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ANAEROBIC STORAGE AND AEROBIC STABILITY OF MOIST BIOMASS FEEDSTOCKS

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Abstract. *Switchgrass, forage sorghum, sweet sorghum, and corn stover, were anaerobically stored in pilot-scale silo bags for an extended period. Material moisture content ranged between 28.5% and 61.5% (w.b.). Storage losses ranged from 0.3% to5.8% of DM with an overall average of 2.4%. Moisture content generally had little statistically significant effect on storage losses. Inoculating feedstocks with* L. buchneri *did not significantly affect storage losses. Losses during aerobic exposure ranged from nil to 5.2% of DM with losses increasing from two to seven days of aerobic exposure. Overall average DM loss after two and seven day aerobic exposure was 1.0% and 1.7%, respectively. Inoculation with* L. buchneri *significantly decreased pH and increased production of fermentation acids during storage, but had small effects on aerobic losses. As quantified by temperature, feedstocks inoculated with* L. buchneri *remained more stable during seven days of aerobic exposure. Fermentation products were generally less than 5% of DM with an overall average of 2.2%. Anaerobic storage was shown to successfully conserve a variety of different moist biomass feedstocks, resulting in low material losses and a uniform moisture distribution upon removal.*

Keywords. *Anaerobic storage; aerobic stability; amendments; biomass; heating; losses.*

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ABSTRACT

Switchgrass, forage sorghum, sweet sorghum, and corn stover, were anaerobically stored in pilot-scale silo bags for an extended period. Material moisture content ranged between 28.5% and 61.5% (w.b.). Storage losses ranged from 0.3% to5.8% of DM with an overall average of 2.4%. Moisture content generally had little statistically significant effect on storage losses. Inoculating feedstocks with *L. buchneri* did not significantly affect storage losses. Losses during aerobic exposure ranged from nil to 5.2% of DM with losses increasing from two to seven days of aerobic exposure. Overall average DM loss after two and seven day aerobic exposure was 1.0% and 1.7%, respectively. Inoculation with *L. buchneri* significantly decreased pH and increased production of fermentation acids during storage, but had small effects on aerobic losses. As quantified by temperature, feedstocks inoculated with *L. buchneri* remained more stable during seven days of aerobic exposure. Fermentation products were generally less than 5% of DM with an overall average of 2.2%. Anaerobic storage was shown to successfully conserve a variety of different moist biomass feedstocks, resulting in low material losses and a uniform moisture distribution upon removal.

INTRODUCTION

Since the dawn of the Industrial Revolution, society has been dependent upon fossil fuels as the primary sources of energy (Larkin et al., 2004). However, concerns about the environment, foreign oil dependence, and the economy have led to an increased interest in fuels generated from biomass feedstocks. The attractiveness of cellulosic biomass stems from its ability to produce liquid fuels, heat, electricity, and other bioproducts, as well as the fact that it is a renewable resource and able to be stored (Perlack et al., 2005). In order to realize the potential of biomass, numerous issues involving the harvest, storage, and transport of these feedstocks need to be addressed.

Presently, biomass is stored either aerobically as dry hay in the form of large round or square bales or anaerobically in the form of silage. If dry bales will be made, the material needs to be allowed to dry as much as possible (<20% w.b.) in order to reduce the risk of detrimental biological activity (Shinners et al., 2011a). Dry bales can be stored outdoors under the proper weather conditions, and this storage system has been shown to be cheaper than storing material as silage (Shinners et al., 2003; Worley and Cundiff, 1996). However, because cellulosic feedstocks will be needed during months outside of their seasonal availability, longer storage periods will be required (Rentizelas et al., 2009). More opportunities exist for material degradation and dry matter (DM) loss as the bales are stored longer. While bales stored indoors have experienced DM losses ranging from 3-5% (Shinners et al., 2007; Shinners et al., 2010), dry matter losses as high

as 15-30% have been reported for bales stored outdoors (Shinners et al., 2007; Shinners et al., 2010; Worley and Cundiff, 1996). Storing these feedstocks anaerobically as silage is one way to ensure feedstock conservation for an extended period of time.

Harvesting and storing biomass as silage uses microbial fermentation to preserve the feedstock. The achievement of a truly anaerobic environment is the primary factor that determines the efficiency of storing animal feed as silage (Woolford, 1990). Farmers have been making silage for centuries in order to consistently supply feed to their animals during the winter and nonproductive months. Provided anaerobic conditions within the silo are maintained, fermented silage can be safely stored for many months (Collins and Owens, 2003). Numerous feedstocks can be harvested moist and stored as silage, and there are many benefits to a silage-based system including fewer field operations and greater robustness due to the short field curing time required (Shinners et al., 2007).

Forage harvesting and ensiling equipment already available for production of animal feed can be used to gather and store biomass feedstocks. By size-reducing and processing the feedstocks in the field and sending a uniform product to the storage site or refinery, the complexities associated with processing dry bales are removed (Hess, et al., 2007). Due to the longer harvest window and because many other crops can be harvested and stored as forage with this machinery, the increased fixed costs of high capacity harvesting equipment are diluted across many acres and crops (Worley and Cundiff, 1996; Shinners et al., 2003).

Research involving the anaerobic storage of moist biomass has proven that this storage option is both viable and efficient. Average dry matter losses of 1.1% were achieved in ensiled bales of switchgrass and reed canarygrass by Shinners et al. (2010). Work by Digman et al. (2010a,b,c) showed that ethanol could be more efficiently produced by pretreating perennial grasses on-farm with dilute acids before anaerobic storage; ethanol yield increases of 7% and 19% were realized for switchgrass and reed canarygrass, respectively. Sorghum varieties with various sugar content have also been successfully fermented and ensiled at moisture contents ranging from 54% to 68% (w.b.) (Philipp et al., 2007). The successful ensiling of agricultural residues has significantly improved the conversion of cellulose and hemicellulose to sugars, resulting in greater ethanol yields compared to fresh crops (Chen et al., 2007). Ensiling corn stover has received a great deal of attention in the last 10 years. Richard et al. (2001) was able to successfully ferment and store corn stover at moisture levels ranging from 53% to 85% (w.b.). Low dry matter losses (between 1% and 10%) for ensiled, moist corn stover have been achieved on a large scale (Shinners et al., 2007; Shinners et al., 2011a). The addition of cellulolytic enzymes to the stover before ensiling allows for a faster reduction of silage pH, encourages fermentation, and helps guarantee a stable product for at least six months under anaerobic conditions (Ren et al., 2006). Subsequent conversion of corn stover to ethanol can also be improved through lime pretreatment of the stover prior to ensiling (Kaar and Holtzapple, 2000; Kim and Holtzapple, 2006).

The handling and management of biomass feedstocks stored as silage should mirror practices currently used by forage producers in order to minimize losses. Depending on the material moisture, packing density, and feed-out rate, losses of chopped forage stored in tower, bunk, or bag silos have been reported by multiple sources in the range of 5 to 20% of dry matter (Muck and Holmes, 2000 and 2001; Muck and

Rotz, 1996; Pitt, 1990). According to Kleinschmit and Kung (2006), spoiled silage is not only a loss of nutrients but also a loss of farm income because animal performance decreases. The same results can be expected if spoiled feedstocks are delivered to and processed by a biorefinery. Worley and Cundiff (1996) emphasized the importance of minimizing time between harvesting and ensiling in order to avoid biological deterioration of the material; this includes eliminating short-term storage or long transport distances. At the same time, care needs to be taken to prevent this degradation once the feedstock is removed from storage. Aerobic spoilage during feed-out has been known to represent up to 30-40% of total animal feed DM (Kung Jr., 2008). Losses of this magnitude can substantially decrease biofuel production. In order to achieve the maximum energy potential from a harvested feedstock, losses associated with storage need to be minimized. Conservation during storage must be achievable on a consistent basis for cellulosic biomass to be a competitive and reliable source of bioenergy. The focus of this research was the anaerobic storage of moist feedstocks; moist was defined here as 30-55% moisture on a wet basis (w.b.).

OBJECTIVES

The objectives of this research were to quantify the anaerobic storage characteristics of moist biomass feedstocks stored in silo bags, including switchgrass, sorghum and corn stover; to investigate amendments to reduce storage losses or improve aerobic stability; and to investigate the aerobic stability of the feedstocks once removed from storage.

