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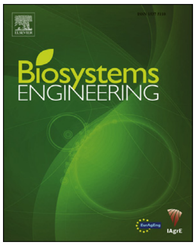

Research Paper

Effect of blade oblique angle and cutting speed on cutting energy for energycane stems

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Energycane is a promising bioenergy crop for warm south-eastern US regions and existing sugarcane machinery is being adapted for energycane cultivation. Because of energycane's comparatively higher fibre content and smaller stem diameters, the cutting blades must be optimized for energycane harvesting and size reduction. To optimize cutting blade designs, this study investigated the effect of cutting speed and blade oblique angle on cutting energy. An impact type cutting mechanism was used to determine the cutting energy cost of individual stems. The results showed that the specific cutting energy increases with cutting speed. The lowest average specific energy was 0.26 J mm^{-1} for a 60° oblique cut at an average cutting speed of 7.9 m s^{-1}, whereas the highest average specific cutting energy was 1.24 J mm^{-1} for a straight cut at an average cutting speed of 16.4 m s^{-1}. The specific cutting energy showed a close correlation with stem diameter and stem cross-sectional area. For a 30° oblique angle at 11.3 m s^{-1} average cutting speed, the cutting energy varied from 4.5 to 15 J as the energycane stem diameter varied from 11 to 17 mm. Comparisons with sugarcane studies indicated that optimisation of cutting speed and blade oblique angle can result in significant savings in cutting energy, whilst simultaneously improving the quality of cut. This study emphasises the need for further investigation of the energycane cutting process especially at higher cutting speeds with cutting devices with varying moments of inertia.

1. Introduction

Worldwide, renewable energy sources are being investigated as an alternative to fossil fuels. Biomass, a renewable energy source, has the potential to supply fuel and electricity compatible with existing transportation and power generation infrastructures. The energy consumed in the US is expected to increase to 120.8 EJ by 2034 from 105 EJ in 2008 (DOE, 2010). The expectation is that renewable energy sources will meet 10–40% of the demand being approximately 17 EJ by 2034 (DOE, 2010). A large portion will come from biomass sources and many alternative crops are being investigated. Energycane is emerging as one of the low-input high-yielding crops suitable for biomass production in warm south-eastern regions of the US (Knoll, Anderson, Strickland, Hubbard, & Malik, 2011).

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Nomenclature

A	Stem cross sectional area, m^2
a	Stem diameter in the cutting direction, m
b	Stem diameter in direction perpendicular to the cutting direction, m
E_c	Energy required to cut energycane stem, J
I	Moment of inertia of the cutting arm, kg m^2
ω_i	Initial speed of the cutting arm before cutting stem, rad s^{-1}
ω_f	Final speed of the cutting arm after cutting stem, rad s^{-1}

Most of the plants called energycanes are hybrid species within the *Saccharum* genus, usually with one *Saccharum officinarum* parent (Youngs & Taylor, 2009). Energycane is a perennial grass species that utilises the energy efficient C-4 photosynthetic pathway. Sugarcanes are also from *S. officinarum* species whereas the ratio of soluble sugar to insoluble fibre distinguishes 'sugarcanes' from 'energycanes' within the *Saccharum* species. The energycanes are further divided into Type I and Type II with a low and high sugar content respectively.

Energycane harvesting is similar to sugarcane harvesting, where the green tops are removed and left in the field. Some harvesters remove the green top and heap the canes that are burnt to remove trash representing about 15% of the total biomass (Youngs & Taylor, 2009). Other harvesters remove the green top, cut the cane approximately 50 mm above the soil, and subsequently cut the harvested stalk into billets which are loaded into a transport bin. The green tops and leaves (trash) are expelled onto the field.

It is expected that sugarcane harvesters and forage equipment will work well for energycane (Mislevy & Fluck, 1992) but there is a great opportunity for efficiency improvement. Cutting forces and cutting speed required to cut plant materials play a significant role in designing energy efficient equipment. The initial knife penetration results in localised plastic deformation, followed by buckling and deformation as the knife advances (Person, 1987). As the knife continues to advance, the fibres in the stem are deflected and eventually fail in tension (Srivastava, Goering, Rohrbach, & Buckmaster, 2007).

