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Research Report

Final Report

Biomass Energy Crop Densification Evaluation

For:
Ontario Federation of Agriculture

Innovative Solutions for Agriculture and Beyond

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AAC
agricultural adaptation council
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OFA Ontario Federation of Agriculture

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1. Executive Summary

The Ontario Federation of Agriculture, the Client, requested that PAMI perform densification research on four types of agricultural biomass crops currently grown in Ontario. PAMI has designed and fabricated a mobile densification system to study the opportunities for increased transportation distances by compact agricultural biomass.

The Client identified corn stover, soybean residue, switchgrass, and miscanthus as candidates for densification research. Each of the four biomass types was delivered to PAMI's facility in Portage la Prairie, Manitoba in the form of round or rectangular bales. Prior to densification, the corn stover, soybean residue, and switchgrass bales were processed through a 75mm screen of a hammer mill. Miscanthus bales were processed through a 35mm screen.

The corn stover used in this trial responded very well to the densification process with an average capacity of 570 kg/h. The corn stover achieved an average bulk density of 424 kg/m^3 with an average durability of 92%.

The soybean residue formed cubes during initial demonstration trials, but a full trial was not performed due to equipment plug ups. A consistent feed rate was not achieved after multiple attempts. It appeared that the fibrous nature of the feedstock, and possibly high moisture caused it to collect in clumps, which would frequently plug the system.

The switchgrass material would not form cubes due to low moisture content. Cubes did form when the feedstock was subjected to a small amount of water mist in the infeed system. The switchgrass achieved an average capacity of 210 kg/h, average bulk density of 498 kg/m^3, and a durability of 87% when subjected to a proper amount of moisture.

The miscanthus did not form cubes consistently. Low moisture was suspected as the problem, but the addition of water in the infeed system did not improve densification. The tests provided mixed results with capacity of 206 kg/h, bulk density of 521 kg/m^3, and durability of 63% for miscanthus product without added moisture.

An engineering assessment of feedstock logistics for agricultural biomass was also conducted. It suggests that densification of biomass may be necessary to access the full range of bioenergy markets that are becoming available. The bioenergy industry is expected to transfer pre-processing responsibilities to producers to achieve a uniform format of biomass products. This means that efficient densification technologies at or near the farm gate must be developed in order for agricultural producers to compete in emerging bioenergy markets alongside forestry and municipal waste biomass producers.

2. Introduction

The Ontario Federation of Agriculture, the Client, represents farmers across Ontario, Canada. The Client is studying the opportunity to utilize crop residues and grow dedicated biomass energy crops in Ontario. Currently, the Client has been granted funding to evaluate the production and economics associated with growing dedicated bioenergy crops. One of the limitations of growing dedicated biomass crops has been the high transportation costs associated with moving bulky materials long distances. PAMI has designed and fabricated a mobile densification system to study the opportunities for increased transportation distances by compact agricultural biomass.

The Client requested that PAMI perform densification research on the dedicated biomass energy crops currently grown in Ontario and other agricultural biomass residuals remaining after harvest. There were four feedstock types that were identified as potential candidates for densification:

- Crop residues;
  - Corn Stover
  - Soybean Residue
- Dedicated energy crops:
  - Switchgrass
  - Miscanthus

The Client also requested that PAMI provide a report detailing the densification research and summarizing the data from the densification research trials. The report includes an engineering assessment of how mobile densification could be incorporated into an agricultural biomass feedstock logistics model. The engineering assessment also explores other alternatives that are becoming available through emerging technologies.

3. An Overview of PAMI's Mobile Densification System

A brief overview of PAMI's Mobile Densification System is included below. The overview is intended to clarify the terminology and outline the process flow. The major components of the densification system are shown in **Figure 1**, below.

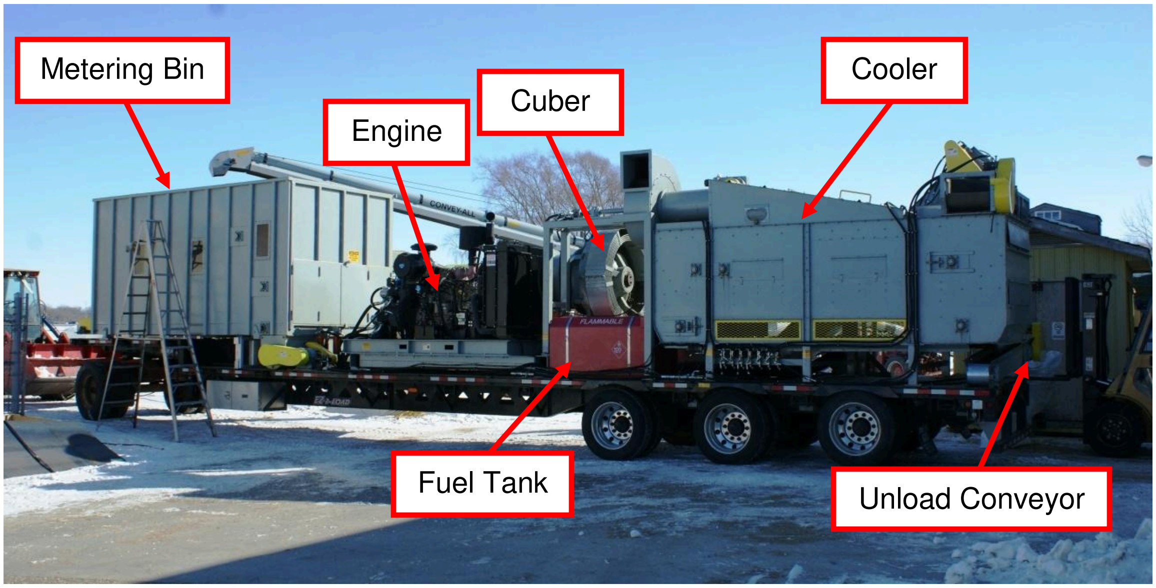

Figure 1. The mobile densification system.

The entire densification system is mounted to a 53 ft (16.2 m) step deck trailer. A 375 hp diesel engine provides the power to the entire system. All components are driven by hydraulic motors except the cuber, which is driven by a power take-off (PTO) belt drive.

The feedstock enters at the front of the trailer and exits at the back. The biomass is fed into the metering bin which acts as a temporary buffer. The feedstock then flows through a series of conveyors at a controlled rate into the cuber. Inside the cuber, a screw pushes the biomass to the end where a rotating press wheel densifies the material and extrudes it through a circular ring of dies. The biomass exits the cuber in the form of cubes as shown in **Figure 2**.

Figure 2. Biomass cubes exiting cuber.

The cubes leave the cuber at temperatures up to, and sometimes exceeding, 90 °C and must be cooled to ambient temperature as quickly as possible to preserve their quality and form. The cubes are fed into a double pass cooler with conveying screens. A large fan draws ambient air over the cubes to bring them as close to ambient temperature as possible. After eight minutes, the cubes leave the cooler and are unloaded at the rear of the trailer.

PAMI's mobile densification system was designed for cereal crop residues. Prior to this project, only barley straw, oat straw, and wheat straw have been fed through the complete mobile densification system. The densification procedures used during this project for the four biomass types are explained in detail in the next section.

4. Project Description

The scope of the project included attempting to densify four biomass types into cubes through PAMI's mobile densification system. All of the research trials were performed on site at PAMI's facility in Portage la Prairie. The Client sourced the biomass and had it transported to Portage la Prairie for the densification trials.

The densification research project started with the first arrival of feedstock on March 20, 2012. The final densification trials were completed on July 20, 2012. This section describes in detail, the project activities that occurred over the test period.

4.1 Biomass Procurement

The selection and procurement of biomass was the responsibility of the Client. The types of feedstock provided by the Client, the quantity, and the arrival dates are listed in Table 1, below:

Table 1. Biomass deliveries.

Biomass Type	Arrival Date	Quantity	Dimensions
Corn Stover	March 20, 2012	42 bales	1.2m x 1.2m round
Soybean Residue	March 22, 2012	29 bales	1.2m x 1.2m round
Switchgrass	April 10, 2012	21 bales	1.2m x 0.9m x 2.4m
Miscanthus	April 10, 2012	27 bales	0.9m x 0.9m x 2.4m

The condition of the feedstock varied. The corn stover arrived in loosely twined bales which were difficult to handle. The corn stover had been stored under roof and arrived at Portage la Prairie under tarps. **Figure 3** below shows the condition of the bales upon arrival.

Figure 3. Corn stover bales delivered to Portage la Prairie, MB.

A total of 29 bales of soybean residue arrived in the same size bale as the corn stover. They were wrapped in plastic and had been stored in the field. The bales were unloaded and stored at PAMI next to the corn stover and left uncovered as shown in **Figure 4** below.

Figure 4. Wrapped soybean residue bales left untarped.

The switchgrass and miscanthus arrived on the same trailer and were much easier to handle and stack due to their rectangular shape. They were stacked at PAMI as shown in **Figure 5** below, and then covered after the photo was taken.

Figure 5. Stacking rectangular switchgrass and miscanthus bales.

A total of four core samples were obtained on April 11 and 12, 2012; one sample for each type of feedstock. Each sample was extracted from ten bales with a minimum of a 305 mm (12 inch) depth for each core and one core per bale. In order to ensure that the core samples represented a larger area of the field, they were extracted from the curved side of the round bales and from the end of the rectangular bales as shown in **Figure 6** on the following page.

Figure 6. Extracting core samples.

The core samples were packaged in sealed bags as shown in **Figure 7**, below. The dark areas in the soybean residue sample (top right) are wet and decaying material extracted from the outer face of the bales just under the plastic wrap.

Figure 7. Core samples to be sent to laboratory.

The bagged core samples were sent to a third party laboratory for analysis. The analysis was required to determine the suitability for densification and to help understand the performance of the material once the trials began.

4.2 Preliminary Trial

Prior to performing a full trial of each feedstock, it was decided that a small amount of each type of material be shredded with a hammer mill and fed through the cuber. This was done to get a glimpse of how each material would perform and to determine a best approach for ensuring success in cubing each material.

One bale of each material was shredded into a flexible intermediate bulk container (FIBC) on April 19, 2012 as shown in **Figure 8**, below.

Figure 8. Shredding biomass for preliminary trial.

Inspection of the shredded material helped predict which feedstocks would cube better, and preliminary densification trials were planned for April 24, 2012 in the following order:

1. Corn Stover
2. Soybean Residue
3. Miscanthus
4. Switchgrass

The FIBC totes were emptied into the metering bin individually. A slow feed rate was achieved since the amount of material did not cover the whole width of the metering bin. The corn stover formed good cubes as expected and the cuber ran smooth. The soybean made the cuber work harder, but the material surprisingly formed good cubes with a glossy surface as shown in **Figure 9**, on the following page.

Figure 9. Soybean cubes from preliminary trial.

When the miscanthus was fed into the cuber, it was noticeably drier, and a few cubes formed. Shortly after feeding miscanthus into the system, a large bang was heard. Several die bolts were sheared off and dies had been pushed out of the cuber damaging the breaker shield as shown in **Figure 10**, below.

Figure 10. Damaged cube breaker shield.

The preliminary trials were aborted and no attempt was made to cube switchgrass at the time. The cuber was repaired and then reassembled on May 3, 2012.

4.3 Bale Shredding

The remaining bales of feedstock were shredded on May 8, 2012 using the same hammer mill as the preliminary trials. Each batch was shredded using 75mm screens as shown in **Figure 11** below, except for miscanthus.

Figure 11. 75 mm screen.

Due to the nature of the miscanthus material, it was decided that two different screen sizes be used. About one third of the miscanthus bales were shredded through a 75mm screen and the remaining miscanthus were shredded through a 35mm screen as shown in **Figure 12**, below.

Figure 12. 35 mm screen.

All feedstock materials were shredded into piles as shown in **Figure 13** below, and then protected from precipitation and wind using tarps**.**

Figure 13. Piles of shredded biomass feedstock.

During the shredding process, it was discovered that the soybean bales had significant deterioration under the plastic wrap. This was a result of excessive moisture content. The origin of the moisture is uncertain, but it seemed to penetrate deep into some bales as shown in **Figure 14**, below.

Figure 14. Deteriorating soybean residue bales.

4.4 Densification Trials

Several densification trials were attempted for each of the materials between May 8 and July 20, 2012. The performance varied among the feedstock materials and with several breakdowns and equipment damage. A description of the trials is given below.

4.4.1 Corn Stover Densification

Corn stover densification trials began on the afternoon of May 8, 2012 after the bales were shredded. This trial was conducted as a demonstration for the Client and visitors on site. Frequent starts and stops caused the operator to forget to turn off the metering bin live floor which pushed excess material into the back end of the bin causing a plug up in the bin.

Once the plug up was cleared, a small amount of corn stover cubes were produced at a very low feed rate later in the afternoon. A low feed rate caused a longer dwell time in the dies and produced charred cube surfaces as shown in **Figure 15**, below.

Figure 15. Charred corn stover cubes from low feed rate.

The trial was stopped and oats were poured onto the infeed belt as shown in **Figure 16** on the following page, to keep the cuber dies cleared for the scheduled trial the next morning.

