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Harvest systems of *Miscanthus x giganteus* biomass: A Review

Sustavi žetve biomase *Miscanthus x giganteus*: Pregled

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ABSTRACT

The agricultural biomass classification includes the biomass obtained from fast growing energy crops. One of these crops is the perennial grass *Miscanthus x giganteus*, which after the third and fourth year of plantation forms a high-density stand with exceptionally high and firm shoots. Thus, special emphasis should be put on the harvesting systems. For *Miscanthus* harvesting, haymaking and silage making machinery is mainly used by applying single-phase or multi-phase techniques. The aim of this paper is to give an overview of the *Miscanthus x giganteus* biomass harvesting systems with regard to the form of harvested biomass, either shredded or/and baled biomass. In addition to application of fertilizers, biomass harvest is the only agro-technical measure that is used when a plantation reaches full maturity and it should be applied with the lowest possible energy input and biomass loss. Due to increased interest in production of energy from *Miscanthus x giganteus* biomass, the existing machinery is being adjusted to these new requirements and new specialised machines are being developed.

Keywords: agriculture machinery, biomass, energy crop, harvest, *Miscanthus x giganteus*

SAŽETAK

Klasifikacija poljoprivredne biomase uključuje biomasu dobivenu iz brzo rastućih energetskih usjeva. Jedna od takvih kultura je i višegodišnja trava *Miscantus x giganteus* koja nakon treće, četvrte godine formira gusti sklop s izuzetno visokim i čvrstim izbojma. Stoga se poseban naglasak treba staviti na sustave žetve. U žetvi Miscanthusa uglavnom se koristi mehanizacija za sjenažu i silažu primjenom jednofazne ili višefazne tehnike. Cilj ovog rada je dati pregled sustava za sakupljanje biomase *Miscanthus x giganteusa* s obzirom i na oblik požete biomase, bilo usitnjene ili/i balirane. Uz primjenu gnojiva, berba biomase je jedini agrotehnički zahvat koji se provodi kada nasada dosegne punu zrelost te ga je potrebno provesti uz što manji utrošak energije i gubitak biomase. Zbog povećanog interesa za proizvodnju energije iz biomase trave *Miscantus x giganteus* dolazi do adaptacije postojeće mehanizacije i razvoja novih, specijaliziranih strojeva.

Ključne riječi: poljoprivredna mehanizacija, biomasa, energetska kultura, žetva, *Miscanthus x giganteus*

INTRODUCTION

Increasing the use of biomass is one of the key tools proposed by the European Community to reduce its dependence on imported oil and oil products. Improving the security of energy supply in the medium and long term (EBTP, 2008). In a longer perspective, more biomass is expected to be converted to energy services in the EU countries to meet long term targets. Demand for biomass will probably increase beyond 2020 and not only in Europe (Scott-Bentsen and Felby, 2012). Biomass has become the largest source of renewable energy in the United States and the U.S. Department of Agriculture (USDA) has planned to increase the use of agricultural crops as biomass for bioenergy (Perlack, 2005).

Biomass is currently the fourth most common energy source in the European Union; after nuclear energy, other types of renewable energy, and solid fossil fuel energy (ABIOM, 2016). One of the potential sources of biomass is the production of annual and perennial energy crops. Unlike annual energy crops, e.g., maize and rapeseed, the cultivation of perennial energy crops (such as common millet, gigantic reed and reed canary grass) is not particularly demanding, primarily in terms of agro-technical measures and quality of soil (Bilandžija, 2015). The investigations aimed to evaluate and develop dedicated biomass crops, over the past 25 years, have focused on perennial species because these have higher energy yields and more favourable energy output/input ratios than annual crops (Sims et al., 2006). In the last decade *Miscanthus x giganteus*, due to its properties, such as potential biomass yields and energy effiency, has been considered as one of the most valuable viable energy crops. (Roy et al., 2015; Sopegno et al., 2016; Xue et al., 2017).

