Size reduction of high- and low-moisture corn stalks by linear knife grid system

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ABSTRACT

High- and low-moisture corn stalks were tested using a linear knife grid size reduction device developed for first-stage size reduction. The device was used in conjunction with a universal test machine that quantified shearing stress and energy characteristics for forcing a bed of corn stalks through a grid of sharp knives. No published engineering performance data for corn stover with similar devices are available to optimize performance; however, commercial knife grid systems exist for forage size reduction. From the force–displacement data, mean and maximum ultimate shear stresses, cumulative and peak mass-based cutting energies for corn stalks, and mean new surface area-based cutting energies were determined from 4–5 refill runs at two moisture contents (78.8% and 11.3% wet basis), three knife grid spacings (25.4, 50.8, and 101.6 mm), and three bed depths (50.8, 101.6, and 152.4 mm). In general, the results indicated that peak failure load, ultimate shear stress, and cutting energy values varied directly with bed depth and inversely with knife grid spacing. Mean separation analysis established that high- and low-moisture conditions and bed depths ≥ 101.6 mm did not differ significantly ($P < 0.05$) for ultimate stress and cutting energy values, but knife grid spacing were significantly different. Linear knife grid cutting energy requirements for both moisture conditions of corn stalks were much smaller than reported cutting energy requirements. Ultimate shear stress and cutting energy results of this research should aid the engineering design of commercial scale linear knife gird size reduction equipment for various biomass feedstocks.

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1. Introduction

Corn stover, the above-ground portion of the corn plant minus the grain, has the greatest potential as a lignocellulosic biomass feedstock for bioenergy including fuel ethanol [1] and bioproducts applications. From the corn grain production of 267.6 Tg [2], the corn stover availability could be estimated to be about 214 Tg using the nominal corn stover to grain ratio of 0.8 [3]. Since half of the quantity of stover can be collected for utilization [4], this amounts to 107 Tg of biomass. Thus, corn stover constitutes an abundant source of field grown local biomass feedstock for several utilization options. Invariably

any biomass utilization process requires the biomass in a freely flowable form, in order to pass through various machinery and processes efficiently. Therefore, the handled biomass needs to be at a reduced particle size. For example, some of the processes and their particle size requirement are: gasification – 6.4 mm [5], chemical conversion – 1 mm [6], simultaneous saccharification and fermentation of corn stover to produce ethanol – 2 to 10 mm [7], and briquetting of corn stover – 5.6 mm [8]. Therefore, biomass needs to be pre-processed through a mechanical size reduction process before actual utilization.

The mechanical size reduction also increases bulk density, flowability, new surface area [9], pore size, and hydrolysis reaction rates [10]. Commonly used biomass size reduction machines are hammer mill, knife-mill, disk-mills, forage choppers, and wood chippers. Some of these grinders were originally developed for dry, friable materials, such as, solid wood, and food grains. However, these grinders were directly utilized to fibrous biomass for want of specialized size reduction machinery. Experience indicates that to produce ground biomass of reduced particle size, utilizing the available machinery, the size reduction should be carried out in multi-stages—involving at least a pre-processing stage (coarse size reduction) that handles the raw biomass feedstock, followed by other secondary stage (finer size reduction) grinding operations. If same machine has to be used, the classifying screens should be changed from coarse to fine.

Straws and stalks of grass and cereal crops have long stems. Such biomass feedstock should be precut to smaller pieces before being ground into much smaller particles in secondary grinders to be finally utilized. Most of the biomass size reduction devices are rotary machines with cutting force applied by cutting elements through rotary tangential action. An alternative to rotary size reduction devices is a linear knife grid system [11], which uses linear action to achieve pre-processing size reduction with straws and stalks biomass. Compression happens when a sharp edge is forced onto the biomass material for cutting [12]. The degree of compression depends upon the sharpness of the cutting edge, and the toughness of the biomass. The compression could take up a significant force and thus consume energy. Cutting speed, material properties, and knife geometry influence cutting force requirement [13].

In Canada, knife grid cutting of forages (alfalfa and timothy) is practiced commercially. The commercial knife grid is arranged vertically and a ram forces baled biomass material horizontally through the knife grid, with cut product collected on the other side and transported by a conveyor. In one such system in Northern Alberta, Canada, the knife grid spacing was 400 mm. Lack of information to ascertain the minimum practical grid spacing and the associated forces to push different biomass feedstock through the grid needs to be addressed.

The operation of size reduction is energy intensive and highly energy inefficient, since the energy required for creating new surfaces involved only 0.06%–1% of total energy input [14]. Neither comprehensive cutting theory nor mathematical model for cutting fibrous materials has been documented [13]. Limited studies examined forage chopping [15], biomass size reduction technology [16], and biomass comminution and separation [17]. No published engineering performance data for corn stover are available to optimize the performance of similar size reduction devices. Based on the major components of corn stover, corn stalks account for approximately 72.6% of the wet stover mass at 62.3% moisture content wet basis [18]. In addition, much of the remaining stover mass (leaves and husks) are lost during collection [4], thereby making stalks as the practically collectible biomass. Hence, only stalk portion of corn stover was considered in this pre-process size reduction research utilizing the linear knife grid device.

The specific objective of this research was to determine the engineering performance characteristics of linear knife grid size reduction of corn stalks in terms of operational variables such as stalk moisture content, knife grid spacing, and bed depths.

