Bioenergy productivity of sugar beet irrigated with reclaimed wastewaters

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Abstract

The use of treated wastewater to irrigate the sugar beet (*Beta Vulgaris* L. var. saccharifera) for bioethanol could play a strategic role to contrast the use of natural water resources and increase the productivity of the crop. The 2-year experiment (2013-2014) was performed on sugar beet irrigated with fresh water and wastewater at different steps of the reclamation process (secondary and tertiary treatments). The data obtained showed that the root sugar beet yield and ethanol production under fresh water treatment (52.2 Mg ha^{-1} and 5446 L ha^{-1}) were lower respect to that obtained from the secondary and tertiary wastewater treatments (66.7 Mg ha^{-1} and 6785 L ha^{-1}, and 58.7 Mg ha^{-1} and 6164 L ha^{-1}, respectively), with the same irrigation volumes. These results can depend on the higher quantity of nutrient uptake when wastewater is used for irrigation. In particular, the average N applied (as nitrate and ammonium) with irrigation during the growing seasons (2013 and 2014) was corresponding to the supply of 4, 28 and 20 kg ha^{-1}, for the fresh water, secondary, and tertiary wastewater treatments, respectively.

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Introduction

The new energy strategy for Europe from 2011 to 2020 has been discussed in European Union (EU) institutions (European Commission, 2010; European Parliament, 2010). It indicates that the use of biofuels (currently 10%) for blending fossil fuels should be increased by 2020 (2009/28/CE; European Commission, 2009).

In the EU, the main inputs in the production of bioethanol are provided by sugar beet, wheat, corn, and barley, while second generation biofuels from waste or residue lignocellulose biomass are still limited (European Commission, 2011). Wheat and sugar beet are most frequently used in North Western Europe at present, while corn is employed in Central Europe and Spain, where barley is also often used (Agrosynergie, 2011).

In the Mediterranean area, the most convenient renewable raw materials for bioethanol production are cereal grain and sugar beet (Schmitz, 2003; Berg, 2004; Van Thuijl and Deurwaarder, 2006). Because of the surplus of sugar production in European Union (it was formerly financially supported by EU agricultural policies), there is possibility for sugar factories to redirect the sugar production from sugar toward bioethanol (it would be supported by EU Commission).

In most of herbaceous cropping systems in Southern Italy, sugar beet has been among the traditional cultivations that opened the rotation. For a long time (about 30 years), this crop has been successfully cultivated and it was one of the main sources of farm income. This has been due to the following factors: i) the autumn sowing which allowed to take advantage of the rain in the cold season; ii) the water deficit irrigation management during the hot-dry season; iii) the availability of cultivars resistant to bolting; iv) the harvest in early summer, allowing the accurate management of the soil for the next crop, usually durum wheat (Cavazza, 1983; Venturi, 1988; Rinaldi, 2012; Palumbo *et al*., 2014).

Once the crop disappeared from the cropping systems of Southern Italy, as a consequence of the new EC agricultural policies, the know-how in growing sugar beet remained in any case unchanged in local farms. This could be considered as a pre-condition for reintroducing sugar beet as an energy crop either for multiple purposes or strictly for the bio-ethanol supply chain (Venturi and Venturi, 2003).

Despite the fact that the yield potential of sugar beet as an energy crop has been repeatedly pointed out (Venturi and Venturi, 2003; Panella, 2010), the agrotecniques for producing under limited water conditions are worthy of further studies (Pidgeon *et al*., 2001). The climate of Mediterranean area is favourable to the sugar beet eco-physiology, but the scarcity of water resources limits its cultivation, unless a suitable exploitation plan of the available water resources are identified, including wastewaters to optimise the root biomass yields.

No conventional waters (saline or waste) often can represent an important contribution for solving the ever-increasing problems of water scarcity. As an example, in Apulia region (Southern Italy) more than 65% of the water resources are allocated to irrigation (Disciglio

et al., 2014). In these conditions, treated wastewater re-use for agriculture needs to be a top priority, mainly in producing no-food crops.

From the agronomic point of view, the re-use of wastewater at a reasonable rate reduces the cultivation cost due to the reduced need for fertilisers (Tamburino *et al*., 1999; Bedbabis *et al*., 2010; Paranychianakis *et al*., 2006). The reuse of wastewater for irrigation is limited by national and regional laws to prevent sanitary risks. By the way, contrary to what is prescribed by law, for irrigating energy crops it is not necessary the same water quality that is required by food crops.

