Evaluating the Physical Quality of an Energy Crop during Storage from a Preprocessing Technology in Feedstock Supply System

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Introduction and Justification

•Lignocellulosic biomass (LCB) energy crops have an important role in meeting the national mandate of advanced biofuels.

•The low bulk density of LCB feedstock is currently impeding the commercialization of this industry so densification of LCB feedstock has been considered a step to improve efficiency in feedstock logistics and improve the economic efficiency of the logistics system.

•Moisture content and resulting dry matter losses (DML) during storage has important implications to the performance of LCB feedstock logistics and feasibility of biofuel production. DML may cause substantial reduction in both quantity and quality of feedstock increasing feedstock cost. Feedstock handled by different technologies in collection and storage may have various DML

•Assessing the storage DML of LCB feedstock processed by alternative and/or innovative technologies in feedstock logistics system is important.

Research Motivation

Larson et al. (2010) suggest a commercial stretch-wrap baler, BaleTech 3 (BT3), to be a potential feasible alternative to the conventional harvesting methods for chopped switchgrass. BT3 compacts chopped biomass into a large round and reduces storage area requirements by more than a factor of three. A key assumption in their study is storage DML with the plastic wrapped bales by the technology was negligible

Two Research Objectives

To estimate DML of stored switchgrass under different particle sizes of feedstock and storage protection using the BT3 technology in the logistic system,

- DML during storage was correlated with particle size of biomass feedstock (Jirjis, R, 1995; Medic D, Darr M, Shah A, and Rahn S., 2012)
- storage protection impacts the DML of stored feedstock (Chaoui and Eckhoff, 2014)

To determine the relationship between DML of biomass with particle size and protection materials over storage time.

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Experiment Design and Data

•A split-split plot design with five replications was used (Kuehl 2000). Three particle sizes of baled switchgrass: a) full length (*PS-1*), b) 3 inches (*PS-2*), and c) < 1" inches (*PS-3*).

•subplots treatments:

- •one set with mesh net wrapped the outside, excluding the two ends, of the round bale (*net only*);
- •the other set, in addition to the net applied to the outside, with high tensile strength plastic wrapped both outside and the ends of the round bales (*net & plastic*).

•sub-subplots were stored days: 75, 150, & 225 days (Table 1)

Table 1. Bale Treatment and Number of Bales

Days in storage	N/ PS-1	N/ PS-2	N/ PS-3	N&P/ PS-1	N&P/ PS-2	N&P PS-3
0	5	5	5	5	5	5
75	5	5	5	5	5	5
150	5	5	5	5	5	5
225	5	5	5	5	5	5

DML Estimation

Table 2. Mean Dry Matter Weights by Particle Size, Wrap Type, and Storage

Treatments	Mean Average Dry Matter Weights of the Bales
	Kg
Particle Size:	
Full Length	1,889
3" Material	1,726
1" Material	1,690
Wrap:	
Net Only	1,696
Net & plastic	1,840
Days in Storage:	
0	1,823
75	1,793
150	1,688
225	1,664

For each of the sub-subplot treatments (i.e., days in storage), bales were destroyed and samples were randomly taken to estimate DM content of each bale. Dry bale weight was determined using the DM content and actual weigh at destruction. Table 2 shows the average dry matter weights for switchgrass bales by particle size, wrap material for storage, and days stored. DML was calculated by subtracting the dry bale weight at destruction from the dry matter weight at harvest (day zero) divided by the dry bale weight at harvest. There were a few instances when DML was negative, which means the dry matter weight of the bale increased over time. These values were assumed to be an artifact of the data and were adjusted by assuming DML was zero, giving an adjusted DML (ADML) value. Table 3 shows the ADML for the switchgrass bales over the storage period by particle size and wrap material for storage.

Table 3. Expected Adjusted Dry Matter Loss by Particle Size and Wrap[a]

	Particle Size			Wrap Material	
Day	PS-1	PS-2	PS-3	N	N & P
			Percent		
75	4.7	4.1	1.2	3.0	3.6
150	8.0	6.1	7.2	10.6	3.5
225	14.6	12.9	2.1	13.1	6.6

[a]PS-1 -- Full Length, PS-2 -- 3" material, PS-3 -- 1" material, N – net wrapped, N&P – net wrapped and plastic wrapped

Methods

ANOVA Analysis

First, an Analysis Of Variance (ANOVA) was conducted to determine the effects of bale wrapping, particle size, and days stored on the ADML following the split-split-plot design analysis. A mixed model was used to perform the ANOVA.

$$ADML_{ijlk} = \mu + \sum_{i=1}^{3-1}\alpha_i PS_i + \beta_j W_j + \sum_{i=1}^{3-1}\delta_{ij} PS_i W_j + \sum_{l=1}^{3-1}\gamma_l D_l + \sum_{i=1}^{3-1}\sum_{l=1}^{3-1}\lambda_{il} PS_i D_l + \sum_{l=1}^{3-1}\theta_{jl} W_j D_l + \sum_{i=1}^{3-1}\sum_{l=1}^{3-1}\omega_{ijl} PS_i W_j D_l + \nu_k + u_{ki} + \upsilon_{kij} + e_{ijlk}$$

Where: $ADML_{ijl}$ is the ADML for particle size i with wrapped and stored in the jth material at the lth day; μ *is* intercept coefficient; PS_i is an indicator variable for the ith particle size; W_j is an indicator variable for the jth wrap; D_l is an indicator variable for the lth day;

α_i, β_j, δ_{ij}, γ_l, λ_{il}, θ_{jl}, and ω_{ijl} are coefficients for the different whole plots, subplots, sub-subplots, and the interaction across the treatments; ν: a random effect for the kth replication; µ: a random effect for replication k and particle size i; υ: a random effect for the k replication and particle size i wrapped and stored in material j; e: the random error term.