Many studies investigated the effect of cutting speed on cutting energy and relevant studies are briefly summarized here. For maize stem cutting, a distinct minimum energy requirement was found at a cutting velocity of 2.65 m s^{-1} (Prasad & Gupta, 1975). This was not the case for forage grasses where the cutting energy monotonically decreased with cutting speed (McRandal & McNulty, 1978). The cutting energy required to cut sorghum stems showed a minimum at 2.9 m s^{-1} cutting speed and it increased as the cutting speed increased above 2.9 m s^{-1} (Yiljep & Mohammed, 2005). As with a maize study (Prasad & Gupta, 1975), cutting energy increased as the cutting speed decreased below 2.9 m s^{-1} (Yiljep & Mohammed, 2005). For harvesting sugarcane, the specific shearing energy was found to be proportional to the blade cutting speed and lower speeds were recommended to reduce the cutting energy requirement (Taghijarah, Ahmadi, Ghahderijani, & Tavakoli, 2011).

Many other studies examined the effect of blade angle and blade design on the cutting energy. A blade peripheral velocity of 13.8 m s^{-1}, oblique angle of 35°, and a tilt angle of 27° were optimum for a revolving knife-type sugarcane base cutter (Gupta & Oduori, 1992). The cutting force required for cutting sugarcane stem depended on the blade design and a difference of 26% was reported between the two designs tested (Clementson & Hansen, 2008). A cutting blade oriented parallel to a corn stalk (0°) compared to perpendicular (90°) resulted in a significant reduction in the specific cutting energy to one-tenth for internodes and about one-fifth for nodes (Igathinathane, Womac, & Sokhansanj, 2010). Optimum knife edge angle, shear angle, oblique angle, and rake angle were 25°, 40°, 40°, and 40°, respectively for *Kenaf* stems (Ghahraei, Ahmad, Khalina, Suryanto, & Othman, 2011). Hammer mills performed better than knife mills represented by various cutting mechanisms for energycane size reduction (Miao, Grift, Hansen, & Ting, 2011).

Many other studies examined the effect of stem diameter on cutting energy and relevant ones are described here. The cutting energy was found proportional to maize stem diameter (Prasad & Gupta, 1975). The cutting force and cutting energy increased with sugarcane fibre content and stem diameter (Kroes & Harris, 1996a, 1996b). The cutting energy increased from 15 to 20 J as the sugarcane diameter increased from 20 to 30 mm while cutting at a commercial harvester speed of 20 m s^{-1} (Kroes & Harris, 1996a, 1996b).

To avoid splitting of sugarcane stubbles which causes fungal and other diseases, it would be beneficial to keep the impact force less than the bending resistance of the remaining stem section for all depths of blade penetration (Kroes & Harris, 1996a, 1996b). The total cutting energy of dry corn stem internodes varied with the stem cross-sectional area and it ranged from 11.3 to 23.5 kN m^{-1} (Igathinathane et al., 2010). A serrated blade required 35% less cutting force than a flat blade while cutting miscanthus stems at 1.7 m s^{-1} cutting speed (Liu, Mathanker, Zhang, & Hansen, 2012).

Thus, this literature surveyed indicates that cutting speed, blade oblique angle, and stem diameter play a key role in the energycane cutting process. However, there are no studies investigating energycane cutting mechanics. To improve energycane harvesting and size reduction equipment, the objectives of this study were to investigate the effect of cutting speed, blade oblique angle, and stem diameter on the cutting energy required for individual energycane stems.

2. Materials and methods

Energycane stems (variety Ho 02-113) cut close to the ground were collected in July 2011 from a first year ratoon crop grown in Highlands, Florida. In the test assembly, the energycane stem was oriented vertically with its base firmly held in place to mimic the mechanical rigidity of the root structure of an energycane plant in the field (Fig. 1; Fig. 4b). The diameters of the stem in the cutting direction, and in direction perpendicular to the cutting direction were recorded at the expected

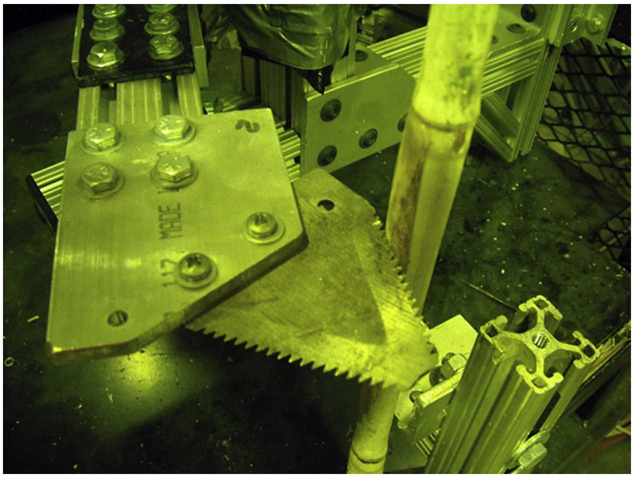

Fig. 1 – Energycane stem and cutting swing arm ready for a 0° straight cut.

cutting location. The stem cross sectional area was expressed as (Yiljep & Mohammed, 2005):

$$A = \frac{\pi}{4}ab \quad (1)$$

where, A is stem cross sectional area in m^2, a is stem diameter in the cutting direction in m, and b is stem diameter in direction perpendicular to the cutting direction in m.