MATERIALS AND METHODS

Crops and Harvest

Switchgrass and sorghum were harvested on the dates indicated in table 1 and were cut and windrowed prior to harvest with a John Deere model 4990 windrower. Switchgrass (*Panicum virgatum L.* - Shawnee variety) required one to two days of field wilting prior to harvest to achieve the target moisture. Both forage (*Sorghum bicolor*, Monsanto FS-5) and sweet (*Sorghum vulgare Pers.*, Coffey Seeds Sugar Graze II) sorghum dried quite slowly and required two and five days of field wilting to achieve the high and low target moistures, respectively. In 2009 Dekalb 52-59 corn stover (*Zea mays L.*) was harvested on dates indicated in table 1 after a single day of field wilting. In 2010 Pioneer 35F37 corn stover was used for the high moisture target; however an unusually dry fall had reduced standing stover moisture to below the target, so after windrow formation rainfall was used to rehydrate the stover windrows to the target moisture. This procedure required the windrows to be raked twice before harvest. The low-moisture target was harvested using Renk 570 VT3 corn the day after windrow formation. Corn stover was harvested using a two-pass system where windrows of stover were formed at the time of grain harvest using a modified combine (Shinners et al., 2011b). All crops were harvested with a John Deere model 7800 self-propelled forage harvester (SPFH) equipped with a windrow pick-up. The harvester theoretical-length-of-cut (TLC) was between 11 and 12 mm. Random samples of all treatments were taken throughout each experiment for later analysis of particle-size following ASABE Standard S424.1 (ASABE, 2007).

Table 1. Experimental treatments, type of biomass crop, date stored and removed, storage duration, target moisture, and type of amendment used in storage experiments.

Crop & Year	Silo Bag No.[b]	Storage Date	Removal Date	Storage Duration days	Target Moisture % w.b.	Amendments[c]
Switchgrass						
'09	1	4 Nov.	1 Apr.	148	30	*L. buchneri*
'10	5	8 Sep.	18 Apr.	222	40, 50	*L. buchneri*
Sorghum[a]						
'10	6	23 Sep.	29 Apr.	218	50	*L. buchneri*
"	7	30 Sep.	29 Apr.	211	40	*L. buchneri*
Corn Stover						
'09	2	4 Nov.	1 Apr.	148	50	*L. buchneri,* $Ca(OH)_2$
"	3	10 Nov.	31 Mar.	141	40	*L. buchneri,* $Ca(OH)_2$
"	4	23 Nov.	31 Mar.	128	45	*L. buchneri,* $Ca(OH)_2$
'10	8	29 Oct.	17 May	200	50	*L. buchneri*, *L. buchneri* + enzyme
"	9	3 Nov.	17 May	195	40	*L. buchneri*, *L. buchneri* + enzyme

[a] Each bag contained both forage and sweet sorghum varieties.
[b] Represents individual bag number in chronological order.
[c] All silo bags with amendments included an untreated control.

Storage and Removal

All of the silo bags for this research were made using a modified Ag Bag model CT-5 Bagger (Williams, 2011). This machine was chosen because of the size bag it produced and the method used to fill and compress material in the bag. The CT-5 made 1.5 m diameter bags, which is smaller than conventional agricultural baggers (usually 2.4 m to 4.3 m). The 1.5 m diameter bags were small enough that they did not require a large harvested area to fill but was still large enough to effectively reflect the scale of conventional bags. Bag thicknesses were 5- and 8-mil in 2009 and 2010, respectively.

Conventional silage baggers utilize a continuous-flow packing process, using an aggressive tined rotor to pack material into the bag. The modified CT-5 bagger used a batch process. A loading hopper was first filled with material, and then a hydraulic cylinder actuated a plunger that pushed contents of the hopper (i.e. charge) into the bag, loading and compressing the material. This method of filling and compressing the bag allowed subsample parcels used to quantify the materials storage characteristics (described later) to be placed undamaged into the silo bag during filling. Modifications made to the CT-5 bagger included changes to the plunger face and the addition of a cable and backstop density control system (Williams, 2011).

Harvested material was transported to the storage location, and randomly collected subsamples of about 2 kg were placed into polypropylene mesh bags measuring 53 cm by 80 cm with 10 mm mesh (MacMaster-Carr part no. 9883T53). Before placing the replicate subsample parcels into the silo bag, two subsamples were collected from

each parcel for moisture determination. Moisture samples were oven dried at 103°C for 24 hours following ASABE Standard S358.2 (ASABE, 2008). Wireless temperature data loggers (Onset model UA-001-08) were placed in every second or third parcel to monitor temperature at a sampling rate of four times per day: 12:00 AM, 6:00 AM, 12:00 PM, and 6:00 PM. Before placing in the silo bag, the subsample parcels were weighed to the nearest 0.005 kg. Six replicate parcels were placed in each treatment. In 2009, support equipment limitations forced the placement of the entire contents of a single treatment into one location in the silo bag, so treatments were placed sequentially into the silo bag. In 2010, more support equipment was available so each treatment was split into thirds and placed in three replicate locations in the silo bag.

A total of nine silo bags were made over a two year period using four different biomass feedstocks (table 1). Initial tests showed that as the bagger's plunger fed and compacted the charge of material from the loading hopper into the silo bag, the subsample parcels were transported and surrounded with the parent material without harming them. The weight of the surrounding material and the force exerted by the plunger ensured the parcels experienced the same relative degree of compaction as the parent material. Subsample parcels were placed in the loading hopper so that they would be located near the center of the silo bag.

Sacrificial material equivalent to roughly the mass of two to three hopper charges was placed in the beginning and end of the bag to reduce edge effects. Additionally, one to two hopper charges of sacrificial material without subsample parcels inserted were used to separate treatments within the silo bag. After filling, the silo bag was sealed and two slits about 10 cm long were cut in the end of the bag to let the trapped gases escape (Saxe, 2007). After 24 to 48 hours, these slits were sealed with silo bag tape. The bags were monitored throughout the storage period, and any damage was repaired.

As the silo bags were deconstructed at the end of the storage period, the subsample parcels were recovered; the parcels weighed to the nearest 0.005 kg; the contents homogenized; and two subsamples taken for moisture determination. Because the material had undergone fermentation, moisture samples were dried at 60°C for 72 hours following ASABE Standard S358.2 (ASABE, 2008). Another subsample was collected and refrigerated for later analysis of mold and yeast populations by Rock River Labs (Watertown, WI). A final subsample was taken and frozen for analysis of pH and fermentation products, which was conducted by the USDA Dairy Forage Research Center and Rock River Labs in 2009 and 2010, respectively, using high performance liquid chromatography.

Aerobic Stability

Aerobic stability was quantified for all of the storage experiments conducted with the exception of switchgrass harvested in 2009. As the material was removed, portions of each treatment were loaded into 200 l HDPE barrels. A total of four barrels were filled for each treatment. Roughly one third of the barrel was filled with material, and then a subsample parcel (described previously) containing roughly 2 kg DM of ensiled material was weighed, equipped with a temperature data logger, placed in the barrel and covered with more parent material. After two-thirds of the barrel was full, another subsample parcel with temperature data logger was placed into the barrel. The top parcel was placed

so that the top surface of the parcel was about 10 cm from the top of the filled barrel. The barrel was then filled level full and left uncovered. The barrels were loosely filled and material was not compacted. The barrels were stored indoors in a ventilated shed for two days or five/seven days. Procedures for sampling from the subsample parcels were similar to that previously described.

Heating in the material during aerobic exposure was quantified by heating degree days accumulated over the aerobic exposure period:

$$\mathbf{HDD} = \sum \left(\frac{\boldsymbol{T_{max} + T_{min}}}{\mathbf{2}} - \boldsymbol{T_{ave}}\right) \qquad (\mathbf{1})$$

where:

HDD	accumulated heating degree days, °C
T_{max}	daily maximum temperature, °C
T_{min}	daily minimum temperature, °C
T_{ave}	daily average temperature, °C

Amendments

Three amendments were investigated (table 1): lime ($Ca(OH)_2$); *Lactobacillus buchneri* (Lallmand Animal Nutrition Biotal 500 containing *L. buchneri* 40788 and *Pediococcus pentosaceus* 12455); and *L. buchneri* + enzyme (Lallmand Biotal 500 plus glucose oxidase; carboxymethylcellulase; xylanase; and polygalacturonase enzymes). Biotal 500 was used to quickly produce fermentation acids and drop pH and to improve the aerobic stability of the removed material. *L. buchneri* is a heterofermentative bacterial inoculant that has been shown to increase the aerobic stability of ensiled animal feed when the inoculation rate is above 10^6 CFU/g, although DM loses during storage increased (Muck, 2004; Kung, 2008; Hoffman and Combs, 2009). The addition of the enzymes to the Biotal 500 was to produce additional soluble sugars for fermentation substrate through fiber degradation, as well as to improve aerobic stability by producing antimicrobial compounds. The bacterial inoculants were applied using an on-harvester Dohrmann model DE-1000 inoculant applicator. The applicator was set to deliver the Biotal 500 so that 100,000 cfu/g *Pediococcus pentosaceus* and 400,000 cfu/g *L. buchneri* were applied. Lime was used as an amendment to enhance the conservation of DM during storage because research has shown that lime stabilized barley silage during storage, while also increasing *in vitro* digestibility (Hadjipanayiotou, 1984). In 2009 corn stover experiments (table 1), lime was applied at the target rate of 5g/100 g DM. A Kuhn Knight model 3130 Reel Mixer was used to mix the lime with the feedstock for 10 min prior to placement in the silo bag.

