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Application of the rollermill and hammermill for biomass fractionation

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Application of the rollermill and hammermill for biomass fractionation

by

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A thesis submitted to the graduate faculty

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Major: Agricultural Engineering (Power and Machinery Systems)

Program of Study Committee:
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Iowa State University

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Abstract

Much research is being done to establish corn stover. Stover as as an economical feedstock for ethanol and other industrial processes has many advantages including low cost, high production, and low competition. However; corn stover has disadvantages due mainly to its low density and heterogeneous make-up. Research was performed to evaluate and compare a hammermill versus a rollermill as two grinding methods to reduce particle size and change chemical distribution. The hammermill generated finer particles of a relatively homogenous nature, while the rollermill generated a broader particle size spread with differences in chemical composition for the different sizes. The rollermill created a 1% shift in lignin content, a 2% shift in ash content, an 8% shift in Hemicellulose content, and a 4% shift in cellulose content compared to the untreated control.

Introduction

Corn stover is the largest biomass residue in the United States. As a yearly byproduct of 10 billion bushels of corn production, 220 million tons of corn stover is available (Perlack and Turhollow, 2002). On a dry matter basis, the generation of corn stover to grain occurs in the ratio 0.8:1—one dry ton of corn kernels is accompanied by 0.8 dry ton of corn stover left in the field (Pordesimo et al., 2004).

However; not all stover can be collected. Some material is lost due to collection inefficiencies. Additionally, a certain amount of stover should be left on the field to maintain soil quality and limit erosion. Current estimates show 80-100 million dry tonnes/yr can be sustainably collected with 60-80 million dry t/yr available for 9 billion gallons of ethanol fermentation in the long term and an estimated consumption of 20 million dry t/yr for other industrial uses. (Kadam and McMillan, 2003) The other industrial uses include the use of corn cobs to produce chemicals such as furfural and industrial products such as absorbants (Tsai et al., 1998).

Corn stover is not without its problems, however. One problem is the difference in moisture levels between the stover and the grain at the optimum harvest point for grain quality. Stover is at too high of a moisture to be stored directly without significant degradation. The feedstock requires certain conditions to preserve the components' value and minimize storage hazards. Analyzing the many variables of storage becomes a difficult and laborious undertaking on an industrial scale, but two main options exist. First, the biomass material can be left on the ground to decrease moisture content before baling. Unfortunately, this requires multiple field operations, and the baling operation results in soil contamination of the stover. The dry bales are vulnerable to fire due to the higher than optimum moisture content unless adequate drying of the bales is ensured. As an alternative to dry storage, the stover may be stored in a wet state as ensilage. At least one study has shown stover may be ensiled successfully at moisture contents as low as 41.7% (Shinners et al, 2007). Unfortunately, industrial ethanol production is inhibited by the presence of acids normally produced by the ensilage process (Richards et al, 2001).

Density of corn stover is extremely low. Depending on the length of cut and moisture, density may be only 40-80 kg/m^3 (Knutson and Miller, 1982). This has a major effect on the economical use of stover. The costs per mile of transport are relatively fixed, so transportation becomes more economical as density increases. Economical cost models assume a density of 88 kg/m^3 on a dry basis, or about 146 kg/m^3 at 40% moisture

(Perlack and Turhollow, 2002). In general, bulk density of stover has been shown to increase with decreased particle size.

The different physiological parts of the plant, as seen in Figure 1, serve vastly different purposes ranging from plant support to energy production and storage. Therefore it serves to reason the different portions of plant materials would have different chemical compositions. Consequently the different constituents of the stover material may be utilized in a wide range of different products. The cellulose and hemicelluloses may be utilized in bio-processing refineries for production of liquid fuels while the fiber constituents are used in the manufacture of natural fiberboard office materials. Therefore, the different constituents may have different values based on industry needs and applications.

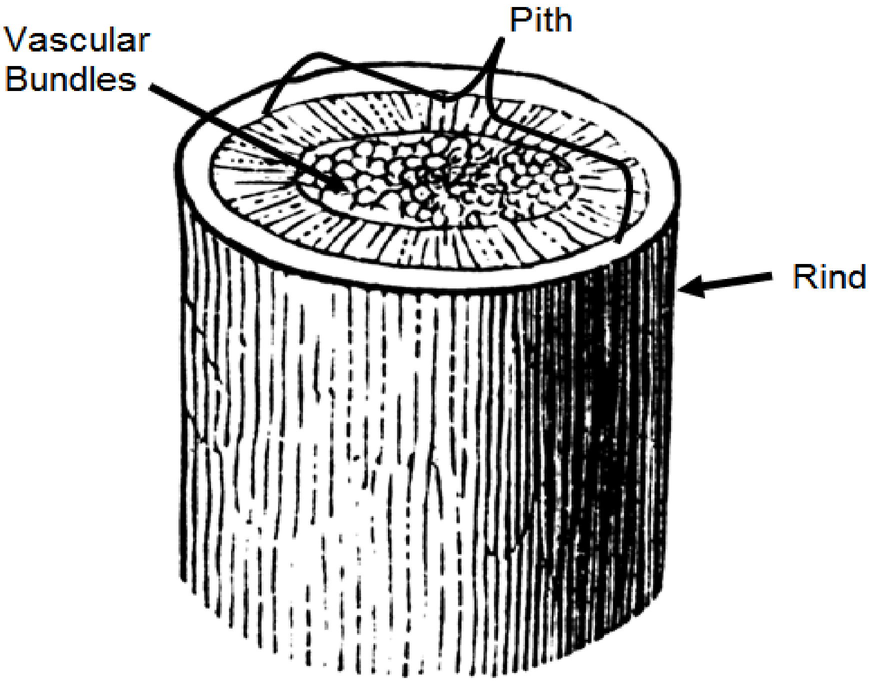


Figure 1. Cross section of a plant stem (Source unknown).

If the components of corn stover can be separated or fractionated so that the most appropriate components go to the most suitable process, efficiencies can be gained. Separation would allow components that are easily broken down to go to ethanol production, while high purity cellulose may go to paper manufacturers, and any residual grain may be sent to the current grain markets. Especially in the case of baling as a collection method, separation would give a chance to remove dirt and dust. Separation is a value added step that will reduce the cost burden of corn stover collection felt by any one industry.

Review of Literature

Over the years, several studies have been conducted to identify the physical and chemical constituents of corn stover. The different components of stover have been reported to be 50.9% stalk, 21.0% leaf, 15.2% cob, and 12.9% husk on a dry matter basis (Pordesimo et al., 2004). A related study by the same authors looked at the energy content and chemical makeup of the different corn fractions. It was found that the energy content varied with crop maturity. However, there was a wide amount of scatter, and it could not be proven that there was a significant variation between the energy content of the fractions in a combustion process. The values tended to be in the range of 16.7-20.9 kJ/g. The chemical components also varied with a significant difference in lignin and xylose content between the leaves and stalks. At harvest time, the lignin content was about 20%, 16%, and 15% in the stalk, leaf, and husk respectively (Pordesimo et al, 2005).

The properties of corn stover may make separation difficult. The density of all components is relatively close with the possible exception of the cob. Many studies have been done to evaluate chemical fractionation methods. Kim and Lee (2005) reported a hot water and aqueous ammonia approach. Other approaches include steam (Avellar and Glasser, 1998), and acidic or basic hydrolysis (Bootsma and Shanks, 2004).

Mechanical processes can be used to separate biomass as well. Patents dating back to 1898 were concerned with mechanically scraping the pith from corn stalks (Wright, 1898). More recently, methods have been developed to scrape the pith from sweet sorghum or sugarcane for sugar production (Cundiff, 1987; Tilby, 1994). These machines deal with product that is wet and harvested with the intention of undergoing the separation process. Whole stalks, or large, discrete billets of stalk are used to provide sufficient substance for the machines to hold onto the stalks. Biomass is generally considered to be a low cost residue, and thus processors may be forced to take what they can get.

Hoskinson et al. (2001) investigated fractionation processes to separate straw leaves from stems. The stems contained less silica and were thus better suited to industrial processes while the leaves, nodes, and sheaths contained more nutrients and were left in the field. A wood chip refiner was tried which used abrasion to grind undesirable components into fine particles while the stems were left in long splinters. In another test, sequentially running wheat straw through a stationary tined-cylinder thresher and a small plot combine yielded primarily stems at the output.

Other studies have been done to separate chopped whole-plant corn silage into grain and stover components. Bilanski et al. (1986) studied the separation of grain from stover after being ensilaged at 50-55% moisture content. The purpose of the separation was to produce a stover fraction for growing cattle, and a grain fraction for high production cattle. They achieved an 89.1% pure grain fraction by combination of sieving and behavior in a vertical air-stream. Coarse sieves removed large stalk particles and a vertical air stream served to remove the leafy fractions. The primary contaminant in the grain was cob pieces which had similar density and size to the corn kernels. No attempts were made to characterize the components of the stover fraction as it was not of interest as cattle feed.

In 1985, Smith and Stroshine separated cobs from corn harvest residues for use in energy or industrial processes. Laboratory tests showed it was possible to separate cob pieces from the stalk pieces using air flow. Prepared samples were relatively easy to separate because terminal velocity in air was 10.3 to 13.8 m/s for the cob pieces, but only 3.5 to 6.2 m/s for the stalk pieces. However, actual material from a straw walker was much more difficult to separate because the suspension velocities of some stalks overlapped with that of cob pieces. Complete separation was not practical, but a significant separation could be achieved at 10 m/s air velocity.

A study of grinding performance by Himmel et al. (1986) would tend to further support the premise that cobs can be separated based upon size after grinding. The cob components were shown to be quite tough, and 70% of the cob pieces were larger than 5 mesh while only 33% of the corn stover fell into the same size range.

Being high in fiber, corn stover may be processed as some other fiber crops. Hemp fiber is processed into clean fiber in the field after a retting operation. A harvester based off of a forage harvester and grain cleaning components was produced by Gratton and Chen (2004). By combining cutting, beating, and scotching operations, the machine achieved 41% to 61% fiber harvest at a purity of 35% to 52%. These processes subject the material to large amounts of shear, which is the intent of the rollermilling process. The fiber is not the only product of interest however, and retting would cause an undesirable loss of cellulose.

Paper companies desire fiber in the form of cellulose and hemicellulose with low lignin content. Corn cobs and stalks are an excellent source although they have a higher mineral content than wood. The internodal region of the plant has the highest cellulose content and tends to have the lowest silica and potassium levels.

The leaves had the least cellulose at 22.2%. Of particular concern is the extremely high level of silica in the leaves with a peak value of 13.6% compared to a peak value of 3.5% in the nodes/internodes. (Hess et al., 2002)

A rollermill reduces particle size of materials passing through two large rolls rotating in different directions at different speeds. Because of the counter-rotating nature, material is pulled into the nip with a specified gap between the two rolls and passed out the bottom. The rolls apply both a crushing action and a shearing action to the material. Depending on the speed difference between the faster roll and the slower roll, called the roll differential, the rollermill may act primarily via shear or crushing action. A higher roll speed differential causes more shear with a corresponding decrease in particle size and an increase in power requirement. A lower differential acts primarily by crushing and yields a coarser particle with lower power requirement. Although the energy demand increases in terms of throughput, the energy demand on a basis of surface area change remains the same. (Fang et al, 1997)

A hammermill crushes material via a crushing action resulting from impact with rotating knife blades. The particle size is regulated by screens surrounding the hammers. Material continues to contact the hammers until the size is reduced sufficiently to pass through the screen.

