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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 and Zhao at 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. 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).

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^+; mg L^{-1}), sodium adsorption ratio (SAR), chlorides (mg L^{-1}) and fluorides (F^-; mg L^{-1}).

The pH was measured with a GLP 22+ pH and Ion-Meter, CRISON, and the EC with a GLP 31+ EC Meter, CRISON. The sodium, calcium, magnesium and potassium levels were determined using ion-exchange chromatography (Dionex ICS-1100; Dionex Corporation, Sunnyvale, CA, USA). The sodium adsorption ratio (SAR) was calculated according to Richards 1954.

2.3 Crop management and irrigation treatments

The sorghum hybrid 'KWS Bulldozer' was cultivated during two growing seasons (2012 and 2013) in the experimental field. This hybrid is characterized by medium-late vegetative cycle, increased height with good tolerance to bending, and high yielding in dry and green biomass (Campi et al., 2014). Sorghum was sown on May 28, 2012 and on May 21, 2013 with a plant density of 18 plants m^{-2} and it was grown following the agro-techniques aiming at reducing the energy inputs: weed control at the initial crop stage and nitrogen fertilization of 100 kg N ha^{-1} after 30 days from sowing. Pest control was no required during the crop cycle due to the absence of phytosanitary problems (with the exception of sporadic presence of aphid colonies).

Sorghum crops were submitted to the following irrigation treatments:

- Fresh water (FW), withdrawn from the water network of the "Consorzio di Bonifica della Capitanata" and directly from the dam "Marana Capacciotti";
- Secondary-treated municipal wastewater (SW) originated from the public plant located near the experimental site. After screening and grit removal, the WW flows to primary clarifiers followed by a partial aerobic stabilization of the sludge (Vivaldi et al., 2013).

- Tertiary-treated wastewater (TW) produced by the same public plant cited above, where the WW is treated in two subsequent phases. Primarily, water is collected in a tank of 180 m^3 and pumped to the sand filter section, including five tanks with the following filling materials: anthracite, quartz sand and gravel support with different diameters. The second phase was represented by ultra-filtration module equipped with hollow fiber membranes with cellulose triacetate double wall. Periodically all the lines were automatically cleaned by back flushing (Vivaldi et al., 2013). This purification process allows to obtain WW with a lower content of suspended solids and nutrients for plants respect to the secondary-treated municipal wastewater (SW);

The irrigation water was scheduled for supplying the amount of water lost by evapotranspiration (ETc) calculated according the FAO-56 methodology (Allen et al., 1998).

WW was reused under a controlled flow rate and distribution conditions specifically aimed to avoid contamination of bordering fields (a dripping irrigation system was adopted) and the underlying groundwater irrigation volumes were scheduled in order to maintain the soil water content lower than filed capacity. The root depth of the sorghum is over 2 m, however when the soil profile is moist, most of the water is taken up from the top one-fifth of the root zone (Steduto et al., 2012). Consequently a depth of 0.5 m was adopted for dimensioning the irrigation volumes.

Irrigation treatments were arranged in a complete randomized experimental design, where blocks of 400 m^2 were replicated 3 times. Soil water content in the whole soil profile (mm d^{-1}) was monitored by capacitance probes. Capacitance probes (10HS, Decagon Devices Inc., USA) were installed horizontally into the soil at three depths (-0.3, -0.6 m and -1.2 m) and connected to a data logger (Grillo MMS, Tecno.El, Italy).

The irrigation volumes were 300 mm during 2012 season and 340 mm during 2013 season.

2.4 Biomass analysis.

At regular intervals (every 7-10 days), leaf area index (LAI) and dry biomass were measured. The LAI was measured by an area meter (LAI-2000 Plant Canopy Analyzer, Li-Cor, USA) and the dry matter was determined on sampled plants by using a dry-oven (at 65°C for 48 h). At the end of the sorghum cycle (the second week of September) all plants were harvested from 20 m^2 plots, and then the aboveground biomass production was determined.

Plant tissue samples were accurately milled into fine pieces (1-2 mm) and stored until were required for the determination of higher heating value, lignin, cellulose and hemicellulose content.

The higher heating value (HHV; MJ kg^{-1}) of sorghum was measured using a LECO AC500 bomb calorimeter (LECO Corp., St. Joseph, MI, USA) with 1g of dried sample. Neutral detergent fiber (aNDFom) content was determined without sodium sulfite and with heat stable amylase (Van Soest et al., 1991). Acid detergent fiber (ADFom) and acid detergent lignin [lignin (sa)] were determined by sequential analysis of the residual aNDFom and expressed as exclusive residual ash (Van Soest et al., 1991). Hemicellulose was calculated as aNDFom–ADFom, and cellulose as ADFom–lignin (sa), and both were assayed sequentially on the same sample. An Ankom apparatus (Ankom220, Fairport, NY, USA) was used for extraction and filtering.

2.5 Calculation and statistical analysis

To asses the energy yield per hectare of sorghum (GJ ha^{-1}), the HHV obtained with the bomb calorimeter was multiplied by biomass production.

A theoretical calculation of ethanol yield from cellulose and hemicellulose was formulated as follows.

Ethanol yield from cellulose and hemicellulose (L ha^{-1}) = cellulose and hemicellulose content (%) in dry matter x dry biomass (t ha^{-1}) x 1.11 (conversion factor of sugar from cellulose and hemicellulose) x 0.85 (process efficiency of sugar from cellulose and hemicellulose) x 0.51 (conversion factor of ethanol from sugar) x 0.85 (process efficiency of ethanol from sugar) x 1000/0.79 (specific gravity of ethanol, g mL^{-1}) (Institution of Japan Energy, 2006).

The seasonal irrigation volumes (I), and biomass (B), energy yield (ey - MJ m^{-2}) and ethanol production (eth) by sorghum were used to determine the water use efficiency indices (WUE) for the different treatments, according to the following formula:

$$bWUE(kg \cdot m^{-3}) = \frac{B(Kg \cdot m^{-2})}{I(m^3 \cdot m^{-2})} \qquad (1)$$

bWUE (biomass-water use efficiency) indicates the amount of biomass (in kg) produced by sorghum using 1 m^3 of irrigation water;

$$eyWUE(MJ \cdot m^{-3}) = \frac{EY(MJ \cdot m^{-2})}{I(m^3 \cdot m^{-2})} \qquad (2)$$

eyWUE (energy yield-Water use efficiency) indicates the amount of energy (in MJ) produced in sorghum using 1 m^3 of irrigation water.

$$ethWUE(L \cdot m^{-3}) = \frac{Ethanol(L \cdot m^{-2})}{I(m^3 \cdot m^{-2})} \qquad (3)$$

ethWUE is ethanol-Water use efficiency that indicates the amount of ethanol (in L) produced by sorghum using 1 m^3 of irrigation water.

Data were analyzed using the statistical package Statgraphics Plus 5.1 (StatPoint Technologies Inc., Warrenton, VA). Duncan’s multiple range test was used to separate treatment means when ANOVA results indicated significant differences.