Considering the aptitude of sugar beet as an energy crop, and the importance of reclaimed wastewater as alternative water resource, this study aims to assess from the agronomic perspective if a reduced level of wastewater treatment is compatible with the sugar beet productivity. In particular, this study compares the productions obtained from sugar beet irrigated with wastewater at different refining degrees, in a typical semi-arid environment.

Materials and methods

The study was conducted in Southern Italy (Trinitapoli, lat. 41° 21', long. 16° 03', alt. 0 m a.s.l.), close to a municipal wastewater treatment plant, which supplied different qualities of reclaimed water for irrigation during two growing seasons (2013 and 2014). The location is characterised by a maritime Mediterranean climate, with temperatures below 0°C in the winter and above 40°C in the summer. The average rainfall is 550 mm (30-year average) with precipitation concentrated mostly during the autumn, while quite scarce during spring and summer. The annual water deficit is 560 mm, because the rainfall is insufficient to meet the evapotranspiration demand of the atmosphere (Campi *et al*., 2009).

Before the experimental trial (2012), the soil was sampled from the experimental plots at the depth of 0-0.40 m in five replicates. Texture, field water capacity, and wilting point were analysed. The soil has a clay-loam texture (U.S. Department of Agriculture classification) with average contents in sand, silt and clay (33%, 34% and 33%, respectively). The soil field water capacity was 30% and the wilting point was 18% (measured through Richards plates on dry soil weight). Because the rhizosphere does not develop below 1.5 m in this soil, it has a moderate available soil water capacity (180 mm).

Sugar beet (cultivar 'Levante') was sown on January 3rd, 2013. The delay of sowing was caused by the continued rainfall in the autumn of 2012 that determined problems in weed control, for which repeated weeding was necessary.

The crop was grown under a standard input of mineral fertiliser (120 kg P_2O_5 ha^{-1} before sowing and 100 kg ha^{-1} of N in two rates) and irrigated according to three treatments:

- fresh water (FW), withdrawn from the water network of the *Consorzio di Bonifica della Capitanata* and coming straight from the dam *Marana Capacciotti*;
- treated and refined municipal (tertiary treatment) wastewater (PW) from the local wastewater treatment plant of Trinitapoli with membrane filtration technology (in conformity with national and regional law);
- treated but middle refined wastewater derived from the secondary treatment (SW).

Wastewaters were re-used under a controlled flow rate to avoid contamination of bordering areas, with irrigation system at low pressure and underlying groundwater, with dimensioned irrigation volumes in order to prevent a deep drainage. In fact, irrigation was scheduled to restored 100% of the readily available soil water (RAW), as calculated according the FAO-56 methodology (Allen *et al*., 1998). The experimental design was a randomised block replicated three times. Each plot was 17 m long and 8 m wide (136 m^2).

During the two seasons, irrigation water was randomly sampled nine times (in 4 replications) from the dripping lines corresponding to the three water quality treatments. The supplied waters were analysed triplicate, according to the Italian standard methods (APAT, IRSA-CNR, 2003) that refer to the common international methods (APHA, AWWA, WEF, 2005) for the parameters reported in Table 1.

Daily soil water content in the whole soil profile was monitored by capacitive probes (10HS, Decagon Devices, Inc., Pullman, WA, USA). They were previously calibrated and then horizontally installed into the

Table 1. Main chemical properties of the water treatments. Mean and standard deviation values of water sampled from May to July in 2013 and 2014 season. The Italian threshold values for wastewater irrigation reuse (MD 152/06) are reported.

Chemical properties		FW		PW		SW		MD 152/06
		Mean	SD	Mean	SD	Mean	SD	
EC	dS/m	0.6	0.0	1.3	0.1	1.3	0.1	3
pH		7.8	0.2	7.5	0.3	7.4	0.3	6-9.5
BOD_5	mgO_2/L	3.0	2.7	7.9	5.0	30.3	12.8	20
COD	mgO_2/L	8.0	0.8	36.9	3.7	73.7	7.4	100
Free chlorine	mg/L	0.0	0.0	6.8	12.0	17.4	25.5	-
Na^+	mg/L	58.5	25.9	129.7	48.2	107.1	25.1	-
K^+	mg/L	9.7	4.4	33.3	10.1	32.5	7.7	-
Ca^{2+}	mg/L	62.7	3.3	95.3	58.5	76.4	21.4	-
Mg^{2+}	mg/L	5.9	3.1	15.3	14.4	9.1	7.0	-
NH_4^+	mg/L	3.9	7.8	13.8	10.2	22.8	7.0	-
Cl^-	mg/L	28.2	4.3	155.3	28.7	158.9	22.4	1200
F^-	mg/L	0.7	0.0	0.9	0.8	0.9	0.8	1.5
NO_3–	mg/L	4.5	1.8	8.5	13.2	4.6	6.7	2
PO_4^{2-}	mg/L	13.8	26.2	7.8	8.9	17.5	27.9	10
SAR		1.54	1.7	3.4	0.7	3.1	0.5	10