A plan to separate corn stover requires an understanding of the end users and their requirements. Although it is relatively obvious that the different parts of the corn plant would have different physical and therefore chemical make-ups, attempts to classify plant parts based on physiology experienced difficulty and significant contamination. Therefore, the intent of this study was to process the material in different methods and analyze the outputs to show what the different processing methods are capable of generating.

One difficulty is in maintaining a suitably narrow range of study. Much work remains to be done to allow multiple millions of tons of low density material to be harvested in an economical manner. Harvest, densification, storage, separation, and transportation all have uncertainties. Some overlap between these different segments does occur. Decreased particle size increases the density as the material packs better. Particle size reduction in turn affects separation. Within separation, many factors influence the operation. Harvest method and storage method likely have the largest impact. Thus, any separation study should use the harvest and storage methods that may be used in commercial operations. Final storage method has not been proposed yet, as it undoubtedly will depend on the specifications of the end user, but breakthroughs in the form of pretreatments remain on the horizon. However; even without different pretreatments, valuable data can be gathered at this stage that will be independent of the previous steps, and may be useful in design of future equipment.   Although significant uncertainty exists, this study concentrated on dry storage based on conversations with companies in the bio-fuel field.

Objectives

The primary objective of this study was to develop a method by which desired chemical constituents of corn stover could be concentrated. A secondary objective was preprocessing material in a manner that would add value for commercial application. This preprocessing includes particle size reduction and densification. The specific objectives were:

- Develop laboratory scale equipment capable of grinding dry stover.
- Measure the power requirements to process material through a hammermill at two feed rates and two screen sizes.
- Measure the power requirements to process material through a rollermill at two feed rates and two screen sizes.
- Measure and compare the post-processing size of product from the hammermill and rollermill.

A secondary study involved classifying the cut capabilities of a shear type chopper developed at Iowa State University compared to the standard flail type chopper. Power measurements for both choppers had already been performed, but it was desirable to characterize the particle size distribution for the choppers.

Materials and Methods

Material Collection and Sampling

The stover separation project had three main components. The first was collection of stover material. A midseason corn variety was harvested from a field near Ames, Iowa in November 2006. A John Deere 9750 STS combine was equipped with a 653 row crop head to collect the entire corn plant at a harvest height of roughly 10cm. The combine was further modified by the addition of a blower at the outlet of the chopper to convey the stover to a wagon. The grain is separated in a conventional manner and then the stover is pneumatically conveyed into a wagon. In this manner, dirt contamination is not an issue as it would be with a two pass harvest system. From the wagon, large nylon bulk bags were filled with approximately 40kg of stover and stored indoors to prevent moisture absorption.

Each bulk bag was dumped onto a tarp from a height of 4m to yield a large spread pile of material with minimal segregation effects. Figure 2 displays the dropped material. Individual samples ranging between 1 and 2kg were pulled from the large pile by taking “pie slices” of roughly 10% of the total material. Each slice was placed in a large plastic tub and sequentially numbered.

Figure 2. Stover material collected from combine prior to sub-sampling.

Figure 3. Sub-sampling of stover material based on "Pie slice" method.

A triple replicated experiment was performed consisting of two mills with two grinding settings and two feed-rates each. With a control sample, this yielded 9 treatments per replication. Random numbers were used to select the sample for each treatment from the 9 plastic tubs. The treatments were tested in a randomized design. Prior to each run, the mill was started and allowed to run for a minimum of 1 minute with no load. The sample was run at the desired feed rate, and the ground product collected.

Apparatus

Hammermill

The hammermill consisted of a Troybilt CS499 wood chipper with the gasoline engine replaced by an electric motor (Figure 4). This hammermill utilized a 0.406 m rotor to which 5 sets of three hammers were attached via a pin through the base of each hammer. The rotor was connected to a tapered 3.01 cm shaft supported by two self aligning pillow block bearings. Directly coupled to this shaft was a 1.5 horsepower 3 phase electric motor rated at 3510 RPM. At rated motor speed, the hammermill achieved a tip speed of 74.6 m/s.

Figure 4. Hammermill showing motor drive and feed system attached.

The Hammermill utilized two different screens to create different grinding conditions. The fine grind was achieved using a screen with 1.9 cm round holes in a staggered pattern. The coarse grind was achieved with a slotted screen consisting of two 1.9 cm by 16.8 cm slots and one 1.6 cm by 16.8 cm slot with the longest dimension of the slots oriented in the direction of knife rotation.

Rollermill

The rollermill was manufactured by Harvestore corporation, although model is unknown (Figure 5). It consists of two corrugated rollers 20.3 cm wide by 15.2 cm in diameter. The corrugations had a pitch of 265 corrugations/m and a zero degree spiral. One roll was mounted rigidly in pillow block bearings while the other roll was held by flange bearings attached to a slide mechanism. The sliding roll was held by spring tension at a distance from the fixed roll determined by the operator. It was able to slide in a horizontal plane against the spring pressure. This was a safety element to prevent the rolls from being damaged in case foreign material was encountered. Power was provided by a 2.25 kW 3 phase motor rated at 1750 RPM. The motor drove the fixed roll via a 60 pitch roller chain with a 14 tooth driver and 26 tooth driven sprocket yielding a 1.86:1 gear reduction. The sliding roll was driven by the fixed roll via a 60 pitch roller chain with a 14 tooth driver and 36 tooth driven sprocket yielding a 2.57:1 gear reduction visible in Figure 5. Tip speed of the rolls at rated motor speed was 7.49m/s for the fast roll and 2.91m/s for the slow roll.

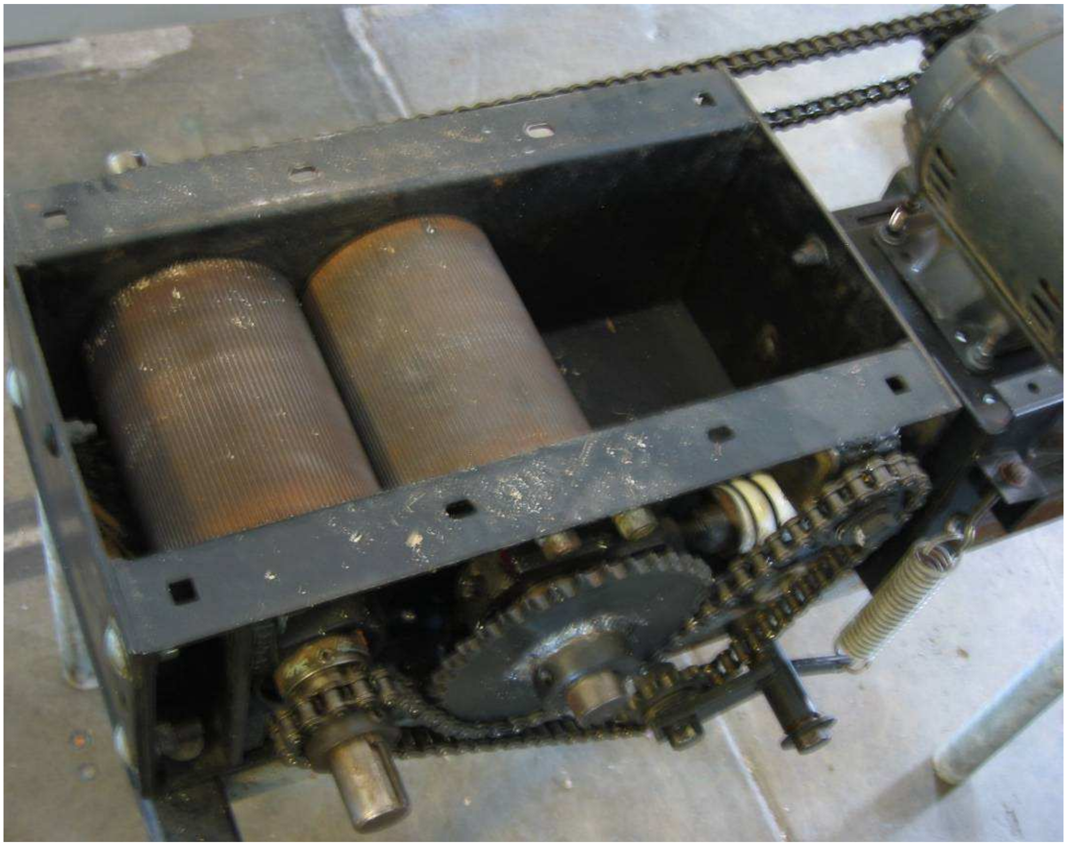


Figure 5. Rollermill, with safety covers removed, showing the fast roll on the left.

The slow roll was held against a stop on each side by spring pressure. Each stop was in turn fixed by a threaded shaft perpendicular to the axis of rotation. The two threaded shafts were linked via a roller chain so both shafts were adjusted at the same rate. Therefore the rollermill gap was adjusted by adjusting the threaded shafts. The rolls could open further against the spring pressure, but the minimum gap was fixed. The rollermill was operated at 0.254 mm for the narrow gap, and 0.889 mm for the wide gap.

Figure 6. Rollermill assembled with feed unit.

Feed Unit

Because of the fibrous nature of the feedstock material, it would not flow in the manner of grains and granular particles. Therefore, a powered feeder was developed consisting of a hopper attached to a chamber containing four rotating rubber paddles. The feeder was equipped with a 0.062 kW gear reduction motor rated at 254 rpm at 60Hz. The paddles were driven via a belt drive with a 5 cm driver and 26.7 cm driven pulley yielding a 5.25:1 gear reduction. Speed variation was achieved by using an Invertek Optidrive E1 variable frequency drive manufactured by Bardac Co. The motor was operated at 50Hz and 75Hz, yielding a rotor speed of 40.3 and 60.5 rpm respectively. The paddles had a swept volume of .0103 m^3/rev and thus the feeder would theoretically provide a volumetric feed rate of 0.415 and 0.623m^3/min. Actual feed rate was considerably less than this, but remained relatively consistent and dependent upon rotation speed. The feed unit was built to be modular and used a tab and slot attachment so the same feeder could be used on either mill. The modular nature can be seen in Figure 6 with the feed unit installed upon the Rollermill.

Sifter

Samples were sifted for particle size comparison using a process based upon ASABE standard S424.1. Alterations were as follows. The shaker used was a G10 Gyrotory Shaker manufactured by New Brunswick Scientific Co. (Figure 7). This shaker provided a pure oscillation motion in the horizontal plane with a frequency of 3.3 Hz (200/cycles/min).

Figure 7. Shaker and screen used to sift material.

The screens called for in the standard were deemed to be unsatisfactory for this application due to the large particle size encountered. Alternate screens were developed with the specifications shown in Table 1 for the chopper evaluation and Table 2 for the grinder evaluation. Screen thickness was kept at least 50% of the screen opening size to prevent long slender particles from sliding through a small height screen such as one made with wire.

Table 1. Screen sizes used for chopper evaluation.