3. Results

3.1 Wastewater properties

The analysis of the main chemical properties of WW utilized for crop irrigation (Table 2) showed a slight alkalinity (mean pH value = 7.4) and a moderate EC (average = 1.4 dS m^{-1}, indicating a moderate salt content). The chemical characteristics varied considerably among the three sources of irrigation water used. The values of most of the chemical parameters, such as EC, COD, BOD_5, Na^+, K^+, Ca^{2+}, Mg^{2+}, NH_4^+-N, NO_3^--N, PO_4^{2-}-P were significantly higher in SW compared to TW (Table 2). The other analyzed parameters showed similar values in all the three irrigation waters. Moreover, the main chemical parameters for TW and SW meet the Italian standard for WW re-use, except for NO_3^--N, PO_4^{2-}-P, BOD_5 and COD (Table 2). The high value of PO_4^{2-}-P in 2013 FW was a consequence of 2 outliner values measured on the two samples collected consecutively in July. Neglecting these exceptional values, probably due to a temporary pollution of the conventional water, the average PO_4^{2-}-P value during the 2013 sorghum season was of 9 mg L^{-1}, corresponding to the average value measured in the previous year.

The contents of N/P/K compounds in both WW (TW and SW) indicate its appreciable potential as fertilizer, in particular for nitrogen (in forms NO_3^--N and NH_4^+-N) which represent one of the most important nutrients for plants.

3.2 Crop growth and biomass yield

In both years (2012 and 2013), the irrigation scheduling prevented that the water content values in the soil profile exceeded the Readily Available Water (p) threshold (0.32 mm mm^{-1}) to avoid water stress (Fig. 2). In particular, at depth of 0.3 m, the soil water content was close to FC following each event of rainfall or irrigation, while at depth of 0.6 m, the soil water content was always close to FC, and at depth of 1.2 m, the soil water content was close to saturation. The high values of the soil water content at a depth greater than 0.6 m were due to the presence of a shallow groundwater, while the moisture variations during the sorghum crop cycle were detected on the 0.5 m top soil (Fig. 2). This 0.5 m soil layer was considered for dimensioning the water amount of each irrigation. The quality of the irrigation water affected the crop growth: the trends of LAI (Fig. 3) and dry biomass (Fig. 4) were consistent in both growing seasons (2012 and 2013). In particular, differences in crop growth started in July, from the stem elongation phase of the sorghum until the crop harvest. During the 2012 growing season (Fig. 3a), the WW treatments (TW and SW) showed an average increase in maximum LAI values by 10% in comparison with the FW treatment, while during the 2013 growing season (Fig. 3b) an increase of 8% and 15% of the maximum LAI values was induced by the TW and SW treatments, respectively, in comparison with the FW treatment.

Data reported in table 3 shows that the highest dry biomass productions were observed on the crops irrigated with the WW (TW or SW) in both growing seasons, being significantly higher than biomass production of sorghum irrigated with FW by 2.2 t ha^{-1} and 3.4 t ha^{-1}, respectively. The statistical analysis showed a significant interaction between the irrigation water treatments and the growing season. In the 2012, the biomass yielded from the FW treatment was lower (by 2.1 t ha^{-1}) than that of the sorghum irrigated with WW (TW or SW). In 2013, the SW treatment led to a final production of sorghum biomass significantly higher respect to the TW and FW treatments, by 2.7 and 5.4 t ha^{-1}, respectively (Fig. 5a).

3.3 Energy yield

The HHV of sorghum was not influenced by the quality of the irrigation water (Table 3). These data allowed the calculation of the energy yield, which could be obtained from the biomass harvested per hectare of sorghum irrigated with different water qualities. The best performance in energy yield was attained by the sorghum irrigated with WW and the higher values of this parameter were estimated in 2013. (Table 3 and Fig. 5c). Statistical analysis indicated an interaction between irrigation water treatments and growing seasons (Fig. 5c).. In particular, during the 2012 season, irrigation with WW led to a significant increase in energy yield, corresponding to + 10%: from 372 GJ ha^{-1} (both WW treatments) to 336 GJ ha^{-1} (FW treatment). During the 2013 season, the energy yield in the SW treatment (423 GJ ha^{-1}) was significantly higher than that obtained by the sorghum irrigated with TW (364 GJ ha^{-1}) or FW (333 GJ ha^{-1}).

3.4 Calculated ethanol yield

Table 4 shows the structural components of sorghum (lignin, cellulose and hemicellulose content). They were not significantly affected by the quality of the irrigation waters. Calculating the production of ethanol by the formula suggested by the Institut of Japan Energy (2006), the WW provided a better conversion of biomass sorghum in ethanol. On average, a significantly higher production of calculated ethanol production was obtained from sorghum grown in 2013 season (Table 4). In particular, during the 2012 season, irrigation with WW (TW or SW) led to a significant increase in ethanol of 500 L ha^{-1}, compared to the FW treatment (Fig. 5e). During the 2013 season the significant increase of calculated ethanol production occurred especially with sorghum irrigated with SW, resulting an increase of 560 and 1440 L ha^{-1}, compared to the TW and FW treatments (Fig. 5e). This was due to the higher irrigation volume supplied during 2013 which caused a reduction of the ratio between ethanol production and irrigation.

3.5 Water use efficiency indices

The water use efficiency (WUE) for biomass (bWUE), energy yield (eyWUE) and ethanol (ethWUE) were significantly affected by both the irrigation treatment and the growing season. These three indicators were consistent, with higher values of WUE in sorghum irrigated with SW (Table 5) and cultivated during 2013 season (with the exception of ethWUE).

The statistical analysis showed an interaction between the irrigation treatment and the growing season (Table 5) for the three WUE indices. The analysis *per* season (Fig. 5b, d and f) showed in 2012, the highest values of WUE indices in both treatments with WW (TW and SW) respect to the irrigation with FW, while in the 2013, the highest WUE indices values were only obtained by the SW treatment respect to TW and FW treatments.

4. Discussion

The trends of leaf development in sorghum obtained with the use of fresh water were consistent with those reported by other authors (Gherbin et al., 1996; Mastrorilli et al., 2011; Cosentino et al., 2012), while the results describing the effects of WW on the bio-energy produced by biomass sorghum can be considered as a novelty.

The increase in plant growth under the WW treatments can be attributed mainly to the nutrients availability, since they are the critical factors responsible of improveing growth of irrigated sorghum in Mediterranean area (Zema et al., 2012). By examining the contributions of nutrients (nitrogen, phosphorus and potassium) during the two seasons (Table 6), the average N supplied (nitrate and ammonium) with irrigation during the growing seasons (2012 and 2013) was corresponding to the supply of 6, 86 and 112 kg ha^{-1}, for the FW, TW and SW treatments respectively.

Through the irrigation waters, crop was also supplied by 7, 12 and 17 kg of P ha^{-1}, and 10, 68 and 67 kg of K ha^{-1}. The analysis of water gave the same results reported by Vivaldi et al. (2013) and Disciglio et al. (2014) for other crops tested on the same experimental site.

In particular, the N content in WW varied with the quality of the treated waters or with the efficiency of the treatment plant (Table 6): in 2012 the nitrogen supply was similar for the two types of WW (100 kg ha^{-1} for TW and 114 kg ha^{-1} to SW), while in 2013 the irrigation with SW provided a greater quantity of nitrogen (110 kg ha^{-1}) respect to TW (71 kg ha^{-1}). As a consequence in the 2012, dry biomass yield of sorghum under SW treatment was similar to TW, while in the 2013 dry biomass yield of SW was significantly higher ($p<0.05$) respect TW treatment. Studies of the nitrogen level on the productivity of sorghum carried on the same environment (Cosentino et al., 2012; Palumbo et al., 2014) indicated that yield was more affected by the soil water status during the sorghum cycle than by the nitrogen level. In our study, should be considered that the distribution of nitrogen is similar to a fertigation and several studies (Steduto, 1984, Boman, 1996; Kafkafi and Tarchitzky, 2011) show that this technique improves crop productivity, but technically it cannot be proposed in the extensive open field crops requiring the irrigation supply. In the case of sorghum, the literature about the effects of fertigation of nitrogen are missing.

