CHEMICAL ENGINEERING TRANSACTIONS
VOL. 58, 2017
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Remigio Berruto, Pietro Catania, Mariangela Vallone

ISBN 978-88-95608-52-5; **ISSN** 2283-9216
DOI: 10.3303/CET1758045

Two Steps Arundo Donax L. Harvesting in South Italy

Salvatore Faugno*[a], Irene Quacquarelli[b], Vincenzo Civitarese[c], Mariano Crimaldi[a,e], Maura Sannino[a,d], Gennaro Ricciardiello[a,e], Giuseppina Caracciolo[b], Alberto Assirelli[c]

[a]Department of Agriculture of the University of Naples “Federico II”, via Università 100, Portici (NA) 80055
[b]Consiglio per la ricerca in agricoltura e l’analisi dell’economia agraria (Crea), Centro di Olivicoltura Frutticoltura Agrumicoltura (OFA), via La Canapona 1 bis, Forlì (FC) 47122
[c]Consiglio per la ricerca in agricoltura e l’analisi dell’economia agraria (Crea), Centro di Ingegneria e Trasformazioni agroalimentali (IT), via la Pascolare 16, Monterotondo (Rm) 00015
[d] Department of Agriculture, Tuscia University, 01100 (VT), Italy
[e]Centro Interdipartimentale di Ricerca «Ambiente» - C.I.R.AM., University of Naples “Federico II”
salvatore.faugno@unina.it

The aim of this study was to evaluate the performance of two-pass harvesting system on giant reed (Arundo donax). The biomass was shredded, dried in the field and baled for logistic chain and storage. The first step was cutting and grinding biomass crops with a specific shredder rear-mounted on an agricultural tractor. Subsequently, after some days of drying in the field monitoring continuously its moisture content, the Arundo biomass was collected in round-bales for storage.
This harvesting system presents the following advantages: immediate and long biomass storage (12-14 % or lower moisture content), better use of farm mechanization for hay making, diversified use of the dried biomass (combustion and II° generation ethanol), reduced fuel consumption (in line or even lower than other ordinary crops present in that area).
The tests carried out showed the technical and energy features of the harvest technology based on the adoption of only one specific shredder machine, designed and developed by an Italian constructor for more biomass herbaceous crops (Arundo, Sorghum, Panicum, Mischantus, etc). This machine is suitable for highly vegetative developed crops and can spread the product in all soil surface or windrows.
The tests, conducted in the South of Italy (Campania region) in an experimental farm of Torre Lama, showed a good system performance, slightly lower than 1.5 ha h^{-1} (1.47), with 4.88 km h^{-1}operative speed.

1. Introduction

The giant reed (*Arundo donax* L.) is one of the most used crops for biomass production for energy purposes due to the numerous agronomic and energy benefits that the use of this plant entails. Among these, the speed of growth and the high efficiency in biomass, combined with the high resistance to pathogens and to water stress and good adaptability to all soil types and weather conditions, are the main ones. Moreover, its high production combined with high calorific value and limited input demand, determines its positive energy balance making it a favorite bioenergy crop.
In the South of Italy, Arundo donax is a new energy crop for many farmers and its most suitable valorization technology is the combustion, where the crop shows good interested (Dahl et al., 2004).
Several studies confirmed that the key cost component in the logistic chain of herbaceous crops, as Arundo, is mainly related to the field operation and the adopted harvesting system (Angelini et al., 2009).
Concerning the cultivation, many progresses have been made in the propagation system, critical until a few years ago, with the development of techniques that use plant rhizomes, reducing the establishment costs significantly and making the mechanization of harvesting operations convenient (Assirelli et al., 2013). Concerning the harvest, in order to have the maximum results from Arundo crop in terms of biomass is very important to choose the most suitable technique allowing to obtain a low level of moisture and a limited amount of fine fraction in shredding case (Assirelli et al., 2015).

Please cite this article as: Faugno S., Quaquarelli I., Civitarese V., Crimaldi M., Sannino M., Ricciardiello G., Caracciolo G., Assirelli A., 2017, Two steps arundo donax l harvesting in south italy, Chemical Engineering Transactions, 58, 265-270 DOI: 10.3303/CET1758045

To optimize the collection and management process of Arundo biomass the baling technique was tested (Pari et al., 2016). This technique decreases the moisture content of the biomass, reducing the problems related to its conservation, by drying and compacting the plant material in square or cylindrical bales. The dry biomass storage (humidity 12-14 %), allowing better aeration of the product, reduces the risks associated with poor fermentation during storage while allowing a diversified use of the dried material as fuel, 2nd generation ethanol or biogas (Corno, 2014).

