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Are herbaceous perennial grasses suitable feedstock for thermochemical conversion pathways?

Danilo Scordia[a,*], Douwe van den Berg[b], Peter van Sleen[b], Efthymia Alexopoulou[c], Salvatore Luciano Cosentino[a,d]

[a] *Dipartmento di Agricoltura, Alimentazione e Ambiente—Di3A, University of Catania, Via Valdisavoia 5, 95123, Catania, Italy*
[b] *Biomass Technology Group BV, Josink Esweg 34, 7545 PN Enschede, The Netherlands*
[c] *Center for Renewable Energy Sources and Energy Saving, 19th Km Marathonos Avenue, Pikermi Attikis, 19009, Greece*
[d] *Consiglio Nazionale delle Ricerche (CNR), Istituto per la Valorizzazione del Legno e delle Specie Arboree (IVALSA), UOS di Catania, Via P. Gaifami 18, 95126 Catania, Italy*

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ABSTRACT

Sustainable production of high value chemicals, biofuels and bioenergy relies on the replacement of fossil oil with low production cost feedstock and low environmental impact technologies. The present study evaluated the dry matter yield and feedstock properties of three different *Arundo donax* L. clones (Fontane Bianche, Piazza Armerina and Capo d'Orlando), two *Miscanthus* species (*M.* × *giganteus* and *M. sinensis* "Goliath") and *Saccharum spontaneum* L. spp. *aegyptiacum* (Willd.) Hack., all grown side-by-side in rainfed conditions for three consecutive years in semi-arid Mediterranean environment. Significant differences were observed among species, as well as among giant reed clones. F. Bianche and Saccharum were the highest yielding species in all growing seasons, followed by P. Armerina and C. Orlando, which did not differ. Out of Miscanthus, Giganteus overyielded Goliath. All species exhibited the highest dry matter yields in the wettest growing season. Saccharum and giant reed clones showed higher biomass water content than both Miscanthus. Ash content was the lowest in Giganteus and the highest in F. Bianche. Low heating value was the highest in Saccharum, both Miscanthus and giant reed P. Armerina. Generally, the bulk density was greater in giant reed and Saccharum than Miscanthus. Cellulose was the highest in both Miscanthus and hemicellulose in Saccharum. Lignin content was the lowest in giant reed clones. Several significant correlations occurred between biomass yield and raw material characteristics, as well as within feedstock properties. To support the development of a suitable bioenergy chain based on perennial grasses, besides biomass yield, feedstock properties should be rigorously considered. Further research is still required in crop management practices, logistic and technology front in order to tackle bottlenecks for improved quality of herbaceous biomass.

1. Introduction

Perennial, herbaceous, energy crops are gaining steady interest worldwide thanks to their climatic adaptability, low input requirement and high biomass yield (Cosentino et al., 2008; Zegada-Lizarazu et al., 2010). However, limitations for their fully exploitation are ascribed to the biomass quality. For instance, biomass quality can drastically affect the net energy output, bioconversion efficiency and lifetime of the equipment in both thermochemical and biochemical conversion of biomass to heat, energy and biofuels (McKendry, 2002; Monti et al., 2008). Most herbaceous perennial crops are largely undomesticated, so their cropping practices, their potential and actual yields, compositions and bioconversion characteristics are not as well-known as those of traditional agricultural crops (Scordia et al., 2010).

There are several potentially available herbaceous, perennial crops to supply lignocellulosic biomass, however, only a few have been extensively explored. Amongst them, perennial grasses are receiving great attention due to their low production costs, suitability to marginal and erosive lands, relative low water needs, low nutrient and agrochemical requirements (Zegada-Lizarazu et al., 2010; Soldatos, 2015). Generally, *Miscanthus* × *giganteus* and other species of *Miscanthus* genus have been indicated as potential dedicated biomass crops in cold and moist temperate environments

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* Corresponding author.
E-mail addresses: dscordia@unict.it, danilo.scordia@tiscali.it (D. Scordia).

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(Lewandowski et al., 2003; Zegada-Lizarazu et al., 2010). Giant reed (*Arundo donax* L.) is best adapted to warm temperate and Mediterranean areas (Lewandowski et al., 2003; Cosentino et al., 2008; Zegada-Lizarazu et al., 2010). Another wild species of the Mediterranean flora, *Saccharum spontaneum* L. spp. *aegyptiacum* (Willd.) Hack., proved to be well adapted to the semi-arid conditions (Cosentino et al., 2015).

Aforementioned species and other perennial grasses produce lignocellulosic biomass, which in turn can be converted by following biochemical or thermochemical pathways.

In biochemical conversions, structural polysaccharides of the plant cell wall, as cellulose (i.e., glucan) and hemicelluloses (i.e., xylan, mannan, galactan and arabinan), are mainly involved. These constituents do not greatly differ in amount rather than in proportion amongst wood, agricultural residues and perennial grasses (Scordia et al., 2014). Generally, woody biomass is more abundant in cellulose and lignin, whereas grass biomass has higher content of hemicelluloses, extractives and ashes (Zhao et al., 2012). However, it has been shown that plant cell wall constituents are crucial not only for biochemical, but also for thermochemical conversion efficiencies. Indeed, consistent differences occurred in the pyrolysis behaviour amongst the three main components, with primary thermal decomposition of hemicellulose and cellulose at relatively mild temperatures, followed by lignin decomposition at higher temperature ranges (Yang et al., 2007). Pyrolytic gas evolution profiles were also affected by biomass composition (Pasangulapati et al., 2012).

