Original Article
Journal of Biosystems Engineering

J. of Biosystems Eng. 39(4):253-260. (2014. 12)
http://dx.doi.org/10.5307/JBE.2014.39.4.253

eISSN : 2234-1862
pISSN : 1738-1266

Required Mowing Power and Bale Density of *Miscanthus × Giganteus* for Field Biomass Harvesting using Different Methods

Hyeon-Jong Jun*, Il-Su Choi, Tae-Gyoung Kang, Yong Choi, Duck-Kyu Choi, Choung-Keun Lee

National Academy of Agricultural Science, Rural Development of Administration, Jeonju, Korea

Received: September 13rd, 2014; Revised: November 4th, 2014; Accepted: November 25th, 2014

Abstract

Purpose: This study investigated the harvesting properties of the giant miscanthus (Miscanthus × giganteus) to measure the required mowing power for different stem conditioning methods in order to shorten the drying time after mowing and the bale density so that the crop can be used as biomass in the winter season. **Methods:** The required mowing power and bale density were measured using a power measurement device, three different mower-conditioners, and a mid-sized round baler under different working speeds and conditioning methods. **Results:** For the various mower-conditioners, the average stem length from mowing was 0.86–0.91 m, and the available working speed was 1.6 m/s. The steel roller-type mower-conditioner showed better stem conditioning but could not mow over a working speed of 1.6 m/s. The required average power of the mower-conditioners varied from 23.8 kW for the steel roller-type rotary disk mower-conditioner with a working width of 2.4 m to 37.2 kW for the flail-type rotary disk mower-conditioner with a working width of 3.2 m at a working speed of 1.6 m/s. The bale densities were 155.8–172.2 kg/m^3. The highest bale density was measured for stems with no conditioning and a moisture content of 11.3% (d.b.) mowed by the rotary disk mower. The bale density was affected by the mowing method because of the low moisture content of the miscanthus stems. **Conclusions:** In terms of the working performance and conditioning statue, the steel roller-type mower-conditioner is a better choice at a working width of 2.4 m, while the flail finger-type mower-conditioner is better at a working width of 3.2 m. The type of mower-conditioner used for giant miscanthus harvesting should be determined by considering the harvest area, workable period, and working performance of a mower-conditioner and baler during the winter.

Keywords: Bale density, Biomass, Miscanthus, Mower-conditioners, Power, Stem conditioning

Introduction

Miscanthus (Figure 1) is an ideal bio-energy crop (Kim, 2013) with high potential because it is a perennial grass that can grow for many years after a single planting (Bullard and Metcalfe, 2001). There are many varieties of miscanthus throughout the world.

Miscanthus is a hardy crop that can live under poor environmental conditions such as drought, brine, and low temperature (Qingguo, 2003). A bio-fuel is a renewable energy source that is produced from natural (bio-based) materials and can be used as a substitute for petroleum fuels. The most common bio-fuels, such as ethanol from corn, wheat, or sugar beets and biodiesel from oil seeds, are produced from classic food crops that require high-quality agricultural land for growth (Ayhan, 2009). Bio-fuels can supply 30% of the global demand in an environmentally responsible manner without affecting food production. To realize this goal, advanced bio-fuels must be developed from dedicated energy crops that are separate and distinct from food crops (Koonin, 2006). There is a conflict between biofuel production and global food security, particularly in developing countries. Bio-fuel has social effects with regard to food security, especially in developing countries, which can increase the price of food staples (Tiziano, 2009). Therefore, non-food energy crops are being actively developed with a focus on solving this ethical dilemma (Moon, 2010).

***Corresponding author:** Hyeon-Jong Jun
Tel: +82-63-238-4045; **Fax:** +82-63-238-4045
E-mail: hjjun@korea.kr

Figure 1. Shape of giant miscanthus.

Non-food crops require resistance to harsh environments, a high ratio of output/input energy, a high energy conversion efficiency, and environmental friendliness (Lewandowski et al., 2000; 2003).

In Korea, research on biomass production using the giant miscanthus (*Miscanthus × giganteus*) is in its early stages. The giant miscanthus is mainly harvested in its full dry state during the winter. However, even in winter, giant miscanthus stems close to the ground have a moisture content of 76%–144% (d.b.) because of snow and rain, which contribute to a soil moisture content of about 22.1% (d.b.). The biomass from the stem should have a moisture content of about 15%–20% (d.b.) for long-term storage (Jun et al., 2013; Kim et al., 1999).