Screen no.	Nominal Size Opening		Hole Diagonal		Screen Thickness		Hole type	Open Area %
	mm	in.	mm	in.	mm	in.		
1	76.2	3	107.696	4.24	50.8	2	Square	85%
2	50.8	2	71.882	2.83	38.1	1.5	Square	79%
3	25.4	1	35.814	1.41	19.05	0.75	Square	64%
4	12.7	0.5	12.7	0.5	6.35	0.25	Circle	48%
5	6.35	0.25	6.35	0.25	6.35	0.25	Circle	20%
Pan	-	-	-	-	-	-	-	-

Table 2. Screen sizes used for grinder testing.

Screen no.	Nominal Size Opening		Hole Diagonal		Screen Thickness		Hole type	Open Area %
	mm	in.	mm	in.	mm	in.		
1	50.8	2	71.882	2.83	38.1	1.5	Square	79%
2	25.4	1	35.814	1.41	19.05	0.75	Square	64%
3	12.7	0.5	12.7	0.5	6.35	0.25	Circle	48%
4	6.35	0.25	6.35	0.25	6.35	0.25	Circle	20%
5	3.175	0.125	3.175	0.125	3.175	0.125	Circle	40%
Pan	-	-	-	-	-	-	-	-

Particle size was further characterized by the use of geometric mean length as defined in ASABE Standard S424.1 and shown in Equation 1. This provided two numbers, geometric mean length (X_{gm}) and standard deviation (S_{gm}), that could be used to describe the output of a grinding process.

Equation 1. Calculation of geometric mean length according to S424.1

$$X_{gm} = \log^{-1} \frac{\sum (M_i \log \overline{X_i})}{\sum M_i}$$

$$S_{gm} = \log^{-1} \left[\frac{\sum M_i (\log \overline{X_i} - \log X_{gm})^2}{\sum M_i} \right]^{1/2}$$

Where

$\mathrm{X_i}$ = diagonal of screen openings of the $\mathrm{i^{th}}$ screen

$\mathrm{X_{(i-1)}}$ = diagonal of screen openings in next larger than the of the $\mathrm{i^{th}}$ screen (just above in a set)

$\mathrm{X_{gm}}$ = geometric mean length

$\mathrm{X_i}$ = geometric mean length of particles on $\mathrm{i^{th}}$ screen $= [\mathrm{X_i \times X_{i-1}}]^{1/2}$

$\mathrm{M_i}$ = mass on $\mathrm{i^{th}}$ screen (actual mass at the conditions of screening
or
percent of total; decimal or percent form)

$\mathrm{S_{gm}}$ = standard deviation

Power Measurement

Energy consumption for the mills was determined by connecting a watt-hour meter in series with each mill. The meter was video-taped during operation to ensure an accurate record of energy consumption. The video tape was analyzed to determine both the power consumed and the time required to grind the material. From the initial 1 minute of no-load operation, two 30 second measurements of power consumption were taken. The average of these two readings was converted into gross power consumption in joules using Equation 2.

Equation 2. Calculation of gross power consumption.

$$\frac{P_g = \left(7.2 \frac{W \cdot hr}{rev}\right) \cdot R \cdot \left(3600 \frac{s}{hr}\right) \cdot \left(1 \frac{J}{W \cdot s}\right)}{30\ s}$$

$$\begin{aligned} &Where: \\ &R\ is\ meter\ revolutions \\ &P_g\ is\ gross\ power\ in\ Watts \end{aligned}$$

Equation 3. Calculation of net grinding energy.

$$E = \left(7.2\frac{W \cdot hr}{rev}\right) \cdot R \cdot \left(3600\frac{s}{hr}\right) \cdot \left(1\frac{J}{W \cdot s}\right) - \left(T \cdot P_g\right)$$

$Where:$

$R\ is\ meter\ revolutions$

$T\ is\ grinding\ time$

$P_g\ is\ gross\ power\ in\ Watts$

$E\ is\ net\ grinding\ energy$

The gross power consumption served as a baseline which was multiplied by the grinding time and subtracted from the operational energy consumption as shown in Equation 3 to yield net grinding energy.

Because of variation in sample sizes fed through the mills, and variation in the mass flow-rate due to the use of a volumetric feeder, it was decided to represent the energy consumption on a unit basis. Therefore, the net grinding energy was divided by the total mass of material from each run to yield the energy consumption in kJ/kg of material as shown in Equation 4.

Equation 4. Energy consumption per unit of throughput.

$$E_u = \frac{E}{M}$$

$Where:$

$E\ is\ net\ grinding\ energy$

$M\ is\ mass\ ground$

$E_u\ is\ unit\ grinding\ energy$

Resulting particle size and variation was measured using a set of fabricated sieve screens. The rollermill was expected to break up the stover into a broader particle range with a differentiation between soft materials and fibrous materials.

After the grinding and sifting steps, a sample of each particle size material was analyzed for moisture, fiber, lignin, protein, energy, and ash content. The values from the three replications were compared.

Statistical Analysis

Statistical analysis was done using Statistical Analysis Systems software (SAS, 2003). The significance of feed rate, gap distance, and their interactions on particle size and partitioning of dry matter constituents was determined using the general linear model (GLM) procedure. Significant main and interaction effects were further investigated using an appropriate least significant difference (LSD). Orthogonal contrast was used to compare gap and feed rate between treatments. Differences among mean values were considered significant at $p \leq 0.05$.

Shear Chopper

The secondary research component involved the characterization of corn stover particle sizes generated by a shear type chopper compared to a flail type. Previous work at Iowa State had focused on development of a novel shear type chopper to replace the flail type chopper in a John Deere 9750 STS Combine. It was known that the shear cutting method required less energy than an impact method. Therefore, a modular slicer design was built which had seven modules of nine sets of three knives around the perimeter with three cutting edges per knife. This gave a total of 189 knives and 567 cutting edges per revolution. The three cutting edges were oriented to allow stalk material to be cut regardless of orientation, a potential limitation with ordinary shear designs. Furthermore, the cutting surfaces were designed to cut all particles into 5.08 cm or smaller pieces. This slicer was mounted in the same housing as the factory flail chopper and fed in the same manner. Whereas the factory chopper was rotated at 2000 rpm, the new slicer was rotated at 750rpm. Power consumption for the two chopper designs was measured and the slicer was found to consume 12kW less power than the flail chopper (Schlesser, 2007).

Results and Discussion

Grinding Results

The cobs did not behave as predicted when processed via the rollermill. Cobs were predicted to pass through the mill mostly intact because of their relative strength and hardness. However, the cobs were consistently shattered into fine pieces. Further review has revealed that cobs are relatively weak when exposed to compression perpendicular to the axis of the cob. Previous work by Yoeger (1957) focused on a cob crusher mechanism that used rollers to fracture cobs into four segments along fracture lines parallel to the cob axis. The cobs were then easier to grind via other methods and required less energy for the overall particle size reduction.

Additionally, the material flow proved to be quite difficult. The long pieces of stalk would lodge in the feed hoppers and the husk would bunch together and cause bridging issues. The stalk material would typically feed properly once it entered the feedwheel. However, the husk would sometimes recycle through the feedwheel instead of dropping into the mill. Agitation of the hopper assisted in flow to the feedwheel, and stalk pieces would usually knock the husk out of the way. However, vigilance was still necessary to catch slow feeding before the material formed a bridge.

Density of the ground material was not measured. However densities directly out of the mills would have been lower than the unprocessed densities of the stover. Both mills had a tendency to fluff up the material that passed through them. The fibrous material particularly bunched together in a fashion similar to cotton fiber. In this manner, the volume of the ground material was greater than that of the unground material. The sole exception was the hammermill operating with a small gap. The small gap hammermill thoroughly disintegrated the material, resulting in less volume occupied than before milling. The downside of the increased density was the existence of significant fine matter which made handling a dusty and unpleasant endeavor.

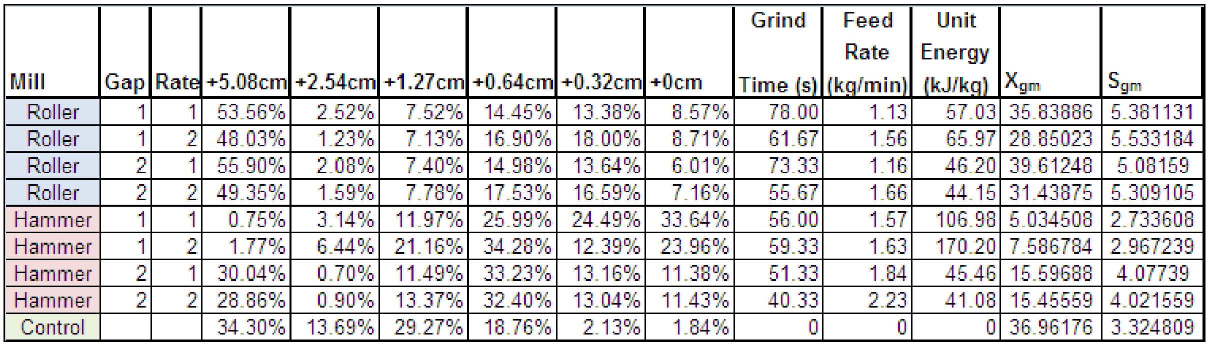
Even though the freshly ground material appeared to be less dense than the unground material, this does not accurately represent the material. Both mills disrupted the structure of the plant material significantly. Anecdotal evidence implied the ground material responded better to pressure than the unground material. Therefore, with equal levels of compaction, the ground material would yield a higher density than the unground material. This would be useful in any situation in which the material is paced into a container for storage or transport.

The ground material was fed directly from the mills into the sifter for size characterization after grinding. The shaker operated in a 2.54 cm circle instead of a 10.16 cm circle as specified by the standard. It was felt that this was actually better for the separation as the short swing would make long cylinders less likely to slide through the screens. Additionally, the standard specifies a shaker design that oscillates on one end and reciprocates on the other end. The shaker used for this experiment oscillated as the sole form of movement, so the entire sample was subjected to the same motion.

The output of the rollermill tended to be quite recognizable. The husk and rind of the stalk remained intact, although the stalk was split open and usually stripped of any pith. As a result, the husk and rind remained over the 5.08 cm screen. The cobs were reduced to fine particles which were found on the 0.32 cm screen and in the pan. Pith was generally found in flakes above the 0.64 cm and 0.32 cm screens. The 2.54 cm and 1.27 cm screens contained primarily slivers of rind and pieces of leaf material. The leaf material was generally quite friable, and was found in all particles from selected screen sizes.

The hammermill tended to disintegrate the material more than the rollermill. Fibrous components such as the husk tended to separate into strings of material that bunched together like cotton fibers and were held over the 5.08 cm and 2.54 cm screens. The pith was shattered into pieces of random size that were found throughout the different screens. The cob as well was shattered into random sized pieces throughout the size samples. All screens contained pieces of nearly every physical component of the plant. This was consistent with the theory that particles would follow a particle size distribution rather than being fractionated by the physical properties.

Table 3. Particle size, expressed in fractions and geometric mean, and energy consumption.