2. Methods

2.1. Test sample

Dekalb 743 variety of corn (field location: 35.8955°N 83.9592°W) from the Experiment Station, The University of Tennessee, Knoxville was selected as the input material. The crop was planted during late May 2006 and the fresh plants were harvested during August 14–18, 2006 for experiments. High-moisture fresh corn plants were manually harvested and tested immediately, whereas matured dry corn plants were mechanically harvested (late September 2006), bundled, and stored indoors for about three months before testing. Indoor storage resulted in slow natural shade drying of the material and the corn stover obtained stable low moisture of roughly 11% wet basis. Since stalk of the stover is the dominant fraction, stalk fraction was separated from ears, leaves, and husk during test material preparation. Moisture contents of the prepared corn stalk samples were determined [19] as $78.8 \pm 1.5\%$ (mean $\pm$ standard deviation) and $11.3 \pm 0.7\%$ wet basis for high- and low-moisture corn stalks, respectively. For moisture measurements, triplicate samples of 50 g were subjected to a temperature of 103 °C in a convection oven for 24 h.

2.2. Developed linear knife grid size reduction device

Major components of the developed linear knife grid model device were ram (pressure plate), feed block (to hold uncut sample), knife grid, knife support block, and product block (to collect cut samples) (Fig. 1). A grid of orthogonal, interlocking knives was supported in grooves spaced at 25.4 mm intervals in the knife support block. Three knife grid spacings of 25.4, 50.8, and 101.6 mm were considered based on anticipated particle sizes as a first cut in sequential size reduction for commercial use.

The constant inside cross-sectional dimensions of the stacked feed block, knife support block, and product block were 203.2×203.2 mm. All components, except knives, were made from 19.05 mm thick mild steel plates bolted together. Knives were made of A2 tool-steel. Knives fabricated from 3.18 mm thick plate, were machined with a leading bevel angle of 30°. The 30° bevel reduced the mean ultimate shear strength of corn stalk by 11% compared to a 45° bevel angle [20]. Lateral clearance of 0.16 mm between ram and feed block minimized friction between them.
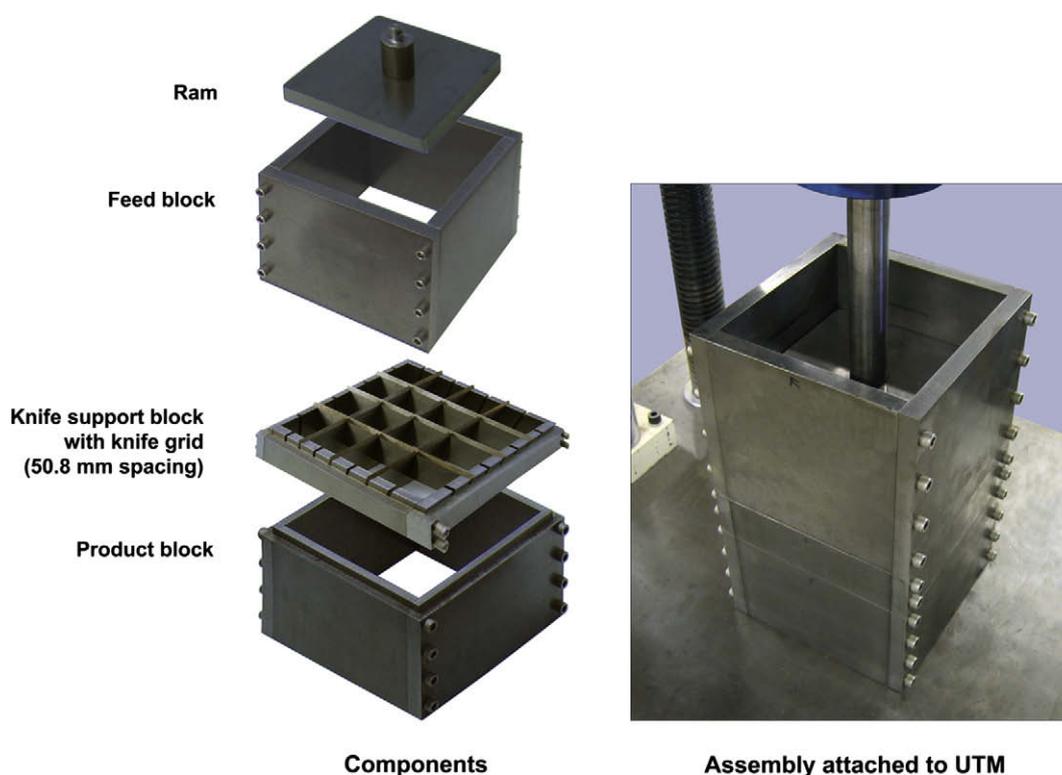
Fig. 1 – Components of linear knife grid model cutting device and the assembly attached to UTM for testing.

2.3. Universal test machine and data acquisition

A universal test machine (UTM) (Measurement Technology, Inc. Model 60K, (MTI) Roswell, GA, USA) applied compressive load required to cut the input material. Linear knife grid device was assembled in UTM (Fig. 1) by connecting the ram to crosshead through a 222.41 kN load cell, while the product block set on the bed of UTM. A maximum available ram velocity of 50.8 mm min^{-1} and an upper load limit of 60% load capacity (133.4 kN) were used, though on some experimental runs 80% (177.9 kN) capacity was used when stress development could be properly observed. A vertical clearance of 3.18 mm was programmed in the software to stop the ram during testing before touching the knife grid. MTI software (32 bit Testing Application Programs, Version 1.15) operated the UTM, and acquired and stored the force–displacement data at 50–75 Hz. The UTM actually quantified the combined effect of shearing stresses, bed consolidation, and frictional resistance to flow of cut products through a knife grid during the tests. The data in the form of a text file were read into Microsoft Excel spreadsheet and analyzed for cutting stress and energy.