There are a few research about effect of WW on productivity of energy crops. In particular, Day and Tucker (1977) with the use of WW and Mendoza et al. (2006) with the use of sludge, show the increase in productivity of sorghum. Zema et al. (2012) performed a study on the use of WW on other herbaceous perennial energy plants (*Typha latifolia*, *Arundo donax* and *Phragmites australis*). Best results were found on *Typha latifolia*. These plants irrigated with WW showed an increase in growth compared to plants irrigated with FW, indicating higher average values of LAI (+86.7%), height (+25.6%) and higher average (+54.5%) and maximum biomass (+146%) yield: this may be ascribed to the indirect fertilizing role of WW. Molari et al. (2014) show that *Arundo donax* represents a real opportunity to produce amounts of high biomass, for energy purposes, in marginal land with marginal irrigation water.

Regarding the structural components of sorghum, we underline that the proportions of cellulose and lignin in biomass are important in biochemical conversion processes for the ethanol production. The biodegradability of cellulose is greater than that of lignin, hence the overall conversion of the plant material containing carbon as cellulose is greater than for plants with a higher proportion of lignin.

For the production of ethanol, a biomass feedstock with a high cellulose/hemi-cellulose content is needed to provide a high yield. While the lignin content represents a potentially large energy source. However, the current techniques involving hydrolysis/enzymatic systems are not performed to convert the lignin (McKendry, 2002). Cellulose and hemicellulose contents in sweet sorghum have rarely been documented. In this study, we observed that cellulose, hemicellulose and lignin contents of sorghum were 32.5%, 24.8% and 7.6 % in dry matter. Our results show a higher content of cellulose and hemicellulose compared to those reported by Zhao et al. (2009) in China, who showed that sorghum contained a range of 19-27% of cellulose and 16-23% hemi-cellulose in relation to different cultivars and phenological phases. Of course, this depends on the genetic component of sorghum and different environment. WW did not affect significantly the structural component of sorghum, only the cellulose content was significantly higher in the 2013 season, probably due to meteorological trend during the sorghum cycle (290 mm of rain in 2012 season and 140 mm in 2013 season) which was favorable to the accumulation of cellulose.

The HHV shown in table 3 is in according to those reported by Bludau (1992b) and Fernando et al. (2010b), which used fresh water for irrigation, while the negligible effects of WW on HHV were also demonstrated by Angelini et al. (2005) and Zema et al. (2012) for other crops.

The increase in biomass yield of biomass sorghum, due to the effect of WW, determined a significant difference of the estimated production of ethanol, energy yield and the WUE indices (bWUE, ethWUE and eyWUE).

Values of bWUE can be retained high, if compared to those reported in literature. As shown by the field results, the efficiency of sorghum in converting water into biomass was higher mainly when WW were applied, even if in the literature are reported (Farrè and Faci, 2006) values of bWUE, between 2.89 and 3.75 kg m^{-3}, obtained by irrigating with fresh water.

Field trials and data from the literature clearly showed that bWUE in sorghum grown in the Mediterranean area can vary remarkably from 5.84 to 22.81 kg m^{-3}, even with similar water amounts of irrigation (Mastrorilli et al., 1998; Mastrorilli et al., 2011; Palumbo et al., 2014). This can be mainly explained by the rainfalls amount and distribution (Garofalo and Rinaldi, 2013).The bWUE values calculated in the 2012 growing season were significantly higher because of greater amount of rainfalls (Fig. 1).

Based on these results we recommend to irrigate with WW, because it allowed high values of WUE, raw biomass production, energy yield and calculated ethanol yield.

The risk of contamination of groundwater from the wastewater is high, if irrigation is not well managed. The monitoring of soil water content shows that a precise irrigation scheduling allows to wet the layer of soil where the roots are more active and to avoid drainage of nutrients into groundwater. In particular, sorghum crop demonstrated a quite good aptitude to uptake nutrients and heavy metals from contaminated soil, by accumulating Pb in leaves and Cd, Zn and Cu in stems (Barbanti et al., 2006; Zhuang et al., 2009).

About the possible contamination of biomass energy crops by microorganism, the problem does not exist because, first of all the soil has a great ability to neutralize and immobilize microorganisms and harmful elements and moreover the microorganisms on the vegetation do not survive to the drastic transformation (cogeneration or fermentation) of biomass. In addition, Disciglio et al. (2014) working in the same area and with WW from the same water treatment plant, showed that there was no soil contamination, due to the high soil capacity to break down the bacterial load and to the high temperature at the soil surface that contributes to creating an environment unfavorable for the microorganisms.

5. Conclusion

This research shows original results regarding the application of WW on dedicated energy crops in the Mediterranean area and indeed has considered possible ways to irrigate energy sorghum in a sustainable way via the use of WW.

In general, biomass yield of sorghum was increased by irrigation with WW and, as consequence, also the ethanol and the energy production per unit of cultivated area.

The indices of calculated WUE show how the use of WW increases the efficiency conversion of water in biomass and in energy. This is an important aspect for a semi-arid climate where the fresh waters are designated primarily for the civil sector.

Even though the results achieved require further verification by mid- or long-term research, the present investigation showed that sorghum crops irrigated with WW can produce appreciable biomass and energy yields.

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7. References

Aiello, R., Cirelli, G.L., Consoli, S., 2007. Effects of reclaimed wastewater irrigation on soil and tomato fruits: A case study in Sicily (Italy). Agric. Water Manage. 93, 65-72.

Alcalde-Sanz and Gawlik, 2014. Water Reuse in Europe, Relevant guidelines, needs for and barriers to innovation. JRC Sience and policy reports. EUR – Scientific and Technical Research series. 48 pp

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration. Guide-lines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56.

Andiloro, S., Aramini, G., Corea, A.M., Tamburino, V., Zema, D.A., Zimbone, S.M., 2010. Planning agricultural utilization of olive oil mill wastewater: a framework model and implementation example in a Mediterranean area. Terr. Aquatic Environ. Toxicol. 4(1), 57-64.

Angelakis, N., Marecos Do Monte, M.H.F., Bontoux, M., Asano, T., 1999. The status of wastewater reuse practice in the Mediterranean basin: Need for Guidelines. Wat. Res. 33(10), 2201-2217.

Angelini, L.G., Ceccarini, L., Bonari, E., 2005. Biomass yield and energy balance of giant reed (*Arundo donax* L.) cropped in central Italy as related to different management practices. Eur. J. Agron. 22, 375-389.

APAT - IRSA CNR., 2003. Analytical Methods for Water. Handbooks and guidelines Apat Irsa Cnr 29/2003. Vol. 1. 490 pp.

APHA – AWWA - WEF., 2005. Standard Methods for the Examination of Water and Wastewater, 21st ed. American Public Health Association, Washington, D.C.

Barbera, A.C., Milani, M., Molari, G., Toscano, A., Villani, G., Zema, D.A., Zimbone, S.M., 2009. Produzione e trasformazione a fini energetici di biomasse erbacee irrigate con acque reflue. in: Atti del IX Convegno Nazionale dell’Associazione Italiana di Ingegneria Agraria “Ricerca e innovazione nell’ingegneria dei biosistemi agro-territoriali”. Ischia Porto (NA), 12-16 settembre.