Mill	Gap	Rate	+5.08cm	+2.54cm	+1.27cm	+0.64cm	+0.32cm	+0cm	Grind Time (s)	Feed Rate (kg/min)	Unit Energy (kJ/kg)	X_{gm}	S_{gm}
Roller	1	1	53.56%	2.52%	7.52%	14.45%	13.38%	8.57%	78.00	1.13	57.03	35.83886	5.381131
Roller	1	2	48.03%	1.23%	7.13%	16.90%	18.00%	8.71%	61.67	1.56	65.97	28.85023	5.533184
Roller	2	1	55.90%	2.08%	7.40%	14.98%	13.64%	6.01%	73.33	1.16	46.20	39.61248	5.08159
Roller	2	2	49.35%	1.59%	7.78%	17.53%	16.59%	7.16%	55.67	1.66	44.15	31.43875	5.309105
Hammer	1	1	0.75%	3.14%	11.97%	25.99%	24.49%	33.64%	56.00	1.57	106.98	5.034508	2.733608
Hammer	1	2	1.77%	6.44%	21.16%	34.28%	12.39%	23.96%	59.33	1.63	170.20	7.586784	2.967239
Hammer	2	1	30.04%	0.70%	11.49%	33.23%	13.16%	11.38%	51.33	1.84	45.46	15.59688	4.07739
Hammer	2	2	28.86%	0.90%	13.37%	32.40%	13.04%	11.43%	40.33	2.23	41.08	15.45559	4.021559
Control			34.30%	13.69%	29.27%	18.76%	2.13%	1.84%	0	0	0	36.96176	3.324809

The percentage by weight over each screen is shown in Table 3. It is relatively easy to see the bias towards large particles with the rollermill. Also the rollermill generated less fines than the hammermill. Table 3 also shows the geometric mean using the procedure illustrated in S424.1 and the energy consumed in grinding in terms of kJ/kg. The geometric mean length is an effective method of describing the particle size in a single number. The results accurately convey the trends in particle size. The particle size reduction caused by the rollermill tended to be more dependent upon the feed-rate than the gap. The possible explanation is that the rolls expanded when fully loaded so the rolls were grinding at a gap other than that set statically. The rolls did make a significant noise and jump slightly with cob passage, so it is possible the gap varied in operation from the static setting. An increased feed-rate would increase the pressure on the rolls and therefore increase the crushing action on the material. This observation would seem to be supported by the increase in splintered material seen over the 0.64 cm and 0.32 cm screens.

The hammermill was much more dependent upon gap setting for final particle size distribution. This is intuitive as the screen will only let particles below the screen size pass, and therefore reducing the screen size will reduce the particle size range. Increased feed-rate appeared to increase the particle size range through a fixed screen. This is possibly due to a shielding effect where the additional mass in the hammermill shields particles from further reduction. It serves to reason that with a fixed RPM, an increase in material flow will subject each individual piece of stover to fewer hammer hits.

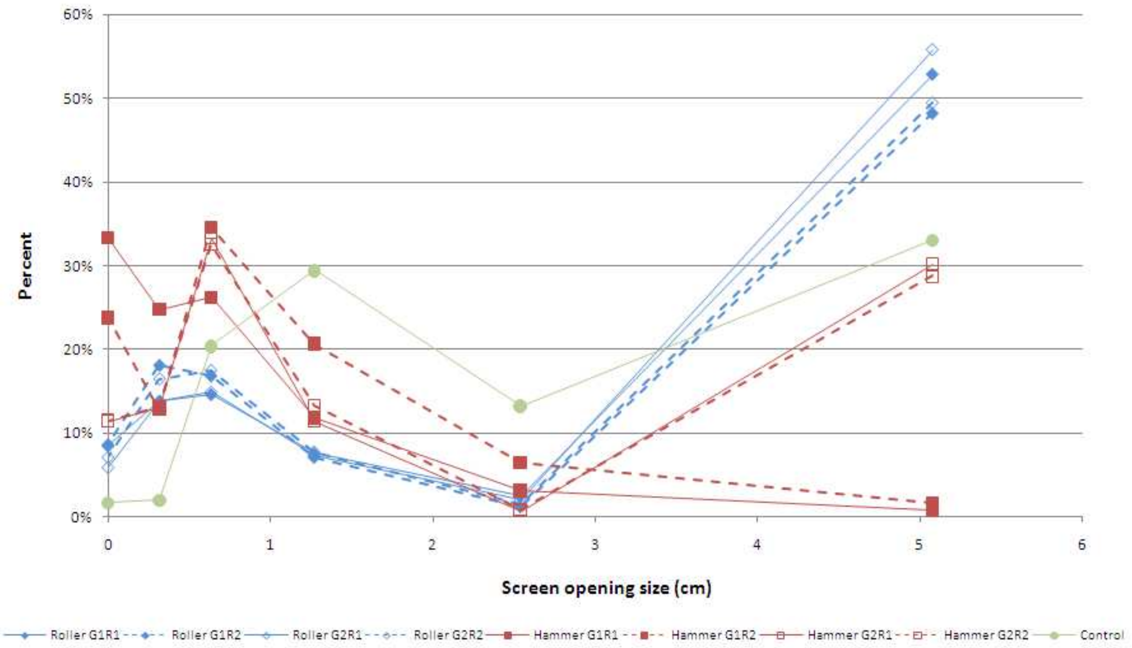


Figure 8. Particle size distribution.

Looking at the graph of percent of material over each screen size in Figure 8, it is easy to see the additional fines created by the hammermill and the bimodal distribution of the rollermill. The rollermill actually generated more large particles than the starting material. Most of the increase appeared to be from flattening stalks that otherwise would have slipped through the largest screen. The material over the 2.54 cm and 1.27 cm screens in the unground samples contained a large amount of cobs which both mills fractured. Therefore the second peak in the particle size was shifted down compared to the standard. The lack of material over the second screen, the 2.54 cm screen, was frustrating to explain. It appeared that long stalks that tipped up to slide through the largest screen continued to fall vertically through the next screen. A deflector place could be useful to prevent long, thin particles from tipping up on end and passing through sequential screens.

Comparing the single number index of particle size distribution, the geometric mean length, to energy input yields some interesting results. The rollermill appears relatively independent of energy consumption when comparing different grinding gaps. In other words, the rollermill consumes a stable amount of energy per kg ground, and yields a range of particle sizes at the different energy consumption. This may be due to the manner in which the geometric mean length is calculated. When looking at the graph showing all particle data, there is little difference between the percentages. Looking at the energy consumption alone, it is easy to see the tighter roll gap requires more energy. The hammermill has a distinct direct relationship between increased energy consumption and reduced particle size. There is visible scatter on the data points for the fine hammermill screen. It was observed that the mill was at the verge of overloading at the high feed-rate, and this may have increased the variation in energy consumption.

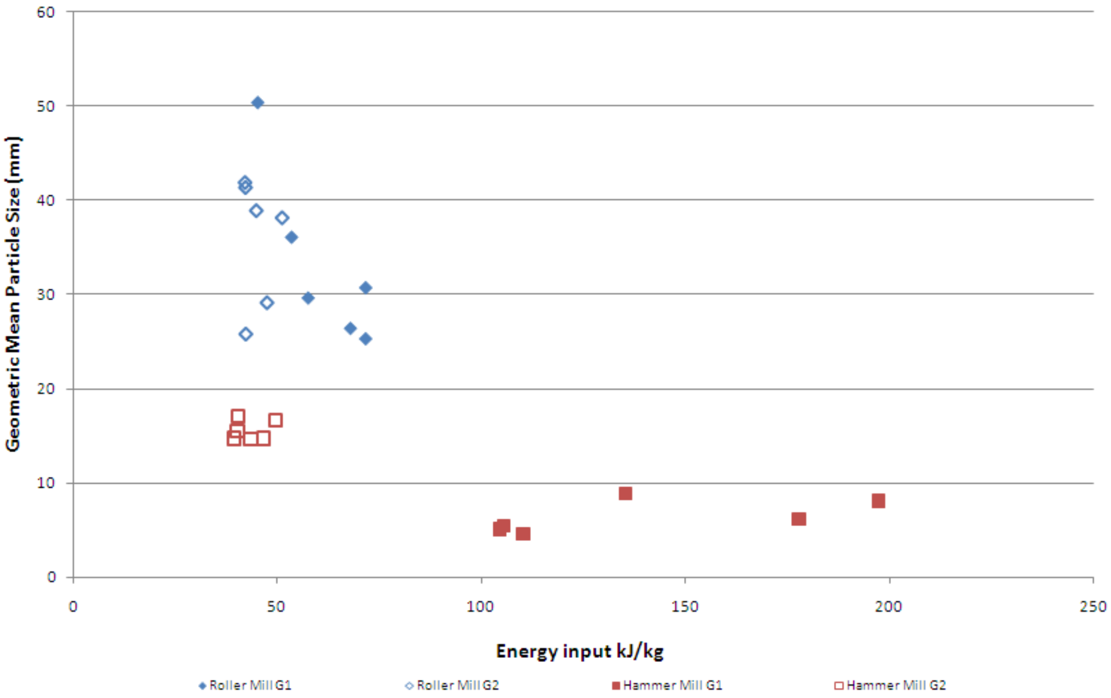


Figure 9. Particle size index compared to mill energy consumption.

Looking at the statistical analysis for the rollermill, the gap was significant in terms of the effect on energy consumption (P=0.0064), but the feed-rate was not significant. For the hammermill, the feed-rate and gap were both significant (P=0.0143 and P<0.0001), as were interactions between the two variables(P=0.0078).

Looking at the chemical analysis of the different stover streams, it is clear that the different mills do yield streams of different chemical composition. Beginning with the lignin content shown in Figure 10, it is visible that the rollermill concentrated the lignin content in the larger particle fractions compared to the control and the hammermill. It is presumed this is due to the low ash pith being scraped from the rind, as well as the crushing and size reduction of cob material. The hammermill tended to smooth out the distribution of lignin, reduce the percentage over the 0.64 cm screen, and increase the percentage in the pan.

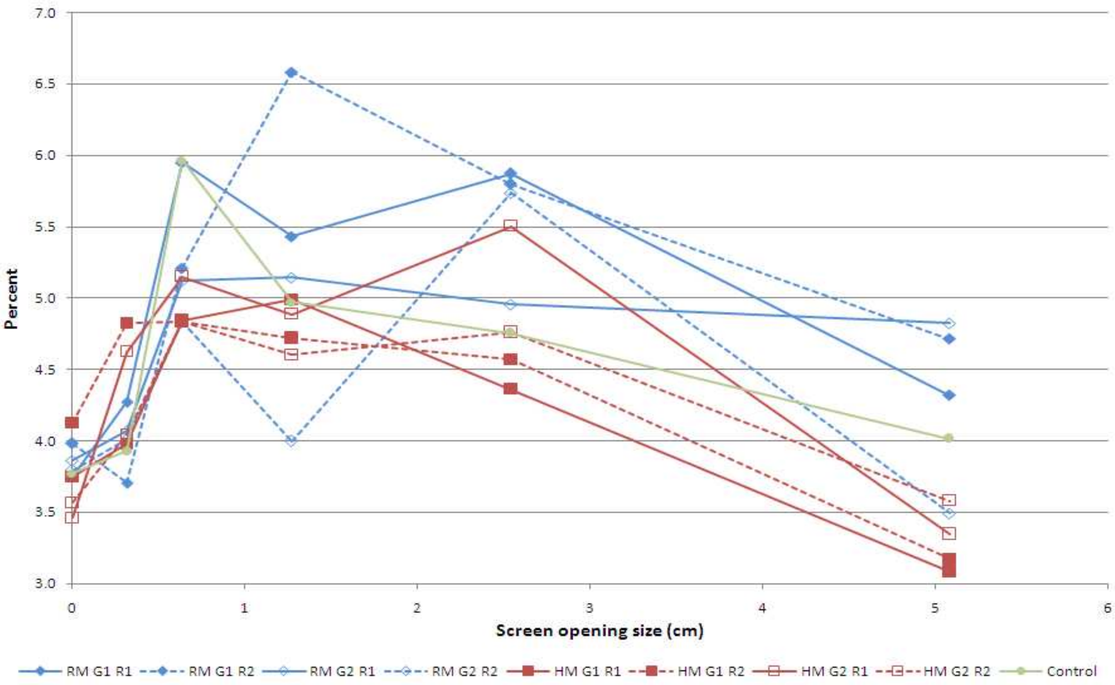


Figure 10. Lignin content of particles from selected screen sizes.