2.4. Experimental procedure

A typical experimental run consisted of loading of prepared corn stalks sample to specified bed depth, measuring the bed depth (prior to compression by ram) before and after run, cutting of samples by downward movement of ram, withdrawing of ram for refill, collecting cut products and measuring their mass, and recording force–displacement data. Subsequent cutting operations were continued with refills and the procedure was repeated until four or five refill measurements were obtained for each test condition. In lieu of replications, emphasis was placed on refills (four or five refills) similar to a commercial operation where each stroke cuts through a mat of new material as it enters the compression chamber.

Independent test variables included knife grid spacings (25.4, 50.8, and 101.6 mm), corn stalks bed depths (50.8, 101.6, and 152.4 mm), and corn stalks moisture contents (78.8 ± 1.5% and 11.3 ± 0.7% wet basis). Tests were conducted on all combinations of variables in a factorial experimental design. Corn stalks were placed in the feed block, held by knife grid, to selected bed depths (50.8, 101.6, and 152.4 mm) indicated by the markings made inside feed block. Actual depths of the bed were measured before and after each test. Mass of cut product collected in the product block after each cycle of the ram movement was determined without disturbing the compressed bed retained in the knife grid. Uncut material after the final run was separated and the cut corn stalks retained inside the knife grid was removed and their mass measured. Sum of masses of inputs and cut products of all runs gave the mass of total input and cut product, respectively.

2.5. Corn stalk new surface area generated by cutting

Cutting of corn stalks, as they pass through the knife grid, generates new surface area that is proportional to the energy expended in the size reduction. Packed circle theory of geometry [21] with relevant assumptions was applied to calculate the theoretical new surface area generated by the

knife cutting through the material filled to a specified bed depth. Corn stalk was comprised of spongy pith enclosed by thick stalk skin and had elliptical cross-section (Fig. 2). However, it was modeled as a cylinder of a combined single material with circular cross-section.

The number of corn stalks loaded in parallel orientation into the feed block in a regular cubic packing order (Fig. 2) was calculated as:

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

where n is the number of packed corn stalks; L is the length of the available area or length of the knife (0.2032 m); D is the depth of the available area or bed depth (m); and d_o is the mean outer diameter of corn stalk (m). If the corn stalks were packed in a regular hexagonal packing order compared to a regular cubic packing order, the number of corn stalks n increases by 33% (1.33 n) [21], which is not considered in this evaluation.

Total cross-sectional area of all corn stalks using Eq. (1) is:

$$a = n\frac{\pi}{4}d_o^2 \qquad (2)$$

where a is the total area of packed corn stalks (m^2).

To express the total cross-sectional area of all corn stalks from the dimensions of the bed and the inner dimensions of feed block, we define a packing density as the ratio of the total area occupied by the material to the total area available. Therefore, using Eq. (2) the packing density is expressed as:

$$\sigma = \frac{a}{LD} \qquad (3)$$

where σ is packing density (dimensionless). Once the packing density σ was evaluated, the total area of packed corn stalks a was calculated from Eq. (3) for other bed depth settings. The total new surface area generated by the knife grid while cutting corn stalks at any bed depth and knife grid spacing becomes:

$$S = 2\sigma LDN \qquad (4)$$

where S is new surface area generated by the knife grid (m^2); and N is the number of knives of the knife grid in particular setting, which varied with the knife grid spacing. The factor '2' in Eq. (4) represents the two new surface areas produced by a single cutting action of the knife in the cut product.

It should be noted that the above calculation assumes only transverse perpendicular cuts to occur across the axis of corn stalk. While half of the knives produced transverse circular sections (Fig. 2), the other half produced longitudinal cuts making rectangular sections of stalks. Any variation in the orientation from that of the assumptions would also create elliptical cross-section of cut stalks. Although transverse and longitudinal cuts produce different sectional areas, we assumed in this work that both cuts produce same defined surface area (Eq. (4)). This consideration is a simplification because in commercial operations with continuous loading, the corn stalks will be oriented at random angles to the knives. Compression of the stalks, low-moisture especially, before cutting will result in apparent loss of new area generated due to flattening; however, this effect is not considered in the analysis.

Corn stalks equivalent diameter, obtained from the major and minor axes dimensions of their elliptical cross-section, varied from 5 to 26 mm from top to bottom of the stalk. A geometric mean dimension of 18 mm was selected as the representative diameter of corn stalks. The number of layers of corn stalks for 50.8, 101.6, 152.4 mm depth were estimated to be 3, 6, and 8. The mean packing density of corn stalks based on the three depths was 0.78 ± 0.05. A theoretical maximum value of 0.9069 was possible in the densest packing scenario [21]; but the regular cubic packing order of uniform cross-sectional stalks and voids were the reason for the observed reduced packing density.

New surface areas of corn stalks generated by single knife were 0.016, 0.032, and 0.049 m^2 for depths 50.8, 101.6, and 152.4 mm, respectively, (Eq. (4)). The three knife grid spacings of 25.4, 50.8, and 101.6 mm needed 14, 6, and 2 numbers of knives, respectively. The corresponding new surface area generated was obtained by multiplying the single knife area by the number of knives, and the values ranged from 0.032 to 0.679 m^2.

2.6. Data analysis

Ultimate shear stresses were determined by dividing the peak load by the cross-sectional area of cut corn stalks ($S/2$, one-half of new surface area used in Eq. (4)). Mean and maximum ultimate shear stresses and energies were calculated from the multiple refill runs. The mean ultimate shear stress averaged the values for the refill runs, whereas the maximum ultimate shear stress was the observed maximum value from the refill runs.

Integration of area under the force–displacement curve gave the cutting energy. Calculated input energy actually included initial corn stalk compression, actual corn stalk cutting, and forcing the cut material through the knife grid. For analysis, cutting energy was expressed in unit mass basis (MJ dry-Mg^{-1}) from cut product mass (excluding the uncut material) as well as in unit new surface area generated basis (kJ m^{-2}). To enable true comparison of energies, calculations were performed on moisture free basis considering only the dry matter content of the input material.