Bastos, R.K.X., Mara, D.D., 1995. The bacterial quality of salad crops drip and fur-row irrigated with waste stabilization pond effluent: an evaluation of the WHO guidelines. Water Sci. Technol. 12, 425-430.

Bedbabis, S., Ferrara, G., Ben Rouina, B., Boukhris, M., 2010. Effects of irrigation with treated wastewater on olive tree growth, yield and leaf mineral elements at short term. Sci. Hortic. 126, 345-350.

Bludau, D. A., 1992b - Storage of sweet sorghum after har- vest . 393-397. In G. Grassi, A. Collina, H Zibetta. Bio- mass for Energy, Industry and Environment: 6th Conference on Biomass for energy and industry. Elsevier Science Publisher Ltd. 1512 pp

Boman, B.J., 1996. Fertigation versus conventional fertilization of Flatwoods grapefruit. Fert. Res. 44, 123-128.

Barbanti, L., Grandi, S., Vecchi, A., Venturi, G., 2006. Sweet and fibre sorghum (*Sorghum bicolor* (L.) Moench), energy crops in the frame of environmental protection from excessive nitrogen loads. Eur. J. Agron. 25, 30-39.

Borin M., Barbera A.C., Milani M., Molari G., Zimbone S.M., Toscano A., 2013. Biomass production and N balance of giant reed (*Arundo donax* L.) under high water and N input in Mediterranean environments. Eur. J. Agron. 51, 117-119.

Campi, P., Palumbo, A.D., Mastrorilli, M., 2009. Effects of tree windbreak on microclimate and wheat productivity in a Mediterranean environment. Eur. J. Agron. 30, 220-227.

Campi, P., Navarro, A., Palumbo, A.D., Solimando, M., Lonigro, A., Mastrorilli, M., 2014. Productivity of energy sorghum irrigated with reclaimed wastewaters. Ital. J. Agron. 9(3), 115-119.

Cosentino, L., Mantineo, M., Testa, G., 2012. Water and nitrogen balance of sweet sorghum (*Sorghum bicolor* Moench [L.]) cv. Keller under semi-arid conditions. Ind. Crops Prod. 36, 329-342.

Dalianis, C.D., 1996. Adaptation, productivity and agronomic aspects of sweet sorghum under European conditions. in: Proceedings of the First European Seminar on Sorghum for Energy and Industry. INRA, Toulouse, France, 1-3 April. pp 15-25.

Day, A.D., Tucker, T.C., 1977. Effects of treated municipal wastewater on growth, fiber, protein and amino acid content of sorghum grain. J. Environ. Qual. 6, 325-327.

Disciglio, G., Gatta, G., Libutti, A., Tarantino, A., Frabboni, L., Tarantino, E., 2014. Use of treated municipal wastewater on artichoke crop. Int J Biol. Biomol. Agric. Food Biotech Eng. 8(4), 224-230.

El Hamouri, B., Handouf, A., Mekrane, M., Touzani, M., Khana, A., Khallayoune, K., Benchokroun, T., 1996. Use of wastewater for crop production under arid and saline conditions: yield and hygienic quality of the crop and soil contaminations. Water Sci. Technol. 10-11, 327-334.

FAOSTAT. 2014. http://faostat.fao.org/

Farrè, I., Faci, J.M., 2006. Comparative response of maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L. Moench) to deficit irrigation in a Mediterranean environment. Agric. Water Manage. 83, 135-143.

Fernando, A.L., Duarte, M.P., Almeida, J., Boléo, S. and Mendes, B. (2010b). Environmental im pact assessment (EIA) of Energy crops production in Europe. Biofuels, Bioproducts & Biorefining , 4, pp 594 - 604

Garofalo, P., Rinaldi, M., 2013. Water-use efficiency of irrigated biomass sorghum in a Mediterranean environment. Spanish J. Agric. Res. 11, 1153-69.

Gherbin, P., Perniola, M., Tarantino, E., 1996. Sweet and paper sorghum yield as influenced by water use in southern Italy. in: Proceedings of the First European Seminar on Sorghum for Energy and Industry. INRA, Toulouse, France, 1-3 April, pp 222-227.

Heaton, E.A., Clifton-Brown, J., Voigt, T.B., Jones, M.B., Long, S.P., 2004. Miscanthus for renewable energy generation: European Union experience and projections for Illinois. Mitig. Adapt. Strat. Gl. 9, 433-451.

Institution of Japan Energy (editor)., 2006. In: Hua, Z.Z., Shi, Z.P. (Translators). Biomass Handbook. Chemistry Industry Press, Beijing, pp. 166-167, 172 (in Chinese).

Kafkafi, U., Tarchitzky, J., 2011. Fertigation. A Tool for Efficient Fertilizer and Water Management. First edition, IFA, Paris, France and IPI, Horgen, Switzerland, 139 pp.

Lopez, A., Pollice, A., Lonigro, A., Masi, S., Palese, A.M., Cirelli, G.L., Toscano, A., Passino, R., 2006. Agricultural wastewater reuse in southern Italy. Desalination 187, 323-334.

Lopez, A., Pollice, A., Laera, G., Lonigro, A., Rubino, P., 2010. Membrane filtration of municipal wastewater effluents for implementing agricultural reuse in southern Italy. Water Sci. Technol. 625, 1121-1128.

Mastrorilli M., Katerji N., Rana G., Ben Nouna B., 1998. Daily actual evapotranspiration measured with TDR technique in Mediterranean conditions. Agric and Forest Meteor., 90, 81-89.

Mastrorilli, M., Katerji, N., Rana, G., 1999. Productivity and water use efficiency of sweet sorghum as affected by soil water deficit occurring at different vegetative growth stages. Eur. J. Agron. 11, 207-215.

Mastrorilli, M., Campi, P., Palumbo, A.D., Navarro, A., Modugno, F., Turci, V., 2011. Water use efficiency of sorghum cultivated for energy in Mediterranean environments. in: Proceedings of the 19th European Biomass Conference and Exhibition, , Berlin, Germany, 6-10 June 2011, pp 565-568.

McKendry, P., 2002. Energy production from biomass (part 1): overview of biomass. Biores. Technol. 83, 37-46.

Meli, S., Porto, M., Belligno, A., Bufo, S.A., Mazzatura, A., Scopa, A., 2002. Influence of irrigation with lagooned urban wastewater on chemical and microbiological soil parameters in a citrus orchard under Mediterranean condition. Sci. Total Environ. 285, 69-77.

Mendoza, J.G., Garrido, T. Castillo, G., San Martin, N., 2006. Metal availability and uptake by sorghum plants grown in soils amended with sludge from different treatments. Chemosphere, 65, 2304-2312.

Molari, G., Milani, M., Toscano, A., Borin, M., Taglioli, G., Villani, G., Zema, D.A., 2014. Energy characterisation of herbaceous biomasses irrigated with marginal waters. Biomass Bioenerg. 70, 392-399.

Ndiaye, M.L., Niang, S., Pfeifer, H.R., Peduzzi, R., Tonolla, M., Dieng, Y., 2011. Effect of irrigation water and processing on the microbial quality of lettuces produced and sold on markets in Dakar (Senegal). Irrig. Drain. 60, 509-517.

Palese, A.M., Pasquale, V., Celano, G., Figliuolo, G., Masi, S., Xiloyannis, C., 2009. Irrigation of olive groves in Southern Italy with treated municipal wastewater: effects on microbiological quality of soil and fruits. Agric. Water Manage. 129, 43-51.