Response Function

Liner and quadratic response functions were estimated to measure the ADML for bales across days.

$$ADML_{ij} = \tau_{1ij} DIS + \tau_{2ij} DIS^2 + \xi_{ij}$$

$$ADML_{ij} = \eta_{1ij} DIS + \varepsilon_{ij}$$

where $ADML_{ij}$ is the ADML for particle size i with wrapped and stored in the jth material; η_{1ij} I τ_{1ij}, and τ_{2ij} are coefficienst; DIS is the days in storage; and the random error term are $\varepsilon_{ij} \sim N(0,\sigma_\varepsilon^2) and \xi \sim N(0,\sigma_\xi^2)$ The Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) were used to determine the response function that was most appropriate for the data. The response function with the lowest AIC and BIC value was selected as the more appropriate response function.

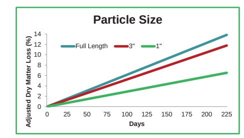
Results

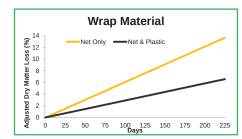
Results for the F-test of the ANOVA model (equation 1) are presented in Table 4. Non-normality and heteroskedasticity were not found to be present in the data. ADML was different ($p \leq 0.05$) across particle sizes, wrap material for storage, and days stored. The fixed effects for the interaction variables were not different

Two response functions used to estimate ADML over time examine particle sizes and wrap materials. For every day in storage, ADML increased by 0.06% day^{-1} for bales with particle size PS-1, while the ADML increased by 0.02% for particle size PS-3. This slower rate of ADML results in bales with particle size PS-1 having roughly twice as much ADML as bales with particle size PS-3. ADML for bales wrapped in net plus plastic was approximately half that of the bales wrapped and stored in net only. The additional plastic wrap material sealed the entire bale from exposure to the weather while using net wrap material alone allowed left the bale exposed to weather. Over the entire 225-day storage, the results indicate ADML ranging from 6.5% to 14.2% depending on the particle size and wrap material.

Table 4. F-Test Results for the Fixed Effects in the ANOVA Model Using the Transformed Data

Fixed Effects	F-Value	P-Value
Particle Size (*PS*)	3.83	0.0302
Wrap (*W*)	6.43	0.0159
PS x W	0.22	0.8852
Day (*D*)	4.28	0.0124
PS x *D*	0.99	0.1300
W x *D*	1.88	0.1405
PS x *W* x *D*	1.30	0.2202





Conclusions

Dry matter loss during storage has important implications to the performance of LCB feedstock logistics and feasibility of biofuel production, but is generally not considered in the evaluation of an alternative and/or innovative logistics technology for LCB materials. This study estimated DML of stored switchgrass with different particle sizes of feedstock and storage protection using a recently studied densification technology, Bale Tech technology, in a switchgrass logistic system. In addition, the correlation between DML of switchgrass with particle size and protection materials over storage time were also analyzed. DML data in this analysis were generated from an outdoor experiment in Vonore, Tennessee with a split-split plot design in 2011-12 for total 120 samples stored up to 225 days.

The ANOVA analysis suggests that the adjusted DML varied across particle sizes, wrap materials for storage and storage duration. Specifically, the storage DML was lower when the particle size of switchgrass baled decreased from full length to less than 2 cm. This finding contradicts to the hypothesis proposed by Chaoui and Eckhoff [2014] that assumed that larger particle sizes may be preferred for a bale or outdoor storage as the erosion by wind and rain is more possible for smaller particles. Our results imply that the condensed bales processed by the stretch-wrap technology provide sufficient protection to prevent the smaller particles from potential erosions. In addition, covering the entire bale with plastic in addition to mesh net reduced ADML relative to a wrapping of sole net on the outside of the cylinder. As anticipated, ADML increased as storage time increased. Finally, a linear response function was found to fit the pattern of ADML better over time. Our findings suggest that applying both mesh net and plastic wrap to switchgrass bales composed by a particle size less than 2 cm can minimize the DML during storage.

As the demand of developing efficient and innovative technologies in a logistics system that also maintains the quality of biomass feedstock has gained recent attention, this analysis can be applied to the evaluation of other potential collection and storage technologies in LCB feedstock logistics. In addition, future study can be extended to assess other characteristics of stored LCB feedstock, such as cellulose, ash or lignin, processed by alternative technologies.