Figure 16. Feeding oats onto infeed belt to clear cuber dies.

A successful densification trial using corn stover was performed on May 9, 2012. The corn stover responded well to the cubing process and ran continuous for several hours. The feed rate was altered throughout the day to determine an optimum capacity of the system. A total of 9 FIBC totes averaging 310 kg of cubes were produced as shown in

Figure 17 below.

Figure 17. FIBC totes filled with corn stover cubes.

Several samples were collected and tested for bulk density and durability. The trial was stopped mid afternoon in order to demonstrate densification of other feedstock materials for the Client who was on site. Throughout the day, material was igniting on the trailer deck causing a fire hazard which had to be doused with water as shown in **Figure 18**, below.

Figure 18. Putting out fires on trailer deck.

Later in the afternoon, undetected fires were discovered on the trailer deck that had burned holes through the trailer. Watering down the trailer and monitoring continued until late evening to prevent additional fires. Unfortunately, undetected smoldering embers under the cross belt conveyor on top of the cooler burned through the belt overnight.

The suspected source of the fires on the cuber deck was the cuber head cooling fan which was extracting hot embers out of the cuber and leaving them on the deck. Therefore, it was decided that moving the fan off the deck of the trailer and onto the ground would eliminate most fire hazards. The repair of the belt and the measures adopted to prevent further fires delayed the trial scheduled for May 10, 2012.

4.4.2 Soybean Residue Densification

Many attempts to densify soybean residue were made. However there was no success in performing a full trial of the material. It was very discouraging since the preliminary trial produced very nice cubes at a slow feed rate. A discussion of each attempt is given below.

A demonstration of cubing soybean residue occurred on May 9, 2012 while the Client was on site. As in the preliminary trial, the engine had to work harder to cube the material. However, about 134 kg of cubes were produced at a slow feed rate.

The first attempt at a full trial of cubing soybean residue occurred on May 10, 2012. The trial was aborted when the damaged cross conveyor belt was discovered as discussed in the previous section.

A second attempt was performed the morning of May 11, 2012. On startup, the engine stalled due to a cuber plug up as soon as infeed conveyors started moving. It appeared that some miscanthus remained in the infeed augers from a demonstration the day before. A large amount of miscanthus was pulled out of the cuber as shown in **Figure 19**, below.

Figure 19. Cleaning out leftover miscanthus from demonstration.

The die groove, through which the press wheel passes, was eventually unplugged by removing the shroud and drilling out the dies in the affected area. The unplugging process consumed most of the day, and the trial was suspended until the next business day.

A third attempt at a full trial of cubing soybean residue was performed on May 14, 2012. The cuber stalled as soon as material was fed into the cuber. The plug up was confined to a specific area of the die ring. Therefore the press wheel was manually reversed from the back end of the cuber. Then the engine was restarted and the cuber was engaged. Upon engagement, a large bang was heard and the main shaft at the front end of the cuber failed. **Figure 20**, on the following page, shows the extent of the damage with the shaft breaking away from the half crank.

Figure 20. Fractured main shaft of cuber.

The cuber was disassembled and the half crank was sent to the original manufacturer in Burley, Idaho for repair. Meanwhile, the dies were removed from the machine and cleaned thoroughly.

A fourth attempt at a full trial of soybean residue occurred on June 25, 2012. A trickle of material was fed into the cuber for about one hour until the bolts from one of the dies sheared and the die was pushed out of the ring. The machine was shutdown and the die was replaced by loosening off the 180 bolts on the head of the cuber, removing some adjacent dies, cleaning the dies, then replacing them.

After a series of problems and unsuccessful attempts at cubing soybean residue, it was decided that a full trial of this particular material could not be performed. A total of nine attempts were made to cube soybean residue with no success. The trial attempts are summarized **Table 2**.

Table 2. Attempts at full trials of soybean residue densification.

Attempt	Date	Description of Problem
1	May 10, 2012	Burned cross conveyor belt.
2	May 11, 2012	Plugged cuber from previous material.
3	May 14, 2012	Plugged cuber and extensive damage to cuber.
4	June 25, 2012	Die bolts sheared.
5	June 27, 2012	Plugged cuber.
6	June 27, 2012	Hydraulic hose crimp failure.
7	June 28, 2012	Die bolts sheared.
8	July 5, 2012	Engine stalled due to fault code, plugging cuber.
9	July 6, 2012	Engine fault codes.
10	July 9, 2012	Plugged cuber.

Some of the failures in the attempts to perform a full trial of soybean residue are not attributed to the feedstock. However, frequent plug ups and inability to provide a consistent feed rate to the cuber is related to the product. The fault may not be in the product itself, but rather the feeding system's inability to adjust to the product's nature. **Figure 21** below shows how soybean residue's stringy nature hangs over the edge of the live floor.

Figure 21. Clumps of soybean residue hanging over edge of live floor.

When the product hangs over the edge, it falls off into the mixing auger in large clumps. These large clumps are then fed into the cuber as shown in **Figure 22**, below.

Figure 22. Clump of soybean residue being fed into cuber.

The infeed system was running at the lowest rate possible and the cuber was still plugging up with soybean residue. The material was manually distributed on the infeed belt as shown in **Figure 23**, but product still fed into the cuber in large clumps.

Figure 23. Manually distributing soybean residue on infeed belt.

Due to limited funding for the project, it was decided that densification of soybean residue could not be performed in a full trial with PAMI's mobile densification system. Therefore, further attempts to cube soybean residue were suspended. A few cube samples were collected for reference, but not enough cubes were produced for bulk density and durability measurements.

4.4.3 Switchgrass Densification

Switchgrass was not included in the preliminary trials due to equipment failure. However a demonstration of switchgrass densification was performed on May 9, 2012 while the Client was on site. The switchgrass material came out of the cuber as a powder and would not form a cube. This indicated that the material was likely too dry and brittle to be cubed in PAMI's mobile densification system.

In anticipation of the full trial of switchgrass, a manifold with sprayer nozzles was installed in the metering bin above the mixing auger to add water at a controlled rate. The nozzles add a mist of water to the feedstock as shown on the left in **Figure 24** below.

Figure 24. Spray nozzles adding mist to feedstock.

An attempt at a full trial of switchgrass densification was performed on July 17, 2012. Prior to feeding the switchgrass, a single front end loader bucket of corn stover was fed into the cuber to warm up the dies. After the corn stover passed through the system, switchgrass material was fed into the cuber dry. As expected, no cubes formed out of the dry switchgrass, but only a fine powder was produced. Water was added to the system at the lowest measurable rate of 1.3 L/min. Immediately following the addition of water, cubes began to form as shown in **Figure 25**, on the following page.

Figure 25. Switchgrass cubes after exiting cooler.

After two FIBC totes of cubes were produced, an attempt of cubing dry material was performed by shutting off the water supply. Again, immediately after shutting off the water supply, cubes stopped forming as shown in **Figure 26**, below.

Figure 26. Switchgrass without water added after cubing.

After about 20 minutes, water was added to the system at 2.7 L/min. The excessive rate of water also produced no cubes. A moist mulch was produced as shown in **Figure 27**, below.

Figure 27. Excessive water addition producing mulch.

The rate of water was returned to 1.3 L/min and cubes began to form. Two more FIBC totes of switchgrass cubes were produced, but inconsistent cube formation was observed. It was noticed that the material was passing through only a few dies while the rest of the dies appeared to be seized. The trial was stopped with plans to drill out the dies before the trial of miscanthus.

4.4.4 Miscanthus Densification

The preliminary densification trial of miscanthus resulted in extensive equipment damage, and there was reluctance to attempt a full trial. A demonstration of cubing miscanthus was performed on May 9, 2012 while the Client was on site. A small amount of miscanthus was fed into the cuber and although there was cube formation, it was sporadic.

An attempt at a full trial of miscanthus densification was performed on July 19, 2012. Prior to feeding miscanthus, the remnants of switchgrass material in the metering bin were fed through the system to warm up the dies. Once the miscanthus material was fed into the system, cubes formed immediately as shown in **Figure 28**, on the following page.

Figure 28. Initial cubes of miscanthus exiting cuber.

The formation of cubes was not consistent and an increase in the rate of feed seemed to reduce the output of good cubes. Therefore, the feed rate was kept to a minimum. A single FIBC tote took over 1.5 hours to fill, with poor cubes.

Water was added at the minimum measurable rate of 1.3 L/min to see of it would improve cube formation and feed rate. However, the cube formation did not improve, nor the ability to increase capacity. The cube formation continued to be loose and inconsistent as shown in **Figure 29**, on the following page.

Figure 29. Miscanthus cubes with added water.

The low feed rate resulted in only a small amount of cubes produced. After 4.5 hours of running, approximately 500 kg of cubes were produced. The trial became hampered with interruptions due to the engine overheating while the ambient temperature in the sun was close to 40 °C. The trial was suspended with a plan to restart the next morning.

An attempt to restart the miscanthus densification trial was performed early morning July 20, 2012. The cuber stalled the engine due to a plug up in the die ring groove. The material was cleaned out and the cuber restarted mid morning. Material was fed into the cuber, but close observation did not reveal any movement in the dies. Continuous operation of the cuber would potentially alleviate the seizing of material in the dies and resultant down time.

It was determined that the cuber dies had seized and plans to continue with densification trials were suspended because of the poor density and feedrate of the miscanthus.

4.4.5 Controlling Moisture Content

The switchgrass and miscanthus trials display PAMI's first ever attempts to control moisture to an optimum level with the mobile densification system. It appears that adding cold water spray to the feedstock immediately prior to cubing does not give sufficient time for the moisture to penetrate the material. Many European companies add water through steam conditioning at least 30 minutes prior to densification. Incorporating this practice into a mobile densification system requires further research.

5. Results and Discussions

The performance of each biomass feedstock was evaluated using several measurements. Physical and chemical analyses were performed on each to determine the characteristics of the feedstocks. During the densification trials, relevant data was collected to evaluate the performance of each feedstock and the mobile densification system. The following sections discuss the performance measurements and analyses.

5.1 Laboratory Analysis of Feedstock

Core samples were obtained from the biomass bales prior to the densification trials. The samples were sent to a third party laboratory for analysis. A summary of the analysis results is given in **Table 3**, below.

Table 3. Feedstock sample analysis summary.

Analysis of Feedstock Samples (% of Dry Matter)				
	Corn Stover	Soybean Residue	Switchgrass	Miscanthus
Moisture (% Total)	23.67	26.18	9.11	13.21
Dry Matter	76.33	73.82	90.89	86.79
Chlorides	0.09	0.00	0.04	0.00
Lignin	7.08	16.72	10.15	11.42
ADF	48.47	62.71	53.94	58.36
NDF	75.77	77.21	83.28	87.84
Sand Silica	1.39	1.57	1.12	1.09
Ash	5.09	7.34	3.02	3.27
Hemi-cellulose[1]	27.31	14.50	29.34	29.48
Cellulose[2]	41.38	45.99	43.79	46.94

1. Hemicellulose = NDF - ADF
2. Cellulose = ADF - Lignin

Lignin and moisture content are often cited as the main contributors to a feedstock's ability to densify. Researchers often give an ideal range of moisture content somewhere between 8% and 12% (Kaliyan and Morey, 2006b; Sokhansanj et al 2003; Sokhansanj et al 2005). Moisture in the material unlocks polymers such as lignin, hemi-cellulose, and cellulose and also aids in sticking the particles together under pressure and heat. Controlling moisture to an ideal amount is a key factor in forming a good densified product. Lignin has the ability to morph under heat and pressure and then retain its shape after densification.

There was a high variance in moisture content among the different types of feedstock. Corn stover and soybean residue were very high at 23.7% and 26.2% respectively while miscanthus was 13.2%. Switchgrass had the lowest moisture content of 9.1% which may have contributed to its brittle characteristics.

The differences in polymer content of both switchgrass and miscanthus were negligible for lignin, hemi-cellulose and cellulose. Corn Stover had polymer content in the same range as switchgrass and miscanthus except for lignin content which was much lower at 7.1%. Soybean residue had the most interesting results with very high lignin content of 16.7%, but very low hemi-cellulose content at 14.5% which was about half of the other feedstocks. The cellulose content of soybean residue was in the same range as the other feedstocks. The complete analysis certificates are included in **Appendix IV**.

5.2 Density

The most important measurement of the performance of any densification system is density. Density measurements included bale density, shredded material bulk density, and cube bulk density. These measurements help track the densification process. A discussion of each density measurement is given below.

5.2.1 Bale Density

Bale densities were measured by weighing a representative bale of each material to determine the mass. At the same time, the dimensions of the representative bales were measured. The bale density is calculated by dividing the mass by the volume. **Table 4** below shows the calculation of bale density for each feedstock material.

Table 4. Bale density calculation.