Palumbo, A.D., Vonella, A.V., Garofalo, P., D’Andrea, L., Rinaldi, M., 2014.Response of a two-year sugar beet-sweet sorghum rotation to an agronomic management approach diversified by soil tillage and nitrogen fertilization. Ital. J. Agron. 9(3), 109-114.

Paranychianakis, N.V., Nikolantonakis, M., Spanakis, Y., Angelakis, A.N., 2006. The effect of recycled water on the nutrient status of Soultanina grapevines grafted on different rootstocks. Agric. Water Manage. 81(1–2), 185–198.

Petterson, S.R., Ashbolt, N.J., Sharma, A., 2011. Microbial risks from wastewater irrigation of salad crops: a screening-level risk assessment. Water Environ. Res. 73(6), 667-672.

Richards, L.A., 1954. Diagnosis and Improvement of Saline and Alkaline Soils. U.S. Department of Agriculture, Handbook No. 60, U.S. Government Printing Office, Washington, DC.

Steduto, P., 1984. Fertigation. Rivista di agronomia. 18(1), 3-20.

Steduto, P., Katerji, N., Puertos-Molina, H., Unlu, M., Mastrorilli, M., Rana, G., 1997. Water-use efficiency of sweet sorghum under water stress conditions. Gas-exchange investigations at leaf and canopy scales. Field Crops Res. 54, 221-234.

Steduto P., Hsiao TC., Fereres E., Raes D., 2012. Crop Yield response to water - FAO Irrigation and Drainage Paper 66, Rome (Italy), 500pp

Tamburino, V., Zimbone, S.M., Quattrone, P., 1999. Storage and land application of olive oil mill. Olivae 76, 36-45.

USDA Soil Survey Staff., 1975. Soil taxonomy. Agricultural Handbook No. 436. Washington, DC. 754 pp.

Van Soest, P.J., Robertson, J.B., Lewis, B.A., 1991. Methods for dietary fiber, neutral detergent fiber, and non-starch polysaccharides in relation to animal nutrition. J. Dairy Sci. 74, 3583-3597.

Vasilakoglou, I., Dhima, K., Karagiannidis, N., Gatsis, T., 2011. Sweet sorghum productivity for biofuels under increate soil salinity and reduced irrigation. Field Crop Res. 120, 38-46.

Vivaldi, G.A. Camposeo, S. Rubino, P. Lonigro, A., 2013. Microbial impact of different types of municipal wastewaters used to irrigate nectarines in Southern Italy. Agric. Ecosyst. Environ. 181, 50-57.

World Health Organization (WHO), 2006. Wastewater use in agriculture. In: Guide-lines for the Safe Use of Wastewater, Excreta and Greywater. WHO, Geneva, pp.100

Zema, D.A., Bombino, G., Andiloro, S., Zimbone S.M., 2012. Irrigation of energy crops with urban wastewater: Effects on biomass yields, soils and heating values. Agric. Water Manage. 115, 55-65.

Zhao, Y.L., Dolat, A., Steinberger, Y. Wang, X., Osman, A., Xie, G.H., 2009. Biomass yield changes in chemical composition of sweet sorghum cultivars grown for biofuel. Field Crops Res. 111, 55-64.

Zhuang, P., Shu, W., Li, Z., Liao, B., Li, J., Shao, J., 2009. Removal of metals by sorghum plants from contaminated land. J. Env. Sci. 21, 1432-1437.

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

Table 2. Main chemical properties of the three irrigation treatments (fresh water-FW, tertiary water-TW and secondary water-SW). Average values and standard deviation (in parentheses) of water sampled from May to August in 2012 and 2013. The Italian threshold values for wastewater irrigation reuse (MD 152/06) are also reported.

Chemical properties		MD 152/06	2012			2013		
			FW	TW	SW	FW	TW	SW
CE	dS/m	3	0.64 (0.01)	1.47 (0.09)	1.52 (0.11)	0.62 (0.05)	1.31 (0.07)	1.33
pH		6-9.5	7.65 (0.22)	7.63 (0.08)	7.57 (0.09)	7.30 (0.26)	7.44 (0.43)	7.30
BOD$_5$	mgO$_2$ L^{-1}	20	6 (0.06)	22 (0.18)	40	3 (0.05)	6 (0.08)	49 (5.8)
COD	mgO$_2$ L^{-1}	100	0 (0)	135 (12.4)	166 (22.1)	10 (0.11)	43 (0.62)	103 (1.8)
Na$^+$	mg L^{-1}		48 (9.1)	119 (7.9)	128 (10.9)	31 (0.41)	104 (10.1)	103 (11.1)
K$^+$	mg L^{-1}		1 (0.11)	23 (4.0)	22 (4.9)	7 (0.9)	29 (3.1)	28 (3.9)
Ca^{2+}	mg L^{-1}		51 (15.2)	92 (27.1)	83 (8.6)	48 (5.8)	116 (22.8)	122 (20.1)
Mg^{2+}	mg L^{-1}		12 (2.7)	20 (3.3)	21 (3.5)	8 (0.9)	21 (3.7)	16 (2.4)
NH$_4^+$-N	mg L^{-1}		2 (0.08)	41 (5.8)	46 (6.1)	0.5 (0.06)	26 (3.4)	37 (4.1)
NO$_3^-$-N	mg L^{-1}	2	5 (0.11)	3 (0.21)	11 (1.80)	3 (0.39)	4 (0.05)	10 (1.3)
PO$_4^{2-}$-P	mg L^{-1}	10	0 (0)	25 (4.8)	23 (5.1)	18 (4.8)	10 (3.8)	22 (4.6)
Free Chlorine	mg L^{-1}	1200	53 (9.8)	197 (51.1)	182 (49.1)	25 (3.5)	138 (13.9)	143 (15.1)
F$^-$	mg L^{-1}	1.5	1 (0.09)	0 (0)	1 (0.10)	0.5 (0.08)	1.6 (0.11)	2 (0.28)
SAR		10	2 (0.14)	3 (0.31)	3 (0.40)	1 (0.16)	2 (0.31)	2 (0.40)

The values for each trait were determined on 8 samples for each season and each irrigation water.

Table 3. Effects of the growing season (S), irrigation treatment (I) and their interaction (SxI) in the biomass production (t ha^{-1}), higher heating value (HHV-MJ kg^{-1}) and energy yield (GJ ha^{-1}).

Treatments		Biomass		HHV		Energy yield	
Season (S)	2012	22.1	a[b]	16.33	a	360	b
	2013	22.5	a	16.58	a	373	a
Irrigation water (I)	FW	20.39	b	16.40	a	335	c
	TW	22.57	a	16.45	a	371	b
	SW	23.87	a	16.52	a	395	a
p[a]	S	ns		ns		**	
	I	*		ns		***	
	SxI	*		ns		***	

[a] *, **, *** and ns denote statistical significance at the 0.05, 0.01 and 0.001 levels and the absence of significance, respectively.

[b] Different letters in the columns indicate significant differences between treatments within the same factor, according to the Duncan's test ($P < 0.05$).

Table 4. Effects of growing season (S), irrigation treatment (I) and their interaction (SxI) in the proportion of lignin, cellulose and hemicellulose (%) and ethanol production (L ha^{-1}).