2.1. Experimental arrangement

The experimental arrangement consisted of an impact type cutting arm (Fig. 1) freely rotating around a pivot. Details of the arrangement are available (Johnson, Clementson, Mathanker, Grift, & Hansen, 2012). The cutting arm was accelerated to a constant rotational velocity by means of an air blast from an air cannon. A standard serrated blade was fixed to the end of the cutting arm. When the cutting blade contacted the stem, the cutting process started and the speed of the cutting arm reduced, owing to energy lost in cutting the stem, as the cutting progressed. After completing the cutting process, the speed of the cutting arm became constant again. The energy lost during the stem cutting process was determined using:

$$E_C = \frac{1}{2}I\left(\omega_i^2 - \omega_f^2\right) \quad (2)$$

where: E_c is energy required to cut energycane stem in J; I is moment of inertia of the cutting arm in kg m^2; ω_i is initial speed of the cutting arm before cutting stem in rad s^{-1}; ω_f is final speed of the cutting arm after cutting stem in rad s^{-1}.

The angular position of the cutting arm was recorded by an optical encoder with an angular resolution of 0.175°, sampled at 100 kHz (model S5-2048-236-I-S-B, US Digital, Vancouver, WA, USA). Angular speeds were determined immediately before and after contact of the cutting blade with the stem. For all the tested stem samples, the cutting process completed within 10° angular rotation of the cutting arm following its first contact with the stems. The cutting arm radius was 0.25 m and the tip of the cutting arm travelled 43.6 mm linear distance when rotated by 10°.

The centre of gravity of the cutting arm was estimated by recording the mass of the cutting arm as it rested partially on a balance while fixed at the pivotal centre. Taking the moment about the pivotal centre of the cutting arm gave the effective length of the cutting arm. Also, the natural pendulum-like response of the cutting arm was recorded to determine its moment of inertia. The coefficients in a second order pendulum response equation were adjusted until the recorded response of the pendulum matched the ideal solution. The optimisation was performed using the ‘ode45’ and ‘lsnonlin’ functions of Matlab® (version R2012b, The Math Works, Natick, MA, USA). Equating the coefficients and substituting known values, the moment of inertia of the cutting arm was calculated. Further details regarding the cutting arm moment of inertia determination are available (Johnson et al., 2012). The cutting mechanism used was equipped with various safety devices to isolate users from its fast moving parts, to prevent accidental pressurisation or firing, and to stop the speeding cutting arm after cutting the stem. A control program was written to control the apparatus and acquire data in LabVIEW® (version 2011b, National Instruments Corporation, Austin, TX, USA).

2.2. Cutting energy experiments

The first experiment was conducted to study the effect of oblique angle and cutting speed on the cutting energy. The parameters were three oblique angles (0, 30, and 60°, Fig. 2) and three air-cannon pressures (0.28, 0.34, and 0.41 MPa) representing three cutting speeds. The experiment was replicated threefold. An additional an air-cannon pressure of 0.21 MPa was tried but it could not cut the stem except in the case of a 60° oblique cut. Similarly, an air pressure of 0.49 MPa was used for the straight cut but it required more energy to cut than the oblique cuts.

To study the effect of energycane diameter on the cutting energy, the second experiment was conducted with a 30° blade oblique angle and 0.34 MPa air-cannon pressure.

3. Results and discussion

To calculate cutting energy using Eq. (2), the moment of inertia of the cutting arm was determined. The mass, effective length and moment of inertia of the cutting arm were recorded for three oblique angle configurations (Table 1). It is clear that there was little difference in the effective length and moment of inertia of the cutting arm for the straight cut mount, and the oblique cut mounts of 30 and 60°. The results of this study are applicable for the selected variety, however they could also serve as reference for other varieties.