The giant miscanthus grows to a height of up to 3.5–4 m, and the stem is hard and lignified during harvest time. Until more harvesting equipment is designed, Lewandowisky et al. (2000) recommend that miscanthus be harvested by mowing and baling. Mowing the giant miscanthus is difficult because a great deal of power is required. Harvesting the giant miscanthus as biomass requires time for the drying process after mowing. To shorten the drying time of the giant miscanthus to improve the harvest efficiency, the stems need to be conditioned. Kim et al. (2011a) measured and analyzed the required power of a tractor for agricultural operations. They also measured and analyzed the power requirements of an agricultural tractor for baling (Kim et al. 2011b).

This study investigated the harvesting properties of the giant miscanthus. The required mowing power of mower-conditioners for different stem conditioning methods was measured to shorten the drying time of the giant miscanthus crop after mowing and improve the bale density of a baler for biomass use in winter season. First, we tested stem conditioning methods like pressing, breaking, and creasing the giant miscanthus using different disk mower-conditioners (rubber roller-type and plastic finger-type) and a flail chopper (Srivastava et al., 2006). The plastic fingers and rubber rollers did not provide good stem conditioning because the stem length was about 0.8 m. For the chopper, the stem length was about 0.25 m long, but stem collection and baling were difficult. Therefore, the stem conditioning and bale density of the conditioning methods needed to be improved by including the material and shape of the conditioner. The required power for each mower-conditioner was measured.

Materials and Methods

Generally, a tractor is used to harvest giant miscanthus crops. In this study, the required moving power and stem conditioning of giant miscanthus crops were identified for different stem conditioning methods and the established harvesting system of using a rotary disk mower or rotary disk mower-conditioners attached to the rear of the tractor. The bale density with different conditioning methods was measured.

Theoretical required mowing power of rotary disk mower

The theoretical required power of the rotary disk mower was calculated from equation (1), which was suggested by the National Institute of Agricultural Engineering (NIAE) of the UK (Persson, 1987):

$$P_{mt} = [P_{Ls} + (E_{sc} \times V_f)] \times W_c \quad (1)$$

where P_{mt}= total PTO power to mower (kW), P_{Ls}= specific power losses due to air, stubble, and gear-turn friction (kW/m of width), 1.5 < P_{Ls} < 4 for disk and drum-type rotary mower; disk mowers are at the lower end of the range, while drum mowers are at the upper end), E_{sc} =specific cutting energy (kJ/m^2) [1.5 (sharp blades)< E_{sc}

< 2.1(worn blades)] V_f= forward velocity of mower (m/s), and W_c= width of mower (m).

To calculate the theoretical power required by the rotary disk mower, P_{LS} and E_{SC} were set to values of 1.5 and 2.1, respectively.

Experiment on required mowing power of rotary disk mower for giant miscanthus

Measurement of required mowing power for rotary disk mower

The required mowing power of the rotary disk mower was acquired with a measurement device during the mowing operation of a giant miscanthus crop. The measured power was compared with the theoretical required mowing power calculated from equation (1).

Two-year-old giant miscanthus plants were used for the experiment. The plant height was 2.09 m, the stem diameter was 7 mm, the plant weight was 0.99 kg/m^2, the number of stems was 46 stems/m^2, and the moisture content was 11.3% (d.b.). The stem moisture content was measured every 0.2 m of the plant height and dried at 105±5°C for 24 h.

Table 1 presents the stem moisture conditions of the giant miscanthus by height. The rotary disk mower was used to measure the required mowing power in the experiment; it had four disks and a cutting width of 1.7 m, as given in Table 2. The required mowing power of the mower was measured with the PTO transducer system (Series 420 PTO system, DATUM electronics, UK), which was connected to the PTO of the tractor. The required mowing power of the rotary disk mower was measured by increasing the working speed of the tractor mounted with the mower within the range of 0.5–2.9 m/s at a tractor PTO of 540 rpm. The working speed of the tractor and required mowing power of the mower were measured every 10 m for the interval length of the field. The maximum power of the tractor used in the experiments was 80 kW, and the mower's knife speed was 76.4 m/s at a tractor PTO of 540 rpm. To assure reliable cutting over a wide range of knife sharpness and stem stiffness, a minimum knife velocity of 50–75 m/s is generally recommended (Srivastava and Goering, 1991).

Table 2 lists the parameters for the rotary disk mower used in the experiment. Figure 2 shows a schematic diagram of the power measurement device, and Figure 3 shows the shape of the rotary disk mower used in the experiment.

