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Size Reduction of Wet and Dry Biomass by Linear Knife Grid Device

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Abstract. *Linear action of forcing biomass materials through a grid of interlocking knives is an alternative method of size reduction, contrast to rotary action involved in existing size reduction machines. A laboratory-scale linear action knife grid device prototype developed earlier was used to determine the size reduction characteristics of selected biomass, namely, corn stalks and switchgrass at several material and operating conditions. This study was aimed at determining and comparing the ultimate cutting stresses and cutting energy variation between corn stalks and switchgrass, moisture conditions (high- and low-moisture), knife grid spacing (25.4, 50.8, and 101.6 mm), and packed bed depth (50.8, 101.6, and 152.4 mm). The device is composed of ram – attached to crosshead of universal testing machine (UTM), feed block – holds feed, knife grid – arranged at variable grid spacing, knife holder block – holds knife grid, and product block – collects product, and the whole assembly is tested in UTM fitted with 222.41 kN (5000 lb) load cell. New surface area generated during size reduction was evaluated based on circle packing theory. Ultimate cutting stresses were evaluated as the ratio of peak load to the cutting plane area (MPa) represented by the knife grid. Cutting energies were evaluated from the area under load-displacement curves and expressed in moisture free basis mass-based energy (MJ/dry Mg) and new surface area-based energy (kJ/m^2). Overall results indicated that ultimate cutting stress and cutting energy of corn stalks were significantly ($P<0.05$) greater (2.2 times) than that of switchgrass. High-moisture material required significantly greater stress and energy (1.3 times) than low-moisture material. Grid spacing produced significant difference in cutting energy but not with ultimate cutting stress. Energy values required in size reduction using linear knife grid device was much smaller than that reported for similar biomass using other methods of size reduction. Therefore, a pre-processing machine, based on linear knife grid principle, with 50 to 100 mm and greater grid spacing would be an efficient first stage size reduction for biomass materials.*

Keywords. Biomass, Cutting, Energy, Knife, Press cutting, Size reduction, Stress

Introduction

Invariably all biomass bioprocessing either for products or for energy should go through a simple but essential mechanical operation of size reduction. Sustainable renewable energy systems from biomass need proper selection and evaluation of candidate biomass materials and processing stages (Kumar and Sokhansanj, 2007). Corn stover, a crop based field residue, holds great potential of supplying over 200 Gg (Sokhansanj et al., 2002). Switchgrass, a perennial grass, was selected as a model herbaceous energy crop due to high productivity; low demand on land fertility, water, and nutrients; and positive environmental benefits (McLaughlin, 1993). The value of switchgrass for bioenergy was developed over two decades of intensive agronomic research (McLaughlin and Kszos, 2005).To widen the supply base further, some crops though established for forage are now being considered for energy (Sanderson et al., 1996). A few review papers on forage chopping (O'Dogherty, 1982), biomass size reduction technology (Yu et al., 2003), biomass comminuting and separation (Miu et al., 2006) are available.

Common biomass size reduction devices or grinders are hammer mill, chopper, chipper, shredder, and disc mill. Some of these grinders were essentially developed for dry and friable materials, such as grains, and being utilized for fibrous of high- and low-moisture biomass. Research work on energy requirement of cutting operation of fibrous materials is limited (Brennan, et al. 1990). Neither a cutting theory nor a mathematical model for cutting fibrous materials has been reported (Dowgiallo, 2005). Size reduction is energy inefficient as only 0.06 to 1% of the energy is used in breaking and creating new surfaces (Mohsenin, 1986). An alternative mode of size reduction, unlike the rotary action of existing grinders, is linear pushing action directly forces biomass through grid of cutting elements and products collected at the other end.

The two major crop based biomass holding promise, namely, the corn stover and switchgrass were selected to determine their size reduction characteristics. A developed model linear knife grid device reported earlier (Igathinathane et al., 2006) was used to determine the size reduction characteristics of these crops under high- and low-moisture conditions. It would be interesting to compare the effects of crop species, moisture conditions, and other operating conditions of knife grid spacing and packed bed depth during size reduction and compare with the published results.

Objectives formulated for the present study were:

1. To determine the size reduction characteristics of corn stalks and switchgrass at high- and low moisture contents in linear knife grid device, in terms of ultimate cutting stress and cutting energy requirements.
2. To compare the results among selected crops, their moisture contents, knife grid spacing, and packed bed depths effects on ultimate cutting stress and cutting energy values, so as to make recommendation for a scale-up device.

Methods

Linear knife grid size reduction device

Linear knife grid model components were product block, knives, ram (pressure plate), support block, and feed block. All components were assembled and tested in universal testing machine (UTM) (Figure. 1). A grid of orthogonal, interlocking knives was supported in grooves spaced at

25.4 mm intervals in the support block. Knife sets were arranged at arbitrarily selected knife grid spacing of 25.4, 50.8, and 101.6 mm. Detail description, specification, and testing procedure of the device was already reported (Igathinathane et al., 2006).