The ash content in Figure 11 also showed that differences in milling were occurring. The rollermill tended to have higher ash with the larger particles. This correlated with the lignin data as minerals and lignin are used by the corn plant to build structure. Since dust and dirt contain high amounts of ash, it was expected that the finest fraction from both mills would be high in ash. Both mills showed an uptick in ash content in the pan, but the percentage was still lower than the control. This is possibly due to dilution from finer particles of other ground stover.

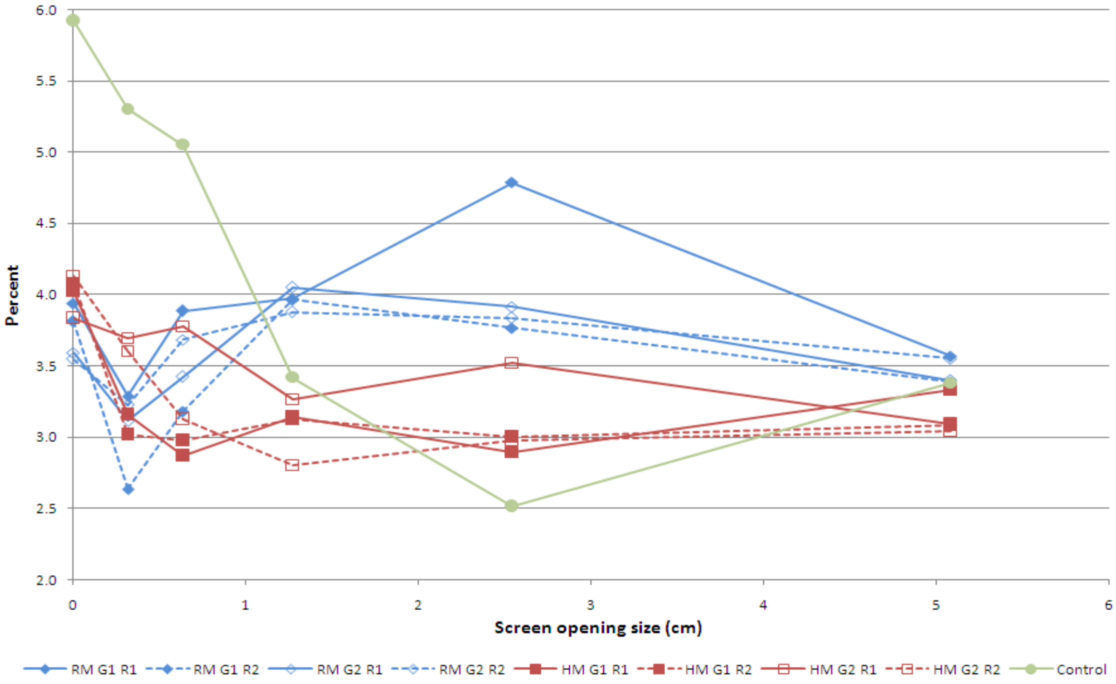


Figure 11. Ash content of particles from selected screen sizes

The hemicelluloses fraction was drastically shifted to the finer fractions by both mills as seen in Figure 12. This is likely due to the ground cobs. The rollermill tended to have a greater reduction in hemicellulose for all screens above 1.27 cm, and a greater concentration effect over the 0.32 cm screen. This would support the theory that cobs were a source of hemicellulose, as those are the locations in which the most cob pieces were seen before grinding and after grinding. The hemicellulose was the constituent which experienced the greatest shift. The average difference in hemicellulose content over the 2.54 cm screen, between the control and the rollermill, was greater than 8%. This represents a 22% shift when comparing the rollermill at 29% to the control at nearly 37%.

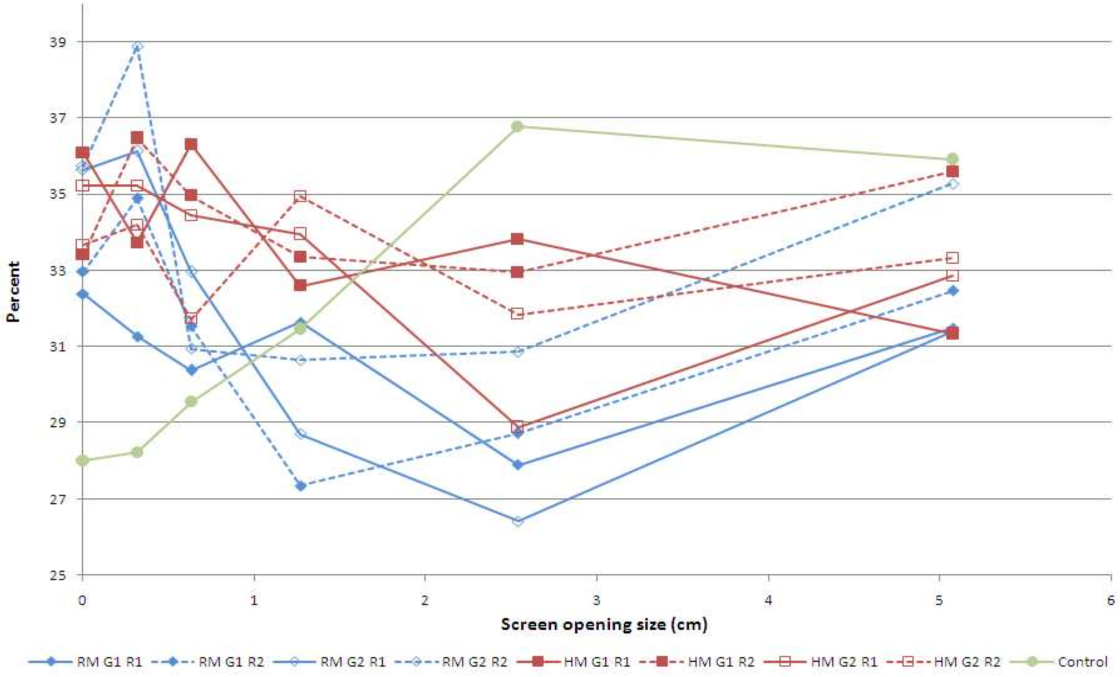


Figure 12. Hemicellulose content of particles from selected screen sizes

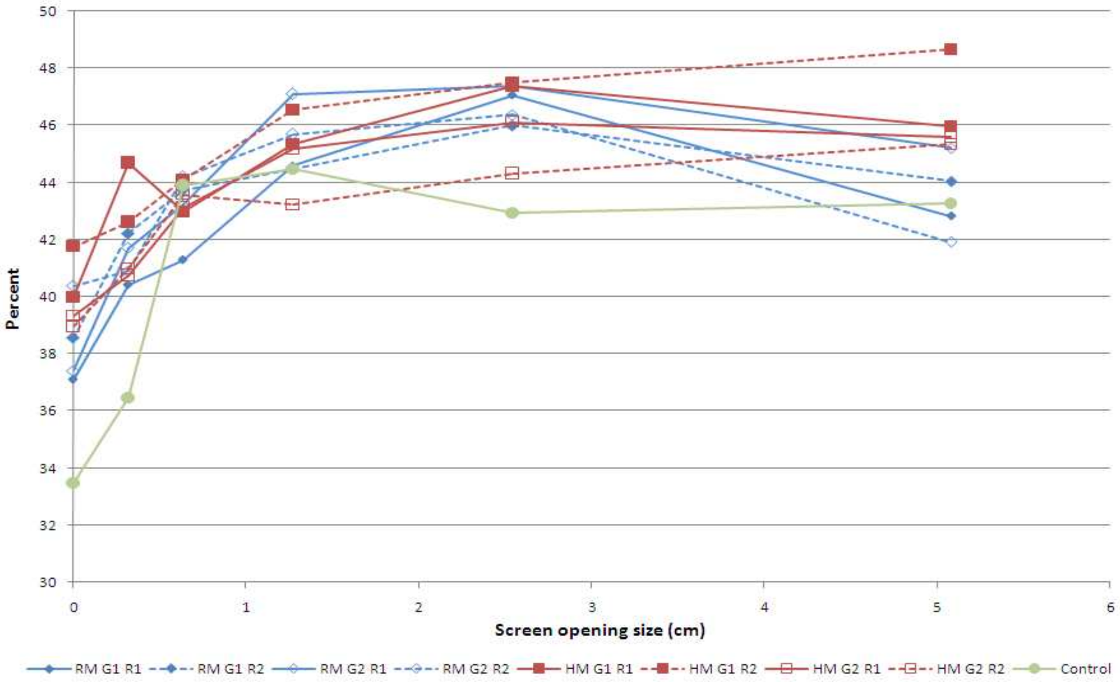


Figure 13. Cellulose content of particles from selected screen sizes

Lastly, the cellulose content in Figure 13 was slightly shifted from the control by both the rollermill and hammermill. The finer particles gained cellulose compared to the control. This is likely due to the influence of ground cobs.

Flail vs. Slicer results.

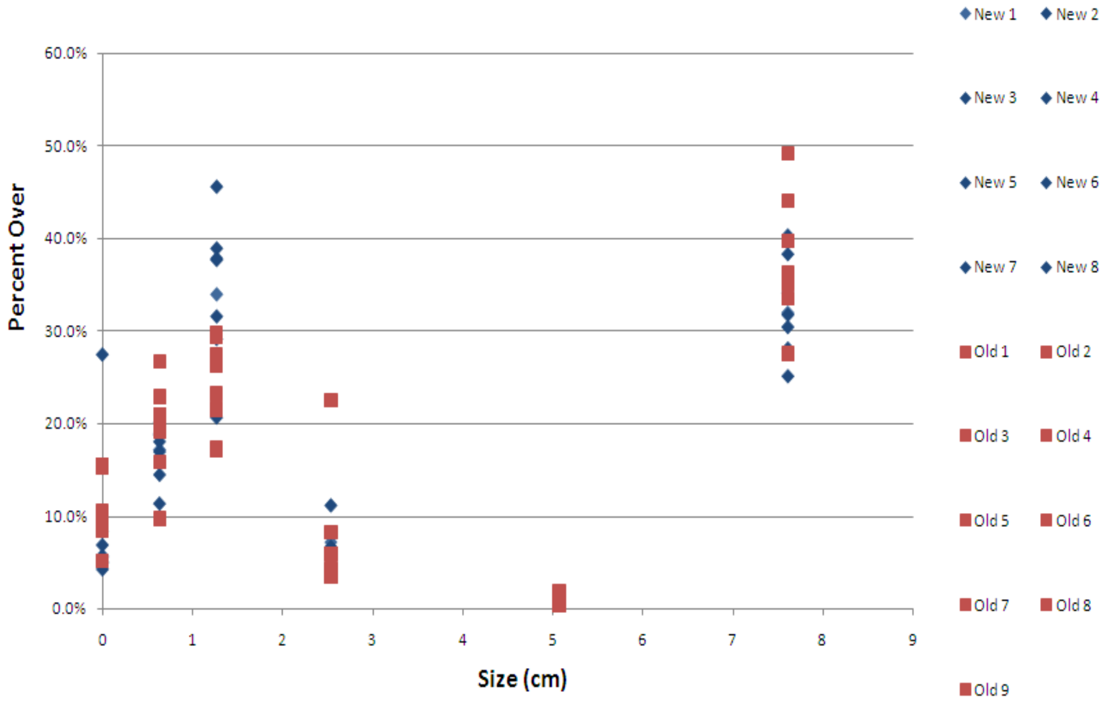


Figure 14. Particle size distribution of new vs. old chopper with a conventional head.