Treatments		Lignin (%)	Cellulose (%)	Hemicellulose (%)	Ethanol (L ha^{-1})
Season (S)	2012	7.80 a[b]	30.2 b	24.9 a	6262 b
	2013	7.34 a	35.1 a	24.7 a	6898 a
Irrigation water (I)	FW	7.23 a	33.8 a	24.5 a	6092 c
	TW	7.61 a	31.8 a	24.8 a	6533 b
	SW	7.87 a	32.8 a	25.1 a	7115 a
p[a]	S	ns	*	ns	***
	I	ns	ns	ns	***
	SxI	ns	ns	ns	*

[a] *, *** and ns denote statistical significance at the 0.05 and 0.001 levels and the absence of significance, respectively.

[b] Different letters in the columns indicate significant differences between treatments within the same factor, according to the Duncan's test ($P < 0.05$).

Table 5. Effects of growing season (S), irrigation treatment (I) and their interaction (SxI) in the biomass water use efficiency (bWUE-kg m^{-3}), energy yield-water use efficiency and (eyWUE-MJ m^{-3}) ethanol-water use efficiency (ethWUE-L m^{-3}).

Treatments		bWUE	eyWUE	ethWUE
Season (S)	2012	7.3 a[b]	120 a	2.03 a
	2013	6.8 b	110 b	2.09 a
Irrigation water (I)	FW	6.5 c	105 c	1.91 c
	TW	7.2 b	116 b	2.06 b
	SW	7.6 a	123 a	2.22 a
p[a]	S	*	***	ns
	I	**	***	***
	SxI	*	***	*

[a] *, **, *** and ns denote statistical significance at the 0.05, 0.01 and 0.001 levels and the absence of significance, respectively.

[b] Different letters in the columns indicate significant differences between treatments within the same factor, according to the Duncan's test ($P < 0.05$).

Table 6. Average nitrogen, phosphorus and potassium supplied (kg ha^{-1}) with irrigation for the three irrigation treatments (fresh water-FW, tertiary water-TW and secondary water-SW), and during the two growing seasons (2012 and 2013).

Season	FW	TW	SW
Nitrogen (kg ha^{-1})			
2012	8	100	114
2013	4	71	110
average	6	86	112
Phosphorus (kg ha^{-1})			
2012	0	17	16
2013	14	8	18
average	7	12	17
Potassium (kg ha^{-1})			
2012	0	56	55
2013	20	80	79
average	10	68	67

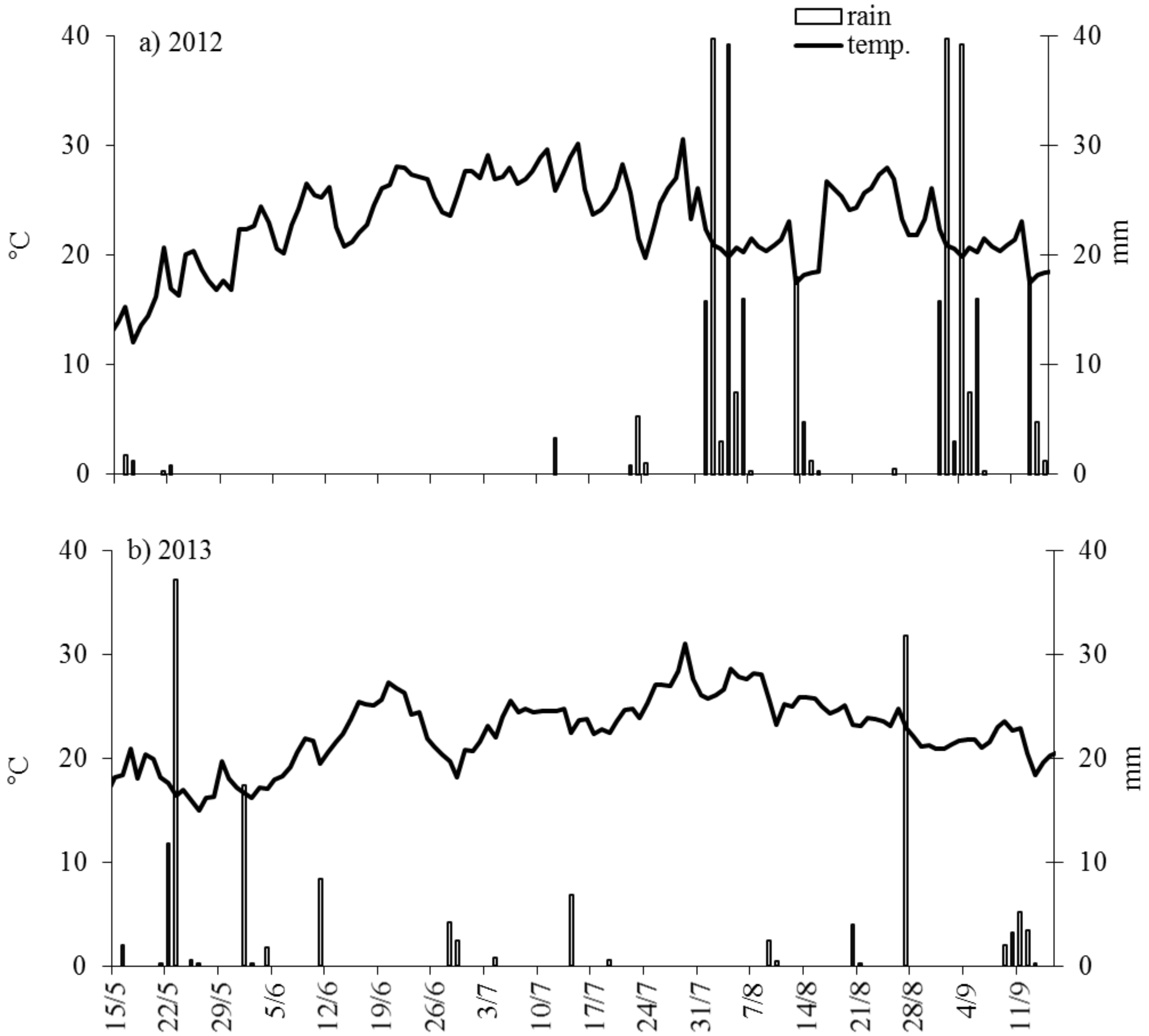
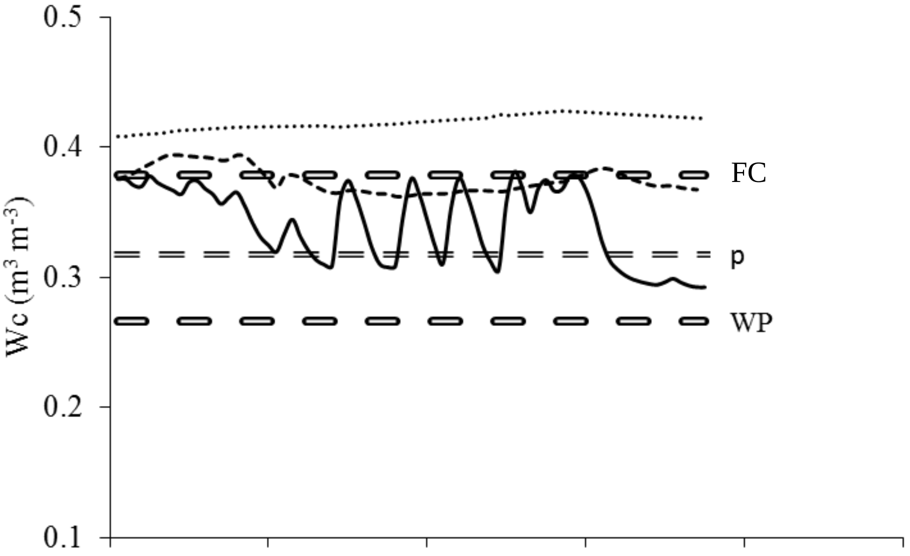