Significant factors for good handling and storage are a low moisture content of the biomass and a strong bulk density of the bales (Cundiff, 1996).

The aim of this study was to analyze the two-step harvesting system of Arundo donax (cutting, baling and field storage) in South of Italy, considering the cutting height, the losses of the biomass for each phase, the performance and the fuel consumption of the machines. These parameters were examined in function of two different working speeds of the combined cutting, shredding and windrowing machine and two different rotational speeds of its rotor.

2. Material and Methods

Giant reed (Arundo donax L.) plantation used for the tests was sited in the experimental farm of Torre Lama, located in Bellizzi (province of Salerno, Campania Region). The crop, established in 2007 on a total area of 0.745 ha (207 x 36 m single plot), was firstly divided into four plots of equal size (100 x 16 m) with different irrigation and fertilizer management (Plot 1: No irrigation and 100 kg/ha of N; Plot 2: No irrigation and 50 Kg ha^{-1} of N; Plot 3: Irrigation and 50 kg ha^{-1} of N; Plot 4: Irrigation and 100 Kg ha^{-1} of N). This culture scheme was adopted for the first growing phases and then uniformed, after four years, without irrigation or fertilizers.

The main crop characteristics measured before harvesting were: average and maximum height, plant density, moisture content, average and maximum diameter, average plant weight and total biomass.

The machine for the first step was a bio-triturator (Figure 1) produced by the company Nobili S.r.l. Italy of Molinella (BO), a combine cutting, shredding and windrowing. The WS (Windrower Shredder) series was used for more crops and it was especially designed and developed for the management of herbaceous energy crops with high vegetative development (Bentini et al., 2008). It was composed by a main rotor with hammers installed on 8 perimeter lines for a total of 40 tools, mechanically driven by multiple belt (5 elements). For tests the purpose the windrowing auger was removed and a second rotor (5 lines with four tools in line) was placed for further shredding the biomass and discharge on the ground. In order to evaluate the possibility of drying in the field to increase the efficiency of the solar radiation, for this set-up, the full field distribution without the simultaneous windrowing of the biomass was preferred. The rear conveyor augers were eliminated for harvesting without windrowing. This change was necessary for spreading the product on the ground to allow a better drying in the field.

The shredder machine was rear mounted in a three-point linkage of a four-wheel drive tractor with 206 kW engine power make Fendt model 828 Vario with mechanical and hydraulic continuous transmission.

Before starting the harvesting operations, some tests were carried out in the near areas to identify the working and rotation speed of the rotor shredding so that to highlight operating ranges to maintain the machine operating efficiency good. Two working speeds and two rotational speeds of the rotor (Table 1) for experimental tests were identified. The manufacturer of the bio-triturator indicates, as recommended rotation speed, 1,000 revolutions/minute to the main rotor, obtained by setting the same speed to the power take off of the tractor. The preliminary tests were used to assess the level of crushing and cutting height obtainable at different advanced and rotor speeds. The maximum length of 100 cm of not shredded crops and the basal cut precision progressively reducing according to the increase of the working speed or the reduction of the rotor speed were considered as limit values.

Table 1: Operating conditions of shredding for test conduction

Thesis	Speed (km h^{-1})	Engine speed (rpm)	Rotor speed (rpm)
1	4	2200	1170
2	6	2200	1170
3	4	1890	1000
4	6	1890	1000

