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ORIGINAL RESEARCH

Response of sweet sorghum to biosolids application under reduced irrigation regimes

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Abstract

Purpose: The response of sweet sorghum to biosolids application under different irrigation regimes was studied in a field experiment conducted during 2010 and 2011 in Central Greece. The study assessed the effects of soil application of biosolids on plant height, biomass production, and water use efficiency.

Method: The experiment consisted of nine treatments with three replications, including the application of biosolids to the soil, the application of fertilizer, and an untreated control, with three levels of irrigation (100%, 80%, and 60% of the crop water needs).

Results: The study found that plant height was similar regardless of whether biosolids or fertilizer was applied. Under reduced irrigation, the application of biosolids at a rate of 5 Mg/ha resulted in a 9.2-11.5% increase in dry biomass production of sweet sorghum compared to dry biomass production from inorganic fertilizer application. When biosolids were applied with reduced irrigation, the dry biomass yield was similar to that produced by inorganic fertilizer application under full irrigation. Additionally, this was achieved while using 31.4% less irrigation water. Biosolids application to soil improved water use efficiency by up to 34% compared to fertilizer application.

Conclusion: The findings of this research suggest that substituting inorganic fertilizers with biosolids application can lead to significant water savings.

Keywords: Biosolids, Sorghum, Irrigation, Biomass, Water use efficiency

Introduction

As traditional fuel sources are depleting at an alarming rate, there is a necessity to find new energy sources such as biofuels, which can be derived from agricultural crops. Oilseed crops can be used to produce biodiesel, while crops with high levels of fermentable carbohydrates such as sorghum can be used to produce ethanol (Venturi and Venturi 2003). It is worth mentioning that sorghum is known to have high yields even under limited water availability conditions (Tabatabaei et al. 2020; Foti et al. 1996). The sweet varieties of sorghum are particularly well-suited for ethanol production due to their higher yield of fermentable carbohydrates (Whitfield et al. 2012; Dolciotti et al. 1998). Nowadays, crop production in certain areas is decreasing due to climate change (Kang et al. 2009) and water availability is also becoming a real problem. On the other hand, biosolids are known to increase the yield and quality of plants, as they enhance the availability of plant nutrients and water

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(Kalavrouziotis and Asrlan-Alaton 2008). Biosolids are also an important source of macro- and micronutrients that are vital for plant growth (Epstein 2003). They also reduce environmental pollution by preventing leaching of nutrients that may occur with chemical fertilizers (US EPA 1999). Additionally, with application of biosolids the soil organic matter and the water holding capacity are increased, while the soil aeration and root penetration are improved (Ippolito et al. 2010; Khaleel et al. 1981; US EPA 1999). Moreover, the soil bulk density and soil compaction are decreased (Khaleel et al. 1981; Pagliai and Antisari 1993), while water loss through evaporation, percolation, and runoff is also reduced (US EPA 1999).

Based on the above, the purpose of this research was to assess the response of sweet sorghum to biosolids application combined with reduced irrigation regimes, in terms of plant height, biomass production and water use efficiency.

Materials and methods

The research was carried out in 2010 and 2011, at the University's farm in Velestino, Greece (39° 23' 41.5'' N 22° 45' 18.3'' E, altitude 70 m). The design of the experiment was a randomized complete block design (RCBD) of nine treatments with three replications, as described below:

a) Biosolids application with three levels of irrigation (100%, 80%, and 60% of the crop water needs; treatments B100, B80, and B60, respectively).

b) Inorganic fertilizer application with three levels of irrigation (100%, 80%, and 60% of the crop water needs; treatments F100, F80, and F60, respectively).

c) Untreated Control (neither biosolids application nor fertilizer) with three levels of irrigation (100%, 80%, and 60% of the crop water needs; treatments C100, C80, and C60, respectively).

Soil properties

The soil texture was clay loam and the soil was classified as a Typic Xerochrept (Inceptisols). It had moderately alkaline pH (8.2), low electrical conductivity (0.36 mS/cm), and low organic matter content (1.3%). Prior to any treatment, the chemical composition of the soil was: 0.14% total Kjeldahl nitrogen, 0.02% total phosphorus, 0.02% total potassium, 0.006% total zinc, and 0.006% total copper. The permanent wilting point and the field capacity of the soil were found to be 21% and 35%, respectively, resulting in an available soil water content of 14%. The soil was found to have a bulk density of 1.3 and to be saturated at 51% capacity, with a saturated hydraulic conductivity of 0.24 cm/h.