Evaluating the slicer, designed to shear all particles to less than 5.08 cm, the design goal was not particularly achieved. The distribution of particle size in Figure 14 show the particle distribution to be relatively equal. The slicer has a slightly higher percentage on the 1.27 cm screen, and slightly less over the 7.62 cm screen. With the row crop head feeding material to the combine, this trend is even less pronounced as seen in Figure 15. These results do agree with visual observations. The prototype shear chopper was still unable to cope with extremely light and fibrous materials such as husks. The husks were able to pass through the slicer intact and made up the primary proportion of material over the 7.62 cm screen. Visual observations in Figure B1.c suggest the particles other than husk are being sheared in 5.08 cm or less segments.

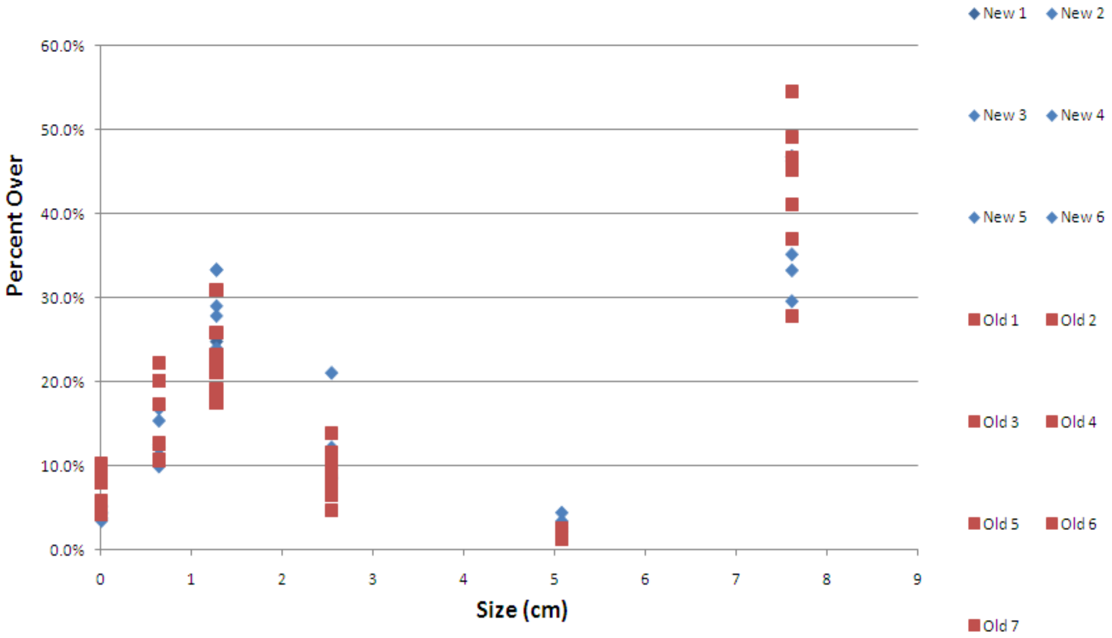


Figure 15. Particle size distribution of new vs. old chopper with a row head.

Statistical analysis of the particle size distribution supports the observation of very little difference between the old and new chopper, with a few exceptions. The calculated P values are shown in Table 4. In nearly all cases, there is no significant difference between the particle size distribution for the shear and flail choppers. The exception is the material over the 5.08cm screen, in which case the head had an effect, and the material over the 1.27cm screen, in which case the chopper had an effect. The effects due to the head may have been due to long stringy material being brought in with the row head. Differences above the 1.27cm screen is an indication of the shear chopper's tendency to cut instead of shred and to produce fewer fines.

Table 4. Calculated P values for material over different screen sizes after processing with the slicer or flail chopper.

	Effect of Head	Effect of Chopper
Screen Size (cm)	P value	P value
7.62	0.0623	0.0737
5.08	<.0001	0.0453
2.54	0.083	0.8868
1.27	0.2477	0.0003
0.635	0.0767	0.0674
Pan	0.0795	0.1476

Conclusion and recommendations

Conclusion

The rollermill was capable of creating a 1% shift in lignin content, a 2% shift in ash content, an 8% shift in Hemicellulose content, and a 4% shift in cellulose content. The hammermill took significantly more power to reduce to the finest size, and generated a large amount of dust. The rollermill was not able to reduce stover to particles as fine as the hammermill, but created less dust.

Based on observed data, the largest particles sizes would be best to burn, or spread on the field for erosion control. The finer particles have reasonable levels of cellulose and hemicellulose and could be used for fermentation. Additionally, not as much particle reduction would be necessary to process the fine fractions for industrial uses.

The first generation prototype shear type slicer yielded nearly identical particle sizes to the flail type chopper with less energy requirement.

Recommendations for further improvement

Possible improvements include testing behaviors at higher moisture levels. The leaves were friable, and tended to dilute all samples. It is possible that, if the samples had more moisture, the leaves would be tougher and stay more intact.

Also, the rollermill could be tested with different roll corrugations and differentials. A less aggressive setting may be able to still scrape the stalks and yet prevent cutting the leaves and stalks into shards.

The different particles from selected screen sizes could be tested for calorie content to see if there is an energy distribution.

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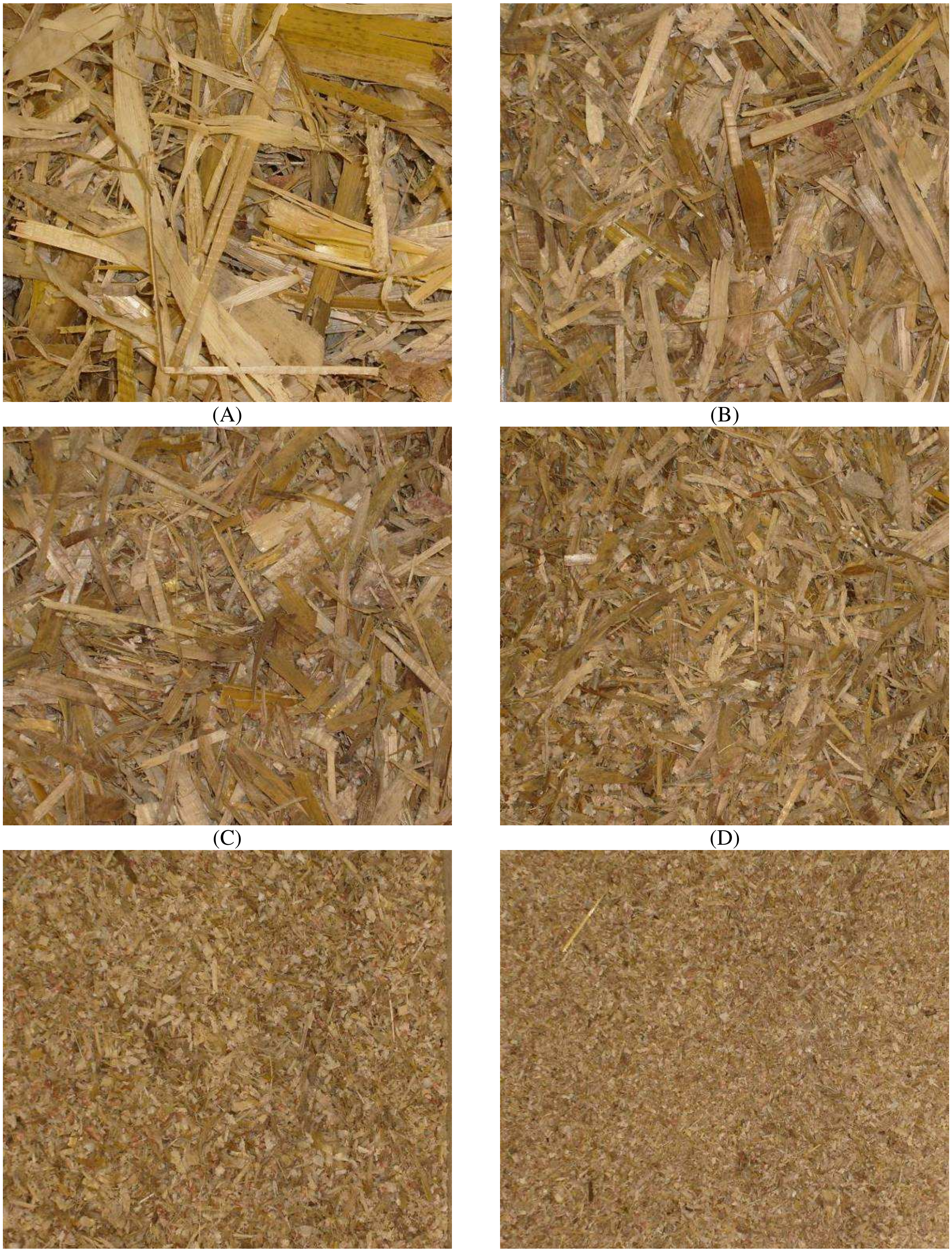
Appendix A

(A) (B)

(C) (D)

(E) (F)

Figure A1. Photographs of raw stover material prior to particle reduction. Material collected over 5.08 cm screen (A), 2.54 cm screen (B), 1.27 cm screen (C), 0.635 cm screen (D), 0.318 cm screen (E) and above pan (F), are shown.