FW, fresh water; PW, tertiary treatment; SW, secondary treatment; SD, standard deviation; EC, electrical conductivity; BOD_5, biochemical oxygen demand; COD, chemical oxygen demand; Na^+, sodium; K^+, potassium; Ca^{2+}, calcium; Mg^{2+}, magnesium; NH_4^+, ammonium; Cl^-, chloride; F–, fluorine; NO_3^-, nitrates; PO_4^{2-}, phosphate; SAR, sodium adsorption ratio.

soil at two layers (–0.6 and –1.2 m) in one plot irrigated with FW. The probes were connected to a data logger (Grillo MMS, Tecno.El Srl, Rome, Italy) that collected the data in a web-server via global system for mobile technology. Seasonal irrigation volumes were 150 mm and 110 mm for 2013 and 2014 seasons, respectively. During the ripening of the roots (100 days after sowing), fresh roots were weighted from a 4 m^2 sampling area of each plot at regular intervals (every 25 days). At the end of the sugar beet cycle, fresh roots and root yield (Mg ha^{-1}) were determined on plants sampled from 20 m^2 plots. Root sugar content was determined by the anthrone method (Hewitt, 1958). Ethanol yield was estimated by total soluble sugar as follows: ethanol yield from sugar (L ha^{-1}) = total sugar content (% on dry matter) x dry root (Mg ha^{-1}) 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, Mg m^{-3}) (Institution of Japan Energy, 2006). Sugar beet yield, sugar content and ethanol production were analysed by the analysis of variance (ANOVA) followed by Duncan's multiple ranged tests for significant effects. Values of $P<0.05$ were considered as statistically significant. All of the analyses were performed using the Statgraphics Plus 5.1 software (Informer Technologies, Inc., Los Angeles, CA, USA).

Results and discussion

The analysis of the main physical and chemical parameters of wastewater utilised for crop irrigation (Table 1) showed that the physical and chemical characteristics varied considerably among the three sources of irrigation water used. The levels of most chemical parameters, such as electrical conductivity, chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), sodium, potassium (K), ammonium (NH_4^+), nitrates (NO_3^-), phosphate (PO_4^{2-}) were higher in wastewater (PW and SW) compared to fresh water. These values meet the Italian standard for wastewaters re-use, except for NO_3^-, PO_4^{2-}, BOD_5 and COD. The high value of PO_4^{2-} (and the high standard deviation) in FW was a consequence of two outliner values measured on the samples collected consecutively in July 2013. Neglecting these exceptional values, probably due to a temporary pollution of the fresh water, also the PO_4^{2-} values of FW can fall within the national standard. The contents of nitrogen (N), phosphorus (P) and K compounds indicated the appreciable fertilising potential of the applied wastewaters, in particular for NO_3^- and NH_4^+, which are among the most important nutrients for plants. The heavy metals concentrations were negligible.

Different response was observed in sugar beet to different rate of nutrients. N affected the leaf growth with consequences on canopy closure, leaf senescence, and capture of solar radiation (Draycott and Christenson, 2003), while K affected the development of the plant, which is involved in carbohydrate metabolism and regulates the water balance (Mannini and Venturi, 1993). Moreover, in our study, it should be considered that the distribution of nutrients is similar to a fertigation as some studies showed (Steduto, 1984; Kafkafi and Tarchitzky, 2011). This technique determines improved crop productivity but, technically, it cannot be proposed in the extensive open field crops. Figure 1 shows that in both years the irrigation scheduling prevented that the values of water content in the soil profile were above the wilting point and, therefore, no water plant stress occurred. At the depth of 0.6 m, in both season, the volumetric soil water content monitored in the FW treatment attained the field capacity after the rain events or irrigation. The irrigation scheduling prevented that the values of soil water content were higher than the RAW threshold ($P=0.30\ m^3\ m^{-3}$). Root growth was affected by the irrigation treatments. In particular, significant differences appeared at the end of the seasons (Figure 2).

