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Research Paper

Cutting energy characteristics of *Miscanthus x giganteus* stems with varying oblique angle and cutting speed

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Previous studies highlighted the need to develop efficient harvesting and size reduction equipment for miscanthus. This study investigated the effect of blade oblique angles and cutting speeds on cutting energy. Cutting blade speed, before and after severing a single miscanthus stem, was used to calculate the cutting energy. The cutting energy was determined at three oblique angles and three cutting speeds. A 60° oblique angle cut required the least energy to cut miscanthus stems averaging about 7.6 J whilst a 30° oblique cut averaged 8.7 J and a straight cut averaged 10.1 J. In general, the 60° oblique cut performed best since it required average lowest specific energy (energy per unit of stem diameter) of 741.9 J m^{-1} at an average cutting speed of 12.9 m s^{-1}. The specific cutting energy was directly proportional to the cutting speed and cutting energy was proportional to the stem diameter. The results indicate that optimisation of cutting speed and blade oblique angle will result in significant energy savings and increased efficiency of miscanthus harvesting machinery.

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1. Introduction

Increasing the share of renewable energy sources is proposed 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 USA 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 or supply approximately 17 EJ of energy by 2034 (DOE, 2010). A large portion is expected to come from biomass sources. However, biomass production raises several questions. To address these questions, the impact and feasibility of biomass production is being studied worldwide (Dohleman, Heaton, & Long, 2010; Jørgensen, 2011). Limited resources and sustainability of the biomass production system are common conclusion from these studies. Many alternative crops are being investigated and the expectation is that high yielding biomass crops would play a critical role. *Miscanthus x giganteus*, hereafter referred as *M. x giganteus*, is emerging as one of the most promising crops suitable for biomass production because it requires low inputs and produces high yields (Heaton, Flavell et al., 2008).

The high-yielding sterile C-4 perennial grass *M. x giganteus* outperformed switchgrass, maize, and other competing crops in trials in Illinois, USA and in Europe. Heaton et al. (2010) reviewed *M. x giganteus* yield studies from Europe and the USA. Average yields ranged from 5 to 55 Mg ha^{-1} making it one

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Nomenclature

E_c	energy required to cut miscanthus stem, J
I	moment of inertia of the cutting arm, kg m^{-2}
ω_i	initial speed of cutting arm before cutting stem, rad s^{-1}
ω_f	final speed of cutting arm after cutting stem, rad s^{-1}
F_{scale}	force applied by scale, N
L_{scale}	length from axis of rotation to force application point on scale, m
m	mass of the cutting arm, kg
g	acceleration owing to gravity, m s^{-2}
L_e	effective length of the cutting arm, m.
θ	angular position, rad
$\dot{\theta}$	angular velocity, rad s^{-1}
$\ddot{\theta}$	Angular acceleration, rad s^{-2}
b	viscous damping coefficient, kg m^2 s^{-1}

of the most productive land plants in temperate climates. Christian, Riche, and Yates (2008) reported that *M. x giganteus* yields were consistent over a period of 14 years with only 5% variation and averaged 12.8 Mg ha^{-1}. Yield trials in the USA started much later because the initial focus was on switchgrass. The trials in Illinois averaged 30 Mg ha^{-1} without irrigation and with only 25 kg ha^{-1} of N fertiliser applied in one season (Heaton, Dohleman, & Long, 2008). The yield levels were 2–4 times higher than the regionally adapted *Cave-In-Rock* switchgrass variety. However, Aravindhakshan, Epplin, and Taliaferro (2010) reported that the switchgrass variety *Alamo* produced more biomass (15.87 Mg ha^{-1}) than *M. x giganteus* (12.39 Mg ha^{-1}) in Oklahoma, USA. Dohleman and Long (2009) reported that *M. x giganteus* was 60% more productive in the USA 'Corn Belt' compared to another candidate biomass crop, maize.