Statistical Analysis

Statistical analysis was performed using data analysis features in Excel. Significant differences between treatments in individual experiments were determined using single factor analysis of variance (ANOVA) based on the variability among subsample parcels within the silo bags. A two-way ANOVA was used to block

confounding effects when analyzing data across more than one experiment. All statistical differences were based on a least significant difference (LSD) with a probability of 95% (Steel et al., 1996). A paired t-test was used to determine significant changes in moisture or composition of the material in the subsamples parcels during storage or aerobic exposure.

RESULTS

Particle Size and Bag Density

The geometric mean particle-size (GMPS) of switchgrass and sorghum was often less than the TLC (table 2), a phenomenon that is rarely seen in chopped animal forages (Shinners, 2003). It was observed that the longitudinal axis of the stems of these three crops were reasonably well oriented in the windrow with the direction of travel which can contribute to the GMPS near the TLC (Shinners, 2003). Also, the switchgrass and sorghum stems were quite brittle and might have burst apart during chopping, which may have contributed to the size-reduction. The GMPS of corn stover was consistently greater than the TLC (table 2). Stover typically has a much greater GMPS than the TLC because the incoming material is poorly oriented with the harvester shearbar (Shinners et al., 2011b). This was the case here where the GMPS was two to three times that of the TLC. The stover harvested for silo bags two and three were also processed through the harvester's crop processing rolls, which contributed to the shorter GMPS compared to the unprocessed material harvested for the final three stover bags (table 2).

The density of the chopped switchgrass in the silo bags (table 2) was greater than that reported for ensiled switchgrass bales which ranged from 154 to 165 kg DM/m^3 (Shinners et al., 2011a) but less than alfalfa haylage where average density was 200 kg DM/m^3 at 60% (w.b.) moisture when compacted with conventional steady-state baggers (Muck and Holmes, 2001). The average density of the stover compressed with the modified compost bagger was 113 kg DM/m^3, 20% less than the density created by conventional steady-state baggers over 10 stover experiments (Shinners et al., 2011a) but similar to round bales of stover wrapped in plastic film (Shinners et al., 2007). Density of switchgrass and sorghum was greater than that of stover presumably due to differences in particle-size and the size and mechanical strength of the stems. Increasing DM content had a negative effect on DM density on the bags (fig. 1).

Table 2. Particle-size and estimated silo bag density for biomass feedstocks stored in plastic silo bags.

Silo Bag No.	TLC[a] (mm)	GMPS[b] (mm)	Density (kg DM/m^3)
1	11	7	139
5	12	9	173
6	12	9	170
7	12	13	125
2	11[c]	19	157
3	11[c]	19	108
4	11	32	119
8	12	31	136
9	12	31	90

[a] Theoretical length of cut.
[b] Geometric mean particle-size determined by ASABE Standard S424.1
[c] SPFH crop processing rolls were active with clearance of ~3 mm.

Storage and Aerobic Exposure Losses

Dry matter losses during storage were quantified as the fraction of dry mass lost in the subsample parcels during storage, expressed as a percent of initial mass. Shinners et al. (2011a) showed that this method adequately estimated the total losses from the entire storage structure. Occasional apparent gains in DM during storage or aerobic exposure were calculated (tables 3 – 6). Weighing the parcels accurately represented their aggregate mass, but only two subsamples were used to estimate their aggregate moisture. If subsampling inadequately represented the aggregate moisture content at the beginning and/or end of the storage period, and DM loss was small, then apparent DM gains could result.

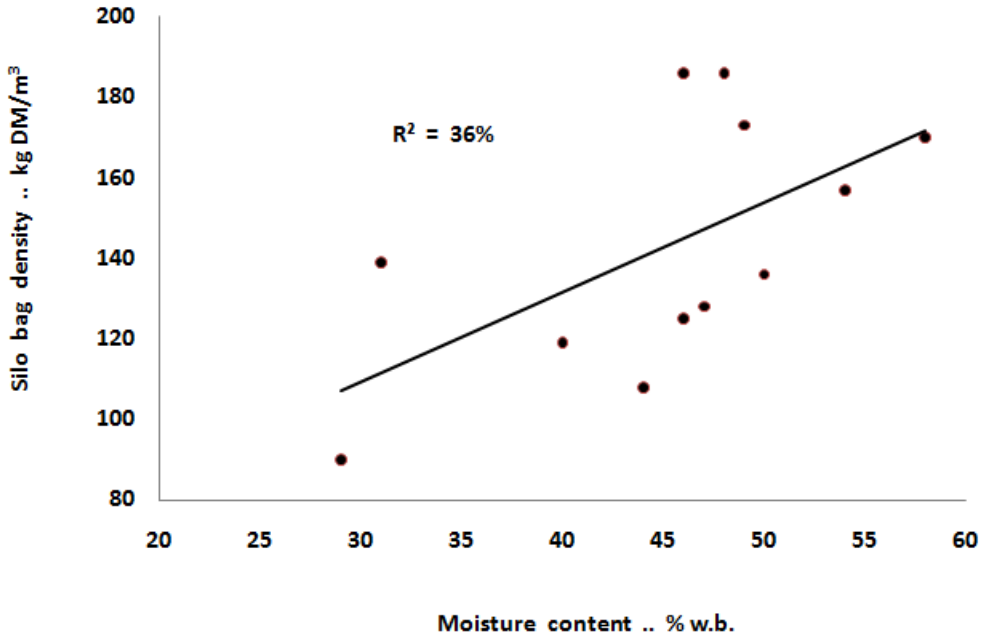

Figure 1. Silo bag density for all crops as a function of moisture into storage.

There was no significant difference in storage DM loss between treatments in the switchgrass silo bags (table 3) with average losses of less than 3%. Neither moisture content nor *L. buchneri* had a significant effect on storage losses. Losses averaged 1.6 and 2.3% of DM during two and seven day aerobic exposure, respectively, with no significant differences between treatments (table 3). Paired t-tests indicated no significant change is moisture in the subsample parcels during storage.

Both sorghum types were well conserved during anaerobic storage with average storage losses of 3.1% of DM (table 4). For an individual sorghum type, *L. buchneri* did not produce statistically greater losses (table 4). Amendments, moisture content and sorghum type had no significant effect on storage losses when data was pooled and analyzed by treatment. Losses during two-day aerobic exposure were not affected by treatments, but losses after seven days of aerobic exposure were significantly less for sorghum treated with *L. buchneri*, and sorghum at low moisture (table 4).

Lime treated corn stover had numerically lower DM loss during storage compared to the control and statistically less than stover treated with *L. buchneri* (table 5). Stover inoculated with *L. buchneri* had numerically greater losses than the untreated control in 2009, but the opposite result occurred in 2010 (table 6). Inoculation of forage crops with *L. buchneri* produced slightly greater losses in storage (Muck, 2004; Kleinschmit and Kung, 2006; and Hoffman and Combs, 2009). Overall stover was well conserved during anaerobic storage with an average DM loss of 2.0% across all experiments and treatments. There was a trend for smaller losses at lower moisture content, similar to that reported in Shinners et al., 2011a. There was no consistent trend for one treatment to produce greater loss than another during aerobic exposure experiments (table 5 and 6).

Table 3. Switchgrass moisture content and DM loss in subsample parcels during anaerobic storage[a] and after aerobic exposure.

Silo Bag No.	Treatment	Moisture content .. % w.b.		Losses .. % of DM		
		Stored	Removed[e]	Storage	After Aerobic Exposure	
					2-days	7-days
Bag 1[a]	Control	31.1a	32.1	2.9		
"	L. buchneri	32.1b	31.9	2.7		
	LSD[b]	0.8	2.3	3.3		
Bag 5[a]	Control	55.5d	55.0d	3.4	2.4	1.3
"	*L. buchneri*	52.8c	52.3c	2.3	1.6	2.4
"	Control	40.4a	41.1a	2.6	1.0	3.8
"	*L. buchneri*	46.4b	45.7b	2.3	1.5	1.7
	LSD[b]	2.5	2.3	2.1	1.8	2.2
"	Control	48.0	48.1	3.0	1.7	2.6
"	*L. buchneri*	49.6	49.0	2.3	1.6	2.1
	LSD[c]	1.7				
"	High MC	54.2	53.7	2.9	2.0	1.9
"	Low MC	43.4	43.4	2.5	1.3	2.8
	LSD[d]	1.7				

[a] Date stored and removed from storage provided in table 1.
[b] Least significant difference, different letters in the same column group are statistically different (P=0.05).
[c] Data was pooled by amendment and analyzed using two-way analysis of variance.
[d] Data was pooled by moisture content and analyzed using two-way analysis of variance.
[e] Paired t-test indicated no significant change in moisture of subsample parcels during storage.

Table 4. Forage and sweet sorghum moisture content and DM loss in subsample parcels during anaerobic storage[a] and after aerobic exposure.