(A) (B)

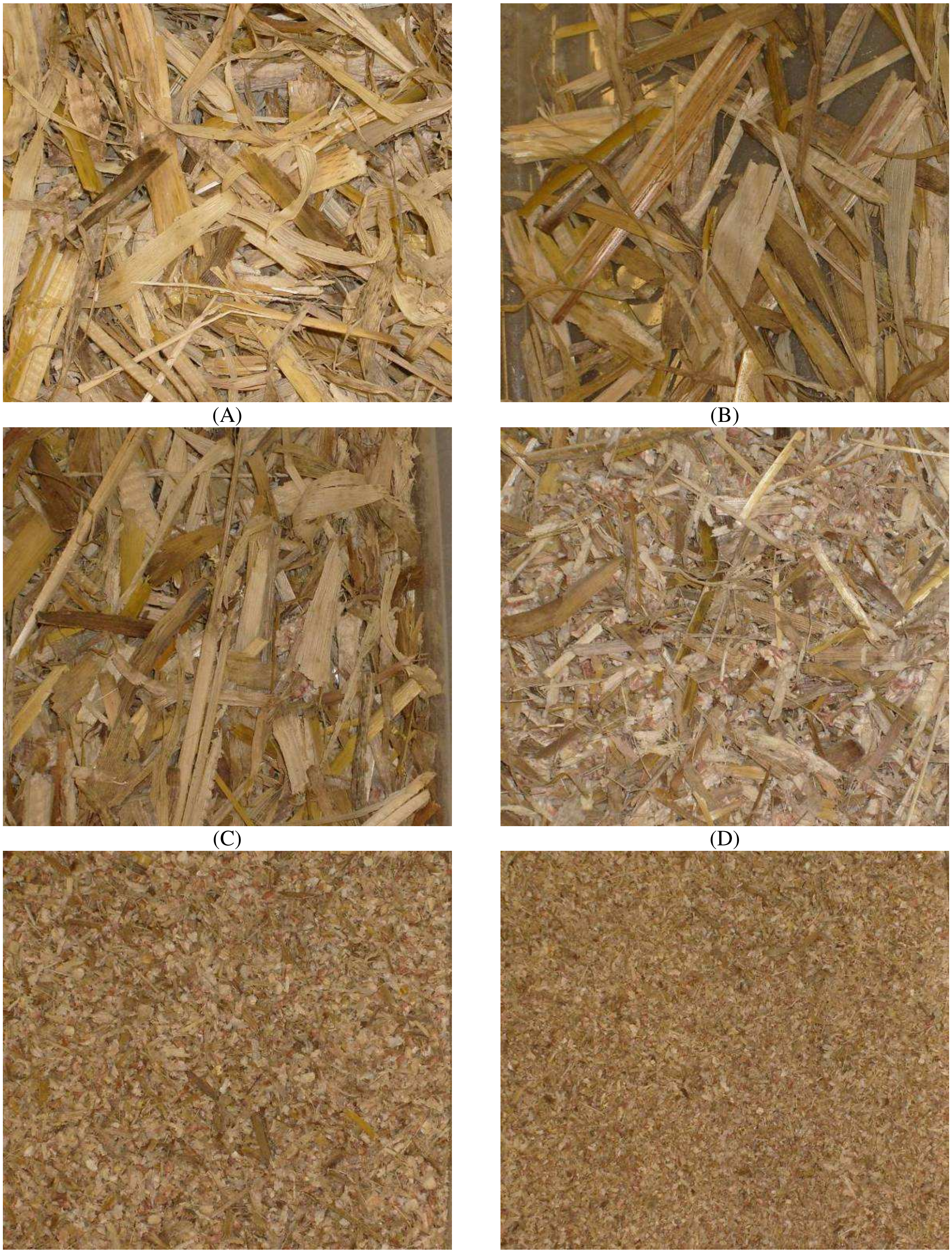
(C) (D)

(E) (F)

Figure A2. Photographs of stover material after particle reduction with a rollermill at a nominal feedrate of 84 kg/hr and roller gap setting of 0.0254 cm. Material collected over 5.08 cm screen (A), 2.54 cm screen (B), 1.27 cm screen (C), 0.635 cm screen (D), 0.318 cm screen (E) and above pan (F), are shown.

(A) (B) (C) (D) (E) (F)

Figure A3. Photographs of stover material after particle reduction with a rollermill at a nominal feedrate of 126 kg/hr and roller gap setting of 0.0254 cm. Material collected over 5.08 cm screen (A), 2.54 cm screen (B), 1.27 cm screen (C), 0.635 cm screen (D), 0.318 cm screen (E) and above pan (F), are shown.



(A) (B)

(C) (D)

(E) (F)

Figure A4. Photographs of stover material after particle reduction with a rollermill at a nominal feedrate of 84 kg/hr and roller gap setting of 0.0889 cm. Material collected over 5.08 cm screen (A), 2.54 cm screen (B), 1.27 cm screen (C), 0.635 cm screen (D), 0.318 cm screen (E) and above pan (F), are shown.

(A) (B)

(C) (D)

(E) (F)

Figure A5. Photographs of stover material after particle reduction with a rollermill at a nominal feedrate of 126 kg/hr and roller gap setting of 0.0889 cm. Material collected over 5.08 cm screen (A), 2.54 cm screen (B), 1.27 cm screen (C), 0.635 cm screen (D), 0.318 cm screen (E) and above pan (F), are shown.

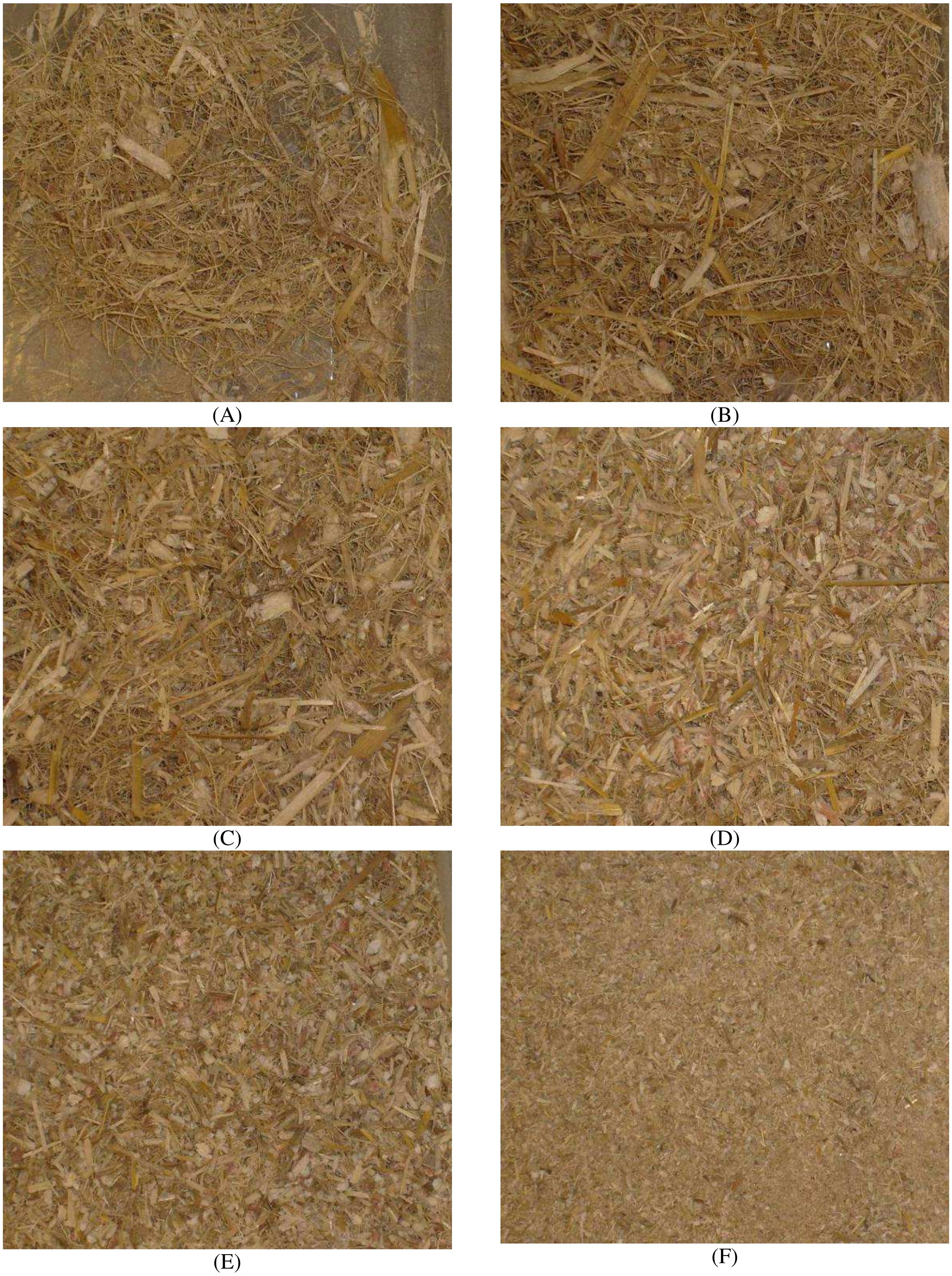
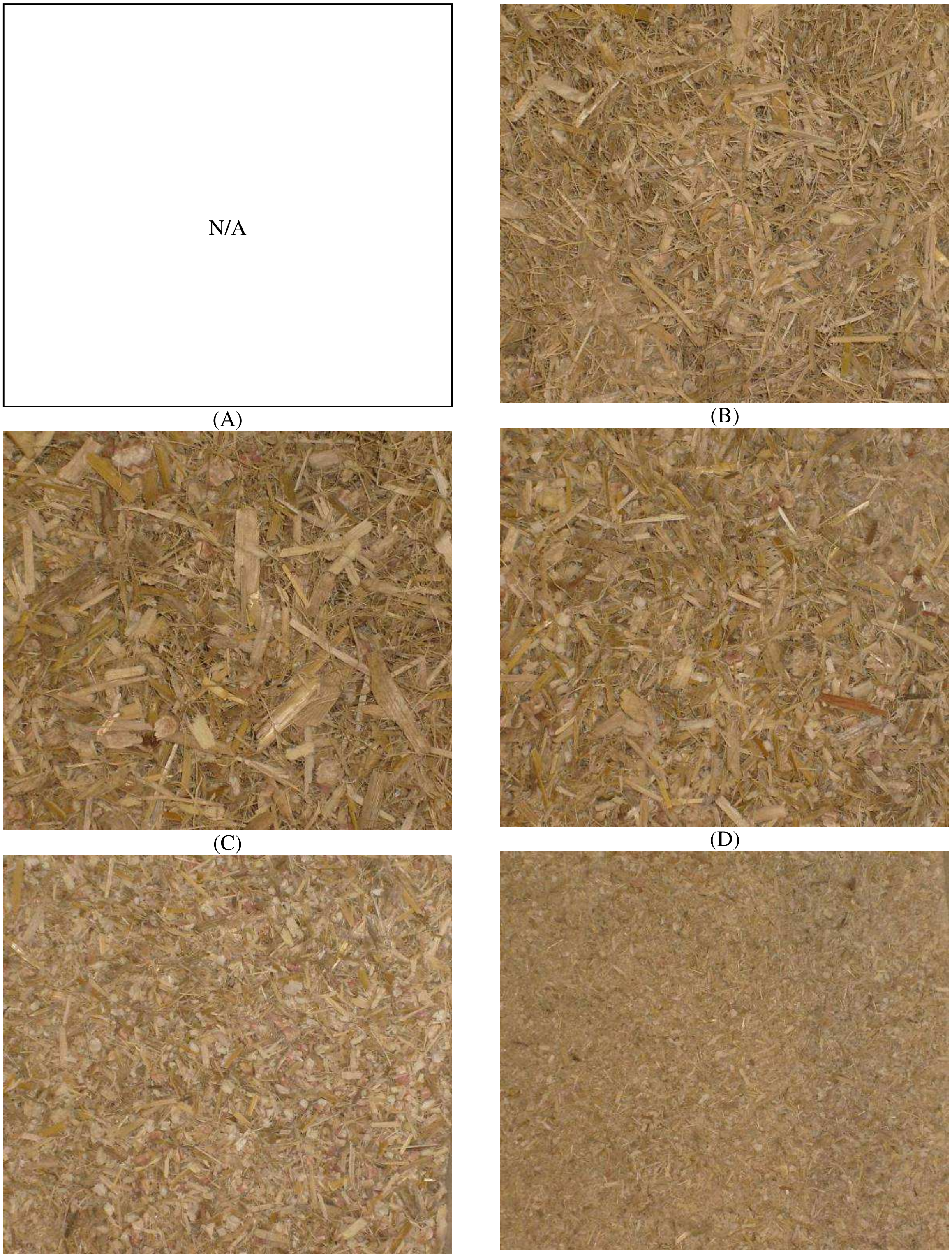
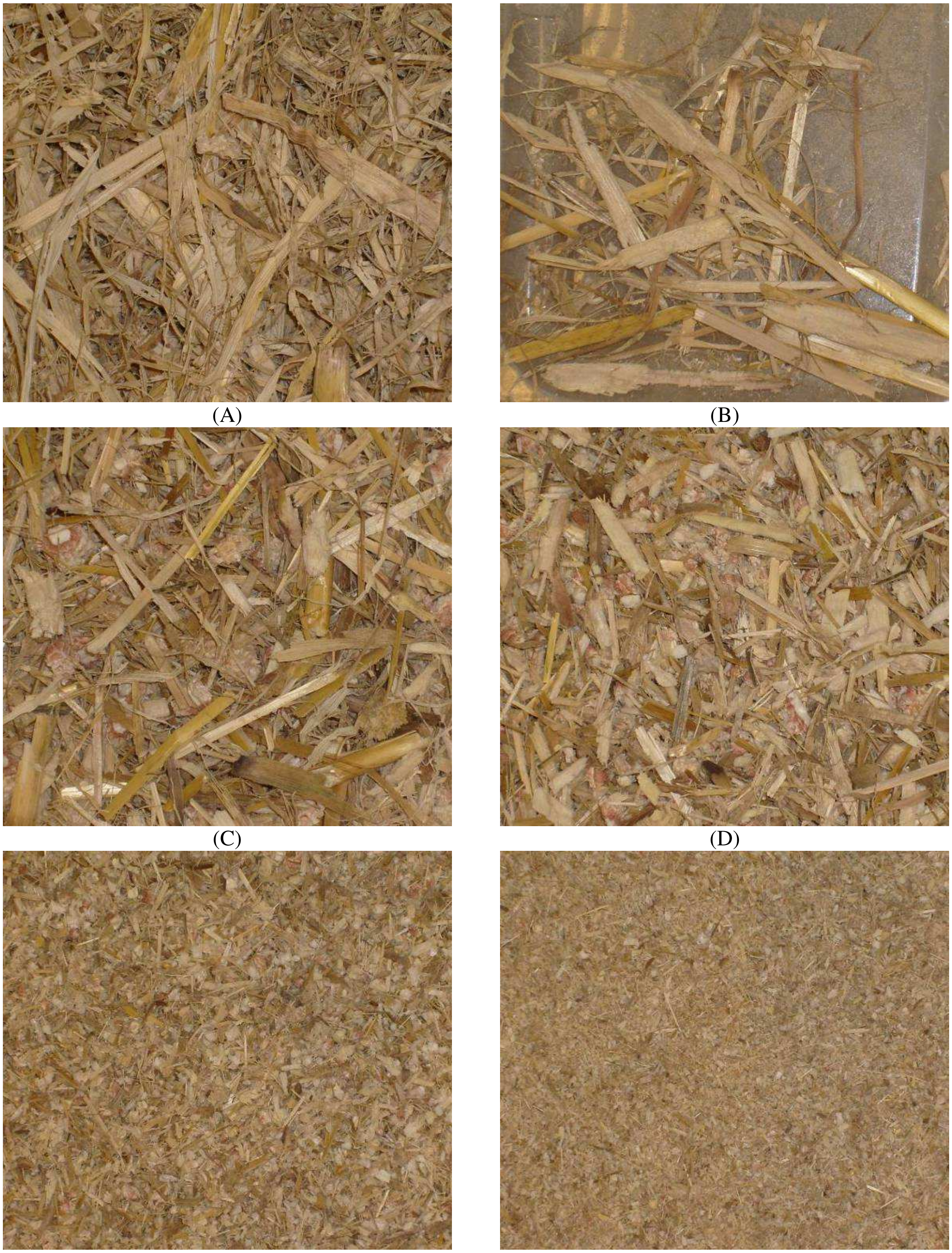