Mass-based cutting energy was evaluated as cumulative energy obtained from summing energies and dividing by product mass of the refill runs. However, the peak energy was obtained from selecting the maximum energy and dividing by mean product mass of the refill runs of a particular experiment. SAS macro (%mmanov) mixed model analysis of variance [22] with log transformation and Tukey–Kramer ($P < 0.05$)
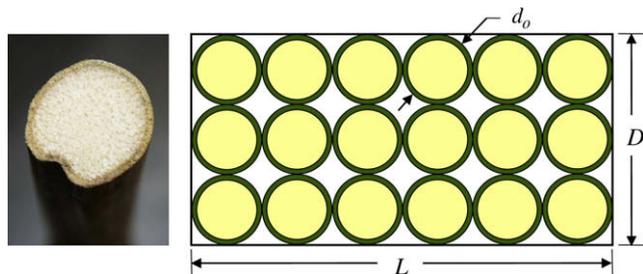
Fig. 2 – Corn stalk's cross-section assumed as circular geometry and regular cubic packing of cylindrical corn stalks inside feed block for theoretical new surface area determination.

Fig. 3 – Corn stalks size reduction at 50.8 mm knife grid spacing (a) loaded corn stalks above knife grid before cutting, (b) view from the underside of knife grid showing cut products caught in the knife grid, (c) cut products collected in the product block, (d) cut products from 25.4 mm knife grid spacing, (e) cut products from 50.8 mm knife grid spacing and (f) cut products from 101.6 mm knife grid spacing.

mean separation was used for data analysis. The dependent analysis variables of mean separation that ran individually were *mean_ultimate_shear_stress*, *maxium_ultimate_shear_stress*, *cumulative_cutting_energy_mass*, *peak_cutting_energy_mass*, and *mean_cutting_energy_area*. The other variables of *%mmaov* procedure were set to *class* and *fixed = moisture_condition knifegird_spacing bed_depth*, *adjust = tukey*, and *transtype = log*. The variation of mechanical properties (stress

Moisture condition	Knife grid spacing (mm)	Corn stalk bed depth (mm)	Peak load (kN) and corresponding displacement (mm) of refill runs				
			1	2	3	4	5
High moisture	25.4	50.8	72.97 (175.5)	111.99 (175.5)	124.49 (175.3)	124.14 (171.7)	162.71[a] (172.8)
		101.6	142.93[b] (172.9)	163.59[b] (164.7)	167.19[b] (152.3)	167.19[b] (143.8)	138.29[b] (138.6)
		152.4	135.44[b] (160.3)	136.07[b] (134.4)	138.84[b] (124.4)	138.82[b] (116.5)	139.91[b] (111.3)
	50.8	50.8	28.11 (175.2)	37.61 (175.1)	41.11 (175.7)	48.47 (171.6)	47.68 (171.8)
		101.6	46.24 (171.9)	58.38 (171.3)	63.21 (173.5)	66.19 (172.6)	68.07 (172.3)
		152.4	53.00 (175.2)	72.24 (172.6)	74.73 (172.7)	72.80 (172.6)	75.15 (172.5)
	101.6	50.8	8.20 (169.8)	7.11 (173.2)	7.49 (174.1)	7.40 (174.9)	7.94 (169.9)
		101.6	10.24 (163.2)	11.01 (170.4)	10.85 (163.1)	13.39 (169.7)	10.85 (166.2)
		152.4	14.15 (160.4)	13.37 (147.4)	11.89 (170.6)	12.61 (171.2)	10.59 (155.6)
Low moisture	25.4	50.8	72.24 (175.7)	151.16[a] (175.8)	175.74[a] (172.4)	175.74[a] (170.9)	–
		101.6	143.86 (175.8)	175.74[b] (170.0)	175.74[b] (163.2)	175.74[b] (160.9)	–
		152.4	138.02[b] (168.4)	137.45[b] (149.1)	138.02[b] (139.6)	138.11[b] (131.1)	–
	50.8	50.8	16.64 (175.2)	28.82 (175.3)	40.10 (175.7)	52.01 (175.7)	48.35 (175.5)
		101.6	33.86 (175.5)	49.86 (172.1)	81.96 (173.6)	74.32 (175.5)	–
		152.4	76.10 (175.4)	82.54 (175.5)	95.31 (175.5)	94.03 (174.1)	96.16 (175.8)
	101.6	50.8	7.31 (175.3)	8.44 (173.3)	11.04 (174.9)	9.14 (170.9)	–
		101.6	10.72 (164.5)	11.40 (162.0)	12.44 (160.5)	9.00 (175.6)	–
		152.4	16.83 (158.8)	12.01 (161.1)	12.26 (149.7)	16.72 (159.0)	–

Table 1 – Peak loads for shearing corn stalks under different experimental settings with linear knife grid device.