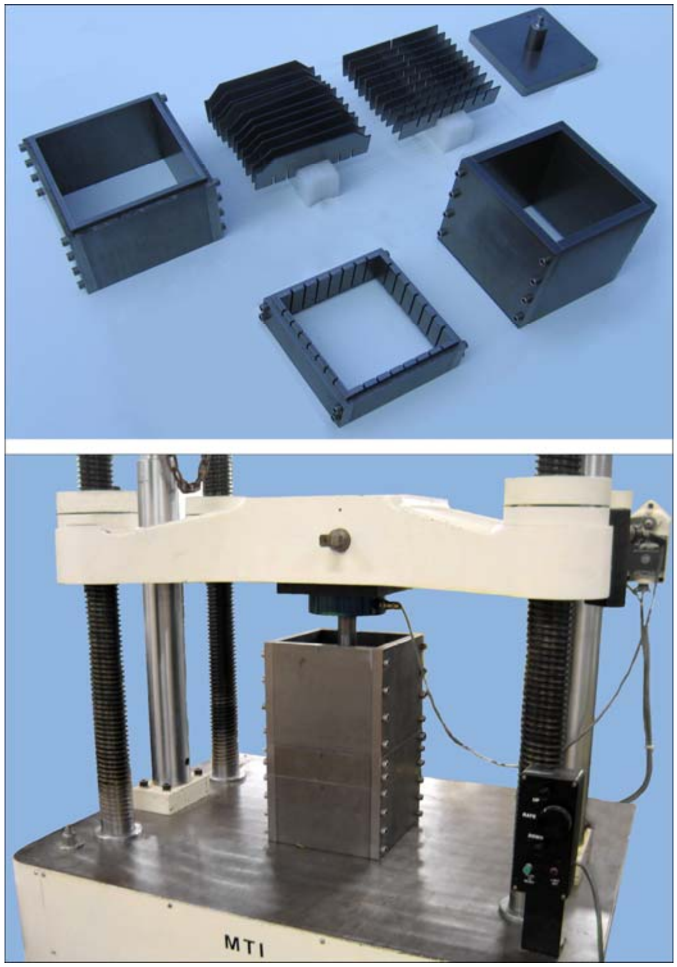

Figure 1. Components of linear knife grid device and their assembly in UTM during testing

Test material

Wet and dry switchgrass (Alamo, Kanlow, and Cave-in-Rock mixture in equal proportion) and corn stalks (Dekalb 743) were the selected test materials. Moisture contents (ASAE Standards, 2003) of materials wet and dry switchgrass were 51.5±4.1% (mean± standard deviation) and 9.0±0.5% (Yu, 2004); and wet and dry corn stalks were 78.8±1.5% and 11.3±0.7% wet basis, respectively. Wet fresh materials were manually harvested from field plots and the dry materials were machine harvested and baled, and stored indoors before for about three months before experiments.

Universal test machine

The linear knife grid ram was placed in a UTM (Model 60 K, Measurement Technology, Inc. (MTI) Roswell, GA) that applied compressive load to the ram through a 222.41 kN load cell

(Fig. 2). MTI software (32 bit Testing Application Programs, Version 1.15) was used to operate the machine, acquire and store load-displacement data (50-75 Hz).

Ram velocity of 50.8 mm/min and an upper load limit of 60% load capacity were generally used, though on a few occasions 80% capacity was used. To prevent contact between ram and knives, a vertical clearance of 3.18 mm was programmed for stopping the ram. Inner walls of the feed block were marked at levels of 50.8, 101.6, and 152.4 mm, measured from the plane of knife edges, to aid in sample filling to specified packed bed depths.

Test procedure

Switchgrass and corn stalks cuts were laid in the feed block to selected packed bed depth (50.8, 101.6, and 152.4 mm, with an average depth variation of maximum 5 mm). Mass of product collected in the product block after each cycle of the ram was determined without disturbing the compressed packed bed. A typical run will have loading of sample to specified depth, size reduction by downward moving ram, withdrawal of ram for next refill, and collection and measurement of cut products. Subsequent cutting operations were continued with refills and the procedure was repeated for four or five times. After the final run, the uncut material was separated and the quantity of cut material retained inside the knife grid was removed, weighed and included in the product. Sum of masses of cut products of all runs makes the total cut product that was used in the analysis. Runs with refills cannot be considered as replications, because the compressed uncut packed bed gets accumulated and the ram experienced progressively increased resistance with refills. Although each refill run was different, the mean data for analysis was obtained actually from these refill runs.

New surface area generated by cutting

New surface area generated by the knife cutting through the material filled to a specified packed bed depth was calculated based on the geometry of packed circle theory (Weisstein, 2006). Although the sample was prepared from the whole plant comprising leaves and stalk stems, it referred as only 'stems' in the analysis. A cross-section of switchgrass plant at internode revealed a hard stem that is hollow and leaf sheathing the stem. Thus the geometry that describes best the switchgrass stems is hollow cylinder (Yu et. al., 2006) and that of corn stalks is solid cylinder, since the inner region is filled with spongy pith. Number of hollow switchgrass or solid corn stalk stems arranged parallel in the feed block in a regular cubic packing order was calculated as:

$$n = \frac{L}{d_o}\frac{D}{d_o} \quad (1)$$

where n is the number of packed stems; L is the length of the available area or length of the knife (m); D is the depth of the available area or packed bed depth (m); and d_o is the mean outer diameter of the considered material stem (m). The number of stems n increases by 33% (1.33 n) when the stems are packed in a regular hexagonal packing order compared to a cubic packing order. The total cross sectional area of all the hollow cylindrical switchgrass stems in cubic packing order using equation 1 will be:

$$s = n\frac{\pi}{4}\left(d_o^2 - d_i^2\right) \quad (2)$$

where s is the total area of packed stems (m^2); and d_i is the mean inner diameter of switchgrass stems (m) and for corn stalks d_i is considered as zero. Packing density, defined as the ratio of the total area occupied by the material and the available area is expressed as:

$$\sigma = \frac{s}{LD} \quad (3)$$

where σ is packing density (dimensionless). The total new surface area generated by the knife grid while cutting of material stems at any packed bed depth and knife grid spacing is given by:

$$A = 2\sigma LDN_k \quad (4)$$

where A is new surface area generated by the knife grid (m^2); and N_k is the number of actually cutting knives of the knife grid perpendicular to the stems, which varied with the knife grid spacing. The '2' in equation 4 represented the two new surface areas produced by a single cut of the knife. Mean outside diameter, and deduced inside diameter from wall thickness, of switchgrass stems dimensions data of Yu (2004) and the measured corn stalks dimensions were utilized to determine the new surface area (eq. 4). It should be noted that the above calculation only considers perpendicular cutting across the switchgrass stems. Variation from transverse or longitudinal cutting across stem would create elliptical cross sectional areas, but this simplified geometrical analysis considered only circular cross-sectional cuts.