Table 1. Stem moisture content of giant miscanthus by height from bottom

Stem height from bottom of giant miscanthus (m)	Stem moisture content of giant miscanthus (%(d.b.))
0–0.2	10.3
0.2–0.4	10.8
0.4–0.6	10.7
0.6–0.8	12.0
0.8–1.0	12.8

Table 2. Parameters of rotary disk mower used in experiment

Parameters	Values
Cutting width (mm)	2400
Diameter of rotating knife (mm)	500
Number of disks	6
Number of knives on each disk	2
RPM of disk and speed of knife at PTO 540 rpm (rpm / m/s)	2918/76.4

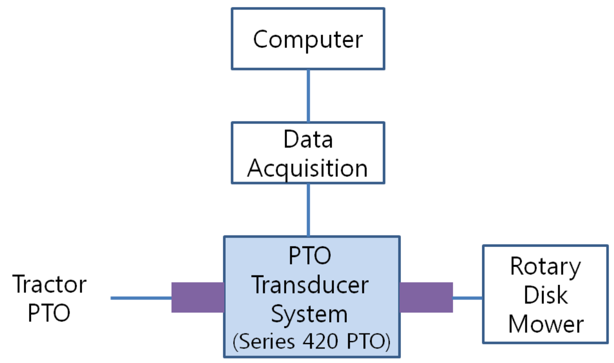

Figure 2. Schematic diagram of power measurement device (420 PTO system).

Figure 3. Shape of rotary disk mower for experiment.

Table 3. Specifications of mower-conditioners used in experiment

Operation Machine		Parameters	Values
Rotary disk mower-conditioner (steel roller type)	Mower	Cutting width (mm)	2400
		Diameter of rotating blade (mm)	500
		Number of disks	6
		Number of knives on each disk	2
		RPM of disk at PTO 540 rpm	2918
	Conditioner (Steel roller type)	Diameter of the steel roller (mm)	200
		Number of rollers	2
		RPM of rollers at PTO 540 rpm	938
Rotary disk mower-conditioner (flail types)	Mower	Cutting width (mm)	3200
		Diameter of rotating disk (mm)	520
		Number of disks	6
		Number of knives on each disk	3
		RPM of disk at PTO 1000 rpm	2930
	Conditioner (finger and L-shaped types)	Diameter of rotating flail (mm)	540
		Number of flails	72
		RPM of the rotor at PTO 1000 rpm	938

Figure 4. Types of mower-conditioners for experiment.

Experiments on required mowing power and bale density of rotary disk mower-conditioners

Measurement of required mowing power of rotary disk mower-conditioners

To measure the required mowing power, the PTO transducer system (Series 420 PTO system, DATUM Electronics, UK) was installed between the tractor PTO and each rotary disk mower-conditioner in order to measure the power from the PTO of the tractor during mowing. As given in Table 3 and Figure 4, the stem conditioning by three conditioning methods (i.e., steel roller, steel finger flail, L-shaped flail) were tested by pressing, breaking, and creasing giant miscanthus stems. The lengths of the broken stems and creased sections of each stem were also measured. The lengths of the creased stem sections were divided into three groups, and the stem conditioning was analyzed according to the section length. Figure 5 shows a schematic of a stem mowed and creased by different mower-conditioners. Figure 6 shows the operation of the different mowing and baling methods for harvesting giant miscanthus crops.

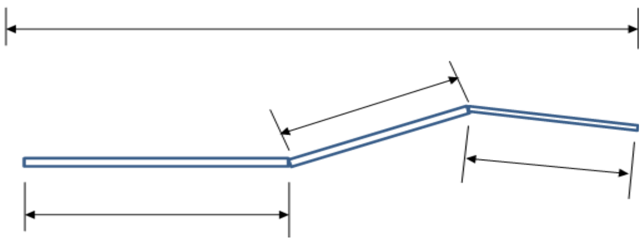

Figure 5. Schematic of stem mowed and creased by mower-conditioner.

Measurement of bale density from rotary disk mower-conditioners

Giant miscanthus plants were baled after being mowed at a working speed of 1.3 m/s with three types of mower-conditioners and 2.0 m/s with a mower.

The bale density was measured according to the stem conditioning using the tractor-mounted baler (RB1000, Myeongsung, Korea). The bale pressure during the operation

Figure 6. View of operation of different mowing and baling methods to harvest giant miscanthus.