The highest productions in root were observed for the plants irrigat-

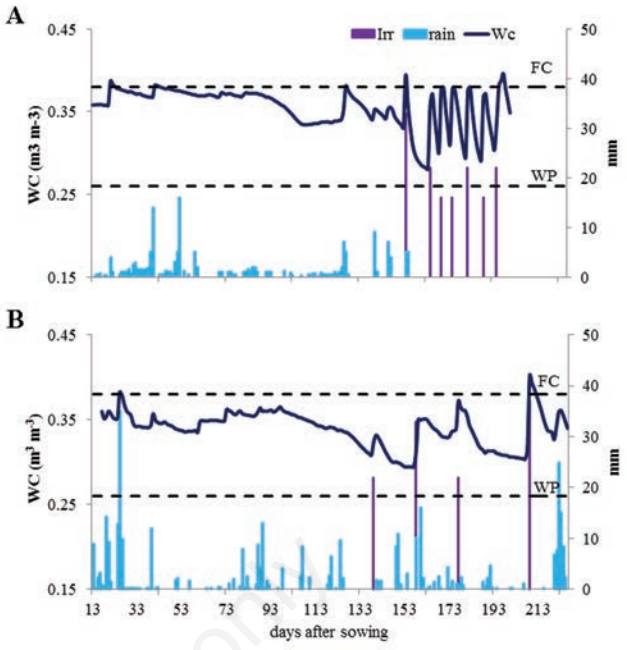

Figure 1. Water contents (WC) of the soil during (A) 2013 and (B) 2014 seasons. The dashed lines correspond to the water contents of the soil at field capacity (FC) and at wilting point (WP). Irrigation and rain events are also reported.

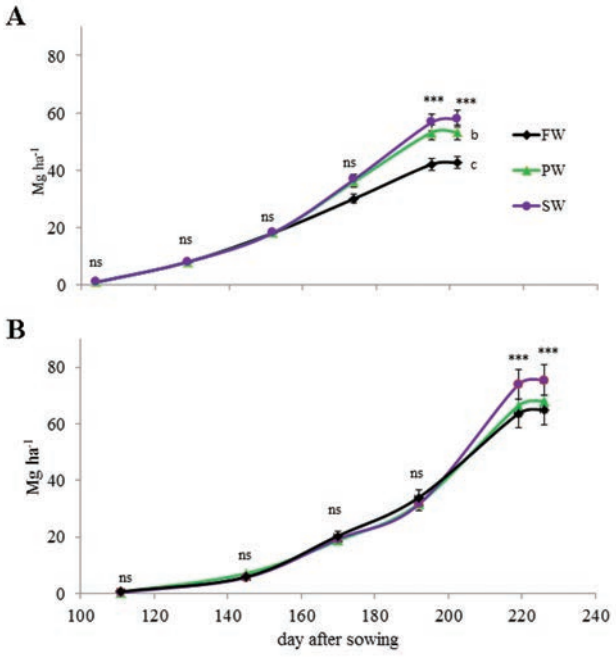

Figure 2. Fresh root growth during two seasons (A: 2013 and B: 2014), under three water regimes. * and ns denote statistical significance at the 0.001 levels and the absence of significance, respectively. FW, fresh water; PW, tertiary treatment; SW, secondary treatment.**

ed with the secondary wastewaters (Table 2). In both season this value, on average, was significantly higher than 8 Mg ha^{-1} or 14.5 Mg ha^{-1} respect to the sugar beet irrigated with tertiary wastewater and fresh water, respectively. In 2014 season, the roots yield was significantly higher respect to that obtained by the sugar beet cultivated in 2013 season (+16 Mg ha^{-1}). This increased production in roots can be due either to the increased beet cycle length (226 *vs* 201 days), and to a more favourable weather, with particular regard to the rain (467 *vs* 157 mm). The highest yield recorded under fresh water was similar to the production levels reported in literature (Pidgeon *et al*., 2001; Hoffmann, *et al*., 2009; Shrestha *et al*., 2010) in different European sites. However literature does not report results regarding the effect of wastewaters on the sugar beet root yield. Only Hassanli *et al*. (2010) have shown in Iran that the highest root yield (79.7 Mg ha^{-1}) was obtained using wastewater whilst the lowest root yield (41.4 Mg ha^{-1}) was obtained using fresh water.