Higher yield might be the driving selection criterion for *M. x giganteus* but it must also meet sustainability and economic criteria. Based on an extensive review of studies, Heaton et al. (2010) concluded that *M. x giganteus* holds great promise as an economically and ecologically viable biomass crop. Jørgensen (2011), while investigating sustainability, concluded that *M. x giganteus* was a very promising bioenergy crop having a number of benefits over other potential bioenergy crops. The demonstrated potential of *M. x giganteus* as bioenergy crop suggests the need to extensively evaluate existing farm machinery to minimise risk and to reduce costs. Planting rhizomes and harvesting are the two major farm operations and might require specialised equipment. The *M. x giganteus* growing season in Illinois, USA starts in April and typically ends in October after the first hard frost. At the end of the growing season, *M. x giganteus* drops leaves and the senesced stems are harvested from November through to March.

In Europe, planting and harvesting equipment were investigated early on by Huisman and Kortleve (1994). It was suggested that mowing and baling could be combined into one operation. The USA manufacturers and research institutions are also investigating equipment systems for cutting, conditioning, windrowing, and baling to improve efficiency and effectiveness. Generally, traditional hay equipment has worked well but it is has to be operated at a slower rate than for hay crops because of the higher plant density and the toughness of the *M. x giganteus* stems (Anderson et al., 2011). The optimum height of cut should be 50–100 mm but some harvesting equipment left stems of more than 0.3 m in height (Heaton et al., 2010). The authors, whilst conducting evaluation of a forage chopper, noticed unequal height of cut and splitting of stems. Heaton et al. (2010) also reported that more than 2 Mg ha^{-1} biomass was left in the field. Thus, one of the challenges for large-scale introduction of *M. x giganteus* production is inefficiency in the available hay and straw harvesting equipment. Based on a survey of literature, it was expected that studying cutting processes would play a critical role in improving the efficiency of harvesting equipment for *M. x giganteus*.

In general, the mechanical properties of plant materials differ from manmade materials. Plant materials are viscoelastic, therefore they possess no strictly defined relationship between stress and deformation. Instead deformation is a function of time (creep), and the modulus of elasticity is variable. Plant materials also behave differently under tensile and compressive forces, and also under static and dynamic loading (Person, 1987). Cutting of the plant stem occurs when the pressure caused by the blade reaches a critical value. Plant cutting results in multiple modes of tissue failure. Initial knife penetration results in localised plastic deformation, followed by significant buckling and deformation as the knife advances (Person, 1987). The plant stem is deformed and compressed ahead of and to the sides of the knife. As the knife continues to advance the fibres composing the stem are deflected and eventually fail in tension (Srivastava, Goering, Rohrbach, & Buckmaster, 2007, chap. 11).

Relatively few studies have been published regarding the basic cutting dynamics of bioenergy crops. However, there are a number of studies examining forage and other crops. Relevant studies are briefly summarised here. Prasad and Gupta (1975) reported that cutting energy increased with maize stem diameter. Initially, as the cutting speed increased the cutting energy reduced but then the cutting energy began to increase as the cutting speed further increased. They could not assign any reason for this phenomenon. McRandal and McNulty (1978) found that crop yield was the most important factor affecting power consumption and it accounted for 46% of the power variations in field tests. O'Dogherty and Gale (1991) reported that the critical cutting speed for grass was 25–30 m s^{-1}. Speeds lower than the critical speed resulted in large stem deflections and higher stubble heights. Tuck, O'Dogherty, Baker, & Gale (1991) defined the cutting speed as the speed below which there is a rapid increase in stubble length as cutting becomes rapidly less efficient. Gupta and Oduori (1992) found that 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. Ghahraei, Ahmad, Khalina, Suryanto, and Othman (2011) found an optimum knife edge angle, knife shear angle, knife approach angle or oblique angle, and knife rake angle as 25°, 40°, 40°, and 40°, respectively for *Kenaf* stems. Taghijarah, Ahmadi, Ghahderijani, and Tavakoli (2011) reported that the specific shearing energy was directly proportional to the loading rate and recommended lower rates of blades to reduce the energy requirement for harvesting sugarcane stems.