Biosolids application

Biosolids were produced at the municipal wastewater treatment plant (MWTP) of the city of Volos, Greece. After the regular treatment of sewage, sewage sludge was being processed at an Infrared Radiation Processor (IRP) which was developed and patented by the Infrared Technology Australia Pty Ltd (ir-tech.com.au). Due to the fact that infrared radiation processing provides direct thermal penetration and transfers high amounts of energy, the sewage sludge incurred a decrease both in volume (about 75%) and weight (about 83%). Therefore, the specific processor produced sterilized (no pathogens) biosolids that were formed into granules (2-4 mm) with approximately 10% moisture. One week before sowing, the produced biosolids were uniformly applied on the assigned plots surface and incorporated in the topsoil (20 cm) by rotavation. Biosolids were produced and applied once a year, at a rate of 5 Mg/ha (dry weight), for two consecutive years (2010-2011). Biosolids had a two-year average content of 4.74% total Kjeldahl nitrogen, 1.78% phosphorus, 0.17% potassium, 0.06% zinc, and 0.02% copper, with a slightly alkaline pH (7.7) and an organic matter of 72%. The heavy metal content of biosolids was below the defined threshold toxicity limits as per EU Directive (86/278/EEC).

Fertilizer application

Along with the application of biosolids, inorganic fertilizer was applied (yearly) to the assigned plots. The fertilizer contained the equivalent quantity of the primary macronutrients (N-P-K) as applied through biosolids (based on their chemical composition). The fertilizer had a two-year average composition of 237 kg N/ha, 88.9 kg P/ha, and 8.7 kg K/ha. The whole amount of phosphorus and potassium, along with the 25% of the nitrogen, were applied as basal fertilization one week before sowing. The fertilizer was uniformly sprinkled on the soil surface and then it was incorporated by rotavation in the soil (20 cm depth). The remaining amount of nitrogen was applied in three equal doses through drip irrigation (i.e. fertigation), twenty to thirty days after crop emergence. This is a commonly used cultivation practice that supplies nitrogen when the plants need it most, while it minimizes nitrogen loss from leaching.

Cultivation and practices

Sweet sorghum hybrid 'Sugargraze' (Pacific Seeds Pty Ltd) seeds were sown yearly, within the first ten days of June. The crop was sown at a density of 120000 plants per hectare. Each plot occupied an area of 40 m2 with a spacing of 1.5 m between the plots.

Each plot had six rows of plants with a row spacing of 0.8 m. Weeds were manually removed from the crop.

Irrigation

Five irrigation applications (through sprinklers) were given during the germination and seedling growth period (25-30 days after sowing), until the plants had developed an adequate root system. Right after that, for the irrigation of the crop (from early July to mid-September), surface drip irrigation was implemented. Drip irrigation laterals were made of polyethylene with a nominal diameter of 0.02 m. Inline drip emitters (Netafim™) had a flow rate of 2.3 L/h, were pressure compensated and self-flushed. Each lateral had an emitter spacing of 0.8 m and was irrigating two rows of plants. The interval of drip irrigation was four days. The irrigation system was fully automated with electrical valves and a programmer (Netafim™). The supplied irrigation water in each plot was measured by accurate flow meters. Crop water needs were estimated according to the methodology described in the 56th FAO Irrigation and drainage paper (Allen et al. 1998). Specifically, the evapotranspiration of the crop (ETc) was estimated as the product of the crop coefficient (Kc) and the reference evapotranspiration (ETo). Reference evapotranspiration (ETo) was estimated with the Penman-Monteith equation (Allen et al. 1998). Air temperature and precipitation were recorded daily by an automated agricultural weather station (iMetos AG, Pessl Instruments) installed near the field. Effective precipitation was estimated as the product of precipitation and a coefficient related to the intensity of the rainfall. The coefficient for the area of the study was found to be 0.8 (Allen et al. 1998).

Crop measurements

Total biomass production (aboveground) and height of the plants were determined at the milky dough stage of the crop (Vanderlip 1993), by harvesting and measuring all the plants from the middle rows of each plot. Total dry biomass production was determined by weighting oven-dried plants at 105 ^{o}C, until constant weight was achieved.