(A) (B) (C) (D) (E) (F)

Figure A6. Photographs of stover material after particle reduction with a hammermill at a nominal feedrate of 96 kg/hr and screen size of 1.9 cm. Material collected over 5.08 cm screen (A), 2.54 cm screen (B), 1.27 cm screen (C), 0.635 cm screen (D), 0.318 cm screen (E) and above pan (F), are shown.



(A) (B) (C) (D) (E) (F)

Figure A7. Photographs of stover material after particle reduction with a hammermill at a nominal feedrate of 144 kg/hr and screen size of 1.9cm. Material collected over 5.08 cm screen (A), 2.54 cm screen (B), 1.27 cm screen (C), 0.635 cm screen (D), 0.318 cm screen (E) and above pan (F), are shown.

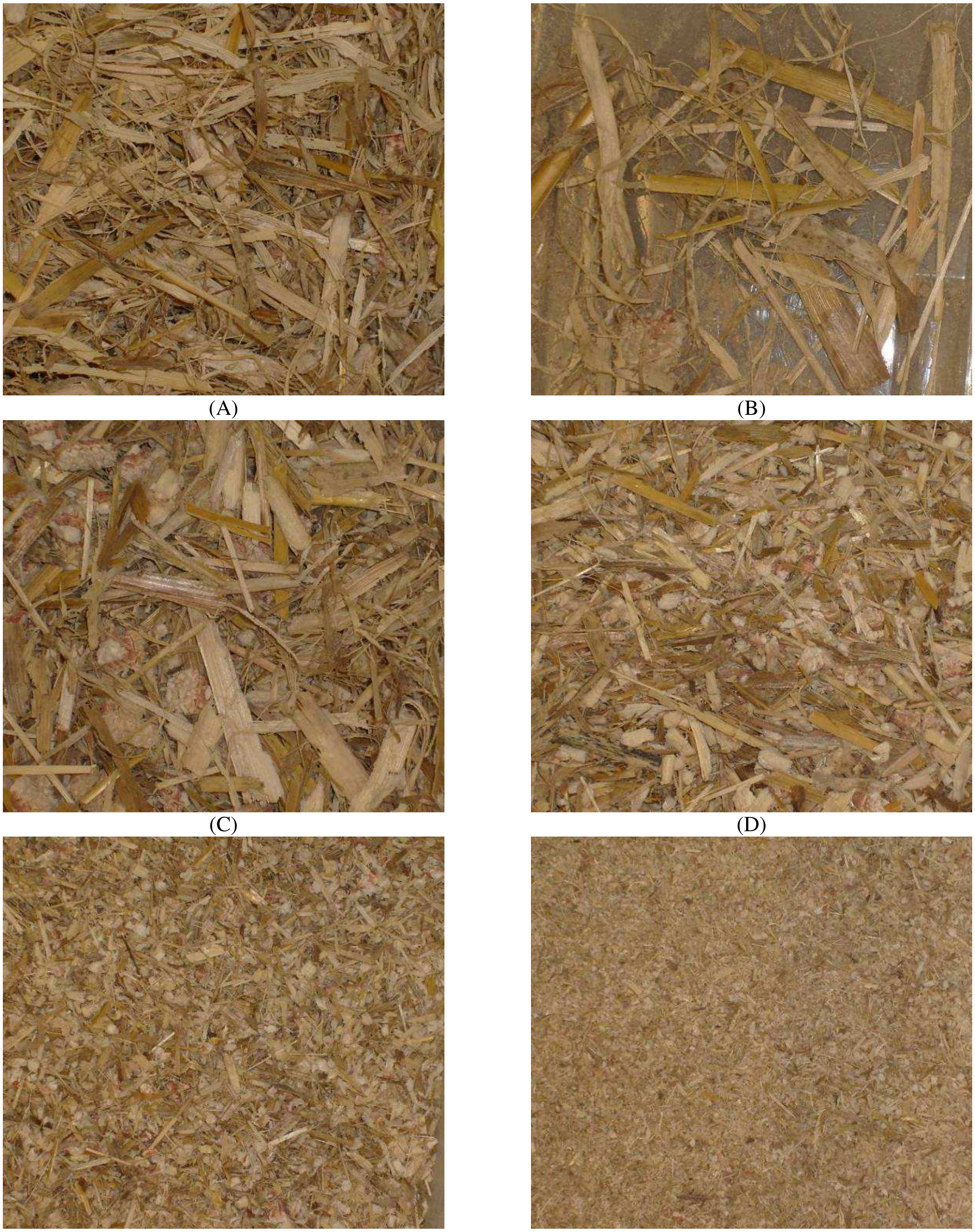


(A) (B)

(C) (D)

(E) (F)

Figure A8. Photographs of stover material after particle reduction with a hammermill at a nominal feedrate of 96 kg/hr and screen size of 16.8 cm. Material collected over 5.08 cm screen (A), 2.54 cm screen (B), 1.27 cm screen (C), 0.635 cm screen (D), 0.318 cm screen (E) and above pan (F), are shown.



(A) (B) (C) (D) (E) (F)

Figure A9. Photographs of stover material after particle reduction with a hammermill at a nominal feedrate of 144 kg/hr and screen size of 16.8 cm. Material collected over 5.08 cm screen (A), 2.54 cm screen (B), 1.27 cm screen (C), 0.635 cm screen (D), 0.318 cm screen (E) and above pan (F), are shown.

Appendix B

(A) (B)

(C) (D)

(E) (F)

Figure B1. Photographs of raw stover material collected from rear of combine with conventional corn head and prototype shear type chopper. Material collected over 7.62 cm screen (A), 5.08 cm screen (B), 2.54 cm screen (C), 1.27 cm screen (D), 0.635 cm screen (E) and above pan (F), are shown.

(A) (B) (C) (D) (E) (F)

Figure B2. Photographs of raw stover material collected from rear of combine with row crop head and prototype shear type chopper. Material collected over 7.62 cm screen (A), 5.08 cm screen (B), 2.54 cm screen (C), 1.27 cm screen (D), 0.635 cm screen (E) and above pan (F), are shown.

(A) (B)

(C) (D)

(E) (F)

Figure B3. Photographs of raw stover material collected from rear of combine with conventional corn head and standard flail type chopper. Material collected over 7.62 cm screen (A), 5.08 cm screen (B), 2.54 cm screen (C), 1.27 cm screen (D), 0.635 cm screen (E) and above pan (F), are shown.

(A) (B)

(C) (D)

(E) (F)

Figure B4. Photographs of raw stover material collected from rear of combine with row crop head and standard flail type chopper. Material collected over 7.62 cm screen (A), 5.08 cm screen (B), 2.54 cm screen (C), 1.27 cm screen (D), 0.635 cm screen (E) and above pan (F), are shown.

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