Silo Bag No.	Treatment	Sorghum Type	Moisture content .. % w.b.		Losses .. % of DM		
			Stored	Removed[f]	Storage	After Aerobic Exposure	
						2-day	7-day
Bag 6[a]	Control	Sweet	61.5c	61.3c	2.7ab	0.4	5.2b
"	*L. buchneri*	"	55.6a	56.6a	4.8b	1.0	0.5a
"	Control	Forage	58.9b	58.4b	0.3a	0.6	1.2a
"	*L. buchneri*	"	54.7a	55.6a	2.6ab	-0.2	1.6ab
	LSD[b]		1.6	1.3	2.7	2.5	3.9
Bag 7[a]	Control	Sweet	44.5b	44.9a	3.4	-0.1	1.4
"	*L. buchneri*	"	42.1a	43.0a	3.5	0.2	-0.2
"	Control	Forage	48.0c	48.5b	3.7	0.8	0.0
"	*L. buchneri*	"	48.8c	48.6b	3.4	1.6	-1.0
	LSD[b]		2.0	1.9	2.5	1.7	3.1
	Control		53.2b	53.3b	2.5	0.4	2.0b
	L. buchneri		50.3a	51.0a	3.6	0.9	0.2a
	LSD[c]		0.9	0.8	1.2	1.0	1.7
	High MC		57.7b	58.0b	2.6	0.7	2.1b
	Low MC		45.9a	46.3a	3.5	0.6	0.0a
	LSD[d]		0.9	0.8	1.2	1.0	1.7
	Sweet		50.9a	51.5a	3.6	0.6	1.7
	Forage		52.6b	52.8b	2.5	0.7	0.5
	LSD[e]		0.9	0.8	1.2	1.0	1.7

[a] Date stored and removed from storage provided in table 1.
[b] Least significant difference, different letters in the same column group are statistically different (P=0.05).
[c] Data was pooled by amendment and analyzed using two-way analysis of variance.
[d] Data was pooled by moisture content and analyzed using two-way analysis of variance.
[e] Data was pooled by sorghum type and analyzed using two-way analysis of variance.
[f] Paired t-test indicated no significant change in moisture of subsample parcels during storage

Table 5. Corn stover moisture content and DM loss in subsample parcels during anaerobic storage[a] and after aerobic exposure in 2009-2010.

Silo Bag No.	Treatment	Moisture content .. % w.b.		Losses .. % of DM		
		Stored	Removed[e]	Storage	After Aerobic Exposure	
					2-day	5-day
Bag 2[a]	Control	56.7b	56.7b	3.0a	0.2	4.8
	L. buchneri	51.7a	54.3ab	5.8b	2.4	3.7
	$Ca(OH)_2$	51.8a	52.1a	1.7a	1.3	2.8
	LSD[b]	2.6	2.5	2.2	3.1	2.5
Bag 3[a]	Control	37.1a	37.3a	1.3	3.9b	0.8
	L. buchneri	42.5b	43.3b	3.1	1.6a	1.0
	$Ca(OH)_2$	39.1ab	39.0ab	1.5	1.2a	3.3
	LSD[b]	5.0	4.5	2.7	2.0	2.9
Bag 4[a]	Control	44.4a	45.0ab	1.6	2.3	3.0
	L. buchneri	41.3a	41.7a	0.8	0.8	3.2
	$Ca(OH)_2$	46.9b	46.4b	-1.3	2.9	3.2
	LSD[b]	3.1	3.6	3.5	3.3	3.1
	Control	46.1	46.3	2.0ab	2.1	2.9
	L. buchneri	45.2	46.4	3.2b	1.6	2.6
	$Ca(OH)_2$	45.9	45.8	0.6a	1.8	3.1
	LSD[c]	2.0	1.9	1.5	1.5	1.5
	High MC	53.4c	54.4c	3.5b	1.3	3.8b
	Inter. MC	44.2b	44.4b	0.4a	2.0	3.1ab
	Low MC	39.6a	39.9a	2.0b	2.2	1.7a
	LSD[d]	2.0	1.9	1.5	1.5	1.5

[a] Date stored and removed from storage provided in table 1.
[b] Least significant difference, different letters in the same column group are statistically different (P=0.05).
[c] Data from silo bags 2, 3, and 4 was pooled by amendment and analyzed using two-way analysis of variance.
[d] Data from silo bags 2, 3, and 4 was pooled by moisture content and analyzed using two-way analysis of variance.
[e] Paired t-test indicated no significant change in moisture of subsample parcels during storage.

Table 6. Corn stover moisture content and DM loss in subsample parcels during anaerobic storage[a] and after aerobic exposure in 2010-2011.

	Treatment	Moisture content .. % w.b.		Losses .. % of DM		
		Stored	Removed[e]	Storage	After Aerobic Exposure	
					2-day	7-day
			Corn Stover			
Bag 8[a]	Control	49.7	50.3	3.6	0.6	-1.4
	L. buchneri	48.7	50.3	2.8	0.1	-0.6
	L. buch + enz	50.9	51.8	3.9	-0.3	-0.4
	LSD[b]	2.3	2.2	3.8	3.7	3.6
Bag 9[a]	Control	30.7b	29.5c	3.6b	-0.4	1.0
	L. buchneri	29.5b	27.2b	0.9a	-0.5	1.0
	L. buch + enz	25.3a	24.9a	-2.5a	-0.5	1.7
	LSD[b]	2.3	2.0	1.3	1.0	1.5
	Control	40.2b	39.9	3.6b	0.1	-0.2
	L. buchneri	39.1ab	38.8	1.9ab	-0.2	0.2
	L. buch + enz	38.1a	38.4	0.7a	-0.4	0.7
	LSD[c]	1.8	1.6	2.3	2.4	1.8
	High MC	49.8b	50.8b	3.4b	0.1	-0.8
	Low MC	28.5a	27.2a	0.7a	-0.5	1.2
	LSD[d]	1.5	1.3	1.8	2.0	1.5

[a] Date stored and removed from storage provided in table 1.
[b] Least significant difference, different letters in the same column group are statistically different (P=0.05).
[c] Data from silo bags 8 and 9 was pooled by amendment and analyzed using two-way analysis of variance.
[d] Data from silo bags 8 and 9 was pooled by moisture content and analyzed using two-way analysis of variance.
[e] Paired t-test indicated no significant change in moisture of subsample parcels during storage.

Fermentation Products and pH

Inoculation of switchgrass with *L. buchneri* significantly increased the production of acetic acid and total fermentation products compared to the control (table 7). Moisture content within the range harvested did not significantly affect total VFA content. There was a consistent trend for loss of fermentation products and rise in pH during the aerobic storage period. *L. buchneri* treated switchgrass had lower pH and greater VFA content after two days aerobic exposure, but the VFA's were almost completely degraded and volatilized after seven days exposure. Shortly after silage is exposed to air, yeasts begin to respire and breakdown lactic acid and other plant sugars, causing the silage to heat (Kung Jr., 2008). Acids produced during fermentation are one of the most abundant groups of compounds emitted from silages (Mitloehner et al., 2010). High temperatures stimulate the growth of aerobic spoilage microbes (Kung Jr., 2008). Silage emissions are greater at higher temperatures (Montes et al., 2009). Acetic acid is particularly prone to volatilization (Alanis et al., 2008; Montes et al., 2009; Mitloehner, et al., 2010).

Sorghum was ensiled at similar moisture to switchgrass (tables 3 and 4) but sorghum produced more fermentation products (tables 7 and 8), likely due to the former's greater fermentable substrate content. The inoculation of sorghum with *L. buchneri* significantly increased the production of lactic, acetic acid and total fermentation products and reduced the rate of volatilization compared to the control. Moisture content in the range harvested and sorghum type did not significantly affect sorghum fermentation. There was greater VFA content and lower pH in sorghum than switchgrass after seven days of aerobic exposure, which might partially explain why DM losses due to aerobic exposure were slightly less for sorghum compared to switchgrass.

In 2009-2010, the corn stover control and *L. buchneri* treatments fermented to an acidic environment while the addition of lime created an alkaline environment (table 9). Total fermentation products increased with moisture content for all treatments and the *L. buchneri* treatment consistently produced the most fermentation products, especially acetic acid. Shinners et al. (2011a) reported that fermentation products ranged from 2.5% to 5.9% of DM for corn stover ensiled between 40% and 55% (w.b.) moisture, similar to these results.

The fermentation production in the 2010-2011 corn stover bags was much less than that produced 2009 (tables 9 and 10). Material harvested for first corn stover bag in 2010 (bag no. 8) was badly contaminated with soil due to two raking operations prior to harvest. Average ash content of stover stored in this bag was 16.7% compared to the average in 2009 of 6.7%. The temperature profiles from this bag showed little evidence of early aerobic stage biological activity (Williams, 2011), so it is likely the soil contamination hindered fermentation. The final corn stover bag was stored at 28.5% (w.b.) moisture, so little fermentation would have been expected at this low moisture. Similar results were reported in Shinners et al. (2011a). By the end of seven days of aerobic exposure, there were no measurable VFA content in any treatment and pH was consistently above seven.

Table 7. Fermentation products and pH for switchgrass in subsample parcels after anaerobic storage[a] and aerobic exposure in 2010-2011.