Table 4. Size of bale by baler for experiment

Baler type	Diameter of bale (m)	Length of bale (m)	Volume of bale (m^3)
Round baler (Fixed roll chamber)	1.0	1.0	0.79

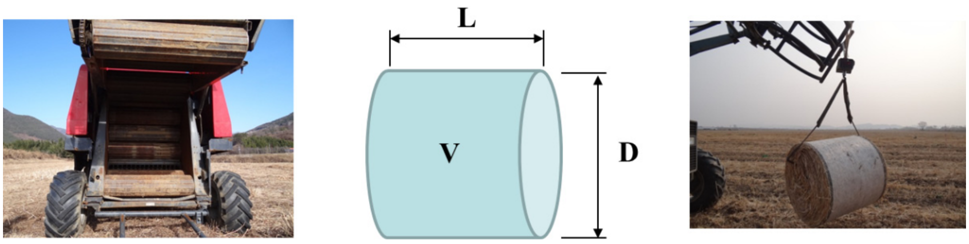

Figure 7. View and size of bale by baler for experiment.

Table 5. Required mowing power of rotary disk mower in experiment

Working speed of tractor (m/s)	Speed of PTO (Rpm)	Torque of PTO (Nm)	Power measured by device (W = 1.7 m) (kW)	Required power for pure cutting (W = 1.7 m) (kW)	Theoretical required power (W = 1.7 m) (kW)
0	554	99.0	5.8	0.0	2.6
0.5	545	120	6.9	1.1	4.2
0.9	537	140	7.8	2.0	5.7
1.5	525	171	9.3	3.5	7.9
2.0	514	197	10.6	4.8	9.8
2.9	497	238	12.5	6.7	12.7

was fixed to 12,000 kPa in the baler chamber. The working speed of the baler stayed at 9–11 km/h, and the tractor PTO was fixed at 540 rpm. The weights of the bales were measured with a digital scale having a capacity of 1 ton. Table 4 lists the bale sizes in the experiment. Figure 7 shows the view and dimensions of the bale from the baler in the experiment.

Results and Discussion

Required mowing power of rotary disk mower for giant miscanthus

Table 5 lists the required mowing power of the rotary disk mower in the experiment. The required mowing power was obtained from a power measurement device and the theoretical formula. The difference between the values for the required power to mow the giant miscanthus decreased as the working speed of the mower was increased to 2 m/s. The required mowing power was 12.7 kW according to the theoretical formula and 12.5 kW according to the power measurement device at a working speed of 2.9 m/s. Both values for the required mowing power were almost the same. The required mowing power used for pure cutting with disk knives was 1.3–6.9 kW at a working speed of 0.5–2.9 m/s and mowing width of 1.7 m.

The measured required mowing power was more than twice the theoretical required mowing power at the initial

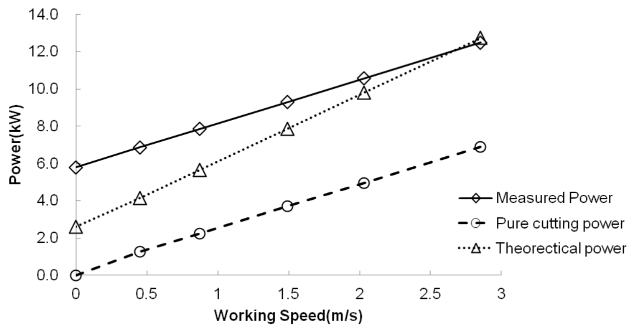

Figure 8. Required mowing power of rotary disk mower from theoretical formula and measurement device.

speed of 0 m/s; this was considered to be the difference in operating power of the mower. The measured and theoretical required mowing powers were about the same at a speed of 2.9 m/s. Therefore, the required mowing power tended to increase in proportion with the working speed. Figure 8 shows the theoretical and measured required mowing powers for the rotary disk mower.

Required mowing power and working conditions of rotary disk mower-conditioners for giant miscanthus

As given in Table 6, the required mowing power of the mower-conditioner increased with the working speed of the tractor. The required average power of the mower-conditioners was between 23.8 kW for the steel roller-type rotary disk mower-conditioner and 37.2 kW for the L-shaped flail-type rotary disk mower-conditioner at the working speed of 1.6 m/s. The required mowing power per unit length (1 m) of cutting width was lowest for the steel roller-type rotary disk mower-conditioner at the working speeds of 0.3–1.1 m/s but was lowest for the steel finger flail-type rotary disk mower-conditioner when the working speed was increased to 1.6 m/s.