Data analysis

Mean and maximum peak failure loads of a given packed bed depth and knife grid spacing were determined from the four or five refill runs' load-displacement data. The area considered in stress analysis was the area representing the cutting plane of knives, which was only half of the new surface area of cut product generated by size reduction (*A/2*, from eq. 4). Ultimate mean and maximum shear stress of each set of four or five refill runs were determined by dividing the respective mean and maximum peak failure load by the cutting plane area (*A/*2) for a specified knife grid spacing and packed bed depth.

Cutting energy was numerically integrated as area under the load-displacement curve. Calculated input energy included material compression, actual cutting of material, and forcing the material through the knife grid – of which all was considered as cutting energy. Cutting energy was expressed in unit mass moisture-free basis (MJ/dry Mg) from cut product mass as well as unit new surface area generated (kJ/m^2) basis, and analyzed. Mass-based cutting energy was evaluated as cumulative energy obtained from summing energies and dividing by product masses, and maximum energy obtained from selecting the maximum energy and dividing by mean product masses, of all refill runs of the experiment. SAS macro (*%mmaov*) mixed model analysis of variance (ANOVA) (Saxton, 2003) with log transformation and Tukey-Kramer (P<0.05) mean separation was used for data analysis. In the SAS code utilizing *%mmaov* procedure, the variables were set as follows: class=, and fixed = material moisture_condition knife_spacing packed_bed_depth, adjust = tukey, transtype = log. For comparing various mechanical properties between crops (corn stalks and switchgrass) appropriate variables were set using the "by" option of the macro.

Results and Discussion

Linear knife grid size reduction device test observations

Typical load-displacement curves revealed common regions of initial consolidation phase of packed bed expelling air in voids, represented by horizontal portion, and final ram withdrawal represented by vertical drop portion. With accumulation of material with refill runs, until stabilization reached, the load-displacement curves will be seen one above the other with each run. It was established that materials undergo lot of compression before the cutting failure occur

(Chancellor, 1958). Momentary undulations of load reduction signify material being cut and passed through knife grid. An increase in the observed peak load at each run and the curves can be progressively grouped based on increased packed bed depths. Peak loads of wet material were much greater than dry material, and they showed clear separation of packed bed depth groups in the case of switchgrass (Figure 2).

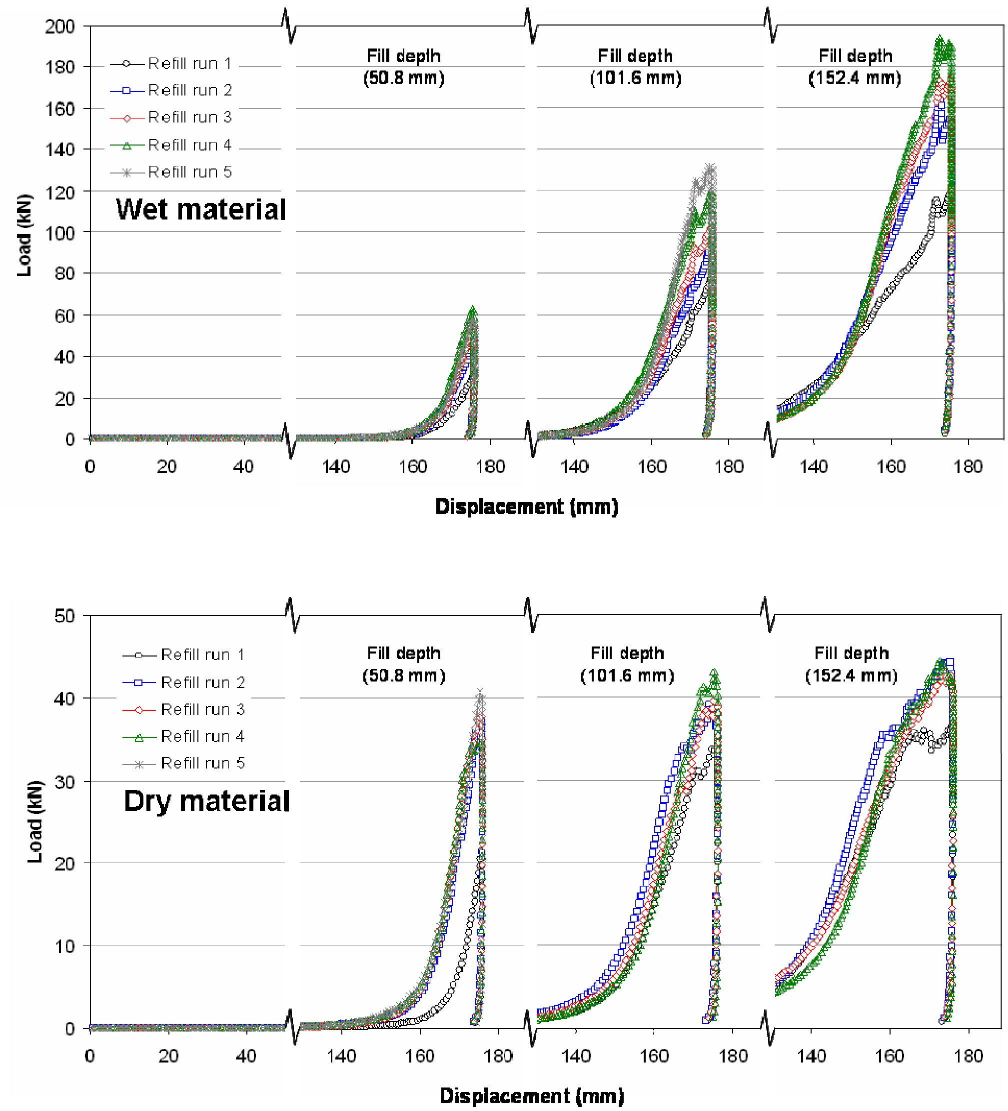

Figure 2. Typical load-displacement curves of wet and dry switchgrass at grid spacing of 50.8 mm