The machines used for harvesting the dried biomass (Figure 2) was the Claas round baler model Rollant 250 trailed by four-wheel drive agricultural tractor Valtra model N141 (Engine power 111.9 kW, Engine speed 2200 rpm and max Engine torque at 1500 rpm).
The baler used showed specific devices for the management of herbaceous biomass of considerable plant development such as compression rolling system and the feeding device with rotor intermediate between pick-up and compression chamber. The adopted round-bale machine was equipped with a fixed compression chamber with parallel steel roller adapted for dried biomass of Arundo donax. It was equipped for tying both on mesh or twine, editable quickly by the operator, although in the tests it was decided to use only twine due to his ability to better maintain in position even small particles. Being the first experience, the number of windings needed is an aspect to investigate in order to develop the most suitable tying system to the physical characteristics of the triturated Arundo. To determine the round baler efficiency, as well as turning time, the time losses due to intermittently stopping to wrap and discharge bales were also considered.
The performance of the machines was evaluated by measuring the working time according to ASABE standard methods (ASAE Standard 2007 and 2011). Other references include the Commission International de l'Organization Scientifique du Travail en Agriculture (CIOSTA-Bodria et al., 2006) and the Italian Society of Agricultural Engineering (AIIA). The harvesting test started on March with shredding and spreading biomass crop on all soil surfaces. The first operation was cutting, shredding and spreading without windrowing with the rear-mounted shredder. At the end of shredding, three replicates (5 x 1.5 m plots) were randomly chosen in the test area for height-cut and loss evaluation. For twelve cuttings (3 replicate x 4 thesis), 45 plants were measured while for ground losses all not shredded Arundo plants, more than 1 meter high, , were harvested and weighted.
For the plants that were shredded, the drying times, in terms of days elapsed between cut and sampling, were evaluated using a completely randomized design.
Seven samples (considered replicates) for seven different dates were randomly collected, immediately weighed, sealed in a plastic bag and delivered to the laboratory to measure the moisture content according to CEN/TS 14774-2:2004.
At this phase, the meteorological conditions were monitored at a nearby weather station of Torre Lama.
As for the consumption of fuel, the measuring system used was the tractor that according to the needs can show data of instantaneous fuel consumption, average and per unit of treated surface. At the end of the baling phase three replicates (1x1m plots) were randomly chosen in the testing area for the loss evaluation. For twelve cuttings (3 replicates x 4 thesis) all fraction parts of Arundo for ground losses were collected in a sail-bag and weighted.
Regarding the losses only 1-meter-longer stems were considered as effect of shredder efficiency; whereby in each same 7.5 m^2 area all sections of stems remained on the field after step 1 of harvest, were taken, collected, and weighed.

Figure 1: Nobili Shredder

Figure 2: Claas round baler

3. Results and Discussion

3.1 Harvesting (step 1)

The Harvesting operations started by the two long sides of the external plot always identifying a turning phase for each thesis continuing towards the inside of the field test, thus defining different thesis in a specific order.
The shredding level obtainable in the different thesis has always been very heterogeneous with an excessive fragmentation of herbaceous parties as leaf blade and simultaneous presence of parts of not crushed 50 cm longer stems. Data analysis relating to working time and performance of the first step showed that the

effective shredding time has always been very high, greater than 90 % (data not shown) also thanks to the favorable conformation of the plots being longer than thicker (205 x 36 m).
Moreover, in all tests conducted, the working speeds have always been slightly higher than the originally set values for the thesis because the automatic engine management system allowed different engine setting: constant speed and/or pto speed. For this test, the engine management was set to pto costant with low speed variation caused by low variation of engine torque.
The effective average field capacity was 1.76 km h^{-1} for the tests carried out at 6 km h^{-1} speed (thesis 2 and 4) and significantly lower (1.17 km h^{-1}) in lower speed tests (thesis 1 and 3). For material capacity, slower rate thesis showed similar values between them (on average 33.9 t h^{-1}) as well as higher speed thesis showing mean values of 50.9 t h^{-1}, significantly higher than the previous ones.
The average moisture value detected from samples of four thesis was equal to 42.51 % while the values of the biomass weight losses during harvesting ranged from 2.28 and 4.74 t, with values always below 10 % of the collected dry biomass.
Concerning the cutting height fifteen reliefs for the three replicates of each thesis were carried out and the obtained values have always highlighted heights greater than 10 cm. This is directly related to the loss of product not involved in the harvest process (data not shown).
For energy aspects from the instantaneous consumption recorded for each thesis it is possible to trace the consumption required per area unit (thesis) to shredder, as reported in Table 2.

Table 2: Shredder fuel consumption

Thesis	Hourly consumption ($L\ h^{-1}$)	Effective field capacity ($h\ ha^{-1}$)	Area consumption ($L\ ha^{-1}$)	Material consumption ($L\ t^{-1}$)
1	18 a	0.85 b	15.3 b	0.53 b
2	20 a	0.57 a	11.4 a	0.39 a
3	21 a	0.85 b	17.85 b	0.62 b
4	22 a	0.56 a	12.32 a	0.43 a

Duncan test (p-value<0.01)

The hourly consumption for chopping remained quite limited despite the class of tractor power adopted which is usually oversized in terms of engine power because of the tractor size and the reversible drive system.
The consumption per area unit reduced significantly from one speed to another (always higher than 25 %),aspect of particular interest as the chopping homogeneity of the product has not been compromised in the various theses.
The WS 320 BIO Nobili is especially conceived for the management of herbaceous plant biomass. Once the picker has been set correctly, the main rotor, operating on the entire front of work, was able to carry out a good crushing of the stems even if, in all considered theses, an important amount of 50-centimeter higher stems has remained. However, this aspect did not cause any problem during the baling phase.
Also the presence of larger particles can increase the biomass stability reducing the risk of harmful fermentation at moisture levels > 15 %. The chopped biomass was well spread in the entire working front even there was often a certain tendency to central accumulation leaving the side edges slightly empty. This aspect, on the one hand, may limit the solar radiation efficiency, especially during the biomass drying phase in the field. On the other hand, it may simplify the subsequent loading operations by the baling pick-up where the operator can be facilitated to identify the different steps of the shredder.