3.1. Specific cutting energy of energycane stems

Figure 3(a–c) show the specific cutting energy in joule per unit of stem diameter (J mm^{-1}) to cut an energycane stem, whereas Fig. 3(d–f) shows the specific cutting energy of the stem (J mm^{-2}). In all cases in Fig. 3, the specific energy increases with increasing cutting speed. This is in agreement with the maize stem study mentioned earlier (Prasad & Gupta, 1975),

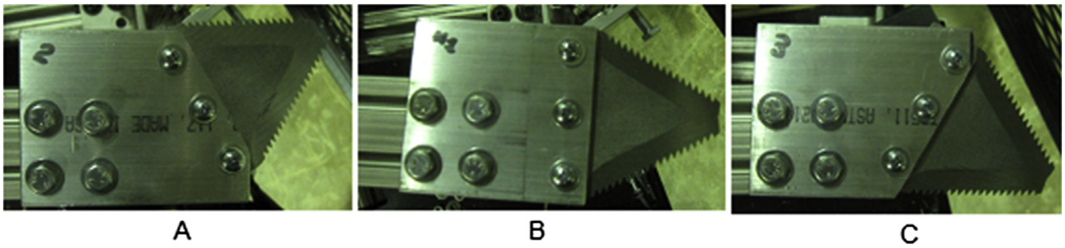

Fig. 2 – Serrated cutting blade mounted at (a) straight cut (0°), (b) 30° oblique cut, and (c) 60° oblique cut.

the sugarcane shear cutting energy study (Taghijarah et al., 2011), and the miscanthus cutting study (Johnson et al., 2012). However, it was not in agreement with forage grass studies (McRandal & McNulty, 1978), where the cutting energy decreased as the cutting speed decreased.

Specific cutting energy per unit stem diameter correlated better with cutting speed than specific cutting energy per unit area did, as seen in Fig. 3a–c and Fig. 3d–f, respectively. The correlations of cutting speed with specific cutting energy per unit stem diameter were 0.51, 0.55, and 0.73 for the three selected blade oblique angles 0, 30, and 60° respectively (Fig. 3a–c). The correlations of cutting speed with specific cutting energy per unit stem cross-sectional area were 0.42, 0.31, and 0.60 respectively (Fig. 3d–f). The correlations of specific cutting energy with cutting speed were affected by the blade oblique angle (Fig. 3).

The best correlation was 0.73 for the 60° oblique angle with specific cutting energy per unit diameter (Fig. 3c). A comparison of serrated and flat blades for cutting miscanthus stem showed that the serrated blade cut the stem in small segments of tissue whereas the flat blade cut large portions of stem cross-section at a time (Liu et al., 2012). This may also explain why in this study, the energycane stem diameter was more strongly correlated with the cutting energy when using a serrated blade.

Table 2 shows the average cutting energy required to cut energycane stems in relation to the average stem diameter and average cutting speed. The lowest average specific cutting energy was 0.26 J mm^{-1} for the 60° oblique cut at an average cutting speed of 7.9 m s^{-1} among studied combinations of cutting speed and blade oblique angle, whereas the highest average specific cutting energy was 1.24 J mm^{-1} for the straight cut at an average cutting speed of 16.4 m s^{-1}. The average cutting energy was 16.5 J, for 13.6 mm average diameter stem at 16.4 m s^{-1} average cutting speed for the straight cut. The latter case was close to the reported cutting energy of approximately 16 J for 20 mm sugarcane stem at 20–22 m s^{-1} cutting speed (Kroes & Harris, 1996a, 1996b). It is evident that by selecting an optimal blade oblique angle and cutting speed, cutting energy can be reduced by a factor of five. These findings could significantly improve the efficiency of existing sugarcane harvesters, but they are even more important for improving the efficiency of comminution, where stems are cut many times to achieve a desired particle size.

For the straight cut at 0.28 MPa air pressure, occasionally partial cutting was observed (Fig. 4a) when the stem diameter was larger but it was possible to cut thin stems (<15 mm, Fig. 4b). With 0.28 MPa compressed air pressure, the cutting arm achieved about 10.7 m s^{-1} average cutting speed which means it contained about 15.6 J of kinetic energy. Table 2 shows that the energy required to cut the energycane stems of 12–15 mm in diameter was approximately 12–15 J. This explains why at lower cutting speeds the cutting arm, possessing a low energy (approximately 15 J), was not able to cut the energycane stems. It can be hypothesised that with a heavier cutting arm, which has a higher moment of inertia, it would be possible to cut the energycane stems at cutting speeds lower than 10 m s^{-1}. Figure 4b also indicates that cutting progressed gradually up to half to two-thirds of the stem diameter (Liu et al., 2012) after which the stem failed under its own weight in bending and/or impact of the cutting arm. On the other hand, Fig. 4a indicates that if the cutting arm did not possess enough energy to shear the stem or continue cutting, or the stem could not break in bending by its own weight, it was incapable of completely cutting the stem.