Corn stalks being more tougher than switchgrass, the maximum set load limit of the UTM (experimental set limit of 80% of capacity = 178 kN) was often reached with 25.4 mm grid spacing at packed bed depths ≥ 101.6 mm even at initial run. Such experiments with corn stalks were incomplete and were not included in analysis.

Ultimate cutting stress of wet and dry switchgrass and corn stalks

Ultimate mean and maximum shear stresses of wet and dry switchgrass and corn stalks varied inversely with knife grid spacing and packed bed depth (Figure 3). Reduced knife grid spacing increased stresses, because the passage clearances through the knife grid gave increased restriction to flow of material. At a given knife grid spacing, ultimate shear stresses decreased as packed bed depth increased, because of greater increase in cutting area with depth than the ultimate failure load increase with packed bed depth.

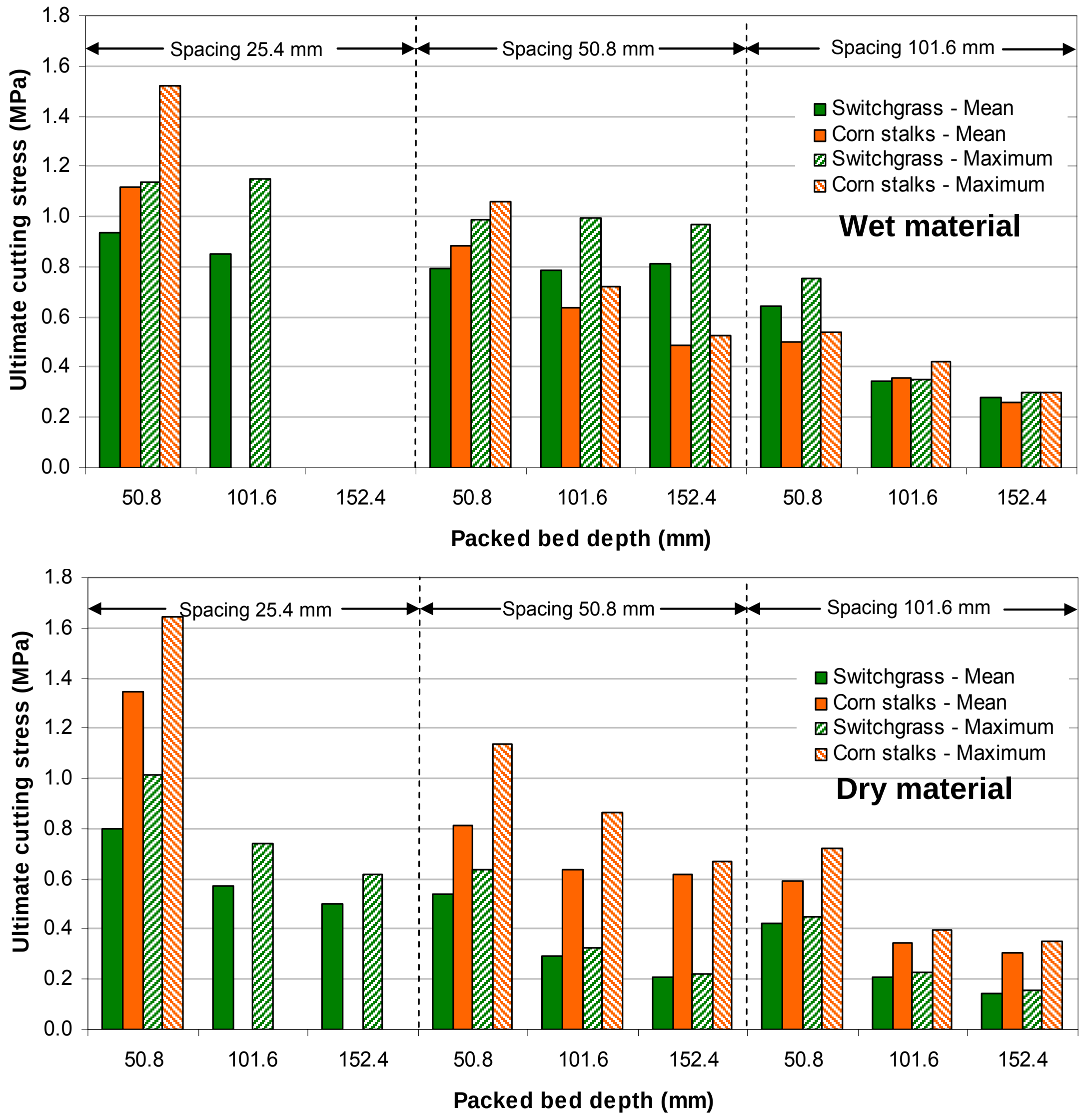

Figure 3. Ultimate mean and maximum cutting stress of wet and dry switchgrass and corn stalks at different knife grid spacing and packed bed depths

On average for both the crops, the maximum ultimate cutting stresses were about 20% greater than mean stresses. The maximum ultimate cutting stress, obtained from the maximum peak load among the refill runs, can be thought of as a design limit for future applications, with similar device configuration. On average for switchgrass, the respective mean and maximum ultimate shear stresses were 0.68±0.24 and 0.83±0.34 MPa for wet material, and they were 0.41±0.21 and 0.49±0.29 MPa for dry material. Similarly the respective mean and maximum ultimate stress values for corn stalks were 0.61±0.30 and 0.73±0.43 MPa for wet material, and they were 0.66±0.35 and 0.83±0.45 MPa for dry material.

