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Energy of biomass sorghum irrigated with reclaimed wastewaters

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ABSTRACT

The sustainability of biomass sorghum (*Sorghum bicolor* L. Moench) in the Mediterranean environments is linked to the potential to increasing the crop productivity using irrigation water of different qualities: fresh and wastewater. An experiment was conducted in Southern Italy during 2012 and 2013 growing seasons to determine the biomass production and to estimate the yielded energy from sorghum irrigated with fresh water and municipal wastewaters. Two stages of wastewater reclamation process were compared: tertiary and secondary treatments.

During the growing seasons, the crop growth (biomass and LAI) was surveyed on sorghum crops irrigated with three water qualities. In order to determine the effects of the irrigation water qualities on the final energy yielded, on the harvested biomass, structural components (cellulose, hemicellulose and lignin contents for deriving the ethanol production) and high heating value were analyzed. The data obtained during two crop seasons showed that, sorghum irrigated with municipal wastewater plant produced more dry biomass (23.3 vs 20.3 t ha^{-1}), energy yield (383 vs 335 GJ ha^{-1}), and ethanol (6824 vs 6092 L ha^{-1}) than sorghum biomass with fresh water. As a consequence, the water efficiency for producing bioenergy increased when the waste waters were supplied in substitution of fresh waters. Different indices were calculated for comparing the effect of the water quality on the water use efficiency (WUE) of biomass sorghum crops.

1. Introduction

Biomass crops have been studied for two decades as the most promising renewable energy sources that can be used for the production of energy obtained by co-generation and fermentation processes. The production of bioethanol using lignocellulosic feedstocks allow a series of benefits derived from the reduction greenhouse gas emissions, as required by the Kyoto Protocol (Heaton et al., 2004; Zhao et al., 2009). From an economic point of view, the replacement of traditional crops with non-food species represent a new opportunity for the rural development, when incomes food crops are no more sustainable (McKendry, 2002); Moreover new vegetal material and biomass are required for the self-energy production by farms and by forestry companies for accumulating biomass commodities (Barbera et al., 2009). Finally the biomass crops allow the reassessment of marginal land from farmers (Zema et al., 2012).

One of the prime sources investigated as energy is the biomass obtained from 'dedicated' crops of sorghum (*Sorghum bicolor* L. Moench). Sorghum, a C4 species (uses the "malate" cycle) of tropical origin, is the fifth most important cereal crop in the world and can be used as green fodder, straw and silage as well as to produce syrup and fuel (ethanol). It is grown in 99 countries around the world on 44 million ha, mainly in those areas which are too dry for growing maize (FAOSTAT, 2014).

Sorghum is more environmentally sustainable (Dalianis, 1996) compared to other energy crops (maize, sunflower, and soybean) particularly because of its relatively lower water requirements (Steduto et al., 1997; Mastrorilli et al., 1999; Vasilakoglou et al., 2011; Garofalo and Rinaldi, 2013) and of its high efficiency to transform the evapotranspired water and the intercepted energy in dry matter.

This is a crucial point under the Mediterranean climates, where high temperatures and solar radiation are beneficial to sorghum eco-physiology, but the scarcity of water resources limits its cultivation. Therefore, anomalous waters (saline or waste) could represent an important contribution to solving the ever-increasing problems of water scarcity, particularly in the Mediterranean areas.

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As an example, in southern Italy (Apulia region), more than 65% of the water resources are allocated to irrigation (Disciglio et al., 2014). In these conditions water re-use for agriculture needs to be a top priority, mainly in producing non-food crops.

In order to reduce the pressure of irrigated cropping systems on the water resources, alternative irrigation strategies, as the use of wastewater (WW) to replace fresh water, require to be tested under field conditions for the biomass crops. The literature shows that the irrigation with WW is a promising solution for crops in semi-arid environments. In these areas, the use of WW allows preservation of the natural water resources and maintains the soil fertility levels and the soil productivity (Lopez et al., 2010).

A large number of studies (Bastos and Mara, 1995; El Hamouri et al., 1996; Lopez et al., 2006; Palese et al., 2009; Ndiaye et al., 2011; Petterson et al., 2011) have shown that the chemical and microbiological contamination (viruses, bacteria and protozoa pathogens) remains a crucial issue to ensure the safe use of WW in agriculture. The European directives laws are restrictive for chemical and microbiological parameters and are not in line with the most recent approaches proposed and recommended by the World Health Organization (WHO, 2006). The reuse of tertiary wastewater is encouraged as a general principle, although the actual laws do not differentiate the wastewater according to the risk associated with the different types of reuse (Alcalde-Sanz and Gawlik, 2014). The irrigated energy crops represent a typical case of a relatively low level of risk because they do not require the same water quality than food crops.

In comparison with an intensive depuration, the use of secondary WW in agriculture reduces: the treatment costs (Angelakis et al., 1999; Paranychianakis et al., 2006; Aiello et al., 2007; Andiloro et al., 2010); disposal of polluting effluents into surface water bodies (Tamburino et al., 1999; Aiello et al., 2007; Andiloro et al., 2010); cultivation cost due to the reduced need for fertilizers (Tamburino et al., 1999; Paranychianakis et al., 2006; Bedbabis et al., 2010). Several experimental evidence underline the improvement of crop growth due to WW irrigation for food species (Meli et al., 2002; Bedbabis et al., 2010; Borin et al., 2013; Vivaldi et al., 2013; Disciglio et al., 2014) and perennial energy crops. (Zema et al., 2012; Molari et al., 2014). Regarding the effect of WW irrigation on the sorghum productivity, recent results on biomass yield are reported by Campi et al. (2014) but not on the energy yielded. Likewise, studies about the effect of WW on the sorghum energy yield are missing in literature.