Water use efficiency

Water use efficiency (WUE), expressed in kg/m^3, was calculated by the equation WUE=Yg/ET that was defined by Viets (1962), where Yg the economic yield (g/m^2), and ET the water use of the crop (mm). WUE is typically expressed by the economic yield, but it has also been expressed as the total or the aboveground biomass (Bos and Nugteren 1990; Howell 2001). Specifically, the WUE (kg/m^3) for each treatment was calculated as the ratio of dry biomass production (Mg/ha) to the total crop water inputs (mm). The total water inputs were expressed as the sum of effective precipitation and irrigation.

Statistical analysis

All recorded data were statistically analyzed with Minitab Statistical Software (Minitab 2010). The General Linear Model - ANOVA RCBD was used for the statistical analysis, while the Tukey's multiple comparisons test (a=0.05) was used for the pairwise comparisons (Montgomery 2009).

Results and discussion

Weather data

The average climatic conditions corresponded to the regular Mediterranean characteristics of hot and dry summers with mild and wet winters, thus, irrigation is very important for summer crops to obtain high yields. The values of mean precipitation and air temperature, which were recorded daily by an automated weather station located at the farm, are illustrated in Fig. 1.

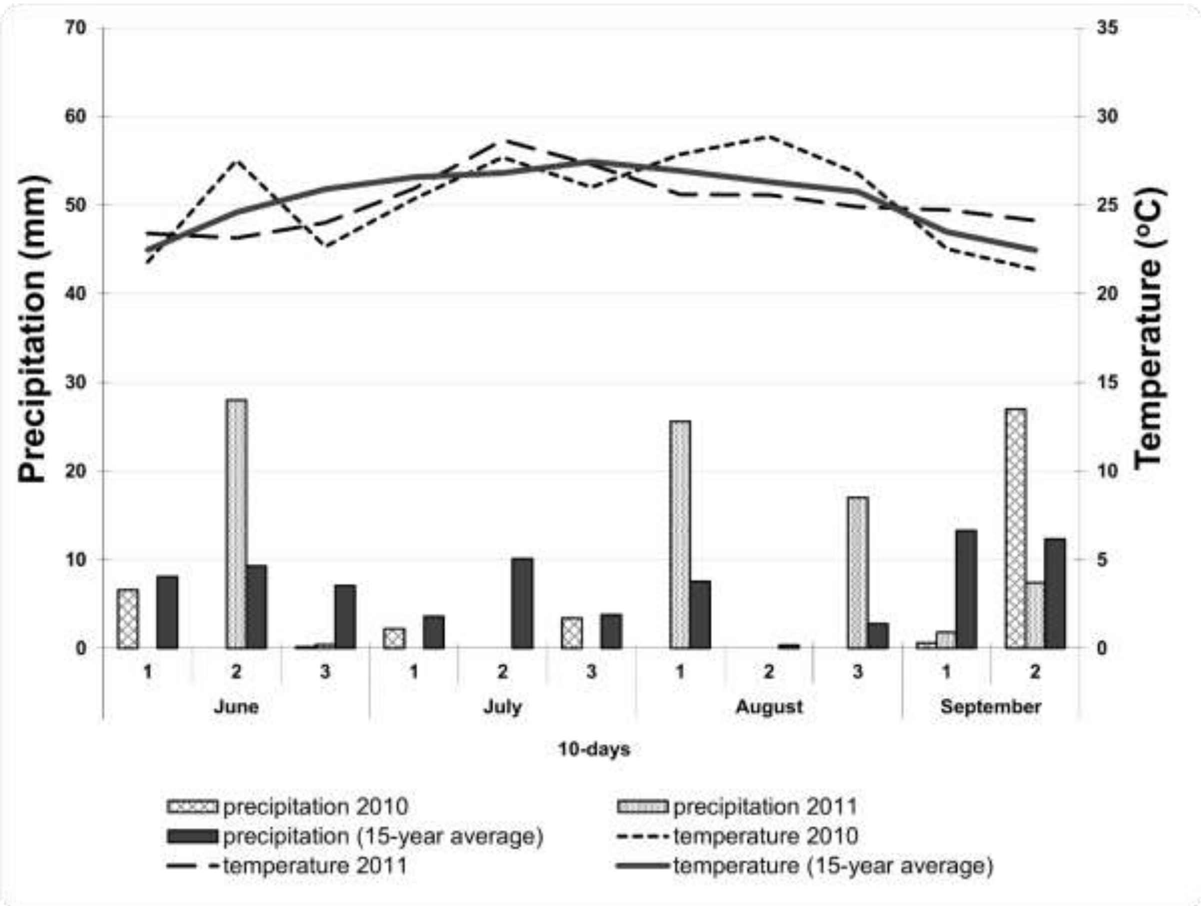

Fig. 1 Mean values of temperature and precipitation (10-day periods) for the years 2010, 2011, compared to the 15-year average

As illustrated in Fig. 1, the year 2010 was warmer than the year 2011 during the second half of June and during August. However, annual air temperature did not have a significant deviation from the fifteen-year average. Recorded precipitation, from sowing to harvest, was 40 mm for 2010 and 80 mm for 2011, while the average precipitation of the last fifteen years was 78 mm.