Mass-based cutting energy of wet and dry switchgrass and corn stalks

To a greater extent, cutting mass-based energy calculated on a moisture-free basis increased the relative energy values for high-moisture switchgrass compared to low-moisture switchgrass. Cutting energy per dry Mg of cut products of switchgrass and corn stalks at wet and dry conditions reduced with increased knife grid spacing and increased gradually with packed bed depth (Figure 4). Wet material consistently required more cutting energy per unit mass than dry material. This result contrasts the results by Yu et al. (2006) and Womac et al. (2005) that showed moisture content had little effect on cutting energy on single stems of switchgrass. Additional complexity of compression prior to entry into the knife grid, and by frictional and compressive forces to move material through the knife grid would have contributed to the difference. Another reason for the greater energy values of high-moisture material was the reduced amount of dry matter present that increased the energy values when expressed in moisture free basis.

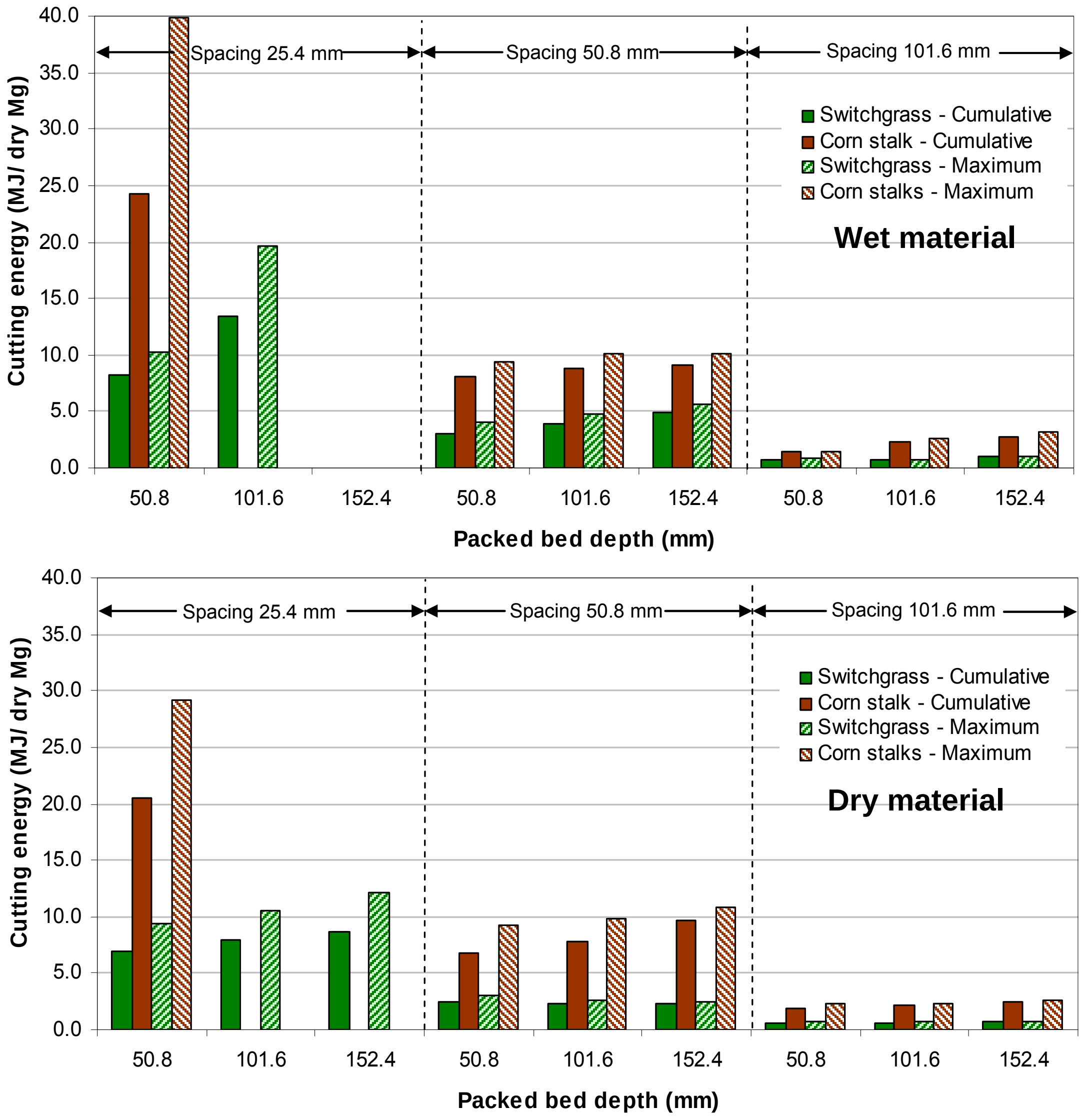

Figure 4. Mass-based cutting energy of wet and dry switchgrass and corn stalks at different knife grid spacing and packed bed depths

On average, the cumulative and maximum mass-based cutting energy for wet switchgrass were 4.50±4.43 and 5.87±6.41 MJ/dry Mg, and for dry switchgrass were 3.64±3.31 and 4.72±4.64 MJ/dry Mg, respectively. The respective cutting energy values of wet corn stalks were 8.09±7.87 and 10.97±13.25 MJ/dry Mg, and for dry corn stalks were 7.32±6.57 and 9.46±9.49 MJ/dry Mg. Published results indicate 53.6 MJ/Mg for switchgrass chopped from bales to 25 to 100 mm size (Jannasch et al., 2005), and 84.6 MJ/Mg using a hammer mill to produce 3.2 mm particles (Mani et al., 2002). For corn stalks, the reported energy values were 25.1 and 39.7 MJ at 7.0 and 11.0% wet basis moisture contents respectively using hammer mill (Mani et al., 2002). Linear knife grid size reduction energy being lower than other reported values from hammer mill appears to hold promise as an energy-efficient means of biomass size reduction.