Miscanthus x giganteus is one perennial grass that has received interest because it displays characteristics that makes it a good source of biomass. These characteristics include high yield, cold tolerance, C4 photosynthesis, perenniality and a low requirement for inputs such as fertilisers and herbicides (Robson et al., 2012). Currently, *Miscanthus x giganteus* is cultivated on more than 43000 hectares in the European Union (ABIOM, 2016).

Minimal nitrogen input, high yield, minimal field operations, and suitability for marginal and arid lands are some of important *Miscanthus* properties that makes it an ideal energy crop (Redcay et al., 2018). *Miscanthus x giganteus* can be harvested from November until the beginning of the following vegetation cycle (March, April).

Generally, early harvest will maximize the yield per hectare while late harvest will lower it (Lewandowski and Heinz, 2003; Zub et al., 2011; Bilandžija et al., 2017).

Harvest postponing from autumn to spring have significant influence on the biomass moisture content, by reducing it to from 64.11% to 19.13%. Determinate moisture content in the spring harvest indicates the potential for storing the harvested biomass without previously exposing it to additional drying, which is beneficial for energy balance but also for cost efficiency of the biomass production (Bilandžija et al., 2018).

Some dry matter yields of *Miscanthus x giganteus* biomass are reported to be between 8 and 44.1 t/ha (Lewandowski et al., 2000; Heaton et al., 2008; Miguez et al., 2008; Maughan et al., 2012). In Europe, the plant's shoots can grow over 2 metres in the first year of plantation and up to 4 metres in each year following (El Bassam, 1994), with 18 (Christian et al., 2001) to 81 (Borkowska and Molas, 2013) shoots per m^2 when the plantation reaches its full maturity. This indicates that these crops have exceptionally tall and dense stands, generating high biomass yields.

Therefore, in order to boost the cost efficiency of *Miscanthus x giganteus* biomass production, special emphasis should be placed on the reduction of harvesting costs (Heaton et al., 2010).

MISCANTHUS HARVESTING SYSTEMS

Mechanisation has been recognised as a key point for the promotion of dedicated energy crops. It has an important effect on the energy and economic balance of the crop and also on the amount of biomass actual crop yield (Dalianis, 1998).

Harvesting and Transportation are the most demanding and costing parts of the entire supply chain of biomass feedstock, including energy crops and forest products (Judd et al., 2012; Koirala et al., 2017).

There is a number of systems for harvesting *Miscanthus x giganteus*. Each of these methods involves utilizing machinery that is already in existence for other agricultural applications (Meehan et al., 2013). These systems commonly use self-propelled forage harvesters (SPFH), and other silage making and haymaking machinery.

Lower efficiency of the existing machinery, if used for harvesting energy crops including *Miscanthus* grass, is a liability in commercial production (Maughan et al., 2014). The machinery that is used for harvest operates at lower working rates than when used for forage because of the density and hardness of *Miscanthus* stem (Anderson et al., 2011).

Single-phase and multi-phase Miscanthus harvesting systems

In terms of number of passes, the harvest can be performed by single-phase or multi- phase harvesting systems (El Bassam and Huisman, 2001). Generally, the available literature allows to assert that, based on the number of machines used, the systems for *Miscanthus* harvesting are categorized in to single-phase (1 pass) and multi- phase (2 or 3 passes) systems (Lewandowski et al., 2000; El Bassam and Huisman, 2001; Mathanker and Hanse, 2015).

Single-phase harvesting systems imply that biomass is picked up and chopped or mowed and then loaded onto trailers or baled in a single pass. A single-phase harvesting system most often uses a self-propelled forage harvester (SPFH) which cuts, chops and blows the crop into a tractor-pulled trailer (Mathanker and Hanse, 2015). The materials harvested with forage harvesting systems are not contained by any twine or wrap (Brownell and Liu, 2011), except when in conjunction with a modified baler or a modified forage combine.

