from moisture content estimation or scale precision. Upon unpacking, mold growth was observed on the outside of the husk, but the grain was mold-free where covered. Without this protection from the husk, mold growth occurred directly on the ear, both on the top and between the kernels, leading to additional losses. Higher ear DM losses were observed in material harvested on the first harvest than on the second harvest date ($p = 0.0014$). This finding indicates that the storage technique would be less efficacious at a higher moisture content, which would limit the harvest window.

Stover DM losses were 13.13 and 6.71% when the husk was located on the ear or mixed in the stover. The DM differences were significant ($p < 0.001$) against the husk location. No detectable difference was found in stover DM loss across harvest years ($p = 0.33$), where losses were reported to be 10.68 and 9.16% for 2020 and 2021, respectively, or harvest dates, where losses were reported to be 11.04 and 8.80% for the first and second harvest date, respectively (Table 3). An interaction effect was observed between whether the husk was on the ear x year ($p < 0.001$), and year x harvest ($p = 0.036$).

Overall DM losses for each treatment were found to be 0.78 and 2.81% for the 2020 and 2021 harvest years, respectively, 3.03 and 0.56% for the first and second harvest, respectively, and 1.74 and 1.85% for whether the husk was located on or removed from the ear, respectively. A difference was only detected across the harvest year and the harvest date ($p = 0.002$ and $p < 0.001$, respectively). In addition to these main effects, husk location x year ($p < 0.001$) and year x harvest date ($p < 0.001$) significantly affected the overall dry matter loss.

The husk's location on or removed from the ear had no impact on the overall DM losses of the aggregate material ($p = 0.84$) (Table 3). A similar storage study has been previously completed [3], but the material studied was chopped high dry matter, whole-plant corn. Whole-plant corn with similar moisture properties as the material used in this study was harvested in 19-L storage containers across two harvest seasons in 2009 and 2010. Ref. [4] reported dry matter losses of generally less than 4%. Ref. [10] conducted a similar study to [4] in 2019 and 2020 and found that DM losses were about 4% on average. While the ear and stover DM losses are variable in this study, the average losses from this process are like those reported by others.

Moisture content changes were observed in the stover, cob, and grain fractions. This is likely due to moisture exiting the higher moisture stover and entering the lower moisture cob and grain fractions. It is important to understand these changes to inform the parameters of future processing steps to ensure the fractions are handled appropriately. Stover moisture changed more ($p < 0.001$) during the 2020 study compared to the 2021 study, by -6.83 and -3.21 percentage points (w.b.), respectively (Table 4). In both studies, more moisture was absorbed by the grain in barrels packed at the first harvest than those at the second harvest. Grain moisture changed more in 2021 than in 2020 ($p = 0.012$), changing 9.68 and 8.07 percentage points (w.b.), respectively. This could be due to less moisture being available in the barrels packed on the second harvest date, or could be an indicator that corn kernels are less receptive to moisture changes after they have reached full maturity. Cob moisture changes were observed to be the same ($p = 0.49$) between the two harvests in 2021 and were not quantified in 2020. No interaction terms reached the significance threshold for any of the fractions.

Table 4. Reported moisture content changes (percentage points wet basis) for the stover, grain, and cob fraction.

Variable	Stover	Grain	Cob
	Percentage Point Change (Wet Basis)		
Harvest year			
2020	−6.83 a	8.07 a	-
2021	−3.21 b	9.68 a	-
p-value	<0.001	0.012	-
SEM	0.71	0.44	-
LSD (p = 0.05)	2.85	1.76	-
Harvest date			
1st [a]	−4.21 c	10.63 c	4.90 a
2nd [b]	−5.82 c	7.12 d	3.75 a
p-value	0.11	<0.001	0.49
SEM	0.71	0.44	1.17
LSD (p = 0.05)	2.85	1.76	4.87

[a] 20 October 2020, 12 October 2021, [b] 6 November 2020, 3 November 2021. SEM—Standard Error of the Mean, LSD—Least Significant Difference, Values in the same column and not separated by a header row followed by different letters are significantly different at the 95% confidence level.

A benefit of the ear storage system was expected to be less damage to the grain fraction during the harvest and storage process. Intact grain averages were reported at 98.30 and 97.17% of the collected mass for the 2020 and 2021 harvests, respectively (Table 5). These values were statistically different ($p < 0.001$). This could be related to the method in which the grain sample was collected. The grain from 2020 was sub-sampled from the grain material after all the grain from a single treatment was threshed and stored in a sealed bag. It is possible that fewer of the fine grain pieces would be in that sub-sample, because they would have sorted to the bottom of the pile. In 2021, the sub-sampling occurred at the exit of the thresher, roughly halfway through ear shelling. This would result in collecting all the fine grain particles associated with the ears that had been shelled.

Table 5. Reported grain damage values.

Variable	Mass of Intact Grain (%)
Harvest year	
2020	98.30 a
2021	97.17 b
p-value	<0.001
SEM	0.10
LSD (p = 0.05)	0.41
Ear shelling [a]	
Before	98.58 a
After	97.80 b
p-value	0.003

[a] A comparison between ears shelled before and after storage was only conducted on the first harvest date in 2020 (20 October 2020). Values in the same column and not separated by a header row followed by different letters are significantly different at the 95% confidence level.

Grain damage between the treatments shelled before and after storage at the first harvest in 2020 was also compared (Table 5). It was found that the ears shelled before ensiling consisted of 98.58% intact grain, while ears shelled after ensiling consisted of only 97.80% intact grain. These values show that shelling the ears before ensiling results in more intact grain ($p = 0.003$). Overall, these results show little evidence that threshing these high moisture ears would cause damage to the grain fraction, and the reported damage still was less than the maximum 3% damage allowed for Grade No. 1 corn [10], regardless of when the ears were shelled, before or after storage.

4. Conclusions

This work demonstrates that harvesting and co-storing ear corn and stover is an effective way to mitigate grain damage compared to direct harvest and anaerobic storage.

- The storage method limited dry matter to 3% across both harvest seasons.
- Moisture was observed to migrate from the ear to the stover.
- Post-storage shelling of ears resulted in less than 3% wt./wt. grain damage.

Another benefit of this method is the easy separation of the two main fractions, the ear and the stover. The ear comprises three subfractions, the cob, the husk, and the grain, while the stover also consists of three subfractions, the upper stalk, lower stalk, and leaves. The ear subfractions are easily separated by mechanical means, and the stover subfractions could be separated by exploiting the terminal velocity properties of each subfraction. This could be less challenging than separating all six subfractions simultaneously using sieving and forced air.

While this work demonstrated that it was possible to store ear corn with stover, more work should be done to quantify the dry matter losses during storage on a larger scale, such as in a wrapped bale, bag, or pile. The stover and ear fractions tend to fractionate easily, which is an asset for separate utilization, but makes handling and storing the aggregate material difficult. A large-scale study could investigate research questions related to storage and handling.

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