Surface area-based cutting energy of wet and dry switchgrass and corn stalks

Mean outside diameter, combining Alamo and Kanlow switchgrass varieties, was 3.57±0.59 mm and wall thickness of stems was 0.71±0.18 mm (n = 863) with moisture contents varying between 17.9 and 35.4% wet basis (Yu, 2004). Corn stalks equivalent diameter varied from 5 to 26 mm from top to bottom of the stalk. From these values, a geometric mean dimension of 18 mm was selected as the representative diameter of corn stalks. Packing density calculated from equation 3 for switchgrass was 0.499 and for corn stalks was 0.788. Smaller packing density of switchgrass was mainly due to the hollowness of the stem. A theoretical maximum value of 0.9069 was possible in the densest packing scenario of solid circles (Weisstein, 2006); but hollowness of the switchgrass stems and the assumption of square pattern arrangement of stems of both crops attributed to the observed smaller values.

New surface area-based cutting energy of wet and dry switchgrass and corn stalks increased with increase in packed bed depth (Figure 5). Except for the wet switchgrass at a knife grid spacing of 50.8 mm, the calculated energy remained somewhat constant among test runs. However, for corn stalks the energy values were directly proportional to the packed bed depths and varied inversely with knife grid spacing.

Mean values of new surface area-based cutting energies for wet and dry switchgrass were 4.12±2.06 and 2.53±0.45 kJ/m^2, and for wet and dry corn stalks were 8.81±2.26 and 8.80±1.70 kJ/m^2 respectively. Womac et al. (2005) reported mean specific cutting energies of 78.0 and 95.2 kJ/m^2 for dry switchgrass and 27.9 and 34.2 kJ/m^2 for dry corn stalks, based on single stem cutting using a Warner Bratzler shear testing procedure, for knife bevel angles of 30° and 45° respectively at a moisture content of around 9% wet basis. Areas generated by knife grids were 2650 to 59126 times greater than the area of single stem cut of switchgrass. This huge variation in the generated surface area was the major source of the difference observed in new area-based energy (kJ/m^2) between the methods, although the energy required for cutting multiple stems with knife grid was much greater than that required for single stems in Warner Bratzler device. The single stem tests may have allowed more deflection, whereas the ram of the knife grid created a tight, less flexible loading. Cutting energy efficiency of linear knife grid device was again demonstrated by new surface area-basis cutting energy values.