Fig. 1. Rain and air temperature during 2012 and 2013 growing seasons

a) 2012



b) 2013

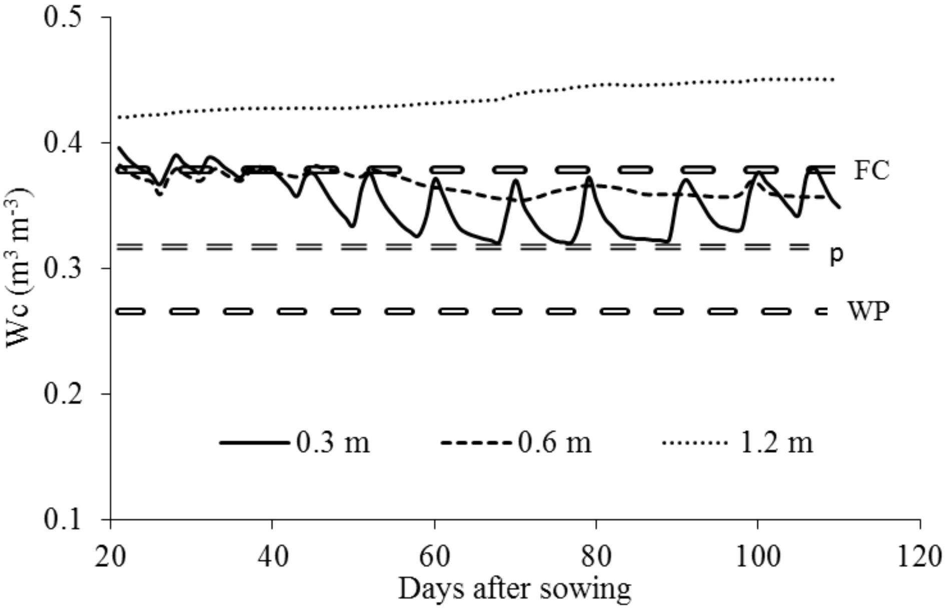


Fig. 2. Water contents (Wc) at three soil depths (0.3, 0.6 and 1.2 m) of the soil during 2012 and 2013 growing seasons. The dashed lines correspond to the water contents of the soil at field capacity (FC) and at wilting point (WP). p = Readily Available Water threshold.

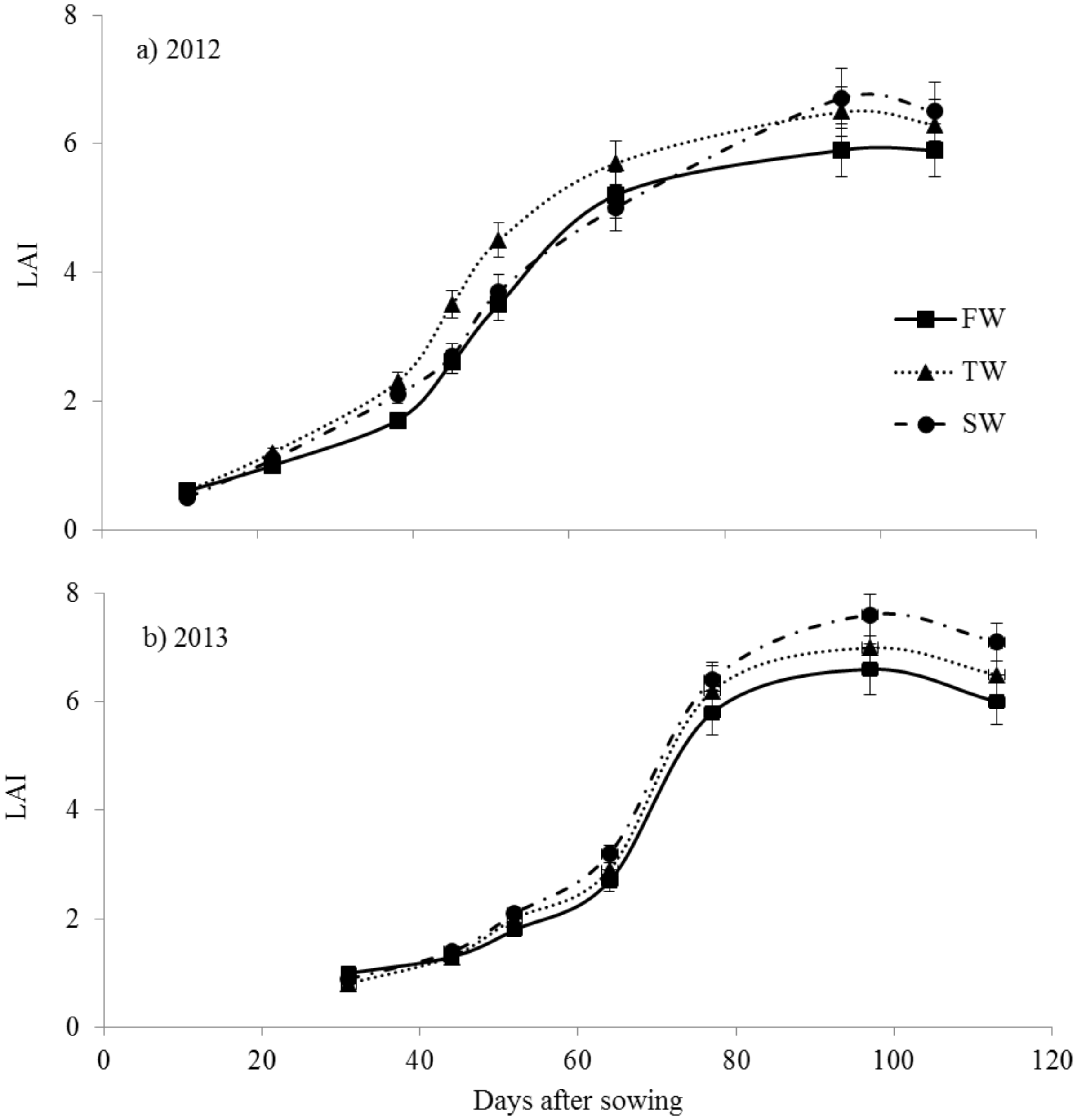


Fig. 3. LAI of sorghum for three irrigation treatments (fresh water-FW, tertiary water-TW and secondary water-SW), and two growing seasons (2012-a and 2013-b).