	Corn Stover	Soybean Residue	Switchgrass	Miscanthus
Bale Type	Round	Round	Square	Square
Mass (kg)	198	196	402	292
Dimensions (m)	Ø1.23 x 1.19	Ø1.28 x 1.22	1.22 x 0.89 x 2.44	0.91 x 0.84 x 2.29
Volume (m^3)	1.41	1.57	2.65	1.75
Density (kg/m^3)	140.4	124.8	151.7	166.9

The soybean residue had the lowest bale density which may be partially due to the large stems of the plant. The coarse stems may have created larger voids in the bale. The miscanthus bale density was the highest, which may be due to the filled stems of the plant. The filled stems increased the mass of the feedstock without adding to the volume.

There is a difference between bale density and bulk density. The bulk density for rectangular bales would be equal to the bale density. This is due to the fact that rectangular bales can be stacked without any voids between the bales. In contrast, there is no possible way to stack round bales without having voids between the bales. Therefore, the bulk density of round bales is much less than their bale density.

5.2.2 Bulk Density of Shredded Feedstock

The bulk density of the shredded feedstock was measured at random intervals for each material. The method used was derived from ASAE S269.4 DEC1991 (R2007) standard which is the specification for determining bulk density of cubes (ASABE, 2007). The procedure involves dropping material into a container of known volume from a height of 610 mm above the top edge of the container. Then, the filled container was dropped five times from a height of 150 mm onto a hard surface. Finally, the shredded material was leveled with the top of the container and weighed to determine the mass. The bulk density was calculated by subtracting the mass of the container, and then dividing the remaining mass of the material by the volume.

The samples were obtained from the front end loader bucket at random intervals during the cubing trials. The average results from the bulk density measurements of the shredded feedstock are given in **Table 5**, below.

Table 5. Bulk density of shredded biomass.

	Corn Stover	Soybean Residue	Switchgrass	Miscanthus
Bulk Density (kg/m^3)	66.1	n/a	86.4	89.8

The shredded corn stover had the lowest bulk density while shredded miscanthus had the highest. No shredded soybean residue samples were extracted since a full trial was not performed. The shredding process reduced the bulk density of each biomass by approximately half the original bulk density.

5.2.3 Bulk Density of Cubes

The bulk density of the cubes was measured at regular intervals for each finished product as it exited the cube cooler. The method used was the ASAE S269.4 DEC1991 (R2007) standard (ASABE, 2007). The procedure involves dropping material into a container of known volume from a height of 610 mm above the top edge of the container. Secondly, the filled container was dropped 5 times from a height of 150 mm onto a hard surface. Lastly, the cubes that have more than one half of their volume protruding above the top edge of the container were removed. The bulk density was calculated by subtracting the mass of the container, and then dividing the remaining mass of the material by the volume. **Figure 30** below shows the container filled with miscanthus cubes.

Figure 30. Miscanthus cube sample for bulk density measurement.

There were many variables which contributed to changes in cube formation, and therefore, bulk density. The variables included feed rates, moisture content, cuber capacity and feedstock variances. **Table 6** below lists a summary of the bulk density measurements that were obtained from the cubing trials.

Table 6. Bulk density of biomass cubes.

	Corn Stover	Soybean Residue	Switchgrass		Miscanthus	
Water Addition (L/min)	0	0	0	1.3	0	1.3
Number of Samples	8	0	1	4	1	1
Bulk Density Range (kg/m^3)	355-480	n/a	n/a	450-533	n/a	n/a
Mean Bulk Density (kg/m^3)	**424**	**n/a**	**388**	**498**	**521**	**386**

Since the goal of the densification process is to increase the density of the biomass feedstock, bulk density is one of the main performance measurements. The process of densification increased the density by up to three times when compared to the original bale density for each of the biomass feedstocks.

The addition of water had a significant effect on bulk density. There was a 28 percent increase in bulk density of switchgrass cubes with the addition of water to the infeed system. In contrast, the addition of water had the opposite effect on the bulk density of miscanthus. There was a 26 percent reduction in bulk density of miscanthus cubes when water was added. The complete results of the bulk density tests are included in **Appendix II**.

5.3 Durability

The durability of the cubes is another very important performance measurement of any densification system. Durability attempts to predict the ability of cubes to maintain their form and size during transportation and handling.

The durability of the cubes was measured from samples taken at regular intervals during the trials. Specifically, one durability sample was extracted from each bulk density sample so that correlations, if any, could be derived between the two measurements.

The method of measuring durability was the ASAE S269.4 DEC1991 (R2007) standard (ASABE, 2007). The complex process involves selecting ten cubes whose mass is within +/-10% of their average. The cubes were then tumbled at 40 rpm for 3 minutes in the apparatus shown on the left in **Figure 31**, below.

Figure 31. Durability testing station.

After the cubes were tumbled, the remaining cube particles were weighed and placed in classes according to mass. The particles whose individual mass was greater than 20 percent of the original average cube mass were designated as cube size material (CSM). The total mass of CSM was then divided by the original total mass of the ten cubes to obtain a percent durability. The size distribution index (SDI) was calculated from the mass classes and varies depending on the amount in each class. SDI is a unitless number and a maximum SDI score of 400 means there was little or no size reduction of the cubes. A summary of the results of the durability tests are shown **Table 7** on the following page.

Table 7. Durability and size distribution index (SDI).

	Corn Stover	Soybean Residue	Switchgrass		Miscanthus	
Water Addition (L/min)	0	0	0	1.3	0	1.3
Number of Samples	7	0	1	4	1	3
Size Distribution Index Range	172-386	n/a	n/a	216-338	n/a	217-306
Mean Size Distribution Index	**264**	**n/a**	**53**	**278**	**134**	**245**
Durability Range (%)	87.8-95.8	n/a	n/a	83.6-91.0	n/a	81.3-86.8
Mean Durability (%)	**92.2**	**n/a**	**32.2**	**87.0**	**63.2**	**83.5**

The corn stover cubes had the highest mean durability rating of 92.2 percent. The switchgrass and miscanthus both showed significant improvement in durability when water was added to the infeed system.

The average size distribution index for corn stover, switchgrass (with water added), and miscanthus (with water added) were in a similar range between 245 and 278. The switchgrass sample that did not have any water added had a SDI of only 53. Similarly, the miscanthus that did not have water added had a poor SDI of 134. Interestingly, one sample of corn stover had a near perfect SDI of 386.

The durability and SDI for miscanthus cubes were somewhat misleading. Much of the end product for miscanthus was not in cube form. Possibly as much as 50% of the product was uncubed material or had fallen apart while in the outfeed conveying system. PAMI's mobile densification system does not have any fines removal component, so a considerable amount of fines was able to pass through the system. This was not observed for any of the other biomass types to the same extent. The cube samples were extracted from the mix of cubes and fines as shown in Figure 32 below, and therefore the durability tests were not a full representation of the end product even though they represented the cubes that were formed. The complete results of the durability tests are included in **Appendix I**.

Figure 32. Mix of cubed and uncubed miscanthus product.

The ASAE S269.4 DEC1991 (R2007) standard (ASABE, 2007) also has a method for determining cube unit density. Although unit density can be an interesting measurement for determining the maximum density achievable by a densification system, it is rarely recorded or reported by researchers. When determining the performance of a densification system, similar characteristics are captured within the bulk density, durability and SDI measurements since they are directly related to unit density. Therefore, it was decided that unit densities would not be measured nor reported.

5.4 Capacity

The output capacity of PAMI's mobile densification system was measured by weighing the FIBC totes as they were filled. The FIBC totes were set on top wheel scales so that a continuous readout of cube output could be monitored and recorded. **Figure 33** below shows the setup for output capacity measurements.

Figure 33. Weighing cube output on scales.

The capacity measurements were recorded when the FIBC totes were filled by recording the time and the weight. The results from capacity monitoring are listed in **Table 8**, below.

Table 8. Output capacity of densification system.

	Corn Stover	Switchgrass			Miscanthus	
Water Addition (L/min)	0	0	1.3	2.7	0	1.3
Number of Readings	8	1	4	1	1	1
Capacity Range (kg/h)	375-897	n/a	174-277	n/a	n/a	n/a
Mean Capacity (kg/h)	**570**	**148**	**210**	**180**	**206**	**142**

The average output capacity of corn stover out-performed all of the other feedstock materials by a factor of nearly 3:1. This may be due to the high moisture content of the corn stover. There was a slight improvement in the output capacity of switchgrass when a small amount of water was added. In contrast, a slight decrease in the output capacity of miscanthus was measured when water was added. The complete results from the capacity measurements are included in **Appendix III**.

5.5 Cube Analysis

Representative samples of each type of cube were sent to a third party laboratory for analysis. Three samples of corn stover cubes were sent to the laboratory ahead of the other samples to gauge the consistency of the analysis. A summary of the results of the cube analysis is given in **Table 9**, below.

Table 9. Cube analysis summary.

	Corn Stover	Soybean Residue	Switchgrass		Miscanthus	
Water Addition (L/min)	0	0	0	1.3	0	1.3
Number of Samples	3	1	1	1	1	1
Mean Moisture (%)	17.9	18.8	8.9	8.5	8.2	11.4
Mean Ash* (%)	6.3	3.5	3.3	6.9	2.8	3.0
Mean Calorific Value* (MJ/kg)	17.9	19.1	19.1	18.2	19.2	17.4

*Measurements reported on a dry basis.

The three corn samples did not have a significant deviation in any of the results except for moisture content which ranged between 15.5% and 19.3%. Interestingly, the addition of water did not affect the moisture content of the switchgrass cubes. The addition of water had an effect on the moisture content of miscanthus cubes by 3%. The corn stover cubes had moisture content twice as high as the other feedstocks.

The ash content of the cubes were all near 3% except for corn stover which was about 6%, and switchgrass with water addition which had an ash content of 6.9%. The difference in ash content between the two switchgrass cube samples is puzzling.

The calorific values of the cube samples were all in the same range between 17.4 MJ and to 19.2 MJ. Interestingly the two limits of energy content results belong to the same feedstock. The full cube analysis results are included in **Appendix V**.

5.6 Energy Balance

The true performance of a densification system is measured by comparing the output value of the product with the input costs. The currency of the value of biomass for energy use is the energy content. If the output energy exceeds the input energy, then there is a positive net energy balance of the system. If the input energy exceeds the energy content of the densified product, then there is a negative net energy balance.

Measuring all of the input energy requirements for creating a densified biomass product is an enormous task and beyond the scope of this project. Instead, assumptions and estimations have been derived from available data in order to approximate actual energy inputs. A discussion on the energy calculations for input and net energy balance is included in the subsections below.

5.6.1 Harvest and Baling

The biomass collection process was different for each of the biomass types evaluated during this project. For example, the collection of the crop residues such as soybean residue and corn stover required baling, whereas the harvest and collection of energy crops like switchgrass and miscanthus required swathing and then baling. PAMI was not involved in the harvest and baling of each biomass type used in this evaluation, so measurements were not available and therefore not included in the scope of the project. It was assumed that collection of biomass from the field was a minor consumer of energy in comparison to densification, so it was not included in the energy balance calculation.

5.6.2 Bale Shredding

The bale shredding method used for this project was a mobile custom shredding operation based in Miami, Manitoba. J. Elias of Miami Welding stated that continuous shredding consumes 70 litres per shredding hour of diesel including cleanup and travel (personal communication, June 21, 2012). The capacity measurements for bale shredding that occurred on May 8, 2012 were recorded for each biomass feedstock. Specific fuel consumption was based on the lower heating value of 42.61 MJ/kg and density of 0.848 kg/L for low-sulfur diesel (Boundy et al., 2011). The estimated resultant energy consumption ratios of the bale shredding demonstration are shown in **Table 10**, below.

Table 10. Estimated energy consumption of bale shredding demonstration.

	Corn Stover	Soybean Residue	Switchgrass	Miscanthus
Amount of Material (kg)	7920	5292	7638	4672
Time (h)	1.0	0.7	1.0	0.7
Fuel Used (MJ)	2529	1771	2529	1771
Energy Ratio (MJ/kg)	0.319	0.335	0.331	0.379

*Shredding was through 75mm screens for all except miscanthus, which used 35 mm screens.

5.6.3 Densification System

The energy consumption of the densification system was calculated from the fuel usage and the output capacity. The fuel usage was measured using a similar method to the output capacity by placing wheel scales under the fuel supply tank and weighing the fuel. This way, the fuel usage could be monitored continuously. Fuel weights were recorded

each time an FIBC tote was filled to coincide with output capacity measurements. Calculations were based on a lower heating value of 42.61 MJ/kg for low-sulfur diesel (Boundy et al., 2011). The energy consumption ratios for the densification system evaluation trials are given in
Table 11, below.

Table 11. Energy consumption of densification evaluations.

	Corn Stover	Switchgrass	Miscanthus
Mean mass of Cubes (kg)	323	250	268
Mean Fuel Used (kg)	18	39	36
Mean Fuel Used (MJ)	767	1662	1534
Energy Ratio (MJ/kg)	2.37	6.65	5.72

*Only switchgrass with water addition and miscanthus without water addition are included in table.

5.6.4 Assumptions

There are several other energy input variables that should be considered. Collecting bales from the field and moving to field side, loading bales into the bale grinder, and loading shredded material into the mobile densification system are also contributors to a true energy input calculation. It is assumed that these energy costs are very minimal in comparison to bale shredding, and densification, so they are not included in the energy balance calculations.