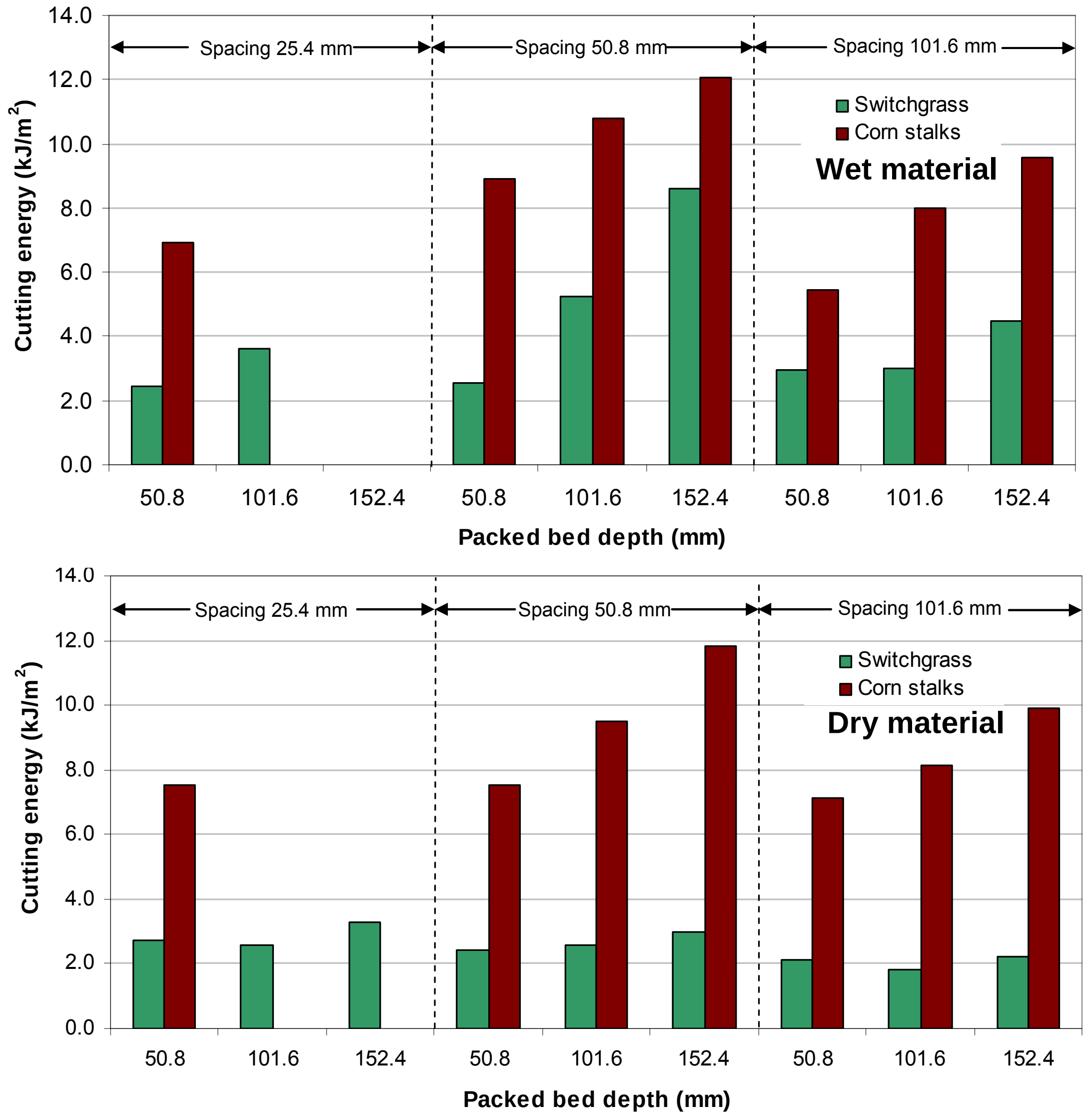

Figure 5. New surface area-based cutting energy of wet and dry switchgrass and corn stalks at different knife grid spacing and packed bed depths

Cutting energy based on new surface area generated was considered specific energy, and the moisture conditions should minimally affect new surface area generated. For a 1 m^2 area of knife grid device with the studied knife grid spacing of 25.4, 50.8, and 101.6 mm and possible commercial grid spacing of 200, 250, and 400 mm, the number of knives required will be 76, 38, 18, 8, 6, and 4 with ratio of knife length to grid spacing will be 2992, 748, 177, 40, 24, and 10, respectively. Energy based on new surface area generated and ratio of knife length to grid spacing may serve as good factors to scale-up the linear knife grid size for commercial use. From the results it can be recommended that a knife grids spacing from 50 to 100 mm and greater may offer an efficient first-stage size reduction in a preprocessing operation. Linear knife grid operations were well suited especially for packaged (baled) biomass.

Crop based comparison of moisture conditions, and operation parameters

Mean separation analysis results of ultimate cutting stresses and cutting energies between corn stalks and switchgrass comparing moisture conditions, knife grid spacing, and packed bed depth of material are presented in Table 1 (Appendices). Except for dry material, the ultimate mean and maximum cutting stresses were not significantly different ($P < 0.05$) between crops. The reason for the low stress values of dry switchgrass can be attributed to material becoming brittle due to loss of elasticity. Cutting energy based on mass and new surface area generated varied significantly, with corn stalks consistently greater than switchgrass energy values among moisture conditions, knife grid spacing, and packed bed depths.

Overall comparison of material, moisture conditions, and operation parameters

On overall basis, the variation of stresses and energy values were compared among crops, moisture conditions, knife grid spacing, and packed bed depths by combining data independently, and the mean separation results are given in Table 2 (Appendices). Stress and energy values of corn stalks were significantly ($P < 0.05$) greater than switchgrass. On average, with combined stress and energy values, corn stalks values were 2.2±0.9 times greater than switchgrass values. Wet material was consistently stronger than dry material and had 1.3±0.0 times greater values on average. Knife grid spacing mean values of stress and energy values showed significantly different groups, except for ultimate mean cutting stress at 25.4 and 50.8 mm knife grid spacing. At reduced knife grid spacing of 25.4 mm, the stress and energy values were 6.9±6.8 times greater than 101.6 mm spacing with combined results, but for mass-based energy values at 25.4 mm spacing was as high as 13.0 to 16. 0 times that at 101.6 mm spacing. When packed bed depths were considered, the smallest depth 50.8 was significantly different from the other depth mean groups, which were similar. A trend reversal of mean group arrangement between stress and energy values was observed (Table 2), with reduced packed bed depths producing greater stress means and smaller energy means. Stress values of 50.8 mm depth were 1.9±0.1 times greater than 152.4 mm depth, whereas the corresponding combined energy values were 1.4±0.2 times smaller.

Conclusions

- Developed linear knife grid model device was successfully for tested high- and low-moisture switchgrass and corn stalks biomass.
- A minimum knife grid spacing of 25.4 mm appears to be a practical lower limit, considering the high ram force that would be required for commercial size reduction operation.
- Ultimate cutting stress and cutting energy values of corn stalks were significantly greater ($P < 0.05$) than (2.2 times) that of switchgrass, on overall basis.
- High-moisture material stress and energy results were significantly greater than (1.3 times) than low-moisture material; hence, recommended to work with dry material when the biomass collection/harvest process can be delayed to take advantage of natural field drying or field storage.
- Significant differences in the mean values of ultimate cutting stress and cutting energy values with grid spacing and packed bed depths were observed on overall comparison; but no significant differences observed with ultimate cutting stress values, when only crops were compared.
- Knife grid spacing from 50 to 100 mm and greater would an efficient first-stage size reduction for a pre-processing machine based on the linear knife grid device principle.

- Future tests need to be research operating effects of a commercial-scale linear knife grid device.

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Appendices

Table 1. Comparison of mechanical properties corn stalks and switchgrass during size reduction using linear knife grid device.