It appears that at cutting speeds below 10 m s^{-1} the bending resistance of the remaining stem section was strong enough to oppose the cutting arm impact. Similarly, the conclusion was drawn for sorghum stems, that the impact force was too small to cut the stem at a cutting speed less than 3 m s^{-1} (Yiljep & Mohammed, 2005). From the results of the energycane study in this research, it may be noted that the critical cutting speed appears to be about 12–15 m s^{-1}. This critical cutting speed is close to the critical cutting speed (13.8–18.4 m s^{-1}) reported for sugarcane (Gupta & Oduori, 1992). For sorghum, a critical cutting speed between 5.2 and 7.3 m s^{-1} was reported (Yiljep & Mohammed, 2005). Overall, it may be concluded that modifications in existing sugarcane harvesting machinery might result in improving quality of cut and savings in cutting energy.

Table 1 – Moment of inertia of the cutting arm for various blade oblique angles.

Blade configuration	Mass (kg)	Effective length, (m)	Moment of inertia, (kg m^2)
Straight cut (0°)	2.59	0.044	0.017
Oblique cut (30°)	2.58	0.045	0.018
Oblique cut (60°)	2.59	0.044	0.017

3.2. *Energycane stem size and cutting energy*

Figure 5 shows the effect of stem size on cutting energy for the 30° oblique cut using 0.28 MPa air cannon pressure. Figure 5(a) shows the required cutting energy to cut an individual