Multi-phase harvesting methods consist of mowing, conditioning, followed by swathing, picking up and baling, or chopping with or without further compaction (Lewandowski et al., 2000; Liu et al., 2013). In such a procedure, the harvest is carried out in several passes in certain time intervals. In a multi-phase harvesting system (with two passes), a mower-conditioner cuts the crop, conditions and gathers it in a swath on the ground; a baler picks up the swath and densifies it in a rectangular or round bale (Mathanker and Hanse, 2015).

Mechanical conditioning, as reported and demonstrated in Kumh ala et al. (2007) and Shinners et al. (2000), makes grass baling easier. By applying crop conditioning, in theory, the potential would be there for *Miscanthus* crops to be more quickly harvested with denser bales (Fasick, 2015). Preferring bales with higher densities and lower volumes, in order to gain efficiency during shipping, due to that not the weight but the volume that the bales occupy being what primarily restricts the shipping and transport of biomass feed (Hofstetter and Liu, 2011). According to the above, from field to refinery, the total costs could be reduced by utilizing these processes (Redcay et al., 2018).

In a multi-phase harvesting procedure an accelerated reduction of water content may occur, which is desirable (Nixon and Hilton, 2006). However, in case of adverse weather conditions, a multi-phase harvesting procedure may lead to a higher water content than a single-phase system (Meehan et al., 2013).

In accordance with prospects of the energy crop production in global terms there is a growing tendency to modify and adapt the existing machinery or develop specialised machines for energy crops harvesting. The single-phase harvesting system which includes baling and shredding, but not the chopping of biomass, is presented in Figure 1 showing a front-mounted shredder and a tractor-driven baler, while Figure 2 shows a self-propelled baler with a possibility to mount a front cutter head.

Figures 3 and 4 show the single-phase harvesting systems used to obtain chopped and baled *Miscanthus x giganteus* biomass, where harvested biomass is blown into a funnel through a discharge spout of SPFH or is directly funnelled into compression chamber of the modified baler.

(Source: What's new in farming, 2014)

Figure 1. Harvesting and baling with front shredder and baler (Kuhn: WS 320 BIO shredder)

(Source: Farm Industry News, 2019)

Figure 2. Self-propelled baler (Freeman: model 1592D Big Baler)

(Source: Miscanthus in 59387 Ascheberg, 2013)

Figure 3. Production of chopped and baled biomass with SPFH and modified baler

(Source: Top Agrar Online, 2011)

Figure 4. Production of chopped and baled biomass with forage harvester and modified baler

Chopped or/and baled transportable forms

In the context of biomass supply chain, *Miscanthus* harvesting systems should transform biomass into transportable and usable forms. The common transportable forms, for agriculture energy crops are baled or chopped biomass (Mathanker and Hanse, 2014). Regardless of their shape, bales are packed tightly to reduce the number of bales transported. This maximizes loads, eases stacking and reduces the storage area required. For nearly all of its applications, *Miscanthus* will need to be chopped prior to use, however the benefit of using forage choppers to harvest *Miscanthus* would be that it is already chopped, thus eliminating a step at the processing plant. Conversely, chopped biomass can be very expensive to transport for even relatively short distances due to lack of density (Caslin, 2012). Thus the biomass harvested by a combination of forage choppers and modified/adapted balers would be in both a chopped and baled transportable form, which would reduce the cost of transportation.

Table 1 describes the harvesting systems for *Miscanthus x giganteus* grass in relation to potential production in (I) chopped, (II) baled and (III) chopped and baled form. The harvesting systems are classified into single-phase and multi-phase systems, and into systems using either tractors with harvesting attachments or self-propelled machines.

Table 1 presents the various harvesting systems used by tractors with attachments or self-propelled machines, where baled biomass is prepared by applying multi-phase or single-phase techniques. One of these single phase harvesting techniques produces chopped or chopped and baled biomass.

Producing chop by use of single-phase harvesting operation with machinery attachments implies the use of a tractor with forage combine and trailer. While self-propelled machines, in addition to SPFH, would require a tractor and trailer.