Mechanical property	Moisture condition				Knife grid spacing (mm)						Packed bed depth (mm)					
	Wet		Dry		25.4		50.8		101.6		50.8		101.6		152.4	
	CS[a]	SG[b]	CS	SG	CS	SG	CS	SG	CS	SG	CS	SG	CS	SG	CS	SG
Ultimate mean cutting stress (MPa)	0.569 ±0.054 a	0.635 ±0.051 a	0.649 ±0.055 a	0.358 ±0.034 b	0.971 ±0.196 a	0.686 ±0.085 a	0.667 ±0.123 a	0.505 ±0.107 a	0.377 ±0.057 a	0.305 ±0.051 a	0827 ±0.066 a	0.665 ±0.059 a	0.590 ±0.112 a	0.448 ±0.069 a	0.506 ±0.207 a	0.372 ±0.136 a
Ultimate maximum cutting stress (MPa)	0.676 ±0.073 a	0.759 ±0.069 a	0.807 ±0.065 a	0.412 ±0.039 b	1.288 ±0.201 a	0.874 ±0.085 a	0.801 ±0.159 a	0.594 ±0.137 a	0.435 ±0.068 a	0.329 ±0.059 a	1.027 ±0.087 a	0.791 ±0.077 a	0.750 ±0.155 a	0.531 ±0.092 a	0.588 ±0.243 a	0.425 ±0.158 a
Cumulative mass-based cutting energy (MJ/dry Mg)	8.014 ±0.158 a	3.327 ±0.091 b	7.428 ±0.094 a	2.267 ±0.043 b	27.240 ±0.718 a	9.203 ±0.215 b	8.327 ±0.217 a	3.034 ±0.131 b	2.089 ±0.091 a	0.717 ±0.053 b	6.447 ±0.133 a	2.403 ±0.081 b	8.255 ±0.248 a	2.768 ±0.102 b	8.932 ±0.426 a	3.008 ±0.189 b
Maximum mass based cutting energy (MJ/dry Mg)	9.994 ±0.273 a	4.059 ±0.155 b	9.264 ±0.113 a	2.710 ±0.051 b	43.826 ±1.194 a	12.671 ±0.331 b	9.897 ±0.273 a	3.576 ±0.164 b	2.366 ±0.125 a	0.787 ±0.072 b	8.371 ±0.236 a	2.988 ±0.141 b	10.315 ±0.360 a	3.322 ±0.144 b	10.971 ±0.482 a	3.578 ±0.211 b
Mean new surface area-based cutting energy (kJ/m^2)	8.812 ±0.229 a	3.897 ±0.136 b	9.027 ±0.132 a	2.494 ±0.058 b	8.353 ±0.480 a	2.995 ±0.148 b	9.969 ±0.351 a	3.591 ±0.211 b	7.878 ±0.274 a	2.646 ±0.159 b	7.166 ±0.161 a	2.535 ±0.096 b	9.185 ±0.348 a	2.975 ±0.140 b	10.889 ±0.715 a	4.027 ±0.333 b

CS – Corn stalks, SG – Switchgrass.

Moisture content: Corn stalks-Wet = 78.8±1.5%, and -Dry = 11.3±0.7%; Switchgrass-Wet = 51.5±4.1%, and -Dry = 9.0±0.5% wet basis

Data presented in each cell represent mean estimate of property±standard deviation and mean separation letter group (SAS macro %manova (Saxton, 2003) with log transformation and Tukey-Kramer).

Different letters, also illustrated by different colored cells, within a mechanical property and independent variable represent a significant difference ($P < 0.05$).

Table 2. Overall mechanical properties of biomass size reduction using linear knife grid device

Mechanical property	Crop		Moisture condition		Knife grid spacing (mm)			Packed bed depth (mm)		
	CS	SG	Wet	Dry	25.4	50.8	101.6	50.8	101.6	152.4
Ultimate mean cutting stress (MPa)	0.606 ±0.059 a	0.475 ±0.045 b	0.617 ±0.056 a	0.467 ±0.046 b	0.785 ±0.094 a	0.580 ±0.058 a	0.339 ±0.045 b	0.741 ±0.066 a	0.506 ±0.061 b	0.411 ±0.060 b
Ultimate maximum cutting stress (MPa)	0.735 ±0.073 a	0.555 ±0.054 b	0.732 ±0.068 a	0.557 ±0.057 b	0.999 ±0.119 a	0.689 ±0.071 b	0.378 ±0.053 c	0.901 ±0.081 a	0.613 ±0.076 b	0.471 ±0.071 b
Cumulative mass-based cutting energy (MJ/dry Mg)	7.671 ±0.120 a	2.718 ±0.061 b	5.103 ±0.092 a	4.085 ±0.078 b	15.472 ±0.239 a	5.026 ±0.098 b	1.224 ±0.048 c	3.936 ±0.087 b	4.660 ±0.107 a	5.190 ±0.121 a
Maximum mass based cutting energy (MJ/dry Mg)	9.556 ±0.166 a	3.275 ±0.083 b	6.268 ±0.127 a	4.993 ±0.108 b	21.574 ±0.352 a	5.949 ±0.133 b	1.364 ±0.064 c	5.001 ±0.122 a	5.685 ±0.146 a	6.159 ±0.164 a
Mean new surface area-based cutting energy (kJ/m^2)	8.880 ±0.186 a	3.093 ±0.094 b	5.898 ±0.143 a	4.656 ±0.121 b	5.269 ±0.202 ab	5.983 ±0.155 a	4.566 ±0.135 b	4.262 ±0.131 b	5.162 ±0.162 ab	6.541 ±0.196 a

CS – Corn stalks, SG – Switchgrass.

Moisture content: Corn stalks-Wet = 78.8±1.5%, and -Dry = 11.3±0.7%; Switchgrass-Wet = 51.5±4.1%, and -Dry = 9.0±0.5% wet basis

Data presented in each cell represent mean estimate of property±standard deviation and mean separation letter group (SAS macro %manova (Saxton, 2003) with log transformation and Tukey-Kramer).

Different letters, also illustrated by different colored cells, within a mechanical property and independent variable represent a significant difference ($P < 0.05$).