To assess if a reduced level of WW treatment is consistent with the energy yielded by sorghum grown in a the Mediterranean environment (southern Italy), this research reports the results on the growth dynamics and energy (ethanol and heat) yielded from the biomass sorghum in relation to the irrigation water quality (urban WW and fresh water), after 2-year of cultivation.

2. Materials and methods

2.1. Experimental site

The study was conducted in southern Italy (Trinitapoli, lat: 41°21', long: 16°03', altitude 0 m a.s.l.), close to municipal WW treatment plant which supplied different qualities of reclaimed water for irrigation during the two growing seasons (2012 and 2013). The area was characterized by a Mediterranean climate with warm and dry summers: a maximum air temperature ranging from 32 °C to 43 °C and a minimum relative humidity ranging from 15% to 40% (Campi et al., 2009). The annual average precipitation was of 560 mm from 1977 to 2011, with rainfall events mainly concentrated in the autumn and late winter seasons and greatly reduced or absent in the spring–summer season. The agrometeorological data (daily rainfall, minimum and maximum temperatures, relative air humidity, solar radiation, wind speed) necessary to calculate the reference evapotranspiration, according to Allen et al. (1998), were recorded at an agro-meteorological station located at a short distance from the experimental site. During the 2012 growing season, mean values of air temperature were similar to those recorded during 2013. The total rainfall was higher in 2013 than in 2012 (150 mm more) and it was concentrated in the last part of the sorghum cultivation cycle, in September (Fig. 1).

Table 1
Main physical-chemical characteristics of the soil.

Parameter	Depth			
	0–0.20 m		0.21–0.40 m	
	Average	sd	Average	sd
Clay (g kg^{-1})	325	36	329	32
Silt (g kg^{-1})	361	23	350	17
Sand (g kg^{-1})	329	3	321	4
E.C. (dS m^{-1})	1.1	0.1	1.4	0.2
pH	8.1	0.2	8.3	0.1
total Limestone (g kg^{-1})	172	111	202	73
active Limestone (g kg^{-1})	9.8	0.5	9.9	0.6
C (g kg^{-1})	14.0	0.6	13.8	0.6
N (g kg^{-1})	1.5	0.05	1.4	0.07
P (mg kg^{-1})	79.75	5.3	62.21	13.73
Ca (mg kg^{-1})	3286	40.4	3283	67.1
Na (mg kg^{-1})	180.2	12.3	231.6	32.4

The soil in north Apulia is predominately clay in all horizons with low percentage of stones. Before the 2012 sowing, the soil was sampled of the experimental plots at two profile depths (0–0.20 and 0.21–0.40 m) in five replicates. The texture and hydrologic constants (field capacity, FC, and wilting point, WP) were determined in the soil-sieved samples. Soil texture was classified as clay-loam (USDA Soil Survey Staff, 1975) with an average content of 318 g kg^{-1}, 355 g kg^{-1} and 327 g kg^{-1} of sand, silt and clay, respectively (Table 1), determined using the hydrometer method. Soil water content in volume at FC (−0.03 MPa) and WP (−1.5 MPa) were 38 mm mm^{-1} and 26 mm mm^{-1}, respectively (measured using the Richards chambers). The soil water reserve was moderate (180 mm), because the root system does not develop below 1.5 m in this soil. The soil chemical fertility was good (Table 1), with adequate content of total nitrogen (1.5 g kg^{-1}), soil organic carbon (14 g kg^{-1}), and available phosphorous (71 mg kg^{-1}).

In late winters of both growing seasons (2012 and 2013), the soil was prepared by ploughing to a depth of 0.25–0.30 m. Immediately before sowing (May), the soil was tilled using a double-disking harrow and finally a field cultivator was used to prepare the seedbed. The sorghum experimental plots were grown within the crop sequence 'wheat–broad bean–sorghum' in 2012; 'sugar beet–broad bean–sorghum' in 2013'.

2.2. Irrigation water quality

During both sorghum growing seasons, irrigation water was sampled nine times randomly (in 4 replications) from the dripping lines corresponding to the three water quality treatments, using a 1 L sterile glass bottles and stored at 4 °C before chemical analysis.

The supplied waters were analyzed in triplicate, according to the Italian standard methods (APAT—IRSA CNR, 2003) referencing the common international methods (APHA—AWWA—WEF, 2005), for the following parameters: electrical conductivity (EC; dS m^{-1}), biological oxygen demand over 5 days (BOD_5; mgO_2 L^{-1}), chemical oxygen demand (COD; mg L^{-1}), chlorine (active Cl^-, mg L^{-1}), ammonium–nitrogen (NH_4-N; mg L^{-1}), nitrate nitrogen (NO_3–N; mg L^{-1}), phosphorus (PO_4–P; mg L^{-1}), sodium (Na^+; mg L^{-1}), calcium (Ca^{2+}; mg L^{-1}), magnesium (Mg^{2+}; mg L^{-1}), potassium (K^+;

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