a Above 60% of load cell capacity (133.45 kN).
b Incomplete due to crossing of 133.45 kN and reaching arbitrary final displacement ≤ 170 mm quickly.
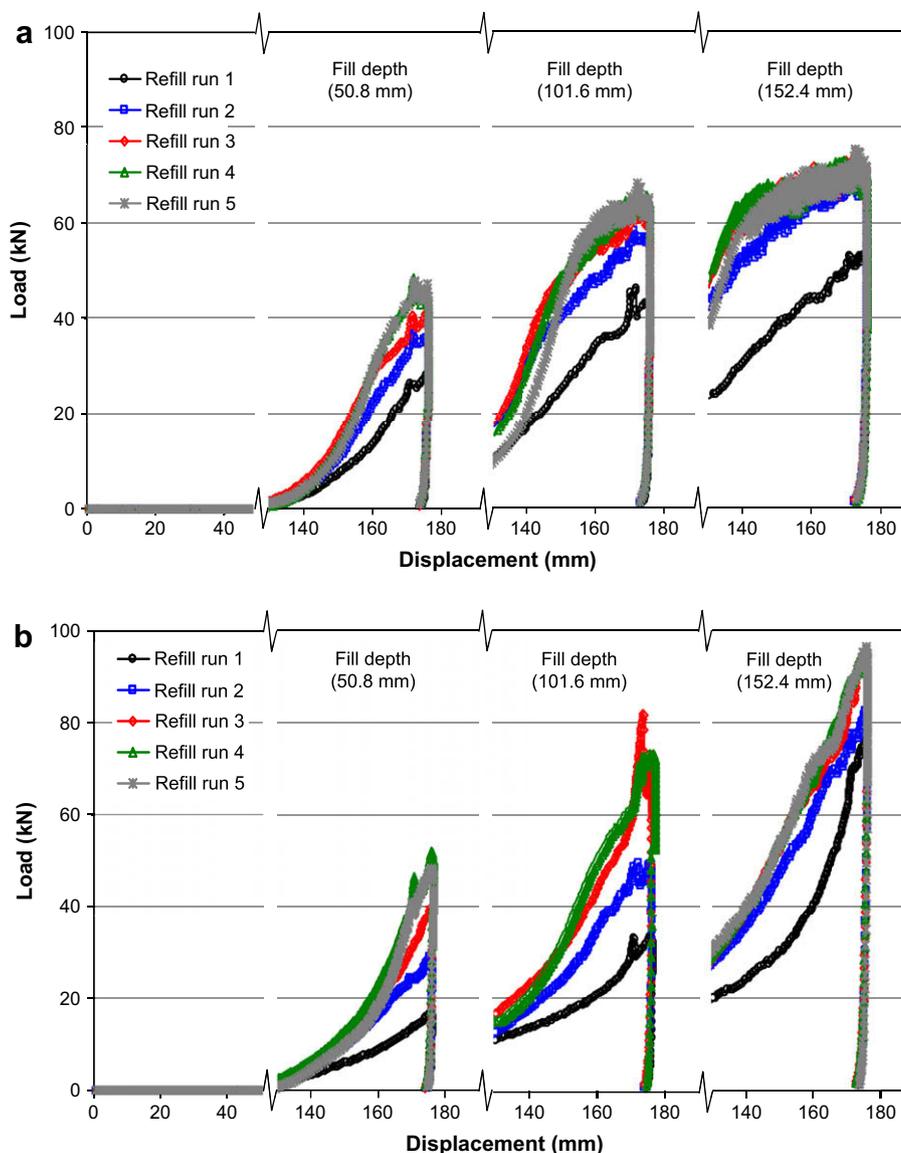
Fig. 4 – A typical force–displacement characteristics at a knife grid spacing of 50.8 mm of (a) high-moisture corn stalks, (b) low-moisture corn stalks.

and energy) between moisture conditions, and operating parameters (knife grid spacing and bed depth) were compared by mean separation analysis with suitable combination of data.

3.   Results and discussion

3.1.   Size reduction of corn stalks in knife grid device

High-moisture corn stalks at different stages of cutting in the linear knife grid are illustrated in Fig. 3. Cut product lengths were proportional to knife grid spacing. In addition, the product was less distorted when knife grid spacing was ≥50.8 mm (Fig. 3). Even at 25.4 mm knife grid spacing, only limited number of longitudinal splits of corn stalks was observed. With high-moisture corn stalks especially at

25.4 mm knife grid spacing a little amount of squeezed juice from the stalks was observed, and the moisture was also partially absorbed by the cut products.

Linear knife grid operation at smaller knife grid spacing can be likened to pelleting-a densification process of forcing the material through a die, and at larger knife grid spacing to chopping of material into smaller pieces. However, pelleting essentially is a finishing densification operation, while linear knife grid is a pre-process size reduction operation with minor emphasis on densification. Although knife grid cutting generated new surface areas in the cut corn stalks, the compression process apparently reduced the generated areas. This reduction was observed only in dry corn stalks, as the high-moisture stalks sprung back showing less distortion (Fig. 3). Reduction of generated areas by consolidation will not be of any adverse consequence, as linear knife grid size reduction is only the first stage operation, and the reaction
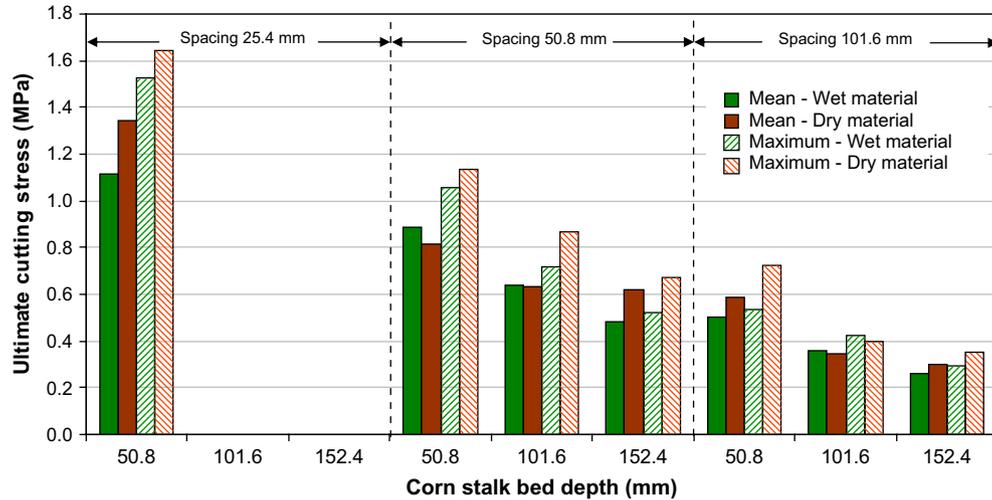
Fig. 5 – Overall mean and maximum ultimate shear stresses of combined refill runs of high- and low-moisture corn stalks at various knife grid spacing and bed depths.

areas will be regenerated in the further grinding operations before presenting the material to final chemical or thermal applications. In addition, the cut products from the linear knife grid systems will be a better flowable compact material to secondary grinding equipment than the feedstock in the original loose form.