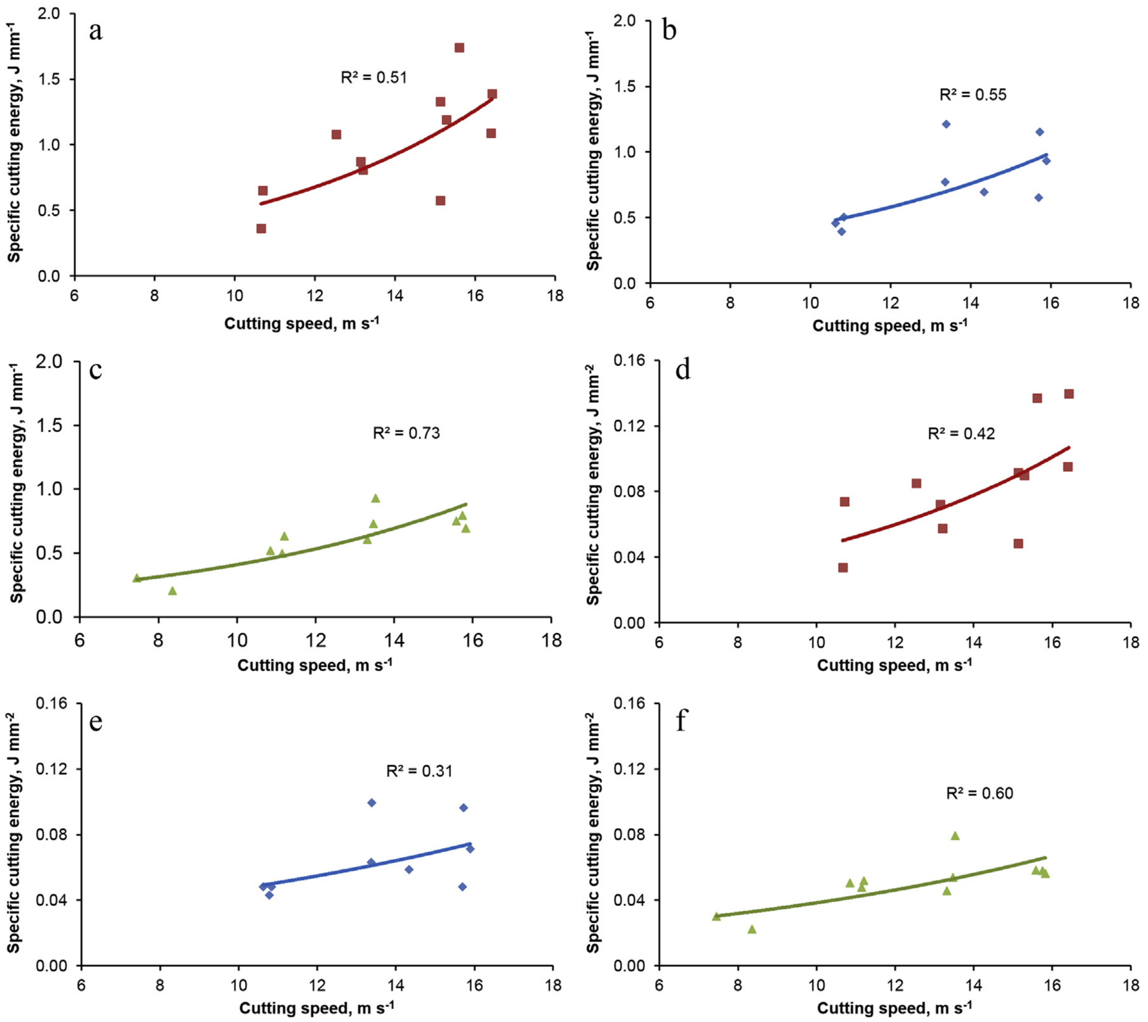

Fig. 3 – **Relationship between specific cutting energy per unit of stem diameter and cutting speed (a, b, c) and between specific cutting energy per unit of stem cross sectional area and cutting speed (d, e, f); (a) Specific cutting energy per mm stem diameter versus cutting speed at 0° straight cut; (b) Specific cutting energy per mm stem diameter versus cutting speed at 30° oblique cut; (b) Specific cutting energy per mm stem diameter versus cutting speed at 60° oblique cut; (d) Specific cutting energy per mm^2 stem cross sectional area versus cutting speed at 0° straight cut; (e) Specific cutting energy per mm^2 stem cross sectional area versus cutting speed at 30° oblique cut; (f) Specific cutting energy per mm^2 stem cross sectional area versus cutting speed at 60° oblique cut.**

Table 2 – Effect of blade oblique angle and cutting speed on specific cutting energy for energycane stems.

Cutting blade angle (degrees)	Air-cannon pressure (MPa)	Diameter in cutting direction (a)[a] (m)	Diameter in direction perpendicular to the cutting direction (b)[a] (m)	Initial cutting arm speed (ω_i)[a] (standard deviation) (m s^{-1})	Final cutting arm speed (ω_f)[a] (standard deviation) (m s^{-1})	Cutting energy per stem (E_c)[a] (J)	Specific cutting energy per unit stem diameter[a] (J mm^{-1})
0	0.28	12.4	12.1	10.7 (0.03)	8.3 (0.93)	6.1	0.51
0	0.34	16.5	16.5	13.0 (0.37)	7.5 (1.67)	15.1	0.92
0	0.41	16.7	16.0	15.3 (0.23)	9.1 (3.09)	19.8	1.21
0	0.49	13.6	13.3	16.4 (0.02)	12.2 (0.75)	16.5	1.24
30	0.28	12.4	11.8	10.7 (0.11)	8.8 (0.32)	5.3	0.45
30	0.34	15.4	14.1	13.7 (0.56)	9.8 (2.19)	12.6	0.89
30	0.41	16.4	15.4	15.8 (0.11)	12.2 (1.00)	14.0	0.91
60	0.21	12.5	12.4	7.9 (0.64)	6.2 (1.33)	3.2	0.26
60	0.28	14.0	15.0	11.1 (0.19)	7.8 (0.77)	8.4	0.55
60	0.34	16.4	16.6	13.4 (0.11)	9.4 (0.53)	12.4	0.76
60	0.41	16.5	15.9	15.7 (0.12)	12.6 (0.44)	11.9	0.75

[a] Average of three replications.

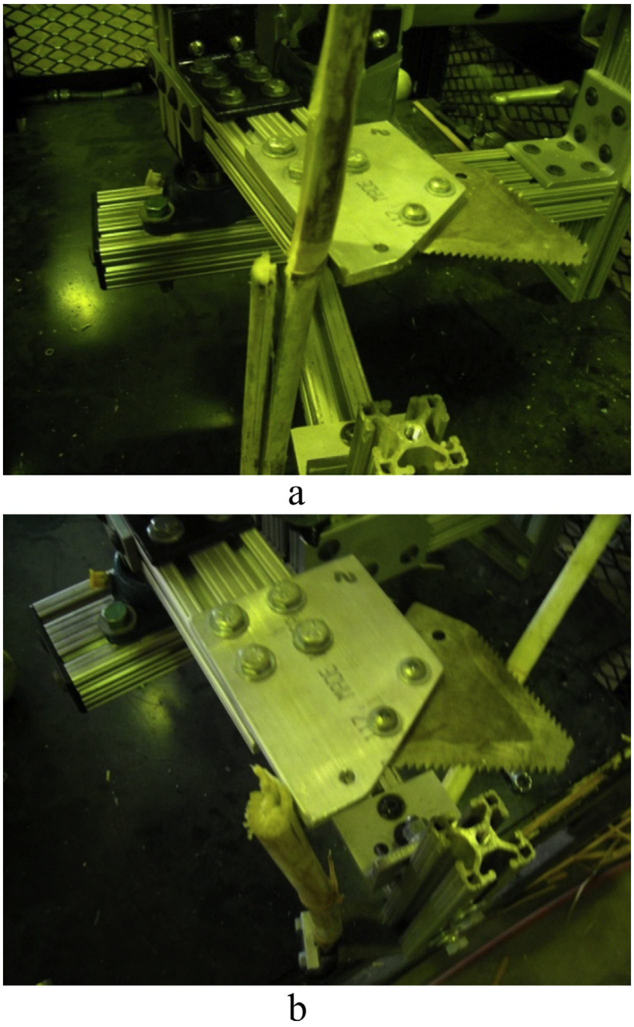

Fig. 4 – **Cutting of energycane stems at lower cutting speed (<10 m s^{-1}) showing stem splitting for a large stem diameter (a), and cutting and shearing of the stem at high speed (b).**