Single-phase harvesting techniques for production of bales include the use of: (I) front mower or plant residue shredder, tractor, and baler or (II) modified, mounted forage combine, tractor, and baler or (III) self-propelled baler with a cutting head (Figures 1 and 2). The mounted forage combine is modified so that the harvested biomass material is not fed into the bladed drum and discharge spout but instead remains on the ground, afterwards baled up in a single pass. A multi-phase harvesting system, using self-propelled machinery, can be conducted by use of a windrower or a modified forage combine SPFH without shredding and then the biomass is baled using conventional methods. Figures 3 and 4 show the possibilities of single-phase techniques (one or two aggregates) in harvesting of chopped and baled biomass.

Biomass losses in Miscanthus harvesting

Biomass losses in stems occur when the stem is broken off before the harvest, as well as during, due to machinery. Huisman (2003) states that the type of harvesting machines and the applied harvesting system inherently causes a part of biomass loss. Total biomass loss in *Miscanthus* between February and April, together with losses during harvest, can be as high as 50% (Beuch et al., 2000). Venturi et al. (1998) find that 10-30% of biomass can be lost during harvest. Furthermore, Nixon and Hilton (2006) determine the biomass loss during harvest to be between 22-26% and state that it is possible to reduce the losses by more intensive conditioning, rotating, and gathering along with bundling multiple swaths into a single unit. Due to more intensive treatments of *Miscanthus*, by conditioning, a larger number of stems result broken enabling more efficient picking up with a baler. As for reducing biomass loss, Meehan et al. (2013) state that the solution is to place deflectors on the sides of the pick-up reel of the baler in order to collect the shredded biomass, which lays by the side of the swaths and outside the operational range of the pick-up machine. The same authors also state that at harvesting, by mower and baler, the average biomass loss is between 9.41% and 14.11%, and determine that such biomass loss is significantly above average, comparing with losses occurring at harvesting by SPFH where they ranged from 4.44% to 7.32%. Furthermore, they have concluded that the biomass losses occurring at headland turns at harvesting by SPFH do not influence the total biomass loss, while such losses influence the total biomass loss at harvesting by mower and baler, where losses are lower on larger and regular shaped field plots.

Loss of biomass at harvest by mower and baler, which are quoted in the literature (Venturi et al., 1998; Lewandowski et al., 2000; Nixon and Hilton, 2006), are higher than losses at harvest by SPFH.

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Table 1. *Miscanthus x giganteus* harvesting systems regarding the forms of harvested biomass

Form of harvested biomass	Tractor with harvesting attachments				Self-propelled harvesting machine			
	Multi-phase harvest technique			Single-phase harvest technique	Multi-phase harvest technique			Single-phase harvest technique
	First phase	Second phase	Third phase		First phase	Second phase	Third phase	
Chopped	--	--	--	Forage harvester[1] + tractor + trailer[6]	--	--	--	SPFH2 + tractor + trailer[5]
Baled	Mower/ Shredder + tractor	Rotary rake + tractor	Baler+ tractor	Front mounted mower/shredder + tractor + baler Modified front mounted forage harvester[3] + tractor + baler	Self-propelled mower / windrower Modified SPFH3	Rotary rake + tractor	Baler+ tractor Self- propelled baler	Self-propelled baler with cutting head[6]
Chopped and baled[5]	--	--	--	Forage harvester[1] + tractor + modified baler[4]	--	--	--	SPFH[2] + tractor + modified baler[4]

[1] mounted or pull-type forage harvester
[2] self-propelled forage harvester (SPFH)
[3] harvested biomass does not pass through the cutter head and discharge spout
[4] modified baler (Figure 1 and 2)
[5] possibility of simultaneous harvest with one, two or multiple aggregates
[6] model on Figure 4

MODIFICATION OF *MISCANTHUS* PICK-UP MACHINERY

The harvesting of energy crops, *Miscanthus* grass included, requires certain modifications to both attachments and to conventional techniques for forage production (hay, haylage, silage) (Anderson et al., 2011). It is imperative, therefore, to re-evaluate the operation and design of harvesters in order to minimize energy consumption and optimize field performance (Gan et al., 2018).