The studies related to bioenergy crop harvesting and cutting are discussed here. Lewandowski, Clifton-Brown, Scurlock, and Huisman (2000) based on 10 years of *M. x giganteus* experiments in Europe, reported that harvesting machinery will need to be adapted to the height and stiffness of the *M. x giganteus* stems and that grass mowers do not work well. The mowing attachment for a maize chopper worked well but the cutting height was kept high to avoid jamming. The mowing attachment needed to be row-independent with a low cutting height. Kaack and Schwarz (2001) determined morphological and mechanical properties of the *M. x giganteus* stem. The moment of inertia was higher for internodes than the nodes, whereas the modulus of elasticity was low for internodes. However, flexural rigidity was highest for internodes. Igathinathane, Womac, and Sokhansanj (2010) reported that the total cutting energy of internodes and nodes varied significantly with stem cross-sectional area. The specific energy per unit cut area of dry maize stem internodes ranged from 11.3 to 23.5 kN m^{-1}, and nodes from 8.6 to 14.0 kN m^{-1}. Also, besides harvesting, size reduction plays a critical role in bioenergy feedstock logistics. Yu, Womac, Igathinathane, Ayers, and Buschermohle (2006) found that size reduction using shear failure rather than tensile failure is expected to be more energy efficient. Igathinathane, Womac, Sokhansanj, and Narayan (2009) also reported that a shearing cut was efficient for size reduction of maize stems. Miao, Grift, Hansen, and Ting (2011) reported that miscanthus size reduction by hammer mills performed better than knife mills represented by different cutting mechanisms. They reported that size reduction to 1 mm size consumed 1.5–10% of the inherent heating value.

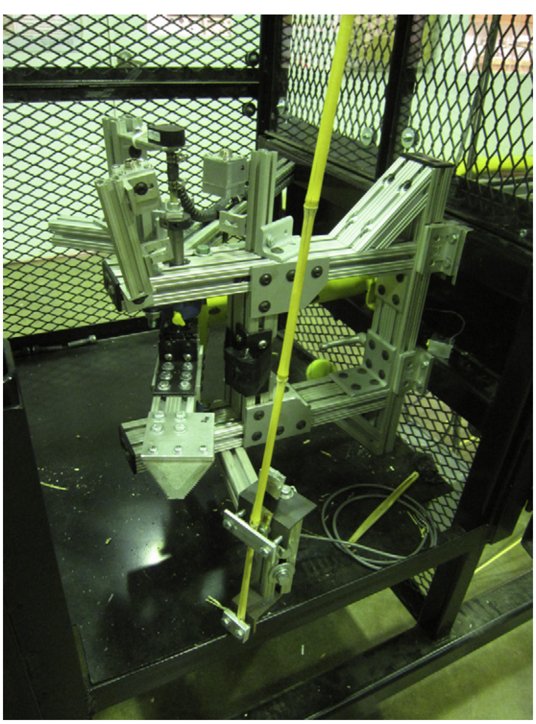

Fig. 1 – *M. x giganteus* stem and cutting arm ready for the 30° oblique cut.

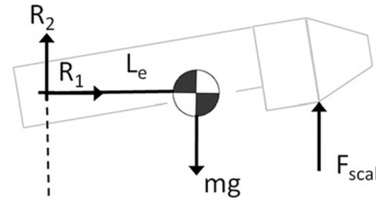

Fig. 2 – Experiment to locate the centre of gravity, shown using free body diagram of the cutting arm.

Thus, harvesting technology for *M. x giganteus* is an active area of research but few studies have been published (Anderson et al., 2011). A critical analysis of literature surveyed indicated that cutting speed and blade geometry, especially oblique angle, play a critical role in the plant material cutting process. To improve harvesting and size reduction processes, the objectives of this study were to develop an impact type cutting apparatus for bioenergy crops; to investigate the effect of cutting blade oblique angle and cutting speed on the cutting energy required for single *M. x giganteus stems*; and effect of *M. x giganteus* stem diameter on cutting energy.

2. Materials and methods

2.1. Experimental setup

The experimental setup consisted of an impact type cutting arm rotating freely around a pivot (Fig. 1). The impact force to the cutting arm was provided through an air-cannon cylinder filled with compressed air. The volume of the cannon cylinder before expansion was 0.028 m^3 and the volume after expansion, including the barrel volume, was 0.035 m^3. When the compressed air was released, simulating firing of cannon, a tennis ball (simulating a shell) was propelled along the cylinder by the compressed air. The tennis ball struck the freely pivoting cutting arm resting on the muzzle of the air-cannon. This set the cutting arm in motion to cut the *M. x giganteus* stem, which was tightly clamped in a vertical position (Fig. 1). A cutting blade mounted on the rotating cutting arm cut the *M. x giganteus* stem. The angular position of the

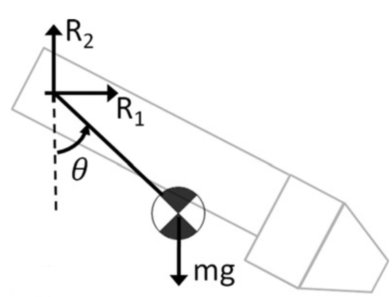

Fig. 3 – Measurement of pendulum-like response of the cutting arm, shown with its free body diagram.