Based on the above results, the required mowing power of the steel roller-type mower-conditioner greatly increased at the working speed of 1.6 m/s because the discharge of the mowed Miscanthus through the clearance between the two steel rollers was not large enough. Thus, it was impossible to operate the steel roller-type mower-conditioner continuously at working speeds of greater than 1.6 m/s.

Also, the required mowing power for the L-shaped flail-type mower-conditioner greatly increased because the L-shaped flails needed more power than the steel finger flails as the working speed of the mower-conditioner was increased.

Stem conditioning and bale density from mower-conditioners

As given in Table 7, the crushed stems of the giant miscanthus were examined at the working speed of 1.6 m/s for the mower-conditioners using different conditioning methods. The flail rotary mower-conditioner's had the lowest average length of broken stems at 0.86 m, which was proximate to the average length for the other mower-conditioners at 0.9 m. For each stem broken by a mower-conditioner, the creased stem length was divided into three groups and analyzed. The steel roller-type rotary mower-conditioner broke 64.8% of the stems into lengths of 0.5 m or less. This mower also generated the highest degree of soft stem conditioning relative to the others. The finger flail-type rotary mower-conditioner broke 22.7% of the stems into lengths of 1.0 m or greater, and it produced the lowest degree of soft stem conditioning. Therefore, the steel roller-type rotary mower-conditioner performed the best at a working speed of 1.6 m/s.

As given in Table 8, the harvested bale density of the giant miscanthus using different types of mower-conditioners was 155.8–172.2 kg/m^3 with a low stem moisture content of 11.3% (d.b.). The bale density was highest for giant miscanthus stems mowed by the rotary disk mower. The

Table 6. Required mowing power of mower-conditioners for giant miscanthus

Working speed of tractor at PTO of 540 rpm (m/s)	Rotary disk mower-Conditioner (steel roller)		Rotary disk mower-Conditioner (finger-shaped flail)		Rotary disk mower-conditioner (L-shaped flail)	
	Required power (width = 2.4 m) (kW)	Unit required power (kW/m)	Required power (width = 3.2 m) (kW)	Unit required Power (kW/m)	Required power (width = 3.2 m) (kW)	Unit required power (kW/m)
0	9.8	0.0	16.9	0.0	16.6	0.0
0.3	10.9	0.5	23.0	1.9	19.9	1.0
0.6	11.7	0.8	23.9	2.2	25.0	2.6
1.1	14.1	1.8	25	2.5	25.6	2.8
1.6	23.8	5.8	33.9	5.3	37.2	6.5

Table 7. Working states of mower-conditioners for giant miscanthus

Operation machine	Installed Power (kW)	Available working speed (m/s)	Average length of stem by mowing (m)	Distribution rate by length (L) of creased sections of stems (%)		
				1.5 m > L ≥ 1.0 m	1.0 m > L ≥ 0.5 m	0.5 m > L
Rotary disk mower-conditioner (steel roller)	68	1.6	0.90	1.3	33.9	64.8
Rotary disk mower-conditioner (steel finger flail)	83	1.6	0.91	22.7	27.3	50.0
Rotary disk mower-conditioner (L-shaped flail)	89	1.6	0.86	16.1	38.1	45.8

Table 8. Giant miscanthus bale density with different conditioning methods

Operation machine	Rotary disk mower-conditioner (Steel roller)	Rotary disk mower-conditioner (Steel finger flail)	Rotary disk mower-conditioner (L-shaped flail)	Rotary disk mower
Working speed (m/s)	1.3	1.3	1.3	2.0
Length of broken stems (m)	0.90	0.91	0.86	2.09
Weight of the bale (kg/roll)	130.8	123.1	124.8	136
Bale density at the volume of 0.79 m^3/roll, pressure of 12,000 kPa (kg/m^3)	165.6 (96.2)	155.8 (90.5)	158 (91.8)	172.2 (100)

bale density was lower for giant miscanthus stems with low moisture content. For the rotary disk mower, some stems were not collected by the baler in the field because they were laid in another direction. Thus, the bale density under low stem moisture content is affected by the mowed stem conditions.

Conclusions

In the experiments, the required mowing power of the mower became almost the same as the theoretical value as the working speed was increased. For the test mower-conditioners, the average creased length of the stem was 0.86–0.91 m, and the available working speed was 1.6 m/s.