Irrigation

Total water inputs, presented in Table 1, are the sum of the effective precipitation and the irrigation water that each treatment received. The irrigation water is the sum of sprinkler (germination/seedling growth period) and drip irrigation. As shown in Table 1, treatments received similar inputs of water in both years.

Table 1 Total water inputs (mm) per treatment and year

Treatments	**B80 – F80 – C80**		**B60 – F60 – C60**		**B100 – F100 – C100**	
Year	**2010**	**2011**	**2010**	**2011**	**2010**	**2011**
Effective precipitation (mm)	32	58	32	58	32	58
Irrigation (mm)	376	348	306	283	447	412
Total water inputs (mm)	408	406	338	341	479	470

Soil properties

The application of biosolids in the soil did not affect its hydraulic parameters, which remained stable throughout the study. Studies have shown that large quantities of biosolids (e.g. 30 Mg/ha) are required to observe any difference in the soil's hydraulic parameters (Pagliai and Antisari 1993). In the treatments where biosolids were applied, some small differences were observed in the chemical parameters of the soil before and after the study. Specifically, the pH of the soil has decreased by 0.2 units, while the soil conductivity increased by 0.3 mS/cm. An increase of 0.1 mS/cm was also observed in the treatments where inorganic fertilizers were applied. In a related study conducted in Larissa, Shaheen and Tsadilas (2013) reported that the application of biosolids resulted in increased soil electrical conductivity and decreased soil pH. No significant changes were observed in other chemical parameters of the soil measured at the end of the study, likely due to the low application rate of biosolids.

Plant height

The values of plant height in each of the nine treatments, for the years 2010 and 2011, are presented in Fig. 2B and Fig. 2C, respectively.

As presented in Fig. 2B, the plant height in 2010 ranged from 3.2 ±0.1 m to 3.9 ±0.1 m with the B100 and F100 treatments having the higher values among all treatments. Statistical analysis of plant height showed that no statistically significant differences were found between six of the nine treatments (B60, B80, F80, F60, C80, and C100). In the year 2011 (Fig. 2C), the plant height ranged from 3.0 ±0.1 m to 3.5 ±0.1 m with six of the treatments to have similar height (B100, B80, B60, F100, F80, and C100). In Fig. 2A, the two-year mean of plant height, per treatment, is presented. Statistical analysis was performed considering the year as a random effect. As presented in Fig. 2A, during the two years of the research, the B80 treatment had the highest plant height among the reduced irrigation treatments, while treatment B100 had the highest plant height among all treatments. Treatment B80 had a similar plant height with treatments B100, F100 and F80, while treatment B60 had a similar plant height with treatments B80, F80, C100, and F60.

The B60 treatment had an equivalent effect on plant height as the F80 treatment, even though the F80 treatment received 18.7% more irrigation water. Similarly, the B80 and F100 treatments had an equivalent effect on plant height, despite a 15.7% difference in the amount of irrigation water. Moreover, the B60 and C100 treatments had similar effects on plant height, despite a 31.4% difference in the amount of irrigation water used. Similar results have been reported regarding the increase in sorghum plant height due to the addition of sewage sludge (Eleiwa et al. 1996; Keskin et al. 2009). Unfortunately, no experiments have been conducted on the specific variety of sweet sorghum under similar conditions, according to existing reports. Further investigation on the specific variety could provide more answers.