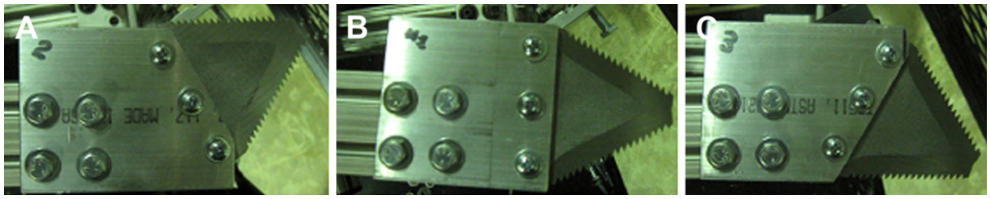

Fig. 4 – Serrated cutting blade mounted at different oblique angles representing: straight cut (0°) (A), 30° oblique cut (B), and 60° oblique cut (C).

cutting arm was recorded by a digital optical encoder with 0.175° angular resolution (US Digital, Washington USA) sampled at 100 kHz. The average speed of the cutting arm was determined by fitting a linear regression model. It was assumed that the cutting arm travelled at a constant speed when it is not cutting the *M. x giganteus* stem. The developed cutting apparatus was equipped with safety devices to isolate users from its fast moving parts, to prevent accidental pressurisation or firing, and to stop the speeding cutting arm after severing the stem. A control program in LabVIEW® (National Instruments Corporation, Texas USA) was written to control the apparatus and acquire the data.

Before contacting the *M. x giganteus* stem, the cutting arm is assumed to have reached a constant speed. When the cutting blade contacts the stem the cutting process starts and the speed of the cutting arm reduces as it loses energy while cutting the *M. x giganteus* stem. When the cutting process ends, the speed of the cutting arm becomes constant again. The energy lost during stem cutting can be determined as:

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

where: E_c = energy required to cut *M. x giganteus* stem (J); I = moment of inertia of the cutting arm (kg m^2); ω_i = initial speed of cutting arm before cutting stem (rad s^{-1}); ω_f = final speed of cutting arm after cutting stem (rad s^{-1}).

Fig. 2 shows the experiment used to locate the centre of gravity of the cutting arm. The centre of gravity of the cutting arm was estimated by recording the weight of the arm as it rested partially on a balance. The height of the balance in Fig. 2 was carefully adjusted until the arm was perpendicular to its rest position. Summing moments about the axis of rotation of the cutting arm (Fig. 2) gives:

$$mgL_e = F_{scale} L_{scale} \tag{2}$$

where: m = mass of the cutting arm (kg); g = acceleration due owing to gravity (m s^{-2}); L_e = effective length of the cutting arm (m). F_{scale} = force applied by scale (N); L_{scale} = length from axis of rotation to force application point on scale (m).

Solving Eq. (2) gives the effective length of the cutting arm (L_e) and thereby the centre of gravity. Figure 3 shows the experiment used to record the natural pendulum-like response of the arm to determine the moment of inertia. The axis of rotation of the cutting arm was oriented horizontally to allow it to swing freely owing to gravity. Figure 3 also illustrates the forces acting on the pendulum in this configuration. Taking the sum of the moments about the axis of rotation of the pendulum (cutting arm) gives:

$$\ddot{\theta} + \frac{b}{I}\dot{\theta} + \frac{m_c g L_e}{I}\sin(\theta) = 0 \tag{3}$$

where: $\theta, \dot{\theta}, \ddot{\theta}$ = the angular position (rad), velocity (rad s^{-1}), and acceleration of the cutting arm (rad s^{-2}); b = viscous damping coefficient (kg m^2 s^{-1}).