Another variable that should be considered is product loss. During the trials, the amount of product fed into the system was not measured. An assumption of zero loss was included in the calculations, even though PAMI's mobile densification system has many areas where losses occur as shown in **Figure 34**, below.

Figure 34. Material losses of mobile densification system.

A fully developed mobile densification system would have components which recycle most of the fines, and therefore, result in near zero loss. PAMI's system however, does not yet have these features installed.

5.6.5 The Energy Balance Calculation

The net energy was calculated from the two main energy inputs of bale shredding and densification along with resultant energy contained in the cubes. **Table 12** below shows the net energy produced from the bale shredding/densification operations.

Table 12. Net energy production of densification system.

	Corn Stover	Soybean Residue	Switchgrass	Miscanthus
Mean Energy Output (MJ/kg)	17.9	19.1	18.2	19.2
Shredding Energy (MJ/kg)	0.319	0.335	0.331	0.379
Densification Energy (MJ/kg)	2.37	n/a	6.65	5.72
Net Energy (MJ/kg)	15.2	n/a	11.2	13.1

*Only switchgrass with water addition and miscanthus without water addition are included in table.

There was a positive balance of net energy output from the shredding/densification process. Due to low capacity, the energy consumption for switchgrass and miscanthus was 38% and 32% respectively, of the available energy in the biomass. Corn performed slightly better with only 15 percent of the available energy consumed by the shredding/densification process.

6. Engineering Assessment

The Client asked PAMI to provide an engineering assessment of implementing a mobile densification system into an agricultural biomass feedstock supply chain. This section discusses the logistics models that can incorporate a mobile densification system and introduces some alternative methods. PAMI has recently completed a logistics study on agricultural biomass feedstock (PAMI, 2012). Much of PAMI's previous research was consulted when performing this assessment.

The harvest methods for biomass feedstocks vary depending on the type of biomass produced. Agricultural biomass grown for bioenergy is usually categorized into two distinct groups:

- Agricultural Crop Residues
- Dedicated Energy Crops

These groups and their harvesting methods are briefly discussed below.

6.1 Agricultural Crop Residues

Agricultural crop residues exist as a secondary byproduct of the primary product which is usually the seed. In order to be economically feasible to harvest the residue, the value as a biomass feedstock must exceed the sum of the nutrient value of the residue if returned to the soil, plus the costs of harvesting the residue (Wortmann et al., 2012). For example, if the cost of baling corn stover is about $20 per tonne and the nutrient value as a fertilizer is $46 per tonne, the market price for a tonne of baled corn stover biomass must exceed $66 per tonne to be economically feasible. The cost of removing crop residues from soil is an important consideration when choosing to use residues for bioenergy.

A conventional seed harvester (combine) leaves the residue in one of the following states:

- Standing in the field.
- Chopped and spread out in the field.
- Windrowed.

Since residues are usually considered a byproduct of seed harvesting, further steps are usually required to harvest the residue. However, there are single pass harvesting methods being developed. Webster (2011) evaluated several single pass harvesting systems which attempt to collect the residue while harvesting the seed. The system shown in **Figure 35** on the following page, bales the residue in the same pass behind a straight cut combine.

Figure 35. Single-pass harvesting operation (Webster, 2011).

The most common method of collecting crop residues from the field is in the form of bales. The bales can then be shredded at field side, or at a central processing site. Another, less common method of collecting residue is in the form of chopped biomass using a forage wagon or other towed cart. Both methods would fit into a logistics model that includes a mobile densification system and is discussed further in section 6.3.

6.2 Dedicated Energy Crops

The development of crops for use as a biomass feedstock is underway in several jurisdictions. Germany, for example, reported a current 1.8 million hectares of energy crop production with a plan to increase to 3 million hectares by 2020 (Biofuels Digest, 2011).

There are a wide variety of crops with potential for biomass to bioenergy conversion. The two most popular dedicated energy crops are switchgrass and miscanthus. Each is available in several varieties with differing yields depending on soil conditions and climate.

The method for harvesting dedicated energy crops can be much different than those used for crop residues. For switchgrass and miscanthus, the harvest is delayed until the moisture content is low enough so that baling can be performed as soon as possible after mowing or swathing (Teel et al., 2003). For both crops, the harvest is delayed until after a killing frost and miscanthus is often left over winter in order to achieve optimum moisture content (Anderson et al., 2011).

6.3 Feedstock Logistics Models

The methods of creating a fossil fuel alternative from agricultural biomass will vary depending on the availability of the feedstock, the type of feedstock, and the end use. However, every agricultural biofuel supply chain can be divided into three main processes:

1) crop production
2) feedstock logistics
3) conversion

From a producer's standpoint, overcoming the challenges of the first two processes is the primary concern. Although a full discussion on the first and third processes is beyond the scope of this project, it is important to consider conversion technologies when deciding how to market agricultural biomass to conversion facilities. For example, a combined heat and power (CHP) conversion facility usually desires the biomass supplied in a different form than a cellulosic ethanol facility or a biocomposite factory. Also, the properties of certain biomass crops may not be suitable for certain conversion processes, so alternative crop varieties, or marketing strategies may have to be developed.

The desired characteristics of the biomass delivered to conversion facilities are beginning to emerge, but industry standards are still not fully established. Currently, almost all pre-processing of biomass feedstock occurs at the point of conversion. This presents challenges of increased transportation, storage, and handling costs.

Producers are faced with various alternatives for meeting the challenges noted above. A survey of some of the existing technologies that are available to producers is given below.

6.3.1 Conventional Baling

Conventional baling technologies have seen much improvement in recent years. With additional compaction components, the new large rectangular balers are able to achieve an average weight of 550 kg of wheat straw (Massey-Ferguson, 2011) in a 1.2 m x 0.9 m bale. This translates to a density of approximately 212 kg/m^3. A trailer loaded with 39 of these bales would use 96% of its allowed 22287 kg capacity. This calculation is based on a proposed NAFTA GVW limit of 36287 kg (Pearson, 2002) with typical tractor and trailer weights of 9000 kg and 5000 kg respectively.

Large rectangular bale weights are now exceeding 800 kg (CaseIH, 2012). It seems possible that transportation costs that are often associated with non-densified agricultural products will be effectively eliminated in the near future. This is already the case in some jurisdictions where GVW limits are more stringent.

New technologies have also improved storage conditions of bales. Preservatives can be added to bales at controlled rates based on real time moisture measurements. Radio frequency identification (RFId) tags can be added to track moisture content, weights, preservatives, etc. for each bale produced (Harvest Tec, 2012).

Even if transportation and storage costs are eliminated through the development of high density balers and RFId tracking, the problem of handling costs still remain. The loading and unloading of bales from a trailer as well as stacking the bales continue to be manual processes.

6.3.2 Bale Compression

Bale compression technologies are a form of densification that also reduces bale size for the purpose of improved manual handling and reduced transportation costs. Bale compression should not be confused with rebaling. Rebaling technologies repackage large square bales into reduced sizes for manual handling, but does not increase the density.

There has been very little research done on bale compression of crop residues and dedicated energy crops. Bale compression is strictly used for the forage export market at the present time. The densities achieved by the process can be as much as 436 kg/m^3 for hay (Hunterwood, 2012) and packaged in a small bale form as shown in **Figure 36** below.

Figure 36. Densified and repackaged hay bale (Hunterwood, 2012)

It is conceivable that there may be a market for smaller scale whole bale CHP facilities that may find use for a smaller, densified bale. However, additional pre-processing would be required for biofuel conversion. Also, although the increased density would reduce transportation costs, the smaller size actually increases handling costs when used as a bioenergy feedstock.

6.3.3 Hammermilling

Hammermilling or grinding technologies have been available for decades. It is often a necessary step in the fractionation process for biofuel production at conversion facilities. Therefore, hammermilled biomass is very close to the desired end product. However, as shown by the low bulk densities of the shredded materials produced during this project, the transportation costs for moving the material in shredded form to a conversion facility would be very high. This has prevented hammermilled biomass from being a marketable product at the producer end of the agricultural biofuel supply chain.

6.3.4 In-Field Densification

In-field densification gained the most popularity during the 1960's. Patents were issued to Deere, Massey Ferguson, Sperry Rand, International Harvester and Ford for in-field systems between 1955 and 1965 (PAMI, 2008). John Deere was the only company to successfully produce and market a large number of working machines similar to the one shown in **Figure 37**, below.

Figure 37. John Deere in-field densification system.

By 1972, most hay producers were moving to stationary systems due to a better controlled environment and longer running hours (Payne, 1972). In-field cubing has since been abandoned due to a small operational window, uncontrollable environment and uncontrollable feedstock properties.

The most recent attempt at producing an in-field densification system was Haimer's Biotruck which was developed in the late 1990's (PAMI, 2008). The machine had a high cost of production and relatively poor performance (Hartmann, 1996). This combined with an unorthodox product (wafers) prevented it from achieving widespread popularity.

The temptation to realize the ideal of creating a quality biomass product at the feedstock source has both intrigued and troubled industry researchers for many years.

6.3.5 Field-Side Densification

When trying to create a biomass product at the feedstock source, the next best thing to in-field densification is field-side densification using a mobile densification system. In a field-side system, minimal collection costs are incurred while moving the feedstock to the edge of the field where a mobile system can produce a densified product. The advantages of a field-side system include a larger operational window that extends beyond the harvest season, continuous processing around the clock, and the ability to add accessory equipment when necessary.

The waning popularity of the in-field systems spurred the development of a few field-side systems in the 1980's which included the Lundell PTO cuber, the KR3 portable cuber, and Bernewode straw cuber (PAMI, 2008). More recent systems include BioEnergy Inc's mobile biofibre densification system (BioEnergy, 2011) and PAMI's own system that was evaluated in this report.

As observed during this research project, there are many challenges to overcome when developing a successful field-side densification system. PAMI's system, for example, is very sensitive to moisture content and feedstock variety. A successful system would require much more versatility and the ability to control variances in feedstock while maintaining a consistent quality product.

6.3.6 Stationary Densification

Stationary densification of agricultural forage products on a commercial scale has been in existence since before the 1970's. Many hay exporters were opting for the stationary system due to longer running hours, a controlled environment, and the ability to mix a variety of ingredients (Payne, 1972). **Figure 38** on the following page shows a stationary hay cubing and pelleting operation.

Figure 38. Stationary densification plant along rail line.

This stationary system was designed to process up to 10 tonnes per hour per cubing machine which translates to more than 80,000 tonnes of biomass per year for each machine. In order to supply the system at maximum capacity with the least amount of transportation costs, adjacent feedstock can be provided in chopped form during haying season, but the rest of the feedstock must be baled, stored in satellite storage locations (SSL) and then transported to the stationary site when needed. Then the bales are shredded and processed into cubes or pellets.

Stationary densification facilities for agricultural biomass that take full advantage of economies of scale require cooperatives or producer groups to operate at optimum capacity. Independent operations are rare at this level of production.

PAMI is not aware of any commercial-scale stationary densification facilities dedicated to bioenergy crop processing that are in full time operation.

6.3.7 Advanced Uniform Format Logistics Model

The technologies presented above describe the more popular techniques that have been available to producers for the past five decades. Some improvements are being made to eliminate high transportation, storage and handling costs, but the uncertain direction of the bioenergy and biofuel industry leave producers on their own to determine the appropriate position in the biomass supply chain. Producers and conversion facilities must work together to confront logistical challenges.

The U.S. Department of Energy (DOE) published a report suggesting that reordering the logistics models so that preprocessing occurs as close to the crop production location (i.e. farm gate) as possible would mitigate the challenges of transportation, storage, and handling (Hess et al., 2009). This reordering is contingent upon conversion facilities adopting a “uniform-format” of biomass feedstock and producers having the ability to produce a uniform product regardless of biomass type. Their proposed logistics model, called the Advanced Uniform-Format bioenergy feedstock supply system is shown in **Figure 39**, below.