		Removed from Storage				After 2-day Aerobic Exposure				After 7-day Aerobic Exposure			
			Fermentation Products … % of DM				Fermentation Products … % of DM				Fermentation Products … % of DM		
Silo Bag No.	Treatment	pH	Lactic Acid	Acetic Acid	Total	pH	Lactic Acid	Acetic Acid	Total	pH	Lactic Acid	Acetic Acid	Total
Bag 5[a]	Control - Hi MC	5.2	0.16a	0.60ab	0.76ab	6.2*	0.25a	0.42ab	0.67a	6.2	0.0	0.0	0.0
"	*Buchneri* - Hi MC	5.0	0.34a	1.52b	1.86bc	5.4	0.36a	1.79c	2.15b	6.4	0.0	0.34	0.34
"	Control - Lo MC	4.8	0.52a	0.0a	0.52a	5.7	0.0a	0.0a	0.0a	7.7	0.13	0.0	0.13
"	*Buchneri* - Lo MC	4.7	1.29b	0.95ab	2.24c	5.2*	1.35b	0.80b	2.15b	5.8	0.0	0.0	0.0
	LSD[b]	0.7	0.74	1.15	1.26	1.9	0.67	0.49	0.93	3.6	0.26	0.67	0.71
"	Control	5.0	0.34	0.30a	0.64a	6.0	0.13a	0.21a	0.34a	7.0	0.07	0.0	0.07
"	*L. Buchneri*	4.9	0.82	1.24b	2.05b	5.3	0.86b	1.30b	2.15b	6.1	0.0	0.17	0.17
	LSD[c]	0.5	0.51	0.79	0.86	1.2	0.42	0.31	0.58	2.2	0.16	0.42	0.44
"	High MC	5.1	0.25a	1.06	1.31	5.8	0.31	1.11b	1.42	6.3	0.0	0.17	0.17
"	Low MC	4.8	0.91b	0.50	1.38	5.5	0.68	0.40a	1.08	6.8	0.07	0.0	0.07
	LSD[d]	0.5	0.51	0.79	0.86	1.2	0.42	0.31	0.58	2.2	0.16	0.42	0.44

[[a] Date stored and removed from storage provided in table 1. Wet basis moisture was 54.2% and 47.4% for Hi MC and Lo MC, respectively.
[b] Least significant difference, different letters in the same column group are statistically different (P=0.05).
[c] Data was pooled by amendment and analyzed using two-way analysis of variance.
[d] Data was pooled by moisture content and analyzed using two-way analysis of variance.
* Indicates that there was a significant change in pH or total fermentation products during aerobic exposure based on paired t-test.

Table 8. Fermentation products and pH for sorghum in subsample parcels after anaerobic storage[a] and aerobic exposure in 2010-2010.

Silo Bag No.	Treatment	Sorghum Type	Removed from Storage				After 2-day Aerobic Exposure				After 7-day Aerobic Exposure			
				Fermentation Products … % of DM				Fermentation Products … % of DM				Fermentation Products … % of DM		
			pH	Lactic Acid	Acetic Acid	Total	pH	Lactic Acid	Acetic Acid	Total	pH	Lactic Acid	Acetic Acid	Total
Bag 6[a]	Control	Sweet	4.3	1.61	0.06a	1.67a	8.7b*	1.56a	0.0	1.56ab	5.3	0.75a	0.0	0.75a
	L. Buchneri	"	4.3	3.50	1.07b	4.57b	4.5a	3.32b	0.90	4.22b	4.4	3.52b	1.06	4.75b
	Control	Forage	4.2	2.27	0.0a	2.27ab	5.3a	1.17a	0.0	1.17a	4.4	0.45a	0.0	0.45a
	L. Buchneri	"	4.1	3.38	1.16b	4.55b	4.1a	3.48b	0.71	4.19b	4.2	3.17b	1.03	4.37ab
	LSD[b]		0.2	2.21	0.62	2.70	1.9	1.75	1.44	2.73	1.9	2.15	1.48	3.99
Bag 7[a]	Control	Sweet	4.5b	2.58	0.50a	3.08a	4.7	3.71	0.90	4.75	4.9b	2.42ab	0.22a	2.64a
	L. Buchneri	"	4.3a	3.10	0.52a	3.62ab	4.3	3.67	0.71	4.38	4.5a	2.80b	0.27a	3.07ab
	Control	Forage	4.3a	3.10	0.81ab	4.10b	4.5	2.61	0.69	3.43	4.5a	1.77a	0.14a	1.91a
	L. Buchneri	"	4.2a	3.10	0.88b	3.98b	4.3	3.39	1.08	4.47	4.4a	3.07b	1.04b	4.39b
	LSD[b]		0.1	0.68	0.35	0.78	0.5	1.35	0.57	2.12	0.2	0.81	0.56	1.37
	Control		4.3	2.39a	0.34a	2.78a	5.9b*	2.26a	0.40a	2.73a	4.8	1.35a	0.09a	1.44a
	L. Buchneri		4.2	3.27b	0.91b	4.18b	4.3a	3.47b	0.85b	4.32b	4.4	3.14b	0.85b	4.15b
	LSD[c]		0.1	0.74	0.22	0.89	0.5	0.60	0.42	0.94	0.5	0.63	0.43	1.15
	High MC		4.2	2.69	0.57	3.27	5.7b*	2.38a	0.40a	2.79a	4.6	1.97	0.52	2.58
	Low MC		4.3	2.97	0.68	3.70	4.5a	3.35b	0.85b	4.26b	4.6	2.52	0.42	3.00
	LSD[d]		0.1	0.7	0.22	0.89	0.5	0.60	0.42	0.94	0.5	0.63	0.43	1.15
	Sweet		4.3	2.70	0.54	3.24	5.6b*	2.44	0.45	2.89	4.8	2.14	0.53	2.67
	Forage		4.2	2.96	0.71	3.72	4.6a	2.66	0.62	3.28	4.4	2.12	0.55	2.67
	LSD[e]		0.1	0.74	0.22	0.89	0.5	0.60	0.42	0.94	0.5	0.63	0.43	1.15

[a] Date stored and removed from storage provided in table 1. Average wet basis moisture for bag 6 and 7 was 57.7% and 45.9%, respectively.
[b] Least significant difference, different letters in the same column group are statistically different (P=0.05).
[c] Data from silo bags 6 and 7 was pooled by amendment and analyzed using two-way analysis of variance.
[d] Data from silo bags 6 and 7 was pooled by moisture content and analyzed using two-way analysis of variance.
[e] Data from silo bags 6 and 7 was pooled by sorghum type and analyzed using two-way analysis of variance.
* Indicates that there was a significant change in pH or total fermentation products during aerobic exposure based on paired t-test.

Table 9. Fermentation products, pH and yeast and mold for corn stover in subsample parcels after anaerobic storage[a] and aerobic exposure in 2009-2010.

Silo Bag No.	Treatment		Fermentation Products … % of DM			Mold[e]	Yeast[e]
		pH	Lactic Acid	Acetic Acid	Totals	log (CFU/g)	log (CFU/g)
Bag 2[a]	Control	5.3a	1.54b	0.60a	2.36a	4.1a	7.2b
	L. Buchneri	4.2a	2.38b	1.81b	4.69b	3.0a	4.4a
	$Ca(OH)_2$	7.7b	0.40a	3.38c	4.53b	7.0b	7.6b
	LSD[b]	1.2	0.97	0.45	1.45	1.5	1.8
Bag 3[a]	Control	5.0a	0.94a	0.53a	1.48a	7.2b	8.6b
	L. Buchneri	4.5b	1.36b	1.25b	2.79b	4.8a	4.0a
	$Ca(OH)_2$	8.0c	0.70a	1.19b	1.91a	7.1b	7.4b
	LSD[b]	0.4	0.39	0.3	0.68	1.7	2.0
Bag 4[a]	Control	4.7a	1.01	0.95a	2.23a	5.6ab	7.3
	L. Buchneri	4.6a	0.88	2.40b	3.63b	3.9a	7.2
	$Ca(OH)_2$	7.8b	1.18	0.91a	2.32a	6.3b	7.8
	LSD[b]	0.2	0.32	0.13	0.51	1.7	1.7
	Control	5.0a	1.16ab	0.69a	2.02a	5.6b	7.7b
	L. Buchneri	4.4a	1.54b	1.82b	3.70b	3.9a	5.2a
	$Ca(OH)_2$	7.9b	0.76a	1.82b	2.92ab	6.8b	7.6b
	LSD[c]	0.7	0.63	0.32	0.97	1.6	1.8
	High MC	5.7	1.44	1.93c	3.86b	4.7a	6.4
	Inter. MC	5.7	1.02	1.42b	2.73a	5.3ab	7.4
	Low MC	5.8	1.00	0.99a	2.06a	6.4b	6.7
	LSD[d]	0.7	0.63	0.32	0.97	1.6	1.8

[a] Date stored and removed from storage provided in table 1.
[b] Least significant difference, different letters in the same column group are statistically different (P=0.05).
[c] Data from silo bags 2, 3, and 4 was pooled by amendment and analyzed using two-way analysis of variance.
[d] Data from silo bags 2, 3, and 4 was pooled by moisture content and analyzed using two-way analysis of variance.
[e] Mold and yeast counts after removal from 2-day aerobic exposure.