Table 2 shows also that sugar content in fresh root was not significantly affected by the quality of the irrigation waters.

Considering the production of ethanol, by the formula suggested by the Institute of Japan Energy, Table 2 shows that the lower values of ethanol were obtained with the fresh water treatment while wastewaters provided for an improved ethanol production. In particular, during both seasons, the use of secondary wastewaters resulted in an increase of 621 and 1339 L ha^{-1} *vs* PW and FW treatments, respectively.

The effect of wastewaters on sugar content and ethanol production can be considered as original, because at the moment they cannot be compared to other observations taken from the literature.

The best response in terms of growth, root yield and, as a consequence, ethanol production, was observed in SW treatment because of the higher quantity of nutrients uptakes when wastewater is used for irrigation.

As an example, by examining the contributions of nutrients (N, P and K) (Table 3), the average N supplied (nitrate and ammonium) with irrigation during the growing seasons (2013 and 2014) was corresponding to the supply of 4, 20, and 28 kg ha^{-1} for the FW, PW and SW treatments, respectively. Through the irrigation waters, crop was supplied also by 5, 3, and 6 kg of P ha^{-1}, and 10, 38, and 36 kg of K ha^{-1}. In fact, application of nutrients through wastewaters induced a faster plant growth during the ripening root phase (Figure 2), which led to a higher fresh root yield.

As for the microbiological parameters, in an experimental trial carried out from May 2012 to May 2013 at the same site using the wastewaters from the same source (Disciglio *et al*., 2014), there was no soil contamination, due to the high soil capacity to break down the wastewater bacterial load. In addition, the high temperature levels at the soil surface contribute to create an environment unfavourable for the persisting *coli bacteria*.

As for the successive contamination of biomass energy crops, problem does not exist because the microorganisms do not survive after the drastic transformation process (cogeneration or fermentation) of the sugar beet biomass.

Table 2. Effects of year, irrigation treatments and their interaction in the roots yield, sugar content in fresh root and ethanol production.

Treatments		Roots yield (Mg ha^{-1})	Sugar (%)	Ethanol (L ha^{-1})
Year (Y)	2013	51.2^{b}	18.04^{a}	5318^{b}
	2014	67.2^{a}	18.84^{a}	6945^{a}
Irrigation water (I)	FW	52.2^{c}	18.22^{a}	5446^{c}
	PW	58.7^{b}	18.36^{a}	6164^{b}
	SW	66.7^{a}	18.75^{a}	6785^{a}
P	Y	***	ns	***
	I	***	ns	***
	YxI	ns	ns	ns

FW, fresh water; PW, tertiary treatment; SW, secondary treatment. $^{a-c}$Different letters in the columns indicate significant differences between treatments within the same factor, according to the Duncan's test (P<0.05); *** and ns denote statistical significance at the 0.001 levels and the absence of significance, respectively.

Table 3. Average of nitrogen, phosphorus, and potassium supplied with irrigation during two growing seasons (2013 and 2014) by using three water qualities.

Nutrients	FW	PW	SW
Nitrogen (kg ha^{-1})	1.2	18.8	28.1
Phosphorus (kg ha^{-1})	4.7	2.6	5.7
Potassium (kg ha^{-1})	10.2	37.6	36.4

FW, fresh water; PW, tertiary treatment; SW, secondary treatment.

Conclusions

The scarce water resources in the Mediterranean environments demand new strategies for using water in agriculture. This is a crucial step for the agronomic management of the energy crops, since their environmental and economic sustainability relies on the reduction of agronomic inputs. This research shows original results regarding the application of wastewater on sugar beet. This specie has new potentials as a dedicated energy crops in the Mediterranean area due to the low requirements in seasonal irrigation volumes (up to 150 mm of supplemental irrigation per season). In addition, the sugar beet can be irrigated with the re-use water. Our results demonstrate that the use of wastewater, even with a reduced reclaimed treatment (SW), increased the production (for an additional contribution of nutrients) without adding heavy metals in the environment.

In general, fresh root yield of sugar beet was increased by irrigation with wastewater and, as a consequence, also the ethanol estimated production per unit of cultivated area. 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 sugar beet crops irrigated with wastewater can produce appreciable biomass and ethanol. This is also an environmentally and economically sound way of wastewater disposal.

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