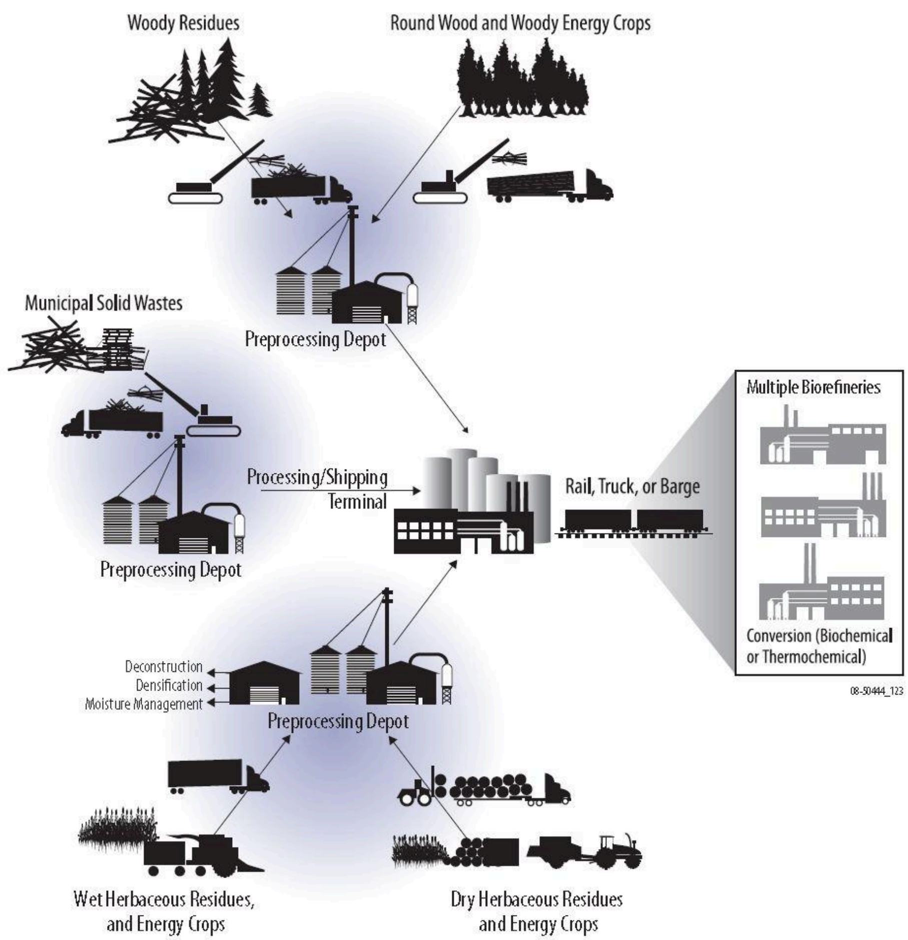

Figure 39. Advanced Uniform-Format Logistics Model (Hess et al., 2009)

The vision for an advanced uniform format supply was triggered by the U.S. Energy Independence and Security Act of 2007 which calls for a biofuel production goal of 60 billion gal/yr (2.27×10^{11} L/yr) by 2030. The main assumption guiding the vision is that a “highly efficient, large capacity, dependable feedstock supply system for bulk solid herbaceous biomass already exists with the nation’s commodity-scale grain handling and storage infrastructure” (Hess et al. 2009). The authors propose that all biomass feedstock supply chains emulate the existing grain commodity handling system. The current grain commodity handling system has been in development for over a century and is used in most developed countries. It would be an enormous challenge to conceive and then develop a more efficient system for biomass by 2030.

In order to tap into the grain commodity transportation and handling system, producers will need to produce a biomass product with similar characteristics to grain. The product must have similar flow characteristics as grain and it must be able to handle long term storage. The pelleting/cubing operations are the only existing processes which are currently creating a biomass product that can be handled by the grain commodity logistics system.

Agricultural producers are not the only bioenergy stakeholders in the advanced uniform system. Forestry and municipal industries are also included. The difference is that agricultural producers have the added challenge of collecting the biomass and transporting it to a pre-processing depot. Woody residues and municipal wastes are usually already collected at the mills and urban areas with easy access to the rail system. The preprocessing depots are usually located on site at the mill or at urban locations. This puts agricultural producers at a competitive disadvantage. Agricultural producers will need to adopt a logistical subsystem that minimizes transportation, handling, and storage costs in order to compete in the advanced uniform-format bioenergy feedstock supply system.

6.3.8 Agricultural Biomass Logistical Subsystems

It appears that agricultural producers will be handed the responsibility for developing a logistical subsystem that will fit into a larger system that emulates, or utilizes the grain commodity handling infrastructure. A method of comparing the different existing agricultural biomass production technologies is given below.

Actual cost estimation is beyond the scope of this project. Therefore, Table 13 below lists the existing technologies using relative comparisons and includes how well they directly fit into the advanced uniform system based on common knowledge of the agricultural industry.

Table 13. Relative comparisons of agricultural biomass technology formats.

	Conventional Baling	**Bale Compression**	**Hammer Milling**	**In-Field Densification**	**Field-Side Densification**	**Stationary Densification**
Transportation Costs	Medium	Low	High	Low	Low	Medium
Handling Costs	Medium	High	Medium	Low	Low	Medium
Storage Costs	High	Medium	High	Low	Low	Medium
Operational Window	Small	Large	Large	Small	Medium	Large
Fits Into Advanced Uniform	No	No	No	Yes	Yes	Yes

There is no agricultural biomass logistical subsystem in existence that eliminates all logistical challenges. Some, however, are better than others. Conventional baling technologies may have improved to lower transportation costs, but pre-processing is still required in order to fit into the advanced uniform system. Bale compression techniques have effectively eliminated transportation costs by producing higher densities, but savings may be negated by higher handling requirements and it does not fit into the advanced uniform model without additional pre-processing. Hammer milling does not fit into the advanced uniform model without further densification due to very low density and high transportation and storage costs.

Densification systems are better suited to the advanced uniform model by creating a product that can be integrated into the existing grain commodity handling system. In-field densification does fit into the advanced uniform system, but history has shown that a small operating window prevents it from reaching a commercial scale. Field-side densification fits into the advanced uniform model at source by providing a product similar in characteristics to grain and is able to take full advantage of the grain handling system directly from the field side, but it is subjected to a moderate operational window in extreme climates (cold, heat, rain, etc.) at different times of the year and in different geographic locations. The stationary densification system fits into the advanced uniform system but incurs some costs associated with the collection of the biomass, transporting to the facility, and storage prior to processing.

The best logistical sub models for agricultural biomass production include either field-side densification or stationary densification. Both field-side and stationary densification methods will include collection from the field. For a stationary system, the method of collection is in the form of bales. For a field-side system, the collection can either be in the form of bales, or in milled form using a forage harvester and wagon.

Continuous improvements in high density conventional baling technologies will favor the stationary system by keeping the relative costs of transportation to a minimum. It is expected that in the very near future, high density bales will achieve the maximum allowable weight limits for highway transportation (see section 6.3.1 for details). Therefore, the advantage of field-side densification for the purpose of reducing transportation costs may soon be gone. However, the required manual handling and storage of bales may perpetuate costs that will never be completely eliminated.

Agricultural biomass producers will be required to densify agricultural residues and energy crops if the advanced uniform-format bioenergy feedstock supply system becomes a reality. Producers in Canada will likely have to follow the U.S. lead in order to take advantage of North American biofuel markets. Competitive producers in the forestry residue and municipal waste industries are ahead of the agricultural sector with densification technologies already in place. Wood pellet production in Canada, for example, has grown from 500 000 tonnes in 2002 to an estimated 2.1 million tonnes in 2011 with additional existing capacity to reach 3.2 million tonnes if the feedstock were readily available (Cocchi et al., 2011). In comparison, PAMI is not aware of any commercial scale facility in Canada that is successfully densifying agricultural biomass for biofuel markets on a continuous basis. There could be many reasons for this situation, but it is clear that densification technologies for agricultural biomass as a biofuel are still in infancy.

6.4 Implementing a Field-Side Densification System

Field-side densification systems can take full advantage of existing grain handling infrastructure. Densified biomass in the form of cubes or pellets is able to utilize transport systems, conveying systems and storage facilities that exist on most farms and in every farming community. The operational window is increased when biomass is collected and stored field-side until a mobile densification system can schedule an appropriate time for densification. This allows for possible year-round field-side densification.

There are several ways to integrate a field-side densification system into the grain commodity infrastructure. Most of the differences in the methods occur at harvest and collection, but the end result is ideally a product with very similar physical characteristics (flow, density, size, etc.) to grain. For PAMI's mobile densification system, the most likely implementation of a biomass feedstock supply chain is shown in **Figure 40**, on the following page.

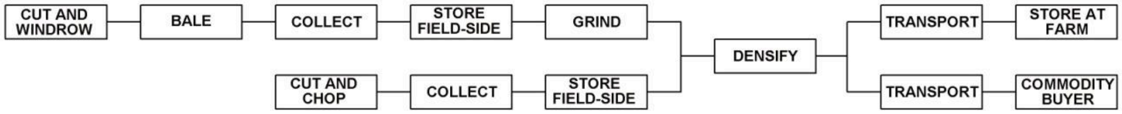

Figure 40. Field-side densification feedstock supply chain.

There are two different harvest streams that are best suited to a densification system. The chopped feedstock method using a forage harvester would seem to be the better option because it has two less harvesting steps than the baling method. However, field side storage of chopped feedstock is challenging due to low density and vulnerability to adverse environmental conditions such as wind and rain. Improved bale densities and rectangular shapes favor the baling method over the chopped method due to more industry accepted storage techniques. Bales are more easily protected from environmental fluctuations using coverings such as the tarps shown in **Figure 41**, below.

Figure 41. Biomass bales stored under tarps.

The densified product in the form of pellets or cubes can be transported from the field side in the same way that grain is transported from the field using grain trucks, semi trailers or grain carts. The pellets or cubes can be stored in bins at the farm site until a favorable market price develops, or sold directly to a biomass commodity buyer in the region.

There are still many challenges with the implementation of a field side densification system. For example, controlling moisture to an optimum level where densification can occur is a major concern. Increased moisture seems to aid in the densification process, but high moisture content contributes to spoilage of the stored biomass feedstock and of the stored pellets or cubes. Also, a high capacity of production is required to offset the input costs of the system. No known mobile densification system has yet been able to attain a production level that offsets input costs to the point of being profitable. In addition, the myriad of agricultural biomass feedstocks that are available makes it difficult to develop a single densification system that can effectively densify each type of feedstock.

The logic behind implementing a mobile densification system seems basic for most reasonable persons. The simplicity of integrating into the existing grain commodity handling infrastructure is attractive to producer groups and researchers alike. However, as discussed, many of the challenges of implementing the system are yet to be eliminated.

7. Conclusions

The evaluation trials using PAMI's mobile densification system were moderately successful. Cube formation was observed for each of the feedstock types. Controlled feed rates and moisture had a significant effect on cube production. Capacity levels varied among the feedstock types with corn having the most success.

Corn stover had the greatest success in cube formation, capacity, and quality in this trial. About two-thirds of the supplied corn stover feedstock was fed into the densification system with a total of approximately 3000 kg of cubes collected. The inherent high moisture content of the corn stover appears to have activated the polymorphic properties of the material which allowed it to produce the best cubes.

The nature of the shredded soybean residue caused several problems with PAMI's densification system. Cube formation was observed during initial demonstrations, but a consistent feed rate was not established due to the material collecting in clumps. The wrapped bales arrived with noticeable deterioration. However, no additional heating or decay was observed in the pile of shredded material. The infeed conveyors of the densification system were not able to compensate for the feedstock's characteristics, therefore further attempts to densify soybean residue were put on hold.

The switchgrass feedstock had very low moisture content initially. Addition of moisture to the product in the infeed system improved the system's ability to densify the switchgrass into cubes. The feedstock was very sensitive to the amount of water added. Increasing the addition of water to the feedstock at 2.3L/min decreased its ability to form cubes.

The miscanthus feedstock also had low moisture content. However, the addition of water did not improve its ability to form cubes. Adding water at the lowest possible rate appeared to decrease its ability to form cubes. Alternatively, steam conditioning has been proven to be far superior to liquid water for densification (Thomas et al., 1997) and should be incorporated into future research

The densification trials exposed deficiencies in the cuber design when used for short-run research trials. The dies of the cuber needed to be cleared before each run which proved to be labour intensive. The cuber is designed for continuous operation with few shutdown periods over a year of operation.

The densification system was also very sensitive to the type of feedstock processed. It appears that much more time is required to define optimum processing conditions for each type of feedstock in order to increase capacity and product quality.