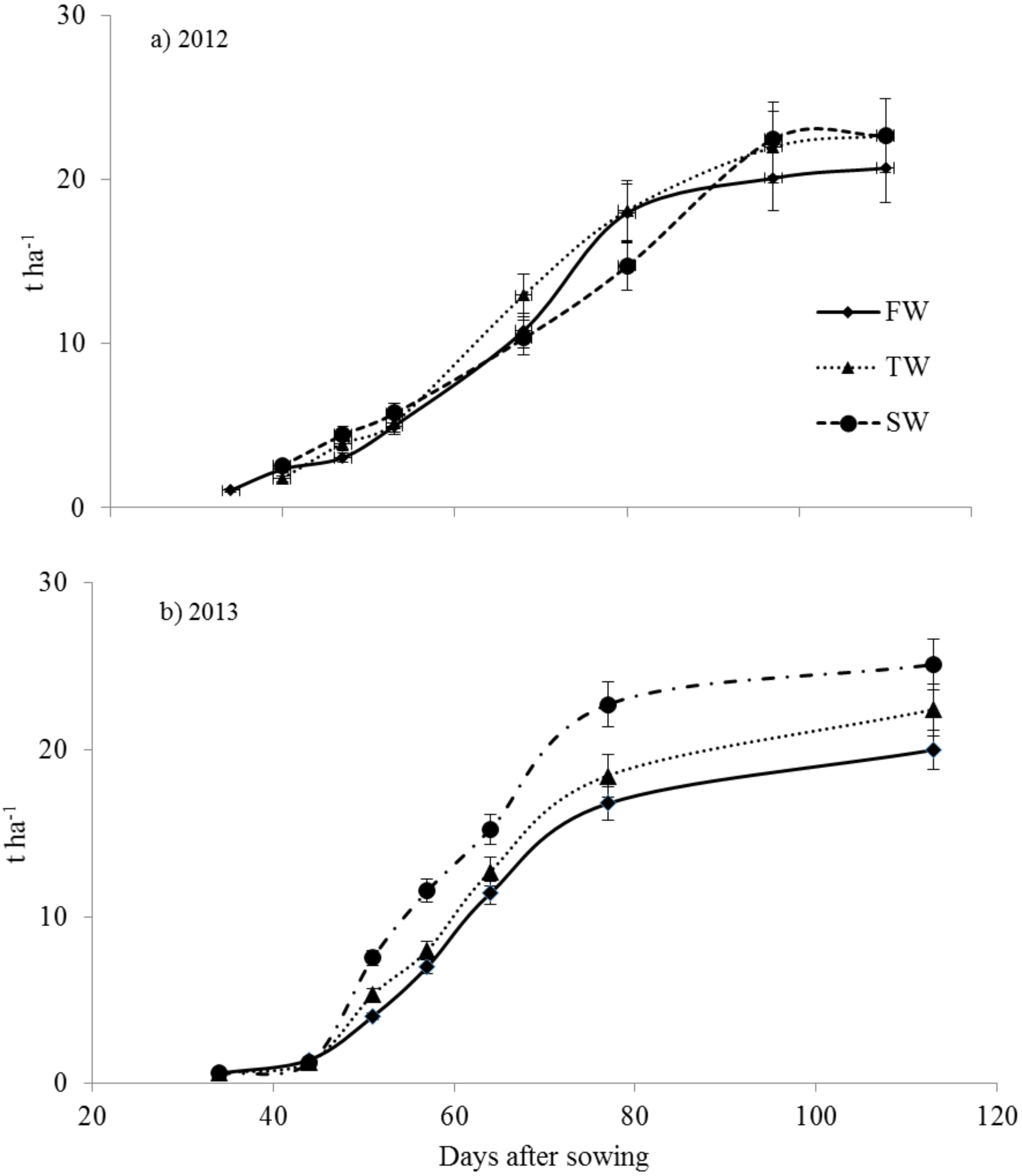


Fig. 4. Dry matter (t ha^{-1}) of sorghum for three irrigation treatments (fresh water- FW, tertiary water-TW and secondary water-SW), and two growing seasons (2012-a and 2013-b).

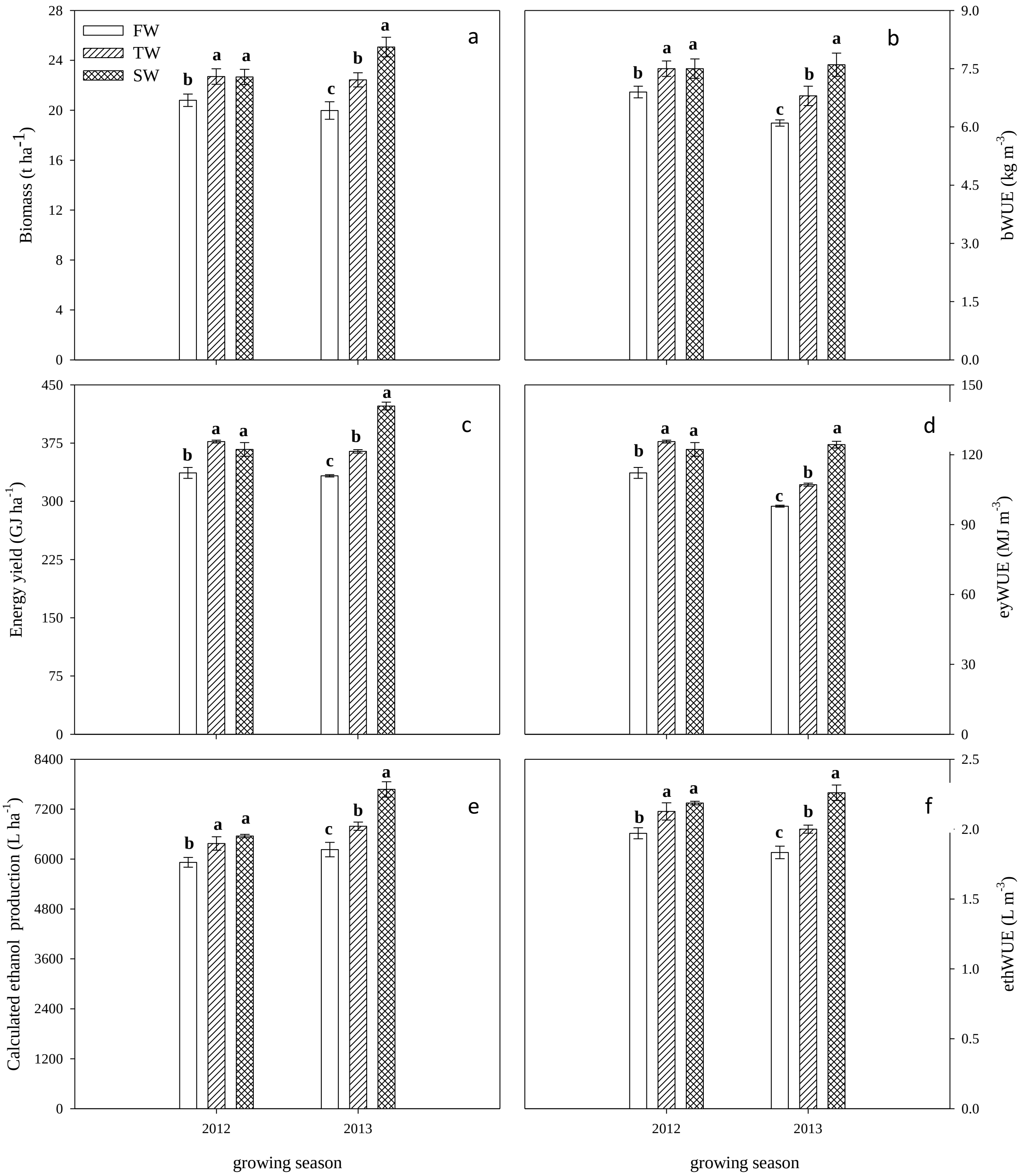


Fig. 5. Biomass production (a; t ha^{-1}), biomass water use efficiency (b; bWUE-kg m^{-3}), energy yield (c; GJ ha^{-1}), energy yield-water use efficiency (d; eyWUE-MJ m^{-3}) calculated ethanol production (e; L ha^{-1}) and ethanol-water use efficiency (f; ethWUE-L m^{-3}) for three irrigation treatments (fresh water-FW, tertiary water-TW and secondary water-SW), and two growing seasons (2012 and 2013). Different letters indicate significant differences among irrigation water qualities for the same growing season, according to the Duncan's test ($P < 0.05$).