3.2 Biomass drying and baling (step 2)

After shredding, in order to define the baling date, the monitoring on the biomass drying in the field was started.
The II° step started when the biomass moisture was 6.09% lower than the minimum between 12-14 cited in the literature.
Following an initial period with quite variable data among the different samples, the drying step showed a loss of moisture necessary to adjust to the minimum value indicated, quite stable for two subsequent sampling intervals. The moisture content stability was achieved a few days after the beginning of the round baling step.
In the feeding step, the pick-up of the harvester did not show any particular difficulty of efficiency operating with regularity also for collecting larger size particles of the chopped yield. During baling, the working time, the performance and the fuel consumption were recorded.

The study of the recorded working time showed that there could be room for improvement in the bale binding times (now between 14 and more than 30 seconds), At the beginning, the number of wrappings was very low, causing some bale deformations that increased together with number of wrappings. The turning times recorded were uniform in the four thesis (21-25 s).
Speed rate was variable in the different thesis with a peak of 6.56 km h^{-1} in the thesis 4 (data not shown). Regarding the round baler performance, material capacity recorded was been of 20.40 t h^{-1}, however this value can be strongly influenced to moisture content of biomass at baling time(about 7 times lower than those recorded at cutting time).
For the fuel consumption, the tractor measuring system was adopted. It is possible to trace the actual consumption per area unit required to perform the baling by examinating the instantaneous consumption recorded for each thesis (Table 3).

Table 3: Baling fuel consumption

Thesis	Hourly consumption ($L\ h^{-1}$)	Effective field capacity ($h\ ha^{-1}$)	Area consumption ($L\ ha^{-1}$)	Material consumption ($L\ t^{-1}$)
1	17.5b	1.41a	24.68b	0.98b
2	19b	1.23ab	23.37b	0.93b
3	13a	1.23ab	15.99a	0.64a
4	12a	1.05a	12.60a	0.50a

Duncan test (p-value<0.01)

The area consumption showed significant reductions from theses 1 and 2 to theses 3 and 4. This is difficult to explain because the harvesting differences are rather contained. Similar considerations could be made on consumption per harvesting unit where the consumption per ton of yield in the thesis 1 is twice the one of thesis 4.
Once the setup phase of the harvester finished, the baling did not show any particular problems thanks to baler lack of belts for compression systems more sensible to the effect of stem cutting particles of Arundo compared steel parallel rollers. The good functionality was verified in the binding system. Bales are well shaped with defined edges and compression level fairly consistent throughout the profile, especially inside.
Once ejected from the compression chamber, the bale is able to maintain its shape and to support storage with the others bales.
In the previously defined plot, all parts of the plant left on the ground were taken and the fine parts of leaves and stems and other particles escaped from the action of the springs of the pick -up were summed. At the end of baling, an accurate assessment of loss on the ground was carried out for each thesis. The lost material, collected in sail-bag and weighed, ranged from 3.22 and 3.61 t ha^{-1}, with little differences in the various thesis.

4. Conclusions

This study carried out on the of Arundo donax two-step harvesting in at the Azienda Torre Lama in Bellizzi (Sa) highlighted some particularities of the adopted crop and harvesting system.
The harvesting system adopted providing the use of two separate steps requires meticulous management of the collecting phase and needs a careful monitoring of soil and weather conditions in order to not compromise the harvesting results as far as the quality and losses concern.
The main advantages showed by this harvest in two steps are: the immediate biomass storage, reaching 12-14 % of moisture points that can be storage for a long time; it allows a better use of farm mechanization, a diversified use of the dried biomass (combustion, 2nd generation ethanol, etc.), fuel consumption similar or even less than other parameters and crops for the Italian area (Assirelli et al., 2005).
Chopping and stacking remain below 1.5 L t^{-1}, in some cases close to 1 L t^{-1} of dried product collected, with values rather similar to those of wheat harvest, and equal to 1/3-1/4 of those required for direct shredding of the fresh product performed with self-propelled forage harvest, employment of machines of lesser economic engagement with respect to the management of fresh products.
Some limits were recorded such as: high product loss on the ground (>18% mainly due to the rate of fine fractions), need for specific machines (both shredders and balers), exposure to meteorological events for a long period (>10 days), especially in spring, with a consequent deterioration of the harvest, execution of repeated passages in the field with machines be hardly equipped for material compaction.