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Appendix I

Durability Analysis

Corn Stover May 9, 2012:

Sample:	COD2		Time: 11:12	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Cube	Wt (g)			100%-80%	80%-60%	60%-40%	40%-20%	20%-0%
1	13.31			14.34 - 11.47	11.47 - 8.60	8.60 - 5.74	5.74 - 2.87	2.87 - 0
2	14.07			11.65	9.21	8.33	4.43	0.78
3	15.35			14.39	10.08	6.20	3.74	1.44
4	14.15			14.00				
5	14.27			12.75				
6	15.14			13.29				
7	13.29			13.00				
8	13.78			12.18				
9	15.34							
10	14.65		Sum	91.26	19.29	14.53	8.17	2.22
Total	143.35		% of material	63.7%	13.5%	10.1%	5.7%	
Average + 10%	15.77		Sum over 20%	133.25				
Average	14.34							
Average - 10%	12.90		Durability Rating	93.0	%	Size Distribution Index		321.0

Sample:	COD3		Time: 11:57	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Cube	Wt (g)			100%-80%	80%-60%	60%-40%	40%-20%	20%-0%
1	14.00			15.38 - 12.30	12.30 - 9.23	9.23 - 6.15	6.15 - 3.08	3.08 - 0
2	14.85			13.65	12.03	6.30	3.38	2.95
3	14.57			14.47	10.19	7.77	3.45	2.75
4	15.06			13.53		8.23	5.18	
5	15.17			13.19		9.18		
6	15.37			14.54				
7	15.47							
8	16.13							
9	16.54							
10	16.67		Sum	69.38	22.22	31.48	12.01	5.70
Total	153.83		% of material	48.4%	15.5%	22.0%	8.4%	
Average + 10%	16.92		Sum over 20%	135.09				
Average	15.38							
Average - 10%	13.84		Durability Rating	87.8	%	Size Distribution Index		292.4

Sample:	COD4		Time: 12:31	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Cube	Wt (g)			100%-80%	80%-60%	60%-40%	40%-20%	20%-0%
1	13.41			13.40 - 10.72	10.72 - 8.04	8.04 - 5.36	5.36 - 2.68	2.68 - 0
2	12.32			12.59	9.51	7.97	3.95	
3	13.44			11.89	8.11	5.98	4.41	
4	12.39			13.61		7.83	3.43	
5	13.25			14.01		7.17	4.33	
6	13.17			11.79				
7	14.42							
8	14.50							
9	14.47							
10	12.79		Sum	63.89	17.62	28.95	16.12	0.00
Total	134.16		% of material	44.6%	12.3%	20.2%	11.2%	
Average + 10%	14.76		Sum over 20%	126.58				
Average	13.42							
Average - 10%	12.07		Durability Rating	94.4	%	Size Distribution Index		266.8

Sample:	COD5		Time: 13:16	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Cube	Wt (g)			100%-80%	80%-60%	60%-40%	40%-20%	20%-0%
1	31.46			29.03 - 23.22	23.22 - 17.42	17.42 - 11.61	11.61 - 5.81	5.81 - 0
2	30.99			27.02	17.83	12.30	6.19	3.40
3	29.14			30.32		14.23	9.42	
4	27.83			30.94		16.80	7.78	
5	28.58			26.95		13.10		
6	31.02			29.93		15.43		
7	30.98			28.16				
8	27.87							
9	30.87							
10	30.37		Sum	173.32	17.83	71.86	23.39	3.40
Total	299.11		% of material	57.9%	12.4%	50.1%	16.3%	
Average + 10%	32.90		Sum over 20%	286.40				
Average	29.91							
Average - 10%	26.92		Durability Rating	95.8	%	Size Distribution Index		385.7

Sample:	COD6		Time: 13:26	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Cube	Wt (g)			100%-80%	80%-60%	60%-40%	40%-20%	20%-0%
1	17.15			17.46 - 13.96	13.96 - 10.47	10.47 - 6.98	6.98 - 3.49	3.49 - 0
2	17.22			16.97	12.40	8.85	3.70	2.84
3	17.81			17.26	12.44	9.00	4.55	3.00
4	16.75			16.56	12.41	9.50	6.19	
5	18.37					8.32	3.88	
6	17.69					7.22		
7	17.25					7.91		
8	17.07							
9	16.86							
10	18.39		Sum	50.79	37.25	50.80	18.32	5.84
Total	174.56		% of material	17.0%	26.0%	35.4%	12.8%	
Average + 10%	19.20		Sum over 20%	157.16				
Average	17.46							
Average - 10%	15.71		Durability Rating	90.0	%		Size Distribution Index	229.5

Sample:	COD7		Time: 14:02	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Cube	Wt (g)			100%-80%	80%-60%	60%-40%	40%-20%	20%-0%
1	15.86			14.80 - 11.84	11.84 - 8.88	8.88 - 5.92	5.92 - 2.96	2.96 - 0
2	13.91			14.31	9.78	8.66	4.72	0.87
3	15.04			14.51		6.33	3.91	2.68
4	14.33			14.76		7.42	5.34	
5	15.72			11.99		6.97		
6	13.87			13.52				
7	13.52			11.92				
8	14.38							
9	15.61							
10	15.72		Sum	81.01	9.78	29.38	13.97	3.55
Total	147.96		% of material	27.1%	6.8%	20.5%	9.7%	
Average + 10%	16.28		Sum over 20%	134.14				
Average	14.80							
Average - 10%	13.32		Durability Rating	90.7	%		Size Distribution Index	179.5

Sample:	COD8	Time: 14:46	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Cube	Wt (g)		100%-80%	80%-60%	60%-40%	40%-20%	20%-0%
1	14.72		13.56 - 10.83	10.83 - 8.12	8.12 - 5.42	5.42 - 2.71	2.71 - 0
2	13.32		12.97	9.30	7.30	3.96	
3	14.07		13.34		8.09	3.10	
4	12.92		12.51		5.60	3.41	
5	13.30		13.57		7.05		
6	13.15		12.58				
7	13.61		14.35				
8	12.64						
9	13.90						
10	13.95	Sum	79.32	9.30	28.04	10.47	0.00
Total	135.58	% of material	26.5%	6.5%	19.6%	7.3%	
Average + 10%	14.91	Sum over 20%	127.13				
Average	13.56						
Average - 10%	12.20	Durability Rating	93.8	%	Size Distribution Index		172.0

Switchgrass July 17, 2012:

Sample:	SWD1	Time: 11:07	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Cube	Wt (g)		100%-80%	80%-60%	60%-40%	40%-20%	20%-0%
1	14.68		13.39 - 10.71	10.71 - 8.03	8.03 - 5.36	5.36 - 2.68	2.68 - 0
2	13.15		11.57	8.59	7.88	3.58	2.13
3	12.23		11.52	8.64	5.98	4.09	1.76
4	14.60		11.66		5.60	3.57	
5	13.85				6.35	3.91	
6	12.85				5.64	3.62	
7	12.38				7.05	2.69	
8	14.71						
9	12.85						
10	12.60	Sum	34.75	17.23	38.50	21.46	3.89
Total	133.9	% of material	26.0%	12.9%	28.8%	16.0%	
Average + 10%	14.73	Sum over 20%	111.94				
Average	13.39						
Average - 10%	12.05	Durability Rating	83.6	%	Size Distribution Index		215.9

Sample:	SWD2		Time: 12:50	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Cube	Wt (g)			100%-80%	80%-60%	60%-40%	40%-20%	20%-0%
1	14.67			15.11 - 12.09	12.09 - 9.07	9.07 - 6.04	6.04 - 3.02	3.02 - 0
2	15.94			13.59		6.90	5.88	1.88
3	14.97			14.03		8.15	4.66	
4	16.17			15.76			4.44	
5	14.70			13.64			3.91	
6	14.77			15.46			3.74	
7	15.62			12.78				
8	14.20			14.60				
9	14.15							
10	15.92		Sum	99.86	0.00	15.05	22.63	1.88
Total	151.11		% of material	74.6%	0.0%	11.2%	16.9%	
Average + 10%	16.62		Sum over 20%	137.54				
Average	15.11							
Average - 10%	13.60		Durability Rating	91.0	%	Size Distribution Index		337.7

Sample:	SWD3		Time: 14.23	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Cube	Wt (g)			100%-80%	80%-60%	60%-40%	40%-20%	20%-0%
1	10.22			11.35 - 9.08	9.08 - 6.81	6.81 - 4.54	4.54 - 2.27	2.27 - 0
2	11.66				8.80	4.57	3.34	1.90
3	11.52					6.23	2.64	1.06
4	11.46					5.50	3.19	1.82
5	10.42						2.27	2.26
6	12.36							2.01
7	11.78							1.37
8	10.79							1.65
9	12.13							
10	11.12		Sum	0.00	8.80	16.30	11.44	12.07
Total	113.46		% of material	0.0%	6.6%	12.2%	8.5%	
Average + 10%	12.48		Sum over 20%	36.54				
Average	11.35							
Average - 10%	10.21		Durability Rating	32.2	%	Size Distribution Index		52.6

Sample:	SWD4		Time: 14:53	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Cube	Wt (g)			100%-80%	80%-60%	60%-40%	40%-20%	20%-0%
1	24.06			23.33 - 18.66	18.66 - 14.00	14.00 - 9.33	9.33 - 4.67	4.67 - 0
2	24.97			24.67	17.27	13.43	5.74	4.41
3	23.50			21.47	14.63	11.97	8.44	4.44
4	23.22			21.54			8.52	1.56
5	22.19			23.20			7.53	
6	23.97			20.75			6.73	
7	25.44							
8	22.51							
9	21.62							
10	21.77		Sum	111.63	31.90	25.40	36.96	10.41
Total	233.25		% of material	47.9%	23.8%	19.0%	27.6%	
Average + 10%	25.66		Sum over 20%	205.89				
Average	23.33							
Average - 10%	20.99		Durability Rating	88.3	%	Size Distribution Index		328.4

Sample:	SWD5		Time: 16:11	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Cube	Wt (g)			100%-80%	80%-60%	60%-40%	40%-20%	20%-0%
1	17.45			18.41 - 14.72	14.72 - 11.04	11.04 - 7.36	7.36 - 3.68	3.68 - 0
2	18.79			17.72	14.23	10.68	6.97	1.81
3	17.27			18.17		10.21	5.38	3.64
4	18.15					9.14	4.30	1.95
5	17.30					10.78	4.54	
6	19.61					9.40	4.85	
7	19.47					8.29	5.59	
8	18.13					8.23		
9	18.04					8.50		
10	19.85		Sum	35.89	14.23	75.23	31.63	7.40
Total	184.06		% of material	15.4%	10.6%	56.2%	23.6%	
Average + 10%	20.25		Sum over 20%	156.98				
Average	18.41							
Average - 10%	16.57		Durability Rating	85.3	%	Size Distribution Index		229.4

Miscanthus July 19, 2012:

Sample:	MID1		Time: 12:10	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Cube	Wt (g)			100%-80%	80%-60%	60%-40%	40%-20%	20%-0%
1	12.94			12.84 - 10.27	10.27 - 7.70	7.70 - 5.14	5.14 - 2.57	2.57 - 0
2	12.59			10.72	9.16	5.24	4.75	2.13
3	12.90				8.43	6.85	3.68	0.48
4	12.45					6.21	3.39	2.46
5	12.16					5.42	4.40	1.43
6	12.65						4.35	1.10
7	12.76						4.73	0.56
8	12.40						3.85	1.01
9	13.98							0.48
10	13.55		Sum	10.72	17.59	23.72	29.15	9.65
Total	128.38		% of material	8.4%	13.7%	18.5%	22.7%	
Average + 10%	14.12		Sum over 20%	81.18				
Average	12.84							
Average - 10%	11.55		Durability Rating	63.2	%	Size Distribution Index		134.2

Sample:	MID2		Time: 13:40	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Cube	Wt (g)			100%-80%	80%-60%	60%-40%	40%-20%	20%-0%
1	10.78			10.72 - 8.58	8.58 - 6.43	6.43 - 4.29	4.29 - 2.14	2.14 - 0
2	10.00			10.12		4.75	4.28	2.13
3	11.01			10.65		5.52	4.16	1.66
4	11.47			10.14			3.18	
5	10.07			10.72			3.00	
6	9.92			9.58			3.77	
7	11.32			8.73				
8	10.91							
9	10.20							
10	11.56		Sum	59.94	0.00	10.27	18.39	3.79
Total	107.24		% of material	46.7%	0.0%	8.0%	14.3%	
Average + 10%	11.80		Sum over 20%	88.60				
Average	10.72							
Average - 10%	9.65		Durability Rating	82.6	%	Size Distribution Index		217.1

Sample:	MID3		Time: 15:05	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Cube	Wt (g)			100%-80%	80%-60%	60%-40%	40%-20%	20%-0%
1	12.14			12.73 - 10.18	10.18 - 7.64	7.64 - 5.09	5.09 - 2.55	2.55 - 0
2	13.12			11.42	8.06	7.56	4.62	1.39
3	12.62			10.83	8.77	6.08	3.06	1.96
4	12.31				9.79		3.69	0.47
5	13.11				7.83		4.22	0.43
6	13.39				8.54		3.31	
7	13.46						3.11	
8	12.07						2.57	
9	12.93							
10	12.15		Sum	22.25	42.99	13.64	24.58	4.25
Total	127.3		% of material	17.3%	33.5%	10.6%	19.1%	
Average + 10%	14.00		Sum over 20%	103.46				
Average	12.73							
Average - 10%	11.46		Durability Rating	81.3	%	Size Distribution Index		210.2

Sample:	MIDx		Time: 14:45	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Cube	Wt (g)			100%-80%	80%-60%	60%-40%	40%-20%	20%-0%
1	12.57			13.83 - 11.07	11.07 - 8.30	8.30 - 5.53	5.53 - 2.77	2.77 - 0
2	13.49			14.25	8.61	8.24	4.96	1.94
3	14.90			13.30		5.91	3.22	1.12
4	13.51			12.68				0.76
5	14.21			11.90				
6	14.75			12.11				
7	13.55			12.29				
8	13.12			12.55				
9	14.12							
10	14.12		Sum	89.08	8.61	14.15	8.18	3.82
Total	138.34		% of material	64.4%	6.7%	11.0%	6.4%	
Average + 10%	15.22		Sum over 20%	120.02				
Average	13.83							
Average - 10%	12.45		Durability Rating	86.8	%	Size Distribution Index		306.1

Appendix II

Cube Bulk Density Analysis

Corn Stover May 9, 2012:

Date:	09-May-12		(Container Wt: 6.22 kg)	
Sample	Time	Gross Weight (kg)	Net Weight (kg)	Density (kg/m^3)
COB1	10:11	28.36	22.14	394.30
COB2	10:47	26.18	19.96	355.48
COB3	11:12	29.68	23.46	417.81
COB4	11:57	29.24	23.02	409.97
COB5	12:31	31.62	25.40	452.36
COB6	13:26	32.24	26.02	463.40
COB7	14:02	29.82	23.60	420.30
COB8	14:46	33.18	26.96	480.14

Switchgrass July 17, 2012:

Date:	17-Jul-12		(Container Wt: 6.22 kg)	
Sample	Time	Gross Weight (kg)	Net Weight (kg)	Density (kg/m^3)
SWB1	11:07	36.14	29.92	532.86
SWB2	12:50	34.68	28.46	506.86
SWB3	14:23	28.02	21.80	388.25
SWB4	14:53	34.34	28.12	500.80
SWB5	16:11	31.50	25.28	450.22

Miscanthus July 19, 2012:

Date:	19-Jul-12		(Container Wt: 6.22 kg)	
Sample	Time	Gross Weight (kg)	Net Weight (kg)	Density (kg/m^3)
MIB1	12:10	35.46	29.24	520.75
MIB2	13:40	27.92	21.70	386.46

Appendix III

Capacity and Fuel Measurements

Corn Stover May 9, 2012:

Sample	Cube Mass	Fuel Mass	Time	Fuel Used	Elapsed Time	Capacity
Units	kg	kg		kg	h	kg/h
CO1	350		10:06:00			
Start Feed		660	10:21:00			
CO2	314	646	10:42:00	14	0.35	897
CO3	282	636	11:03:00	10	0.35	806
CO4	326	612	11:50:00	24	0.78	416
CO5	312	598	12:25:00	14	0.58	535
CO6	350	574	13:21:00	24	0.93	375
CO7	338	556	13:56:00	18	0.58	579
CO8	336	536	14:38:00	20	0.70	480
CO9	328	520	15:20:00	16	0.70	469

Switchgrass July 17, 2012:

Sample	Cube Mass	Fuel Mass	Time	Fuel Used	Elapsed Time	Capacity
	kg	kg		kg	h	kg/h
Start Feed	0	406	10:52:00			
SW1	322	350	12:35:00	56	1.72	188
SW2	246	308	14:00:00	42	1.42	174
SW3a	74	294	14:30:00	14	0.50	148
SW3b	30	288	14:40:00	6	0.17	180
SW4	264	250	15:58:00	38	1.30	203
SW5	166	232	16:34:00	18	0.60	277

Miscanthus July 19, 2012:

Sample	Cube Mass	Fuel Mass	Time	Fuel Used	Elapsed Time	Capacity
	kg	kg		kg	h	kg/h
Start Feed	0	504	11:54:00			
MI1	268	468	13:12:00	36	1.30	206
MI2	220	430	14:45:00	38	1.55	142

Appendix IV

Core Sample Analysis

CENTRAL TESTING LABORATORY LTD.
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Unit 9-851 Lagimodiere Blvd
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202, 509-11 Avenue
Nisku, Alberta T9E 7N5
Ph: 1-877-955-7861

Laboratory #: 271697-12

TEST REPORT

Submitted By:

Prairie Agricultural Machinery Institute
390 River Rd, PO Box 1060
Portage la Prairie, MB R1N 3C5
Attn: Lorne Grieger, EIT

Date Received: April 13, 2012
Phone #: (204) 239-5445 x229
Fax #: (204) 239-7124

Client: PO# 3093 PAMI
Product: FORAGE
Description: CORN STOVER

Package #: MR ADF NDF CL SAND/SILICA LIGNIN ASH
Complete ☐
Sample #: CO1-1

Analysis:	AS RECEIVED	DRY MATTER
Moisture (%)(test date 4/17/2012)	23.67	
Dry Matter (%)	76.33	
Ash (%)(test date 4/17/2012)	3.73	4.89
Sand/silica (%)(test date 4/20/2012)		0.76
Chlorides (%)(test date 4/18/2012)	0.09	0.12
Lignin (%)(test date 4/25/2012)	5.31	6.96
Acid Detergent Fibre (%)(test date 4/17/2012)	36.94	48.39
Neutral Detergent Fibre (%)(test date 4/17/2012)	58.39	76.50

Date Reported: **April 25, 2012**

Arrival Condition
Acceptable

Results are based on the sample received and liability is limited to the cost of analysis

Approved By

Technical Manager

Page 1 of 12

ISO 17025 Laboratory Accredited for:
Protein by AOAC 990.03
Calcium by Modified AOAC 968.08, 935.13A
Total Coliform / Fecal Coliform by Modified 9222A-D

Standards Council of Canada
Conseil canadien des normes

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202, 509-11 Avenue
Nisku, Alberta T9E 7N5
Ph: 1-877-955-7861

Laboratory #:
271698-12

TEST REPORT

Submitted By:

Prairie Agricultural Machinery Institute
390 River Rd, PO Box 1060
Portage la Prairie, MB R1N 3C5
Attn: Lorne Grieger, EIT

Date Received: April 13, 2012
Phone #: (204) 239-5445 x 229
Fax #: (204) 239-7124

Client: PO# 3093 PAMI
Product: FORAGE
Description:
SOYBEAN STRAW

Package #: MR ADF NDF CL SAND/SILICA LIGNIN ASH
Complete ☐
Sample #: SO1-1

Analysis:	AS RECEIVED	DRY MATTER
Moisture (%)(test date 4/17/2012)	26.18	
Dry Matter (%)	73.82	
Ash (%)(test date 4/17/2012)	4.94	6.70
Sand/silica (%)(test date 4/20/2012)		1.55
Chlorides (%)(test date 4/18/2012)	< 0.01	< 0.01
Lignin (%)(test date 4/25/2012)	12.78	17.31
Acid Detergent Fibre (%)(test date 4/17/2012)	47.09	63.80
Neutral Detergent Fibre (%)(test date 4/17/2012)	57.73	78.21

Date Reported: **April 25, 2012**

Arrival Condition
Acceptable

Results are based on the sample received and liability is limited to the cost of analysis

Approved By

Technical Manager

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Laboratory #: 271699-12

TEST REPORT

Submitted By:

Prairie Agricultural Machinery Institute
390 River Rd, PO Box 1060
Portage la Prairie, MB R1N 3C5
Attn: Lorne Grieger, EIT

Date Received: April 13, 2012
Phone #: (204) 239-5445 x 229
Fax #: (204) 239-7124

Client: PO# 3093 PAMI
Product: FORAGE
Description:

SWITCHGRASS

Package #: MR ADF NDF CL SAND/SILICA LIGNIN ASH
Complete ☐
Sample #: SW1-1

Analysis:	AS RECEIVED	DRY MATTER
Moisture (%)(test date 4/17/2012)	9.11	
Dry Matter (%)	90.89	
Ash (%)(test date 4/17/2012)	2.59	2.85
Sand/silica (%)(test date 4/20/2012)		1.04
Chlorides (%)(test date 4/18/2012)	0.01	0.02
Lignin (%)(test date 4/25/2012)	9.70	10.67
Acid Detergent Fibre (%)(test date 4/17/2012)	48.85	53.75
Neutral Detergent Fibre (%)(test date 4/17/2012)	75.68	83.27

Results are based on the sample received and liability is limited to the cost of analysis

Date Reported: **April 25, 2012**

Arrival Condition
Acceptable

Approved By

Technical Manager

ISO 17025 Laboratory Accredited for:
Protein by AOAC 990.03
Calcium by Modified AOAC 968.08, 935.13A
Total Coliform / Fecal Coliform by Modified 9222A-D

Standards Council of Canada
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Laboratory #: 271700-12

TEST REPORT

Submitted By:

Prairie Agricultural Machinery Institute
390 River Rd, PO Box 1060
Portage la Prairie, MB R1N 3C5
Attn: Lorne Grieger, EIT

Date Received: April 13, 2012
Phone #: (204) 239-5445 x 229
Fax #: (204) 239-7124

Client: PO# 3093 PAMI
Product: FORAGE
Description: MISCANTHUS

Package #: MR ADF NDF CL SAND/SILICA LIGNIN ASH
Complete ☐
Sample #: MI 1-1

Analysis:	AS RECEIVED	DRY MATTER
Moisture (%)(test date 4/17/2012)	13.21	
Dry Matter (%)	86.79	
Ash (%)(test date 4/17/2012)	2.71	3.12
Sand/silica (%)(test date 4/20/2012)		0.86
Chlorides (%)(test date 4/18/2012)	< 0.01	< 0.01
Lignin (%)(test date 4/25/2012)	10.07	11.61
Acid Detergent Fibre (%)(test date 4/17/2012)	50.14	57.78
Neutral Detergent Fibre (%)(test date 4/17/2012)	76.24	87.84

Results are based on the sample received and liability is limited to the cost of analysis

Date Reported: **April 25, 2012**

Arrival Condition
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Technical Manager

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Laboratory #: 271719-12

TEST REPORT

Submitted By:

Prairie Agricultural Machinery Institute
390 River Rd, PO Box 1060
Portage la Prairie, MB R1N 3C5
Attn: Lorne Grieger, EIT

Date Received: April 13, 2012
Phone #: (204) 239-5445 x 229
Fax #: (204) 239-7124

Client:	PO# 3093 PAMI	**Package #:**	MR ADF NDF CL SAND/SILICA LIGNIN ASH
Product:	FORAGE	**Complete** ☐	
Description:		**Sample #:**	CO1-2
	CORN STOVER		

Analysis:	AS RECEIVED	DRY MATTER
Moisture (%)(test date 4/17/2012)	23.67	
Dry Matter (%)	76.33	
Ash (%)(test date 4/17/2012)	3.78	4.96
Sand/silica (%)(test date 4/20/2012)		1.41
Chlorides (%)(test date 4/18/2012)	0.06	0.07
Lignin (%)(test date 4/25/2012)	5.86	7.68
Acid Detergent Fibre (%)(test date 4/17/2012)	37.23	48.77
Neutral Detergent Fibre (%)(test date 4/17/2012)	57.51	75.35

Results are based on the sample received and liability is limited to the cost of analysis

Date Reported: **April 25, 2012**

Approved By

Arrival Condition
Acceptable

Technical Manager

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Laboratory #: 271720-12

TEST REPORT

Submitted By:

Prairie Agricultural Machinery Institute
390 River Rd, PO Box 1060
Portage la Prairie, MB R1N 3C5
Attn: Lorne Grieger, EIT

Date Received: April 13, 2012
Phone #: (204) 239-5445 x 229
Fax #: (204) 239-7124

Client: PO# 3093 PAMI
Product: FORAGE
Description:
SOYBEAN STRAW

Package #: MR ADF NDF CL SAND/SILICA LIGNIN ASH
Complete ☐
Sample #: S01-2

Analysis:	AS RECEIVED	DRY MATTER
Moisture (%)(test date 4/17/2012)	26.18	
Dry Matter (%)	73.82	
Ash (%)(test date 4/17/2012)	5.09	6.89
Sand/silica (%)(test date 4/20/2012)		1.46
Chlorides (%)(test date 4/18/2012)	< 0.01	< 0.01
Lignin (%)(test date 4/25/2012)	12.36	16.74
Acid Detergent Fibre (%)(test date 4/17/2012)	46.61	63.14
Neutral Detergent Fibre (%)(test date 4/17/2012)	57.78	78.27

Results are based on the sample received and liability is limited to the cost of analysis

Date Reported: **April 25, 2012**

Arrival Condition
Acceptable

Approved By

Technical Manager

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Laboratory #: 271721-12

TEST REPORT

Submitted By:

Prairie Agricultural Machinery Institute
390 River Rd, PO Box 1060
Portage la Prairie, MB R1N 3C5
Attn: Lorne Grieger, EIT

Date Received: April 13, 2012
Phone #: (204) 239-5445 x 229
Fax #: (204) 239-7124

Client: PO# 3093 PAMI
Product: FORAGE
Description:
SWITCHGRASS

Package #: MR ADF NDF CL SAND/SILICA LIGNIN ASH
Complete ☐
Sample #: SW1-2

Analysis:	AS RECEIVED	DRY MATTER
Moisture (%)(test date 4/17/2012)	9.11	
Dry Matter (%)	90.89	
Ash (%)(test date 4/17/2012)	2.62	2.88
Sand/silica (%)(test date 4/20/2012)		0.88
Chlorides (%)(test date 4/18/2012)	0.06	0.07
Lignin (%)(test date 4/25/2012)	8.76	9.64
Acid Detergent Fibre (%)(test date 4/17/2012)	49.60	54.57
Neutral Detergent Fibre (%)(test date 4/17/2012)	76.13	83.76

Results are based on the sample received and liability is limited to the cost of analysis

Date Reported: **April 25, 2012**

Approved By

Technical Manager

Arrival Condition
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Laboratory #: 271722-12

TEST REPORT

Submitted By:

Prairie Agricultural Machinery Institute
390 River Rd, PO Box 1060
Portage la Prairie, MB R1N 3C5
Attn: Lorne Grieger, EIT