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Table 10. Fermentation products and pH for corn stover in subsample parcels after anaerobic storage[a] and aerobic exposure in 2010-2010.

Silo Bag No.	Treatment	Removed from Storage				After 2-day Aerobic Exposure				After 7-day Aerobic Exposure			
			Fermentation Products … % of DM				Fermentation Products … % of DM				Fermentation Products … % of DM		
		pH	Lactic Acid	Acetic Acid	Total	pH	Lactic Acid	Acetic Acid	Total	pH	Lactic Acid	Acetic Acid	Total
							Corn Stover						
Bag 8[a]	Control	4.8a	0.0	0.0	0.0	6.7b	0.0	0.0	0.0	7.6	0.0	0.0	0.0
	L. buchneri	5.0ab	0.52	0.71	1.31	5.6ab	0.46	0.17	0.63	7.6	0.0	0.0	0.0
	L. buch + enz	5.1b	0.58	1.71	2.43	5.1a	0.34	1.78	2.12	7.8	0.0	0.0	0.0
	LSD[b]	0.2	1.22	2.23	3.55	1.4	1.47	4.65	5.73	3.4	--	--	--
Bag 9[a]	Control	7.6	0.0	0.0	0.0	8.0	0.0	0.0	0.0	8.6b	0.0	0.0	0.0
	L. buchneri	7.1	0.03	0.0	0.03	8.1	0.04	0.0	0.04	8.0a	0.0	0.0	0.0
	L. buch + enz	7.2	0.0	0.06	0.06	7.8	0.0	0.05	0.05	8.6b	0.0	0.0	0.0
	LSD[b]	0.8	0.07	0.12	0.14	2.5	0.09	0.13	0.16	0.2	--	--	--
	Control	6.2	0.0	0.0	0.0	7.4	0.0	0.0	0.0	8.1	0.0	0.0	0.0
	L. buchneri	6.1	0.28	0.36	0.67	6.9	0.25	0.09	0.34	7.8	0.0	0.0	0.0
	L. buch + enz	6.2	0.29	0.89	1.25	6.5	0.17	0.92	1.09	8.2	0.0	0.0	0.0
	LSD[c]	0.4	0.53	0.97	1.55	1.0	0.52	1.65	2.04	1.2	--	--	--
	High MC	5.0a	0.37	0.81	1.25	5.8a	0.27	0.65	0.92	7.7	0.0	0.0	0.0
	Low MC	7.3b	0.01	0.02	0.03	8.0b	0.01	0.02	0.03	8.4	0.0	0.0	0.0
	LSD[d]	0.3	0.43	0.79	1.26	0.8	0.42	1.33	1.64	1.0	--	--	--

[a] Date stored and removed from storage provided in table 1. Average wet basis moisture content for bag 8 and 9 was 49.8% and 28.5%, respectively.
[b] Least significant difference, different letters in the same column group are statistically different (P=0.05).
[c] Data from silo bags 8 and 9 was pooled by amendment and analyzed using two-way analysis of variance.
[d] Data from silo bags 8 and 9 was pooled by moisture content and analyzed using two-way analysis of variance.
* Indicates that there was a significant change in pH or total fermentation products during aerobic exposure based on paired t-test.

.**Yeast and Mold**

Inoculation of switchgrass and corn stover (2009) with *L. buchneri* reduced the mold and yeast development both during storage and after aerobic exposure (table 9 and 11). Generally mold and yeast populations increased from storage through the two and seven day aerobic exposure. Low moisture sorghum had statistically smaller mold and yeast populations than high moisture sorghum (table 12). Moisture did not affect populations in switchgrass or corn stover (2010) (table 13). Type of sorghum had no significant effect on mold and yeast populations. Corn stover mold and yeast populations were greater than those for perennial grasses and sorghum. This might have been caused by soil contamination of windrows used to make fourth stover bag and the subsequent unfavorable inoculation from the soil. The moisture of the last stover bag was low (28.5% w.b.) and little fermentation took place (table 9), so there may have been a more favorable environment for microbial growth. Mold and yeast counts for ensiled alfalfa haylage and corn silage typically ranged from 3 to 5 log CFU/g (Dairyland Labs, 2011) which was less than the range here of 3.6 to 8.1 log CFU/g. Ensiled animal feeds are typically stored at higher moisture and have more readily fermented substrate than these biomass crops, so more fermentation products are produced and less microbial growth occurs at removal.

Temperature In Storage

Temperatures within the subsample parcels followed a similar pattern for all crops and treatments. Shortly after the silo bags were sealed, the temperature increased quickly during the aerobic phase (fig. 2). The temperature typically peaked within five to seven days. Once the aerobic phase was completed, the temperatures gradually declined and stabilized for the remainder of the storage period. Temperature histories of this type indicate that stable conditions existed in the bag silos during the storage period (Pitt, 1990). Lime treated corn stover had the greatest peak temperature of the three treatments in the first three corn stover experiments (fig. 2). The lime may have had a slightly exothermic reaction with material moisture causing the temperature rise. Once the aerobic phase was over, lime treated stover had the same equilibrium temperature history as the other two treatments. The peak temperatures for crops stored late in the harvest season were typically less than those formed early in the fall.

Table 11. Mold and yeast counts in switchgrass subsample parcels after anaerobic storage[a] and aerobic exposure in 2010-2011.

Silo Bag No.	Treatment	At Removal		After Aerobic Exposure			
				2-day		7-day	
		Mold	Yeast	Mold	Yeast	Mold	Yeast
		log (CFU/g)	log (CFU/g)	log (CFU/g)	log (CFU/g)	log (CFU/g)	log (CFU/g)
		Switchgrass					
Bag 5[a]	Control - Hi MC	6.3	6.3	7.3b	6.3ab	6.0a	7.8b
"	*L. Buchneri* - Hi MC	5.2	4.5	5.3a	5.3a	6.5a	7.2ab
"	Control - Lo MC	5.0	6.0	6.5ab	8.0b	6.4a	7.6b
"	*L. Buchneri* - Lo MC	4.8	4.6	5.8a	5.7a	7.4b	6.5a
	LSD[b]	3.2	2.1	1.3	2.1	0.8	1.1
"	Control	5.7b	6.2b	6.9b	7.2b	6.2a	7.7b
"	*L. Buchneri*	5.0a	4.6a	5.6a	5.5a	7.0b	6.9a
	LSD[c]	2.2	1.4	0.8	1.3	0.5	0.7
"	High MC	5.8b	5.4	6.3	5.8	6.3	7.5
"	Low MC	4.9a	5.3	6.2	6.9	6.9	7.1
	LSD[d]	2.2	1.4	0.8	1.3	0.5	0.7

[a] Date stored and removed from storage provided in table 1. Wet basis moisture was 54.2% and 47.4% for Hi MC and Lo MC, respectively.

[b] Least significant difference, different letters in the same column group are statistically different (P=0.05).

[c] Data was pooled by amendment and analyzed using two-way analysis of variance.

[d] Data was pooled by moisture content and analyzed using two-way analysis of variance.

Table 12. Mold and yeast counts in sorghum subsample parcels after anaerobic storage[a] and aerobic exposure in 2010-2011.

Silo Bag No.	Treatment	Sorghum Type	At Removal		After Aerobic Exposure			
					2-day		7-day	
			Mold	Yeast	Mold	Yeast	Mold	Yeast
			log (CFU/g)	log (CFU/g)	log (CFU/g)	log (CFU/g)	log (CFU/g)	log (CFU/g)
Bag 6[a]	Control	Sweet	7.1	6.1b	7.5	6.5	7.0ab	7.2ab
	L. Buchneri	"	5.8	3.9a	5.7	4.7	5.5a	5.2ab
	Control	Forage	6.3	3.8a	6.2	5.7	8.5b	7.4b
	L. Buchneri	"	5.4	5.1ab	5.6	4.0	6.0a	4.0a
	LSD[b]		2.6	2.0	3.4	4.0	1.6	3.3
Bag 7[a]	Control	Sweet	4.9	4.7	4.5	4.3	6.0	3.5ab
	L. Buchneri	"	5.3	4.0	3.2	3.0	5.7	3.0a
	Control	Forage	4.7	4.4	5.1	3.0	4.9	4.5b
	L. Buchneri	"	3.8	3.0	4.7	3.4	3.7	3.0a
	LSD[b]		2.3	2.6	2.8	1.5	3.6	1.2
	Control		5.8	4.8	5.8	4.9	6.6b	5.7b
	L. Buchneri		5.1	4.0	4.8	3.8	5.2a	3.8a
	LSD[c]		1.1	1.0	1.2	1.2	1.1	1.0
	High MC		6.2b	4.7	6.3b	5.2b	6.8b	6.0b
	Low MC		4.7a	4.0	4.4a	3.4a	5.1a	3.5a
	LSD[d]		1.1	1.0	1.2	1.2	1.1	1.0
	Sweet		5.8	4.7	5.2	4.6	6.1	4.7
	Forage		5.1	4.1	5.4	4.0	5.8	4.7
	LSD[e]		1.1	1.0	1.2	1.2	1.1	1.0

[a] Date stored and removed from storage provided in table 1. Average wet basis moisture for bag 6 and 7 was 57.7% and 45.9%, respectively.
[b] Least significant difference, different letters in the same column group are statistically different (P=0.05).
[c] Data was pooled by amendment and analyzed using two-way analysis of variance.
[d] Data was pooled by moisture content and analyzed using two-way analysis of variance.
[e] Data was pooled by sorghum type and analyzed using two-way analysis of variance

Table 13. Mold and yeast counts in corn stover subsample parcels after anaerobic storage[a] and aerobic exposure in 2010-2011.