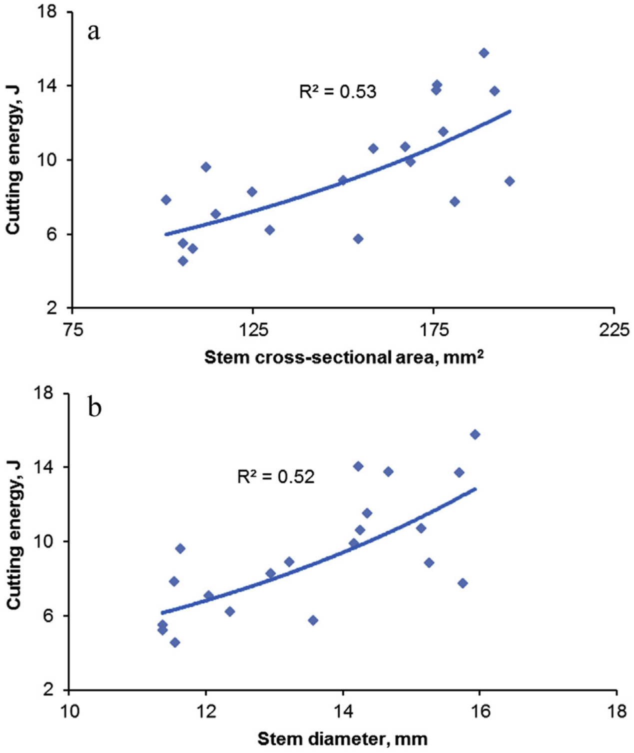

Fig. 5 – **Effect of stem properties on cutting energy required to cut an energycane stem at an average cutting speed of 11.2 ms^{-1} at a 30° oblique angle; (a) Cutting energy versus stem diameter; (b) Cutting energy versus stem cross-sectional area.**

energycane stem as influenced by the stem diameter and Fig. 5(b) as affected by its cross-sectional area. The average stem diameter in the cutting direction was 13.9 ± 1.6 mm and the average cross-sectional area was 149.3 ± 33.2 mm^2, whereas the average cutting speed was 11.2 m s^{-1}. The average cutting energy per stem for a cross-sectional area less than 125 mm^2 was 6.9 J, for a cross-sectional area between 125 and 175 mm^2 it was 9.2 J, and for a cross-sectional area greater than 175 mm^2 it was 12.2 J. Similarly, the average specific cutting energy for a stem diameter less than 12 mm was 5.8 J, for a stem diameter between 12 and 15 mm it was 8.0 J, and for a stem diameter greater than 15 mm it was 12.0 J. In conclusion, the cutting energy was found to be proportional to both stem diameter and cross-sectional area. These results are in agreement with other plant cutting studies (Igathinathane et al., 2010; Kroes & Harris, 1996a, 1996b; Prasad & Gupta, 1975). For sugarcane stems, the cutting energy varied from approximately 15 to 25 J as the stem diameter varied from 20 to 30 mm (Kroes & Harris, 1996a, 1996b). In this study, it varied from 4.5 to 15 J as the energycane stem diameter varied from 11 to 17 mm. It may be concluded that stem diameter has strong influence on cutting energy requirement and considerable energy saving could be achieved by modifying the machinery developed originally for use with sugarcane for use with energycane.

4. Conclusions

An air-cannon powered impact type cutting mechanism was used to determine the energy required to cut individual energycane stems at various oblique angles and cutting speeds. The cutting energy per unit of either stem diameter or cross-sectional area was found to increase with the cutting speed. Specific cutting energy per unit stem diameter correlated better with cutting speed than specific cutting energy per unit area.