3.2. Corn stalks force–displacement characteristics

Peak loads occurred around the point when the ram was at its final stages of descend around 176 mm final displacement or limited by the considered load cell capacity (Table 1). The final displacement values indicate the location of ram, from which the compressed bed thickness corresponding to the peak load can be determined. These peak loads increased with increase in number of refills and bed depths, and decreased with increase in knife grid spacing. Whereas, the final displacement values decreased with increased number of refills and increased bed

depths. Experiment runs were stopped when the peak load rapidly crossed the 60% load cell capacity of 133.45 kN, and up to 80% load cell capacity (177.93 kN), as long as the increase was gradual. Overall, high-moisture corn stalks had reduced peak loads than low-moisture corn stalks. The 60% load cell capacity limit (133.45 kN) was always exceeded with knife grid spacing of 25.4 mm at bed depths ≥ 101.6 mm (Table 1). Since the tests of corn stalks both high- and low-moisture material at 25.4 mm knife grid spacing and packing bed depths of 101.6 and 152.4 mm were incomplete due to high load stoppage, these incomplete runs were not included in the analysis.

Typical force–displacement characteristics of high- and low-moisture corn stalks showed increasing initial load during initial consolidation, reaching the peak load accompanied by cutting, and rapid reduction in load during ram withdrawal (Fig. 4). Other researchers noted compression of a bed of fibrous biomass against a sharp edge prior to shearing [11]. Load fluctuations observed in the force–displacement
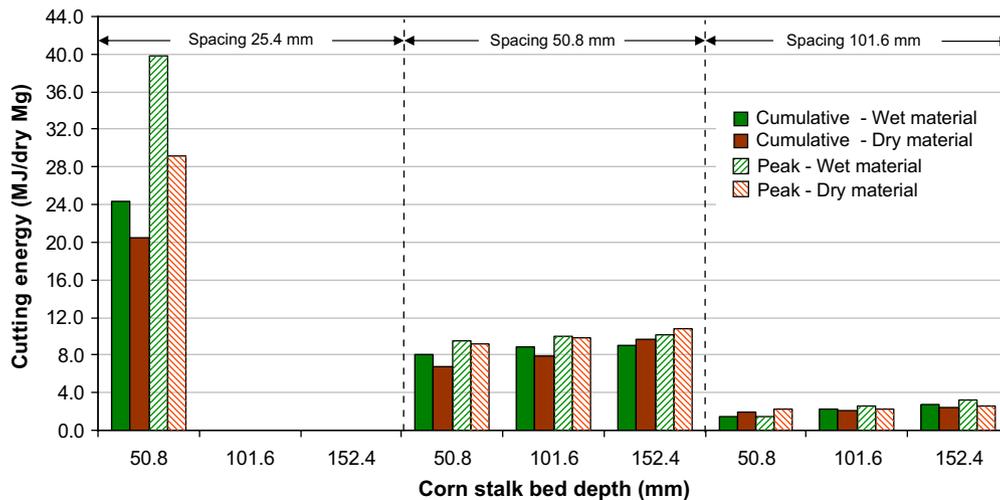
Fig. 6 – Overall mass-based cumulative and peak cutting energies of combined refill runs of high- and low-moisture corn stalks at various knife grid spacing and bed depths.

curve, after the initial compression, indicated the on-set and subsequent cutting of corn stalks. Momentary drops of loads in the region where cutting occurred were expected due to formation of failure planes, which offered reduced resistance to cutting knives. The load corresponding to the initial point of rupture indicated the force required to compress the material before initiating the cutting process.

Peak loads for initial runs were generally observed to be of lesser magnitude in comparison with the corresponding peak loads of the subsequent refill runs. This is because during the initial run the clean knife grid is free of corn stalks and, therefore, offers less resistance than the subsequent refill runs. Since the knife blade thickness (19.05 mm each) reduced the cross-sectional area (203.2 × 203.2 mm) of material flow, the cut materials were caught in the spaces between knives of the grid (Fig. 3b), and this material retention offered added resistance to cut products flow. Refill runs beyond the second showed convergence of force–displacement curves for all knife grid spacings. This signifies that the subsequent refills will have similar force characteristics, and a continuous operation will proceed likewise. High-moisture corn stalks appear to fail early (Fig. 4a) in contrast to low-moisture corn stalks that showed increased compression and sudden cutting failure (Fig. 4b). Furthermore, it can be seen that low-moisture corn stalks produced greater peak loads than high-moisture corn stalks. Overall, a knife grid spacing of 25.4 mm could be a practical lower limit for commercial application owing to large force requirement (peak loads ≈176 kN at 25.4 mm grid spacing and ≈17 kN at 101.6 mm grid spacing). However, a knife grid spacing from 50 to 100 mm or greater may offer an efficient first-stage size reduction of biomass.