In thermochemical processes (e.g., pyrolysis, combustion, gasification), woody and forestry species can be considered the reference feedstock, while herbaceous biomass has received little attention (Tanger et al., 2013). Woody and forestry species are characterized by a high C/N ratio, low ash content, and their ash are generally poor in mineral avoiding slagging, fouling and corrosion of the equipment (Monti et al., 2008). Furthermore, they possess a high biomass density and high heating values, decreasing transportation costs, on the one hand, and increasing energy conversion efficiency on the other hand (Tanger et al., 2013).

However, woody species show relatively less flexibility in terms of land allocation than many herbaceous perennial grasses and their annual biomass yield is generally lower due to a slow growth rate in the post-establishment years (Rettenmaier et al., 2010; Laurent et al., 2015; Amaducci et al., 2016). In addition, harvest is quite more problematic and much more energy is required for biomass comminution due to greater biomass recalcitrance (Pochi et al., 2015; Pari et al., 2016).

As such, further research on low production cost feedstock is needed. To this end, an established field trial was employed with the aim to compare the biomass yield and raw material composition of three different clones of giant reed (*Arundo donax* L.), two miscanthus (*M.* × *giganteus* and *M. sinensis* "Goliath") and a saccharum (*Saccharum spontaneum* L. spp. *aegyptiacum* (Willd.) Hack., all grown side-by-side in rainfed conditions in semi-arid Mediterranean area.

2. Material and methods

2.1. Biomass recovery

Three different clones of *Arundo donax* L. (Capo d'Orlando, Piazza Armerina and Fontane Bianche), two species of *Miscanthus* (*Miscanthus* × *giganteus* Greef et Deu. and *Miscanthus sinensis* "Goliath") and one of *Saccharum* genus [*Saccharum spontaneum* L. spp. *aegyptiacum* (Willd.) Hackel] were grown at the experimental fields of the University of Catania (10 m a.s.l., 37°25′N lat., 15°03′E long.) in a randomized block design with three replications.

Establishment was carried out in spring 2002 by transplanting rhizomes into plots of 16 m^2 at a density of 4 rhizomes m^{-2} on a typical Xerofluvent soil (22.4% silt, 49.3% sand, 28.3% clay, 1.4 g kg^{-1} organic matter, 1.0 g kg^{-1} total nitrogen, 5.0 mg kg^{-1} assimilable phosphorus, 244.8 mg kg^{-1} exchangeable potassium, pH 8.6).

A basic fertilization (80 kg N ha^{-1} as ammonium sulfate, and 100 kg P_2O_5 ha^{-1} as mineral superphosphate) was applied during soil-bed preparation.

Irrigation was constantly supplied in the first spring-summer (between May and September), for a total of 350 mm. Weeds were controlled manually during the establishment year, while no pesticides were used. In the post-establishment years weed control was no longer needed because of the well and uniform crop establishment, no fertilization was applied, while supplemental irrigation was provided when symptoms of drought stress were detected in summer-time (i.e., leaf rolling). Plots were managed without any inputs supply from 2005/06 growing season. Harvest occurred every winter when plants usually reach the minimum water content in this environment.

Main meteorological parameters, as maximum and minimum air temperatures and rainfall, were measured by a weather station connected to a data logger (CR10, Campbell Scientific, USA), located nearby the experimental field. Monthly average air temperature was calculated from maximum and minimum air temperature for each growing season, between stem sprouting (March) and up to the onset of senescence (November).

The fresh biomass yield was determined in the center of the plot (4 m^2) after removing all plants from each plot edge. Subsamples of stems and leaves were placed in a ventilated oven dry at 65 °C until constant weight to determine the water content (% w/w). In this work biomass dry matter yield of 2011/12, 2012/13 and 2013/14 growing seasons is reported, corresponding to the tenth, eleventh and twelfth growing season, respectively. Biomass of 2012/13 growing season was used for analytical determinations.

2.2. Analytical determinations

The whole dry biomass (stems and leaves) was used. The bulk density was determined in two different ways: the first method was to "stack" the biomass horizontally, creating the highest density possible, while the second method was to pile "randomly" the biomass. The water content of the samples was measured by using a Kern MLB_N moisture meter (Kern and Sohn GmbH, Balingen, Germany). The remaining part of the sample was oven dried at 105 °C for 24 h. After drying, the samples were grinded into smaller particles for ash and Micro Carbon Residue Testing (MCRT) analysis and into a fine powder for further CHN-composition.

The CHN-composition was analysed on a dry basis by using a EuroVector EA (EuroVector S.p.A., Milan, Italy), while the ash content by using the ASTM E1755-01 (Standard Test Method for Ash in Biomass) in a Carbolite AAF—Standard Ashing Furnaces (Carbolite Gero GmbH, Neuhausen, Germany).

The MCRT was determined by the standard ASTM D4530-11 (Standard Test Method for Determination of Carbon Residue) in combination with the Alcor Micro Carbon Residue Tester to determine the carbon residue. The residue was tested on a dry basis.

For the analysis of the ash melting behaviour (i.e., initial deformation temperature—IT, softening temperature—ST, hemispherical temperature—HT, and fluid temperature—FT) the standard Seger cone method (ASTM D3174-12) was used in a Carbolite CWF—Standard Chamber Furnace (Carbolite Gero GmbH, Neuhausen, Germany). Ash was mixed with a solvent (dextrin/salicylic acid/acetone) and a cone was prepared. From each sample three cones were placed inside the furnace, which can be operated up to 1300 °C. During a test the temperature of the furnace was slowly increased, and meanwhile the shape of the cones