The lowest average specific cutting energy was 0.26 J mm^{-1} for a 60° oblique cut at an average cutting speed of 7.9 m s^{-1} among studied combinations of cutting speeds and blade oblique angles. The highest average specific cutting energy was 1.24 J mm^{-1} for the straight cut at an average cutting speed of 16.4 m s^{-1}. It is evident that by selecting an optimal blade oblique angle and cutting speed, the cutting energy could be reduced by a factor of five. The experiments on energycane stems in this study led to the conclusion that a lower blade cutting speed translates into a lower harvester speed if other parameters are kept constant. It would be possible to improve or maintain current harvester speeds by adopting wider cutting blades or a higher number of blades on rotary harvesting cutters. For the 30° oblique angle at 11.3 m s^{-1} average cutting speed, the cutting energy varied from 4.5 to 15 J as the energycane stem diameter varied from 11 to 17 mm. Comparison with sugarcane studies indicated that optimisation of cutting speed and blade oblique angle will result in significant savings in cutting energy and improvement in quality of cut. The results of this study are applicable for the selected crop variety, however, they could serve as a reference for other varieties. This study emphasises the need to further investigate the energycane cutting process especially at higher cutting speed with cutting mechanisms of varied moment of inertia.

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REFERENCES

Clementson, C., & Hansen, A. (2008). Pilot study of manual sugarcane harvesting using biomechanical analysis. *Transactions of the ASABE, 14*(3), 309–320.

DOE. (2010). *Annual energy outlook 2010. U.S. Department of energy*. Washington, DC: Energy Information Administration, Office of Integrated Analysis and Forecasting. http://www.eia.gov/oiaf/archive/aeo10/index.html Accessed 04.08.11.

Ghahraei, O., Ahmad, D., Khalina, A., Suryanto, H., & Othman, J. (2011). Cutting tests of Kenaf stems. *Transactions of the ASABE, 54*(1), 51–56.

Gupta, C., & Oduori, F. (1992). Design of the revolving knife-type sugarcane base cutter. *Transactions of the ASABE, 35*(6), 1747–1752.

Igathinathane, C., Womac, A., & Sokhansanj, S. (2010). Corn stem orientation effect on mechanical cutting. *Biosystems Engineering, 107*, 97–106.

Johnson, P., Clementson, C., Mathanker, S., Grift, T., & Hansen, A. (2012). Cutting energy characteristics of miscanthus stems with varying oblique angle and cutting speed. *Biosystems Engineering, 112*, 42–48.

Knoll, J., Anderson, W., Strickland, T., Hubbard, R., & Malik, R. (2011). Low-input production of biomass from perennial grasses in the coastal plain of Georgia, USA. *Bioenergy Research*, 1–9.

Kroes, S., & Harris, H. (1996a). *Cutting forces and energy during an impact cut of sugarcane stalks*. Madrid, Spain: EurAgEng.

Kroes, S., & Harris, H. (1996b). *Splitting of the stool during an impact cut of sugarcane stalks*. Madrid, Spain: EurAgEng.

Liu, Q., Mathanker, S., Zhang, Q., & Hansen, A. (2012). Biomechanical properties of miscanthus stems. *Transactions of the ASABE, 55*, 1125–1131.

McRandal, D., & McNulty, P. (1978). Impact cutting behaviour of forage crops. *Journal of Agricultural Engineering Research, 23*, 313–328.

Miao, Z., Grift, T., Hansen, A., & Ting, K. (2011). Energy requirement for comminution of biomass in relation to particle physical properties. *Industrial Crops and Products, 33*(2), 504–513.

Mislevy, P., & Fluck, R. (1992). Harvesting operations and energetics of tall grasses for biomass energy production: a case study. *Biomass and Bioenergy, 3*(6), 381–387.

Person, S. (1987). *Mechanics of cutting plant materials*. St. Joseph, Michigan: ASABE.

Prasad, J., & Gupta, C. (1975). Mechanical properties of maize stalk as related to harvesting. *Journal of Agricultural Engineering Research, 21*(1), 79–87.

Srivastava, A., Goering, C., Rohrbach, R., & Buckmaster, D. (2007). Hay and forage harvesting. In *Engineering principles of agricultural machines* (2nd ed.). (pp. 325–402). St. Joseph, Michigan: ASABE.

Taghijarah, H., Ahmadi, H., Ghahderijani, M., & Tavakoli, M. (2011). Cutting forces and energy during an impact cut of sugarcane stalks. *Australian Journal of Crop Science, 5*(6), 630–634.

Yiljep, Y., & Mohammed, U. (2005). Effect of knife velocity on cutting energy and efficiency during impact cutting of sorghum stalk. *Agricultural Engineering International: the CIGR EJournal., 8*.

Youngs, H., & Taylor, C. (2009). *EBI scenario series: Saccharum sp. to ethanol via dual fermentation, current to near-term technology, Louisiana-organic soil scenario*. Berkeley: Energy Biosciences Institute.