From an economic point of view, in the bibliography data, it is not always easy to divide the costs between cultivation and harvest/storage, since they are frequently estimated and grouped according to different needs. Predictive software and models which, according to requirements and parameters, define these costs in different context (Pignedoli et al., 2008; Soldatos et al. 2004) are often used.
The total fuel consumption for Arundo donax harvest in two steps, 1.25 L t^{-1} of dry biomass (6.09 moisture percentage), is interesting and favorable for the energy aspect of the mechanical harvest. Local logistic chains for Arundo have not been established yet.
The most negative point of this experience was the yield loss that was much higher compared to the data of CREA-IT previous experiences when the direct harvest of stems cut at a more-than-25-centimeter height with self-propelled machines used for forage collection remained within 1.5 t ha^{-1}; the energy aspects of tested harvesting system were instead a positive aspect both for the low content fuel consumption and the rationalization of the use of agricultural machinery.

References

Angelini LG, Ceccarini L, Nassi N, Bonari E., 2009, Comparison of Arundo donax L. and Miscantus x giganteus in a long-term field experiment in central Italy: analysis of productive characteristics and energy balance, Biomass Bioenergy, 33, 635-43.

ASAE. Agricultural machinery management. St. Joseph (MI), 2007, American Society of Agricoltural and Biological Engineers, Standard ASAE EP 496.3.

ASAE. Agricultural machinery management. St. Joseph (MI), 2011, American Society of Agricoltural and Biological Engineers, Standard ASAE EP 497.7.Assirelli A., Pignedoli S., 2005, Costo di esercizio delle macchine agricole. Bollettino C.R.P.A., 5,1-10.

Assirelli A., Santangelo E., Spinelli R., Acampora A., Croce S., Civitarese V., Pari L., 2013, Mechanization of Rhizome Extraction in Giant Reed (Arundo donax L.), Nurseries. Appl. Eng.Agr, 29(4), 489-494.

Bentini M., Caliceti M., Zucchelli M., 2008, Development of a prototype implement for Arundo donax harvesting for combustion purpose, In: Proceedings of the 16th European biomass conference & exhibition from research to industry and markets, Valencia, Spain. Florence: ETA-Florence Renevable Energies, 523-526.

Bodria L., Pellizzi G., Piccarolo P., 2006, Meccanica Agraria Vol. II, Bologna, Italy, Il Sole 24 Ore Edagricole

BSI. DD CEN/TS 14774-2:2004: Solid biofuels; Methods for the determination of moisture content; Oven dry method; Total moisture; Simplified method. London, U.K. British Standards Insitute

Corno L., Lonati S., Cantaluppi E., Pilu R., Tosca A., Adani F., 2014, Arundo ottima specie da biogas grazie alle altissime rese. L'Informatore Agrario, 5, 21-4.

Cundiff JS., 1996, Simulation of five large round bale harvesting systems for biomass. Bioresour Technol, 56, 77-82.

Dahl J., Obernberger I., Evaluation of the combustion characteristics of four perennial energy crops (Arundo donax, Cynara cardunculus, Miscanthus x giganteus and Panicum virgatum). Proceeding of the second world biomass conference, biomass for energy, industry and climate protection, 2, 265-1270.

Pari L., Assirelli A., Acampora A., Del Giudice A., Santangelo E., 2015, A new prototype for increasing the particle size of chopped Arundo donax (L.), Biomass and Bioenergy, 74, 288–295.

Pari L., Curt M.D., Sánchez J., Santangelo E., 2016, Economic and energy analysis of different systems for giant reed (Arundo donax L.) harvesting in Italy and Spain, Industrial Crops and Product, 84, 176–188.

Pignedoli S., Bettati T., Assirelli A., 2008, Colture no food, un software aiuta a stimare costi e ricavi, Agricoltura, 2, 104-105.

Soldatos P.G., Lychnaras V., Asimakis D., Christou M., 2004, BEE-biomass economic evaluation: a model for the economic analysis of biomass cultivation, In: Proceedings of the second world conference and technology exhibition on biomass for energy, industry and climate protection, Rome, Italy.