The steel roller-type mower-conditioner provided better stem conditioning than the others but was unable to work continuously as the speed was increased. Therefore, with regard to the working performance and conditioning state, the steel roller-type mower-conditioner is best for a working width of 2.4 m, while the flail finger-type mower-conditioner is best at a working width of 3.2 m.

The densities of the bales harvested by the baler were 155.8–172.2 kg/m^3. The bale density was higher for stems without stem conditioning at a stem moisture content of 11.3% (d.b.). The bale density was affected by the mowing method because of the low moisture content of the miscanthus stems.

Based on the above results, the type of mower-conditioner used to harvest giant miscanthus crops should be determined by considering the harvest area, workable period, and working performances of the mower conditioner and baler during the winter.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

Acknowledgement

This study was carried out with the support of the Research Program for Agricultural Science &Technology Development (Project No PJ 009142) by the National Academy of Agricultural Science, Rural Development Administration, Republic of Korea.

References

Ayhan D. 2009. Political, economic and environmental impacts of biofuels. Applied Energy 86:108-117.

ASAE. 1999. CIGR Handbook of Agricultural Engineering, Vol.3 : Plant Production Engineering 348-380.

Bullard, M. and P. Metcalfe. 2001. Estimating the energy requirements and CO_2 emission from production of the perennial grasses Miscanthus, switchgrass and reed canary grass. ADAS Consulting Ltd, USA, 94.

Jun, H. J., I. S. Choi, T. K. Kang, Y. Choi and C. k. Lee. 2013. Study on required power and bale density by mowing method for Giant Miscanthus for biomass in field. In : CIOSTA, 35th CIOSTA and CIGR V Conference 2013 on from effective to intelligent farming and forestry, Billund, Denmark, 3-5 July 2013.

Kim, J .E., H. J. Park and K. U. Kim. 1999. Effect of moisture content and density to the decay of rice straw bale during storage. *Proceeding of the KSAM 1999 conference*. 4(2):221-227 (in Korean).

Kim, Y. J., D. H. Lee, S. O. Chung, S. J. Park and C. H. Choi. 2011a. Analsys of power requirement of agricultural tractor during baler operation. J. of Biosystems Eng. 36(4):243-251(in Korean).

Kim, Y. J., S. O. Chung, S. J. Park and C. H. Choi. 2011b. Analsys of power requirement of agricultural tractor by major field operation. J. of Biosystems Eng. 36(2): 79-88 (in Korean).

Kim D. S. 2013. Prospect of Miscanthus Biomass production in overseas. In: *Proceedings of the International Symposium on The future of Bioenergy "Miscanthus"*, pp. 214-227, Seoul national Univ., Korea.

Koonin S. E. 2006. Getting serious about biofuels, Science, 311- 435.

Lewandowski, I., J. C. Clifton-Brown, J.M.O. Scurlock and W. Huisman. 2000. Miscanthus : European experience with a novel energy crop. Biomass and Bioenergy 19(4):209-227.

Lewandowski, I. and A. Heinz. 2003. Delayed harvest of Miscanthus-influences on biomass quantity and quality and environmental impacts of energy production. Eur. J. Agron 19:45-63.

Moon, Y.H., B.C. Koo, Y.H. Choi, S.H.Ahn, S.T. Bark, Y.L. Cha, G.H. An, J.K. Kim and S.J. Suh. 2010. Development of "Miscanthus" the promising bioenergy crop, Kor. J. Weed sic. 30(4):330-339 (in Korean).

Persson, Sverker. 1987. Mechanics of cutting plant material. ASAE publishers, St. Joseph, MI.

Qingguo, X. 2003 Potential of giant grass Triarrhena lutarioriparia to grow in cold, dry and saline conditions as energy source. *Proc. of International Conference on Bioenergy Utilization and Environment Protection-6th LAMNET project Workshop*, Dalian, China SESSION 5 : BIOMASS RESOURCES.

Srivastava, A. K. and Carroll E. Goering. 1991. Hay and forage harvesting. Engineering Principles of Agricultural Machines, Draft copy.

Srivastava, A. K., Carroll E. Goering, Roger P. Rohrbach and Dennis R. Buckmaster. 2006. (rev.) Hay and forage harvesting. Engineering Principles of Agricultural Machines, St. Joseph, Michigan: ASABE. 325-402.

Tiziano, G, Maurizio G. Paoletti and David Pimentel. 2009. Bio-fuels: efficiency, ethics, and limits to human appropriation of ecosystem services. Agricultural and environmental ethics, 23(5):403-434.