3.3. Mean and maximum ultimate shear stress of corn stalks

The maximum ultimate shear stress values were found to be 19.7% and 24.5% greater than the corresponding mean stresses for high- and low-moisture corn stalks, respectively.

On average, the mean and maximum ultimate shear stresses were 0.61 ± 0.30 and 0.73 ± 0.43 MPa for high-moisture corn stalks, and 0.66 ± 0.35 and 0.83 ± 0.45 MPa for low-moisture corn stalks, respectively, (Fig. 5). These results were smaller than the reported mean shear stress of 1.85 ± 0.61 MPa utilizing a modified Warner–Bratzler shear test of dry single corn stalk (≈9% wet basis) for a 30° knife bevel angle [19]. Results variation may be attributed to the basic technical difference in the device (single and multiple knives) and the presentation of material to the cutting elements. From these results it can be concluded that dry corn stalks would require a more robust-design of knife grid device than required for high-moisture corn stalks.

3.4. Mass-based cutting energy of corn stalks

Considerable reduction of cutting energy for high- and low-moisture corn stalks was observed with increased knife grid spacing (Fig. 6). For 50.8 and 25.4 mm spacing, there were three and seven times as many numbers of knives with reference to 101.6 mm spacing (two knives). However, the increase of cutting energy with increased bed depths was only small; partly due to only two and three times increase from the reference 50.8 mm for 101.6 and 152.4 mm bed depths. These results indicate that the cutting energy on unit mass basis is fairly constant irrespective of bed depths, but varies only with the knife grid spacing. Moisture content of corn stalks did not show clear difference in mass-based cutting energy.

The peak mass-based cutting energies were 14.5% and 20.3% greater for high- and low-moisture corn stalks, respectively, with reference to corresponding cumulative energy values considering only the complete 50.8 and 101.6 mm knife grid spacings results. On average, the cumulative and peak mass-based cutting energies were 8.09 ± 7.87 and 10.97 ± 13.25 MJ dry-Mg^{-1} for high-moisture corn stalks, and 7.32 ± 6.57 and 9.46 ± 9.49 MJ dry-Mg^{-1} for low-moisture corn stalks. Reported cutting energy values were 25.1 and
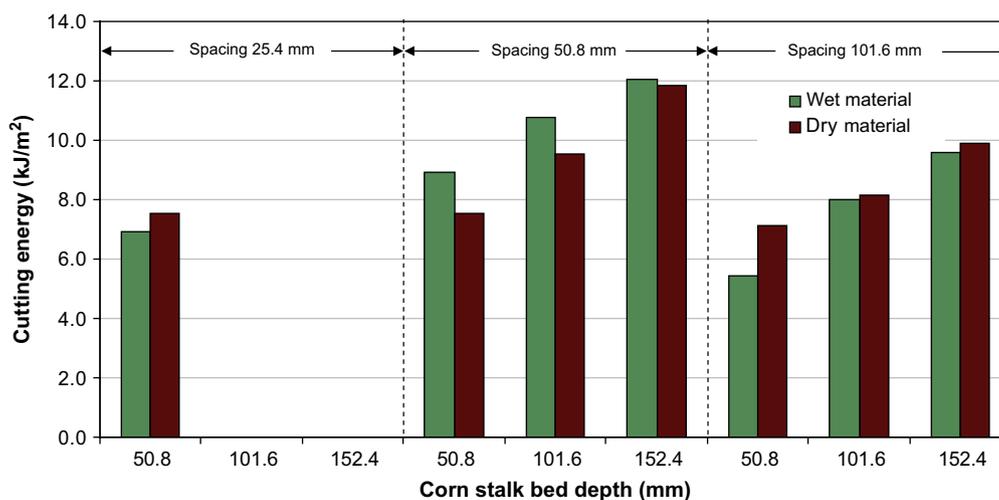
Fig. 7 – New surface area-based cutting energy of combined refill runs of high- and low-moisture corn stalks at various knife grid spacing and bed depths.

39.7 MJ Mg^{-1} at 7.0% and 11.0% wet basis moisture contents, respectively, using hammer mill [23]. The observed energy being much smaller than other reported values from hammer mill appears to hold promise of linear knife grid device as an energy-efficient means of biomass size reduction, especially as a first stage pre-process size reduction.

3.5. New surface area-based cutting energy of corn stalks

Unlike mass-based cutting energy, new surface area-based cutting energy of high- and low-moisture corn stalks showed a gradual linear increase with increase in bed depth (Fig. 7). With combined data, the new surface area-based cutting energy was 8.81 ± 2.26 kJ m^{-2} for high-moisture corn stalks, and 8.80 ± 1.70 kJ m^{-2} for low-moisture corn stalks.

Reported mean area-based cutting energy values were 27.94 ± 5.65 and 34.19 ± 6.80 kJ m^{-2} for 30° and 45° knife bevel angle, respectively, for dry single corn stalk ($\approx 9\%$ wet basis) in the modified Warner–Bratzler shear tests [19]. Reasons for the difference can be attributed to the newly generated areas from knife grids at various spacings were 120–1127 times greater than that from single stem cutting tests. The greater surface area generated was the major source of the difference observed in new area-based energy (kJ m^{-2}) between the methods, even though the actual peak loads encountered for cutting corn stalks with knife grid (7.3–175.7 kN; Table 1) was much greater than that required for single stems (<0.075 kN) [19]. The increased value of new area generated makes the value of surface area-based energy small, as it is defined as the ratio of actual cutting energy to the new area generated. Differences may also be attributed to energy expended in packing the material before cutting (compression), and different cutting blade geometries; straight knife edges with knife grid and inverted V-shape knife with Warner–Bratzler device. Overall, the factors that affect the relation between cutting single stems and beds of corn stalks include the differences in blade geometry, corn stalks consolidation, and knife grid space resistance to cut material flow.