Silo Bag No.	Treatment	At Removal		After Aerobic Exposure			
				2-day		7-day	
		Mold	Yeast	Mold	Yeast	Mold	Yeast
		log (CFU/g)	log (CFU/g)	log (CFU/g)	log (CFU/g)	log (CFU/g)	log (CFU/g)
Bag 8[a]	Control	5.4	8.1	4.8	8.1b	7.3	7.9
	L. buchneri	5.2	6.7	3.9	7.4b	6.7	8.0
	L. buch + enz	3.6	5.9	3.0	5.7a	4.3	7.9
	LSD[b]	3.1	2.4	5.1	1.0	3.4	0.3
Bag 9[a]	Control	4.2a	7.5	4.1	7.4	4.4	7.7
	L. buchneri	4.2a	7.2	5.1	7.5	4.8	7.3
	L. buch + enz	5.6b	7.5	5.5	6.9	6.3	7.3
	LSD[b]	1.3	0.6	2.9	1.9	1.8	1.9
	Control	4.8	7.8	4.5	7.8b	5.9	7.8
	L. buchneri	4.7	7.0	4.5	7.5b	5.8	7.7
	L. buch + enz	4.6	6.7	4.3	6.3a	5.3	7.6
	LSD[c]	1.5	1.1	2.1	0.7	1.4	0.7
	High MC	4.7	6.9	3.9	7.1	6.1	7.9
	Low MC	4.7	7.4	4.9	7.3	5.2	7.4
	LSD[d]	1.2	0.9	1.7	0.6	1.1	0.5

[a] Date stored and removed from storage provided in table 1. Average wet basis moisture content for bag 8 and 9 was 49.8% and 28.5%, respectively.

[b] Least significant difference, different letters in the same column group are statistically different (P=0.05).

[c] Data was pooled by amendment and analyzed using two-way analysis of variance.

[d] Data was pooled by moisture content and analyzed using two-way analysis of variance.

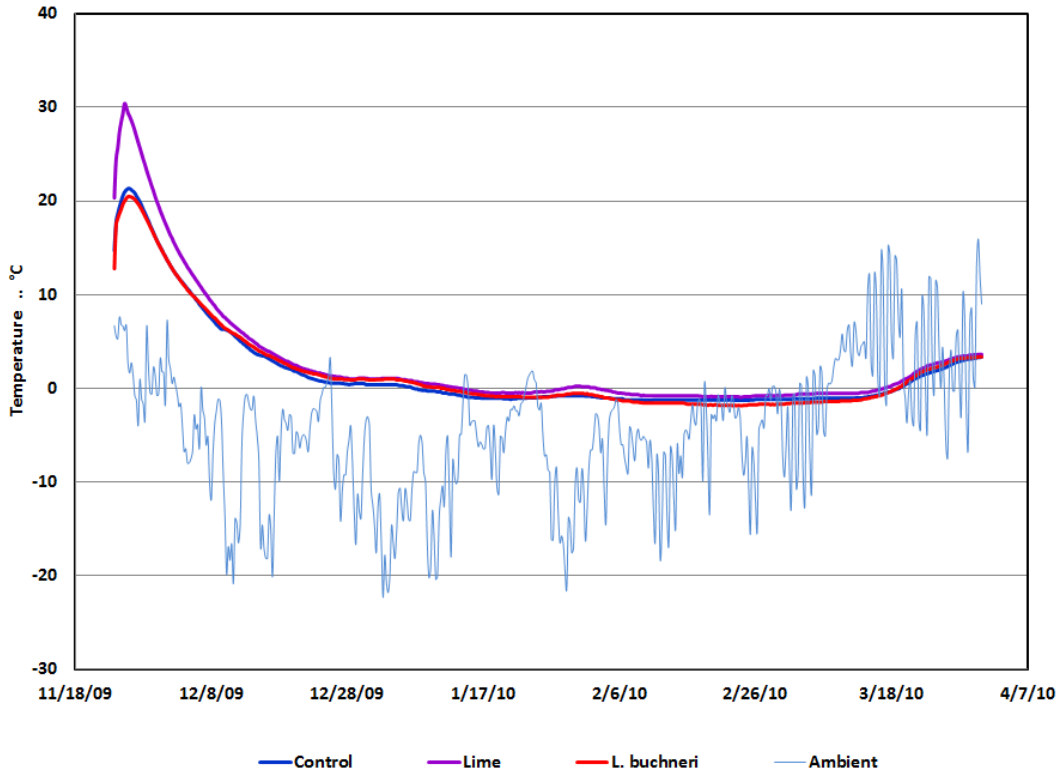

Figure 2. Temperature history of corn stover in subsample parcels stored in silo bags during 2009-2010.

AEROBIC STABILITY

For switchgrass, only the low moisture control treatment was unstable during aerobic exposure (table 14). Fermentation products were least for this treatment and these products were degraded most quickly (table 7). Switchgrass inoculated with *L. buchneri* was more stable than the control because the inoculated treatments produced more fermentation products. Switchgrass without inoculation was relatively stable during the first two days of exposure, but the control treatment began to heat rapidly by the third day (fig. 3).

Both sorghum types were relatively stable during the first two days of aerobic exposure (table 14). The forage sorghum was slightly more stable than the sweet sorghum over the seven day exposure period. The low moisture sorghums heated less than the high moisture sorghums because they had slightly greater fermentation products and had less water to support biological activity. The material inoculated with *L. buchneri* was more stable in those circumstances when heating did occur in the control treatment. Ambient temperature was not recorded on an hourly basis in 2009 so quantification of aerobic stability was limited to the temperature history (fig. 4). The material inoculated with *L. buchneri* was more stable than the control or lime treatments. In 2010, the high moisture control treatment exhibited instability during aerobic exposure (table 14) which was likely due to the soil contamination and subsequent poor fermentation that occurred in storage (table 10). Inoculation with *L. buchneri* did improve stability of the high moisture stover, but heating still occurred. The low moisture stover heated less than the high moisture stover presumably because there was less water to support biological activity.

Table 14. Aerobic stability as quantified by heating degree days (°C) for aerobic exposure experiments in 2011.

Crop	Treatment	Aerobic Exposure Duration			
		2 Days		7 Days	
		Container Position[e]		Container Position[e]	
		High	Low	High	Low
Switchgrass - Hi MC[a]	Control	1	0	0	0
"	L. buchneri	0	0	0	0
Switchgrass - Lo MC[a]	Control	3	6	77	59
"	L. buchneri	0	0	4	11
Forage Sorghum - Hi MC[b]	Control	1	0	23	15
"	L. buchneri	0	0	3	2
Forage Sorghum - Lo MC[b]	Control	0	0	3	3
"	L. buchneri	0	0	2	2
Sweet Sorghum - Hi MC[c]	Control	6	4	138	67
"	L. buchneri	0	0	3	2
Sweet Sorghum - Lo MC[c]	Control	0	0	2	3
"	L. buchneri	0	0	3	2
Corn Stover - Hi MC[d]	Control	12	13	111	109
"	L. buchneri	5	7	74	74
"	L. buch + enz	2	1	48	47
Corn Stover - Lo MC[d]	Control	4	2	19	23
"	L. buchneri	1	1	6	6
"	L. buch + enz	0	0	18	17

[a] Switchgrass wet basis moisture averaged 54.2% and 47.4% for Hi MC and Lo MC, respectively.
[b] Forage sorghum wet basis moisture averaged 58.9% and 44.0% for Hi MC and Lo MC, respectively.
[c] Sweet sorghum wet basis moisture averaged 57.0% and 48.6% for Hi MC and Lo MC, respectively.
[d] Corn stover wet basis moisture averaged 49.8% and 28.5% for Hi MC and Lo MC, respectively
[e] The subsample parcels were approximately 10 and 45 cm from the material surface for the high and low positions, respectively.