The coefficients in Eq. (3) (b/I, $m_c g L_e/I$) and the initial angle of the pendulum (θ_0) were adjusted until the recorded response of the pendulum matched with the ideal solution. The initial velocity of the pendulum $\dot{\theta}$ was assumed zero. This optimisation was performed by solving Eq. (3) using 'ode45' and 'lsnonlin' functions of Matlab® (Mathworks, MA USA). Equating the coefficient ($m_c g L_e/I$) to the coefficient value obtained by modelling and substituting known values (m_c, g, and L_e) the moment of inertia of the cutting arm was calculated.

2.2. *Miscanthus cutting energy experiments*

M. x giganteus stems were collected from a mature second year planting after overwintering in March, 2011. The stems were cut close to the ground leaving 10–40 mm high stubbles. Moisture content, weight, height, and diameter of the stems were recorded. Single *M. x giganteus* stems were held in vertical position in the test assembly with their bases held firmly in place similar to the root structure of *M. x giganteus* plants in the field (Fig. 1). The diameter of the stem was measured where the cutting blade was expected to cut the stem. The stem diameter represented the travelled distance of the cutting blade to cut the *M. x giganteus* stem assuming minimal deflection of the stem. The first

Table 1 – Moment of inertia of the cutting arm for different oblique angle configurations.

Blade configuration	Mass, m_c (kg)	Effective length, L_e (mm)	Coefficient of dynamic model (Eq. (3)), $m_c\ g\ L_e/I$ (s^{-2})	Model R^2	Moment of inertia, I (kg m^2)
Straight cut (0°)	2.59	44.1	65.6	0.99	0.0171
Oblique cut (30°)	2.58	44.8	64.2	0.99	0.0177
Oblique Cut (60°)	2.59	44.3	66.3	0.99	0.0170

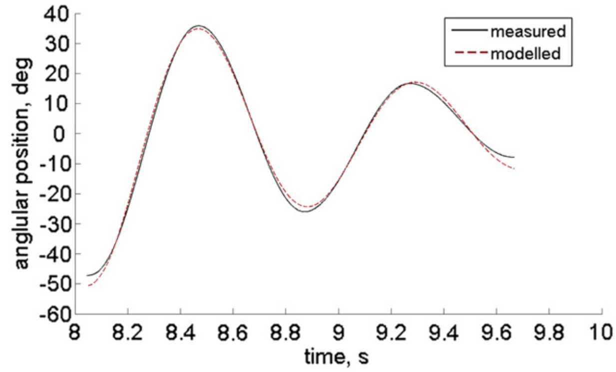

Fig. 5 – Recorded and modelled response of the cutting arm.

experiment was conducted to study the effect of oblique angles and cutting speed on the cutting energy. The parameters were: three oblique angles (0, 30, and 60°) (Fig. 4); three air-cannon pressures (0.10, 0.14, and 0.17 MPa) representing three cutting speeds; and two stem cutting positions (node and internode). To study the effect of *M. x giganteus* diameter on the cutting energy the data from above experiments were pooled and the effect of the oblique angles and the air-cannon pressures (cutting speeds) was studied.

3. Results and discussion

3.1. *Moment of inertia and cutting speed*

To calculate the stem cutting energy, the moment of inertia of the cutting arm was calculated. The mass and effective lengths of the cutting arm were recorded for three oblique angle configurations and are given in Table 1. The recorded and modelled response of the cutting arm, as a freely rotating pendulum, is shown in Fig. 5. By equating the coefficient ($m_c g L_e / I$) in Eq. (3) with the modelled value and substituting known values, the moment of inertia was calculated as shown

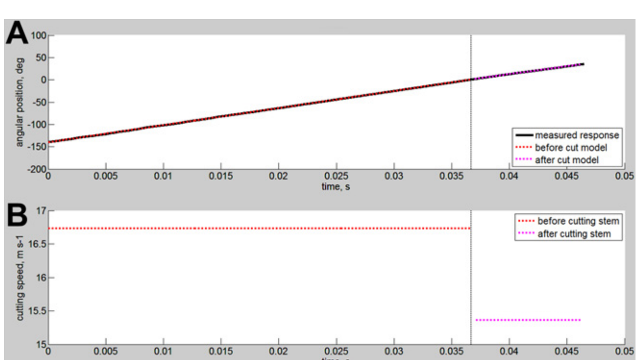

Fig. 6 – A) Angular movement of the cutting arm, B) estimated speed of the cutting arm, before and after cutting the *M. x giganteus* stem.

in Table 1. Fig. 5 shows that the recorded and modelled response matched well indicating that the cutting arm behaved similar to a freely rotating pendulum. There was little difference between the effective length of cutting arm and moment of inertia values for all three oblique angle configurations of the cutting arm (Table 1).