Date Received:	**April 13, 2012**
Phone #:	**(204) 239-5445 x 229**
Fax #:	**(204) 239-7124**

Client:	**PO# 3093 PAMI**	**Package #:**	MR ADF NDF CL SAND/SILICA LIGNIN ASH
Product:	**FORAGE**	**Complete** ☐	
Description:		**Sample #:**	**MI 1-2**
	MISCANTHUS		

Analysis:	AS RECEIVED	DRY MATTER
Moisture (%)(test date 4/17/2012)	13.21	
Dry Matter (%)	86.79	
Ash (%)(test date 4/17/2012)	2.76	3.18
Sand/silica (%)(test date 4/20/2012)		1.62
Chlorides (%)(test date 4/18/2012)	< 0.01	< 0.01
Lignin (%)(test date 4/25/2012)	9.73	11.21
Acid Detergent Fibre (%)(test date 4/17/2012)	50.94	58.69
Neutral Detergent Fibre (%)(test date 4/17/2012)	76.66	88.32

Results are based on the sample received and liability is limited to the cost of analysis

Date Reported: **April 25, 2012**

Approved By

Technical Manager

Arrival Condition
Acceptable

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Ph: 1-877-955-7861

Laboratory #: 271723-12

TEST REPORT

Submitted By:

Prairie Agricultural Machinery Institute
390 River Rd, PO Box 1060
Portage la Prairie, MB R1N 3C5
Attn: Lorne Grieger, EIT

Date Received: April 13, 2012
Phone #: (204) 239-5445 x 229
Fax #: (204) 239-7124

Client: PO# 3093 PAMI
Product: FORAGE
Description: CORN STOVER

Package #: MR ADF NDF CL SAND/SILICA LIGNIN ASH
Complete ☐
Sample #: C01-3

Analysis:	AS RECEIVED	DRY MATTER
Moisture (%)(test date 4/17/2012)	23.67	
Dry Matter (%)	76.33	
Ash (%)(test date 4/17/2012)	4.14	5.42
Sand/silica (%)(test date 4/20/2012)		2.01
Chlorides (%)(test date 4/18/2012)	0.06	0.08
Lignin (%)(test date 4/25/2012)	5.04	6.61
Acid Detergent Fibre (%)(test date 4/17/2012)	36.82	48.24
Neutral Detergent Fibre (%)(test date 4/17/2012)	57.61	75.47

Date Reported: **April 25, 2012**

Arrival Condition
Acceptable

Results are based on the sample received and liability is limited to the cost of analysis

Approved By

Technical Manager

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Nisku, Alberta T9E 7N5
Ph: 1-877-955-7861

Laboratory #: 271724-12

TEST REPORT

Submitted By:

Prairie Agricultural Machinery Institute
390 River Rd, PO Box 1060
Portage la Prairie, MB R1N 3C5
Attn: Lorne Grieger, EIT

Date Received: April 13, 2012
Phone #: (204) 239-5445 x 229
Fax #: (204) 239-7124

Client:	PO# 3093 PAMI	**Package #:**	MR ADF NDF CL SAND/SILICA LIGNIN ASH
Product:	FORAGE	**Complete** ☐	
Description:		**Sample #:**	SO1-3
	SOYBEAN STRAW		

Analysis:	AS RECEIVED	DRY MATTER
Moisture (%)(test date 4/17/2012)	26.18	
Dry Matter (%)	73.82	
Ash (%)(test date 4/17/2012)	6.22	8.42
Sand/silica (%)(test date 4/20/2012)		1.71
Chlorides (%)(test date 4/18/2012)	< 0.01	< 0.01
Lignin (%)(test date 4/25/2012)	11.89	16.11
Acid Detergent Fibre (%)(test date 4/17/2012)	45.18	61.20
Neutral Detergent Fibre (%)(test date 4/17/2012)	55.48	75.16

Results are based on the sample received and liability is limited to the cost of analysis

Date Reported: **April 25, 2012**

Approved By

Arrival Condition
Acceptable

Technical Manager

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202, 509-11 Avenue
Nisku, Alberta T9E 7N5
Ph: 1-877-955-7861

Laboratory #: 271725-12

TEST REPORT

Submitted By:

Prairie Agricultural Machinery Institute
390 River Rd, PO Box 1060
Portage la Prairie, MB R1N 3C5
Attn: Lorne Grieger, EIT

Date Received: April 13, 2012
Phone #: (204) 239-5445 x 229
Fax #: (204) 239-7124

Client: PO# 3093 PAMI
Product: FORAGE
Description:
SWITCHGRASS

Package #: MR ADF NDF CL SAND/SILICA LIGNIN ASH
Complete ☐
Sample #: SW1-3

Analysis:	AS RECEIVED	DRY MATTER
Moisture (%)(test date 4/18/2012)	9.11	
Dry Matter (%)	90.89	
Ash (%)(test date 4/17/2012)	3.04	3.34
Sand/silica (%)(test date 4/20/2012)		1.45
Chlorides (%)(test date 4/18/2012)	0.02	0.02
Lignin (%)(test date 4/25/2012)	9.21	10.13
Acid Detergent Fibre (%)(test date 4/17/2012)	48.62	53.50
Neutral Detergent Fibre (%)(test date 4/17/2012)	75.27	82.82

Results are based on the sample received and liability is limited to the cost of analysis

Date Reported: **April 25, 2012**

Approved By

Technical Manager

Arrival Condition
Acceptable

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202, 509-11 Avenue
Nisku, Alberta T9E 7N5
Ph: 1-877-955-7861

Laboratory #: 271726-12

TEST REPORT

Submitted By:

Prairie Agricultural Machinery Institute
390 River Rd, PO Box 1060
Portage la Prairie, MB R1N 3C5
Attn: Lorne Grieger, EIT

Date Received: April 13, 2012
Phone #: (204) 239-5445 x 229
Fax #: (204) 239-7124

Client: PO# 3093 PAMI
Product: FORAGE
Description:
MISCANTHUS

Package #: MR ADF NDF CL SAND/SILICA LIGNIN ASH
Complete ☐
Sample #: MI 1-3

Analysis:	AS RECEIVED	DRY MATTER
Moisture (%)(test date 4/18/2012)	13.21	
Dry Matter (%)	86.79	
Ash (%)(test date 4/17/2012)	3.05	3.51
Sand/silica (%)(test date 4/20/2012)		0.79
Chlorides (%)(test date 4/18/2012)	< 0.01	< 0.01
Lignin (%)(test date 4/25/2012)	9.92	11.43
Acid Detergent Fibre (%)(test date 4/17/2012)	50.87	58.61
Neutral Detergent Fibre (%)(test date 4/17/2012)	75.83	87.37

Date Reported: **April 25, 2012**

Arrival Condition
Acceptable

Results are based on the sample received and liability is limited to the cost of analysis

Approved By

Technical Manager

Appendix V

Cube Analysis

LORING LABORATORIES (ALBERTA) LTD.
629 Beaverdam Road N.E. Calgary, Alberta T2K 4W7
Tel : (403) 274-2777 Fax : (403) 275-0541
ISO 9001:2008 Certified

TO : PRAIRIE AGRICULTURE MACHINERY INSTITUTE
ATTN : Les Funk
PROJECT :

LLL FILE # : 5 5 4 8 1
DATE : Jul 5, 2012
REPORT BY : R. BUCKINGHAM

SAMPLE TYPE : Corn Stover Cubes

P.O.# 3146

PROXIMATE ANALYSIS

SAMPLE	BASIS	MST (%)	ASH (%)	V.M. (%)	F.C. (%)	S	Calorific Value KJ/Kg
COD3A	A.R.	19.31	5.28	62.83	12.58	0.22	14420
	A.D.	4.30	6.26	74.52	14.92	0.26	17103
	Dry	-----	6.54	77.87	15.59	0.27	17871
COD5A	A.R.	15.46	5.66	65.01	13.87	0.20	15250
	A.D.	4.72	6.38	73.27	15.63	0.23	17188
	Dry	-----	6.70	76.90	16.40	0.24	18039
COD7A	A.R.	18.80	4.57	63.00	13.63	0.06	14357
	A.D.	4.16	5.39	74.36	16.09	0.07	16945
	Dry	-----	5.62	77.59	16.79	0.07	17681

ULTIMATE ANALYSIS

SAMPLE	BASIS	MST (%)	C (%)	H (%)	ASH (%)	N (%)	S (%)	O (%)
COD3A	A.R.	19.31	36.55	4.53	5.28	0.62	0.22	33.49
	A.D.	4.30	43.35	5.37	6.26	0.74	0.26	39.72
	Dry	-----	45.30	5.61	6.54	0.77	0.27	41.50
COD5A	A.R.	15.46	38.66	4.73	5.66	0.57	0.20	34.71
	A.D.	4.72	43.57	5.34	6.38	0.64	0.23	39.12
	Dry	-----	45.73	5.60	6.70	0.67	0.24	41.06
COD7A	A.R.	18.80	37.14	4.64	4.57	0.67	0.06	34.13
	A.D.	4.16	43.83	5.48	5.39	0.79	0.07	40.28
	Dry	-----	45.73	5.72	5.62	0.82	0.07	42.03

Analyses performed using ASTM D2013, D3173, D3175, D3178, D3179, D5865

NOTE : Hydrogen and oxygen do not include H and O from sample moisture.
Value of oxygen by difference.

Samples received on: June 15, 2012

ASSAYER

Prox

LORING LABORATORIES (ALBERTA) LTD.

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Tel : (403) 274-2777 Fax : (403) 275-0541

ISO 9001:2008 Certified

TO : PRAIRIE AGRICULTURE MACHINERY INSTITUTE
ATTN : Les Funk
PROJECT : BIOMASS

LLL FILE # : 5 5 6 2 1
DATE : Aug 24, 2012
REPORT BY : David Ko

SAMPLE TYPE : Corn Stover Cubes

P.O.# 3179

PROXIMATE ANALYSIS

SAMPLE	BASIS	MST	ASH (%)	V.M. (%)	F.C. (%)	S	Calorific Value KJ/Kg
SOD.A Soybean Residue Cubes	A.R.	18.79	2.85	65.24	13.13	0.05	15495
	A.D.	5.83	3.30	75.65	15.22	0.06	17968
	Dry	——	3.50	80.33	16.16	0.06	19080
SWD2A Switchgrass Wet Cubes	A.R.	8.51	6.31	69.73	15.45	0.08	16678
	A.D.	6.66	6.44	71.14	15.76	0.08	17015
	Dry	——	6.90	76.22	16.88	0.09	18229
SWD3A Switchgrass Dry Cubes	A.R.	8.85	3.02	74.36	13.77	0.04	17425
	A.D.	5.61	3.13	77.00	14.26	0.04	18044
	Dry	——	3.32	81.58	15.11	0.04	19116
MID1A Miscanthus Dry Cubes	A.R.	8.21	2.58	75.30	13.91	0.03	17617
	A.D.	4.93	2.67	77.99	14.41	0.03	18246
	Dry	——	2.81	82.03	15.16	0.03	19192
MID2A Miscanthus Wet Cubes	A.R.	11.41	2.65	73.09	12.85	0.03	15429
	A.D.	4.92	2.84	78.45	13.79	0.03	16560
	Dry	——	2.99	82.51	14.50	0.03	17417

ULTIMATE ANALYSIS

SAMPLE	BASIS	MST	C (%)	H (%)	ASH (%)	N (%)	S (%)	O (%)
SOD.A Soybean Residue Cubes	A.R.	18.79	38.82	4.75	2.85	0.48	0.05	34.27
	A.D.	5.83	45.01	5.50	3.30	0.56	0.06	39.74
	Dry	——	47.80	5.84	3.50	0.59	0.06	42.20
SWD2A Switchgrass Wet Cubes	A.R.	8.51	41.34	5.06	6.31	0.85	0.08	37.85
	A.D.	6.66	42.18	5.16	6.44	0.87	0.08	38.61
	Dry	——	45.19	5.53	6.90	0.93	0.09	41.36
SWD3A Switchgrass Dry Cubes	A.R.	8.85	43.62	5.30	3.02	0.48	0.04	38.69
	A.D.	5.61	45.17	5.49	3.13	0.50	0.04	40.06
	Dry	——	47.85	5.81	3.32	0.53	0.04	42.44
MID1A Miscanthus Dry Cubes	A.R.	8.21	44.24	5.26	2.58	0.26	0.03	39.42
	A.D.	4.93	45.82	5.45	2.67	0.27	0.03	40.83
	Dry	——	48.20	5.74	2.81	0.28	0.03	42.94
MID2A Miscanthus Wet Cubes	A.R.	11.41	42.63	4.99	2.65	0.22	0.03	38.08
	A.D.	4.92	45.75	5.35	2.84	0.24	0.03	40.87
	Dry	——	48.12	5.63	2.99	0.25	0.03	42.98

Analyses performed using ASTM D2013, D3173, D3175, D3178, D3179, D5865

NOTE : Hydrogen and oxygen do not include H and O from sample moisture.
Value of oxygen by difference.

Samples received on: July 26, 2012

ASSAYER

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