Mower

Investigation into the energy needed for cutting *Miscanthus* shows that modifications of blades can lower the consumption of energy required for harvesting (Johnson et al., 2012; Liu et al., 2012; Mathanker and Hansen, 2014). The obvious focus being the cutting mechanism itself including the blade design and cutting speed, as well as adaptations designed to improve material throughput (Gan et al., 2018).

Standard blades used in disc mowers are of rectangular shape and standard blades are at a 0 ° angle to the blade's bisector. It is possible to reduce the amount of energy that mowing machines consume by increasing the blade angle. With using larger blade angles, e.g. 20 ° or 30 ° or 40 ° or 60 ° angles, the needs for cutting energy are lower than in case of using a 0 ° blade angle. Cutting with standard blades requires an average of 8.4 MJ/ha compared to 5.6 MJ/ha for cutting with a 60 ° angle blade and 6.7 MJ/ha for cutting with a 30 ° angle blade (Johnson et al., 2012). Another field study (Maughan et al., 2014) looked into the effect of cutting speeds (31.5, 47.3 and 63.0 m/s), blade oblique angle (0 °, 30 °, 40 °), and blade mounting (fixed, flexible) in a field setting. The results indicate that the cutting speed and blade oblique angle are directly related to the energy requirements and efficiency of the *Miscanthus* harvesting machinery. A 40 ° oblique angle operating at 31.5 m/s had the lowest energy consumption, averaging 9.1 MJ/ha, while a 30 ° oblique angle consumed 16.9 MJ/ha and a straight blade consumed 23.1 MJ/ha. In regular field conditions of *Miscanthus* grass harvesting, a mower-conditioner requires 18.5 MJ/Mg when using standard blades, while with 30 ° oblique angle blades the total energy requirement is 27% lower at 13.5 MJ/Mg, and with 20 ° angle blades it requires 14% less energy compared to standard blades, with an energy requirement of 15.9 MJ/Mg (Maughan et al., 2014).

Gan et al. (2018) compared energy consumption during harvest of *Miscanthus* with a self-propelled mower-conditioner (windrower). Three blade types were compared: 0 ° straight blade, 30 ° angled blade, and serrated blade. For the machine and header energy consumption, significant differences were found for straight versus serrated blades and angled versus serrated blades. The results showed that using serrated blades saved 18% of machine energy compared to angled blades and 24.7% compared to straight blades. The operator can maintain a higher working speed and the theoretical field capacity increased from straight blades at 1.35 ha/h, to angled blades at 1.52 ha/h and to serrated blades at 2.32 ha/h. When the blades become dull, the energy required for cutting crops increases markedly (Tuck et al., 1991).

Baler and forage combine

For *Miscanthus* crop picking-up systems that use forage combine and balers, modifications need to be made either on the baler or forage combines. Such modifications facilitate production of chopped and baled or baled only biomass. For the chopped and baled biomass, the harvested material is blown with a discharge spout into a compression chamber through the discharge basket (funnel), which is placed above the pick-up cylinder. When harvested by a modified forage combine, the biomass is laid on the ground without being passed through a chopper and is then collected by the baler over the pick-up reel.

CONCLUSION

The chopped, and chopped and baled biomass is produced by use of a single-phase harvesting technique, while only baled biomass is produced by a single-phase or a multi-phase technique. In the production of baled biomass by multi-phase techniques, often a mower or tractor-driven baler is used, where average loss is higher than in a single-phase harvesting technique using a SPFH. A single-phase harvest technique can be performed by use of one or two aggregates in the same pass. Certain modifications, such as installing deflectors on the side of the pick-up reel and enlarging the blade angle on the harvesting machinery, make it possible to achieve higher efficiency of biomass collecting with reduced energy consumption at the same time. With the view of lowering transportation costs and energy consumption in further biomass processing, the shredded biomass can be baled with modified balers; which are not yet produced on an industrial scale.

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