In addition to moment of inertia, cutting speed of the cutting arm before and after cutting was required to determine the cutting energy (Eq. (1)). A typical angular movement of the cutting arm recorded from the encoder is shown in Fig. 6A. The speed of the cutting arm was determined by fitting a straight line to the motion of the cutting arm. It was assumed that the speed of the cutting arm before and after cutting the *M. x giganteus* stem was constant. Typical estimated values of the cutting speeds are shown in Fig. 6B corresponding to the curve in Fig. 6A.

3.2. *Cutting miscanthus node and internode*

Fig. 7A shows the specific cutting energy in joules per unit of *M. x giganteus* stem diameter (J m^{-1}), to cut the *M. x giganteus*

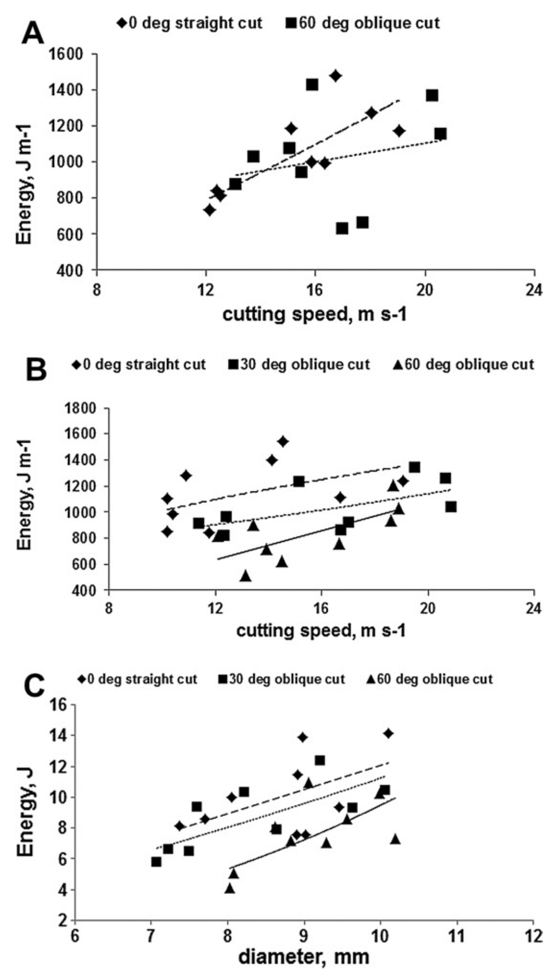

Fig. 7 – A) Effect of blade oblique angle on cutting energy to cut *M. x giganteus* stem at the node. B) Effect of blade oblique angle on cutting energy to cut miscanthus stem at the internode. C) Effect of blade oblique angle and miscanthus stem diameter on cutting energy.

Table 2 – Cutting energy required to cut 1 ha *M. x giganteus* crop for different blade oblique angles and cutting speed.

Blade oblique angle	Low cutting speed		Medium cutting speed		High cutting speed	
	Cutting speed ($m\ s^{-1}$)	Cutting energy ($MJ\ ha^{-1}$)	Cutting speed ($m\ s^{-1}$)	Cutting energy ($MJ\ ha^{-1}$)	Cutting speed ($m\ s^{-1}$)	Cutting energy ($MJ\ ha^{-1}$)
0.0	10.5	8.4	14.3	10.0	16.6	9.9
30.0	12.0	6.7	16.3	7.5	20.3	9.1
60.0	12.9	5.6	15.0	5.2	18.7	7.9

stem at the node. The specific cutting energy was directly proportional to the cutting speed at the node. For the straight cut, the effect was well pronounced but for the 60° oblique it was not well pronounced. The cutting energy for the straight cut increased until 16 $m\ s^{-1}$ cutting speed. The average specific energy was 1057.3 ± 244.3 $J\ m^{-1}$ for the straight cut and 1017.2 ± 276.3 $J\ m^{-1}$ for the 60° oblique cut. Fig. 7B shows the specific cutting energy ($J\ m^{-1}$) required for cutting a *M. x giganteus* stem at the internode. For selected blade oblique angles, the cutting speed was directly proportional to the cutting energy required. The average specific energy was 1151.3 ± 240.6 $J\ m^{-1}$ for the straight cut and 1037.9 ± 191.7 $J\ m^{-1}$ for the 30° oblique cut. The 60° oblique cut required the lowest average cutting energy of 833.3 ± 212.9 $J\ m^{-1}$.