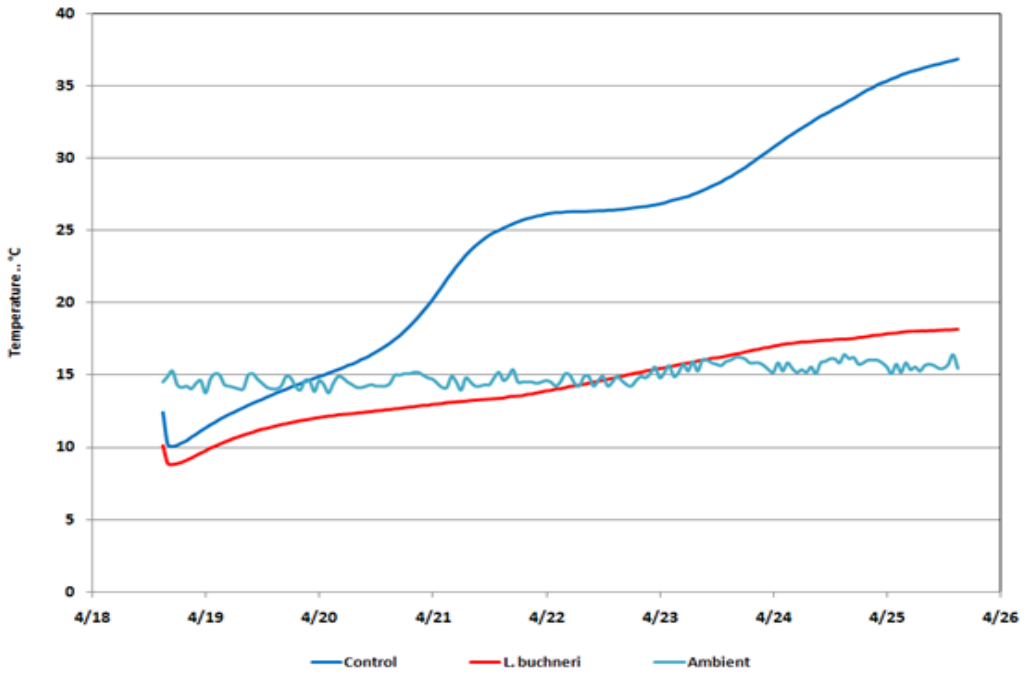

Figure 3. Temperature history of switchgrass at 47.4% (w.b.) moisture in subsample parcels during seven day aerobic exposure experiment conducted in 2011.

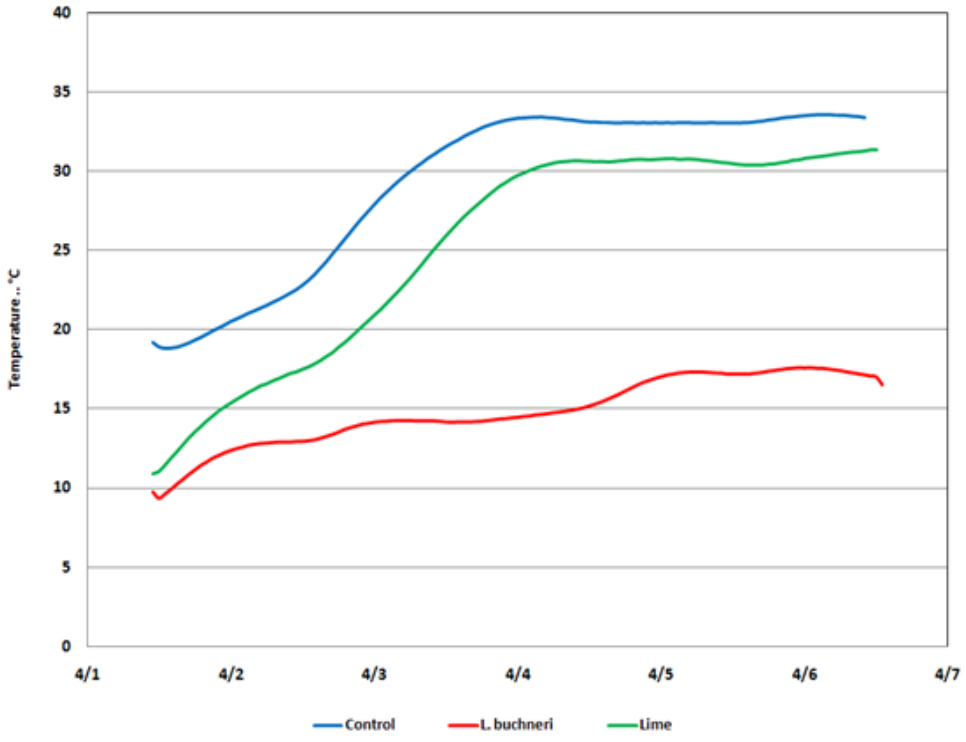

Figure 4. Temperature history of corn stover at 54.4% (w.b.) moisture in subsample parcels during five day aerobic exposure experiment conducted in 2010.

DISCUSSION

Animal forages conserved by anaerobic storage are typically stored between 55 and 65% (w.b.) moisture so that a strong fermentation occurs. Storing at lower moistures would produce low levels of fermentation products and create concerns with aerobic stability at feed-out because of the slow rate of removal and long aerobic exposure. Biomass feedstocks must be transported off the farm and transportation costs can be reduced when the dry mass transported is maximized. From this standpoint, conserving biomass feedstocks by anaerobic storage at 30 to 55% (w.b.) moisture would be desirable. For instance, if legal road weight limits can be achieved, 44% more DM can be transported when feedstock moisture is 35% (w.b.) compared to when it is 55% (w.b.). All the biomass crops stored in this research were well conserved by anaerobic storage even when moisture was much less than 50% (w.b.). Storage losses were generally below 4% of DM when anaerobic conditions were maintained.

The removal rate of biomass destined for a biorefinery would be comparatively much faster than ensiled animal feed. All feedstocks were relatively stable after two days of aerobic exposure, but the temperature of untreated feedstocks occasionally increased rapidly after two days. Inoculation of feedstocks with *L. buchneri* improved the aerobic stability of all feedstocks so that little heating occurred during a seven day exposure. It is likely that most feedstocks would be consumed in that time given the mass input requirements of large scale biorefineries.

Losses of DM during aerobic exposure were small, averaging 1.0% and 1.5% of DM during two- and seven day exposure durations. Some of this loss could have been due to microbial consumption of fermentation acids. Mold and yeast populations increased during aerobic exposure. Inoculation with *L. buchneri* generally had little significant effect on losses during aerobic exposure but reduced mold and yeast populations.

Biorefineries desire feedstocks with very consistent properties. Moisture content of material removed after many months of anaerobic storage was similar to the harvested moisture for all crops and the spatial distribution within the silo bag was uniform (Williams, 2011). Moist biomass crops stored anaerobically in silo bags should produce a more desirable feedstock than outdoor stored bales because of lower losses and more consistent properties.

CONCLUSIONS

A moist biomass feedstock harvest and storage system has many advantages compared to a dry bale system. The moist harvest system is more robust and has fewer risks than the dry bale system because it has greater weather tolerance, longer harvest window, and greater harvesting productivity. Additionally, the system produces a value-added, size-reduced product at harvest which lends itself to pretreatment during storage. However, moist feedstocks must be anaerobically stored and preserved by fermentation. Switchgrass, sorghum, and corn stover were anaerobically stored in pilot-scale silo bags for extended periods at moisture contents that ranged between 28.5% and 61.5% (w.b.) with an overall average of 44.3%.

Storage losses averaged 2.7%: 3.1%; and 2.0% of DM, for switchgrass, sorghum and corn stover, respectively. Moisture content did not significantly affect storage losses for switchgrass or sorghum, but there was a trend for lower corn stover losses stored at lower moisture. Across all crops, material inoculated with *L. buchneri* did not significantly affect storage losses compared to untreated feedstocks. Stover mixed with lime had significantly lower losses than the untreated stover.

Losses during aerobic exposure ranged from nil to 5.2% of DM with losses increasing from two to seven days of aerobic exposure. Overall average DM loss after two and seven day aerobic exposure was 1.0% and 1.7%, respectively. Sorghum aerobic losses were significantly less when inoculated with *L. buchneri*, otherwise inoculation did not significantly affect aerobic losses. Lower moisture significantly reduced aerobic losses with sorghum and corn stover (2009 only).

Fermentation products, mainly lactic and acetic acid, were generally less than 5% of DM with an overall average of 2.2%. Across all crops, material inoculated with *L. buchneri* produced significantly greater level of fermentation products during storage. The pH of all feedstocks increased during aerobic exposure due to the degradation and volatization of fermentation acids. Material inoculated with *L. buchneri* remained at a lower pH after aerobic exposure, except in the corn stover treatments where limited fermentation acids were produced during storage. As quantified by temperature, feedstocks inoculated with *L. buchneri* remained more stable during seven days of aerobic exposure than untreated material.

Anaerobic storage was shown to successfully conserve a variety of different moist biomass feedstocks, resulting in low material losses and a uniform moisture distribution upon removal. Maximum value of these feedstocks will be realized if they can be utilized soon after removed from the silo, but inoculation with *L. buchneri* will improve the stability of feedstocks experiencing aerobic exposure for several days.

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