Additional complexity of material compression prior to entry into the knife grid, and the associated frictional and compressive forces to move material through the knife grid would likely have affected the results of the knife grid tests. In single stem modified Warner–Bratzler tests [19] the knife directly applied force to corn stalks, whereas tests conducted herein applied force through a bed. Moreover, packing the bed may have included a consolidation process, not only among corn stalks pieces, but also within a given piece of corn stalks during air and moisture expulsion. Based on the observations and results, the issues of scaling from a single stem to a bed of material become evident. Therefore, for proper scale-up design of commercial systems results of this and similar studies involving tests on cutting of bulk material will be more appropriate.

The new surface area-based cutting energy values, although varied inversely with knife grid spacing, did not show any consistent variation with moisture conditions, also the values belonged to a narrow range of 5.4–12.1 kJ m^{-2}. Therefore, an average value from the range might fairly

Table 2 – Mean separation results of moisture conditions and operating parameters of linear knife grid size reduction of corn stalks.

Mechanical property	Moisture condition		Knife grid spacing (mm)			Corn stalk bed depth (mm)		
	High	Low	25.4	50.8	101.6	50.8	101.6	152.4
Mean ultimate shear stress (MPa)	0.585 ± 0.041 a	0.638 ± 0.041 a	0.906 ± 0.078 a	0.667 ± 0.039 b	0.377 ± 0.039 c	0.827 ± 0.039 a	0.576 ± 0.055 b	0.478 ± 0.055 b
Maximum ultimate shear stress (MPa)	0.683 ± 0.034 b	0.786 ± 0.034 a	1.130 ± 0.065 a	0.801 ± 0.033 b	0.435 ± 0.033 c	1.027 ± 0.033 a	0.706 ± 0.046 b	0.543 ± 0.046 c
Cumulative cutting energy – product based (MJ dry-Mg^{-1})	7.920 ± 0.050 a	7.594 ± 0.050 a	26.809 ± 0.095 a	8.327 ± 0.048 b	2.089 ± 0.048 c	6.447 ± 0.048 b	7.932 ± 0.067 ab	9.121 ± 0.067 a
Peak cutting energy – product based (MJ dry-Mg^{-1})	9.922 ± 0.072 a	9.607 ± 0.072 a	39.749 ± 0.137 a	9.897 ± 0.068 b	2.366 ± 0.068 c	8.371 ± 0.068 a	10.004 ± 0.097 a	11.114 ± 0.097 a
Mean cutting energy based on new surface (kJ m^{-2})	8.843 ± 0.039 a	8.962 ± 0.039 a	8.983 ± 0.074 ab	9.969 ± 0.037 a	7.878 ± 0.037 b	7.166 ± 0.037 b	9.084 ± 0.052 a	10.837 ± 0.052 a

Data represent mean estimate of property ± standard deviation and mean separation letter group (SAS macro %manova [21] (Saxton, 2003)) with log transformation and Tukey-Kramer ($P < 0.05$). Different letters within a mechanical property represent a significant difference.

represent all material and operating conditions; and the new surface area-based cutting energy can be considered as the specific energy that quantifies the size reduction process. For a knife grid device of 1 m^2 cross-section, with the studied knife grid spacing of 25.4, 50.8, and 101.6 mm as well as possible commercial grid spacing of 200, 250, and 400 mm, the number of knives required will be 76, 38, 18, 8, 6, and 4, which gives a ratio of total knife lengths to grid spacing as 2992, 748, 177, 40, 24, and 10 for the above knife grid spacings, respectively. Energy based on generated new surface area and ratio of knife length to grid spacing may serve as good factors for scale-up to commercial linear knife grid system.

3.6. Overall mean comparison of moisture conditions, and operating parameters of corn stalks size reduction

High- and low-moisture conditions of corn stalks did not show any significant difference ($P < 0.05$) on mechanical properties, except for maximum ultimate shear stress (Table 2). Knife grid spacing mean groups produced significant differences in all mechanical properties, except for mean new surface area-based cutting energy that showed both mixed and separate mean groups. Similarly, corn stalks bed depths did not produce three clear mean separation groups on all mechanical properties, but had some group overlaps, other than at the maximum ultimate shear stress. Based on overall observation on studied mechanical properties (Table 2), barring a few instances, it can be concluded that knife grid spacings were significantly different ($P < 0.05$), but moisture conditions and bed depths ≥ 101.6 mm of corn stalks were not significantly different.

4.   Conclusions

Effects of moisture contents, knife grid spacing, and bed depths, on ultimate stresses and energies involved in the size reduction of corn stalks in linear knife grid device were determined. Corn stalk consolidation, new surface area generated by cutting, and frictional resistance to cut product flow through the knife grid collectively influenced the size reduction energy expended in the linear knife grid device. In general, moisture conditions and bed depths ≥ 101.6 mm of corn stalks were not significantly different ($P < 0.05$) for ultimate stress and cutting energy values; however, knife grid spacings were significantly different. Reduced energy requirement (7–11 MJ dry-Mg^{-1}; 8 kJ m^{-2}) compared with reported values (25–40 MJ dry-Mg^{-1}; 28–34 kJ m^{-2}) from existing methods makes the linear knife grid device as an energy-efficient initial size reduction equipment for biomass. The cut product lengths matched closely with the knife grid spacing and the cut products were subjected to less distortion. A knife grid spacing from 50 to 100 mm and greater may offer an efficient first-stage size reduction of biomass. Preliminary tests required to scale-up the linear knife grid device to handle different biomass should be based on a bed of material similar to that followed in this work, as strength characteristics based on single stalk of biomass were found not to represent size reduction in bulk.

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