For the 60° oblique cut, the average specific energy was 741.9 $J\ m^{-1}$ and the average cutting speed of 12.9 $m\ s^{-1}$ yielding the optimal combination of cutting speed and oblique angle. On the other hand, at average higher speed of 18.7 $m\ s^{-1}$ the average specific energy was 1058.3 $J\ m^{-1}$. The optimum oblique angle and higher speed appeared to contribute significantly to reduce specific cutting energy requirement and these results were in agreement with Taghijarah et al. (2011) who reported specific shear energy increased as the loading rate increased and recommended a lower speed for harvesting operations for sugarcane. Prasad and Gupta (1975) reported that, for maize stems, at higher cutting speeds the cutting energy increased. It appears that more energy is transferred to the stem at higher speeds which might be absorbed in impact, vibration, and deflection.

The cutting energy required to cut one ha of miscanthus was calculated and is presented in Table 2. It was assumed that stem density was 75 stems per m^2 (Danalatos, Archontoulis, & Mitsios, 2007) and an average stem diameter of 10 mm was assumed based on observations of this study. The energy saving by optimising blade oblique angle and cutting speed would be about 4.3–4.8 $MJ\ ha^{-1}$or about 43.4–48%. Based on findings of this study, it might be worthwhile exploring the possibility of using oblique blade angles and optimising cutting speeds in commercial disc mowers with flat and serrated blades as well as with fixed and flexible blade mountings. The trends found in this study for serrated blade were similar to those for flat blades (Prasad & Gupta, 1975; Taghijarah et al., 2011) so it might be expected that similar trends would be possible with commercial disc mowers.

3.3. *Miscanthus diameter and oblique angles*

Figure 7C shows the effect of the *M. x giganteus* diameter and oblique angles on the cutting energy required. The highest cutting energy was required for the straight cut and the lowest energy for the 60° oblique cut. In general, as stem diameter increased more cutting energy was required. For a straight cut, the average cutting energy was 10.07 ± 2.56 J and the average diameter was 8.72 ± 0.86 mm. Similarly, for the 30° oblique cut the average cutting energy was 8.73 ± 2.19 J and average diameter was 9.25 ± 0.97 mm; for the 60° oblique cut, the average cutting energy was 7.62 ± 2.20 J and average diameter was 9.07 ± 0.77 mm. The 60° oblique cut required the lowest cutting energy with a lower standard deviation indicating a more efficient cut (Tuck et al., 1991). It should be noted that the 60° oblique cut also required the lowest specific cutting energy at various cutting speeds (Fig. 7B).

4. Conclusion

An air-cannon powered pendulum type cutting mechanism was designed and used in a miscanthus (*M. x giganteus*) stem cutting study. The specific cutting energy ($J\ m^{-1}$) to cut the *M. x giganteus* stems was directly proportional to the cutting speed. The 60° oblique cut required the least amount of energy to cut *M. x giganteus* stems, averaging approximately 7.62 J. The 30° oblique cut averaged 8.73 J and the straight cut averaged 10.07 J. In general, the 60° oblique cut performed the best and the average lowest specific energy was 741.97 $J\ m^{-1}$ with an average cutting speed of 12.9 $m\ s^{-1}$. Cutting energy was proportional to the stem diameter. The results demonstrate that optimisation of cutting parameters and cutting blade oblique angle will result in cutting energy savings and in a more efficient cuts, thus reducing biomass loss in the field. This study further indicates the need to investigate the *M. x giganteus* cutting process in detail to understand the cutting process in commercial disc mowers with flat and serrated blades and also with fixed and flexible blade mountings. Further studies would help in developing the efficient *M. x giganteus* harvesting and size reduction equipment required for the large-scale introduction of *M. x giganteus* as a bioenergy crop.

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