(A)

Treatment	Height (m)	
B100	3.72 ±0.23	a
F100	3.60 ±0.31	ab
B80	3.50 ±0.15	abc
F80	3.38 ±0.22	bcd
C100	3.37 ±0.21	bcd
B60	3.34 ±0.14	cde
F60	3.24 ±0.12	de
C80	3.23 ±0.17	de
C60	3.11 ±0.13	e

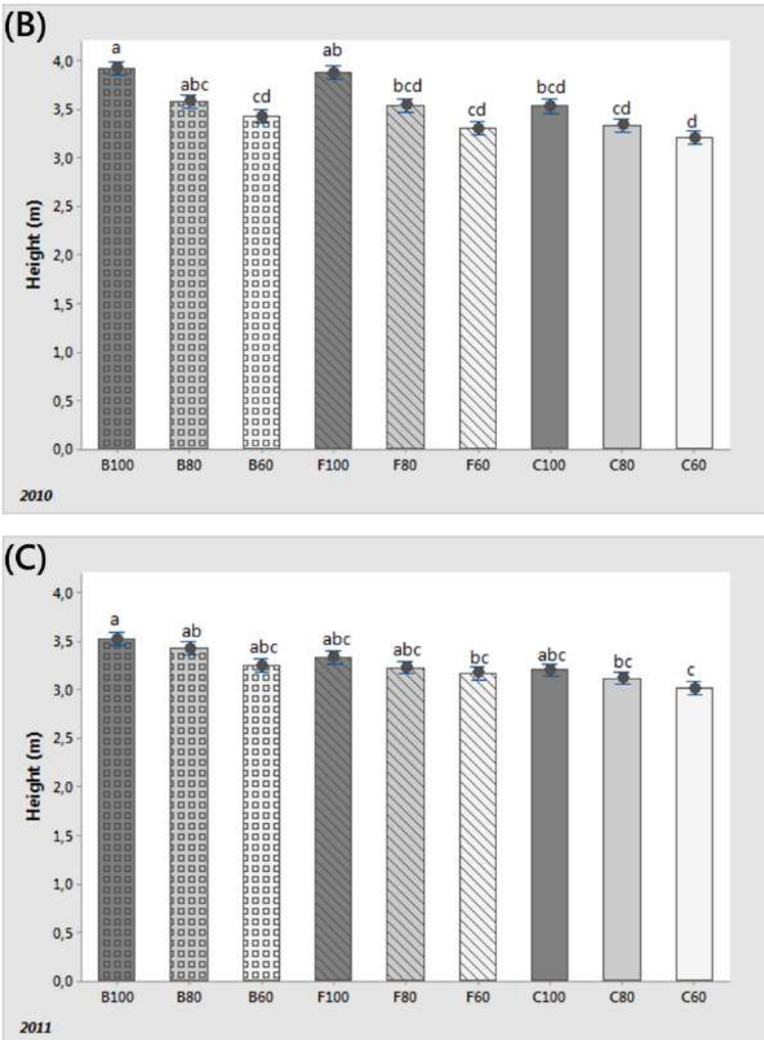

Fig. 2 The values of plant height in each of the nine treatments, for the years 2010 and 2011

(A) Two-year mean of plant height per treatment (means which do not share common letter(s) are significantly different)

(B) Height of the plants (m) per treatment in the year 2010 (error bars represent ±1SE from the mean; means which do not share common letter(s) are significantly different)

(C) Height of the plants (m) per treatment in the year 2011 (error bars represent ±1SE from the mean; means which do not share common letter(s) are significantly different)

Biomass production

The data on total dry biomass production of each of the nine treatments, for the years 2010 and 2011, are presented in Fig. 3B and Fig. 3C, respectively.

As presented in Fig. 3B, the aboveground biomass production in 2010 ranged from 28.6 ±0.2 Mg/ha to 41.0 ±1.7 Mg/ha with the B100 treatment having the highest value. Similar results were observed in the year 2011 (Fig. 3B), with the biomass production ranging from 24.0 ±0.6 Mg/ha to 41.0 ±1.2 Mg/ha. Statistical analysis indicated that no statistically significant differences were found in biomass production among the treatments B60, B80, and F100. The two-year mean of dry biomass production (aboveground), per treatment, is presented in Fig. 3A. Statistical analysis was performed by considering the year as a random effect. As presented in Fig. 3A, during the two years of the research, the B80 treatment produced the highest dry biomass among the reduced irrigation treatments, while treatment B100 treatment produced the highest dry biomass among all treatments.

(A)

Treatment	Dry Biomass (Mg/ha)	
B100	40.88 ±1.31	a
F100	36.13 ±1.48	b
B80	35.52 ±2.65	b
B60	34.56 ±1.99	bc
F80	32.52 ±2.80	cd
C100	31.67 ±0.91	d
F60	30.98 ±2.41	d
C80	27.94 ±3.06	e
C60	26.28 ±2.53	e

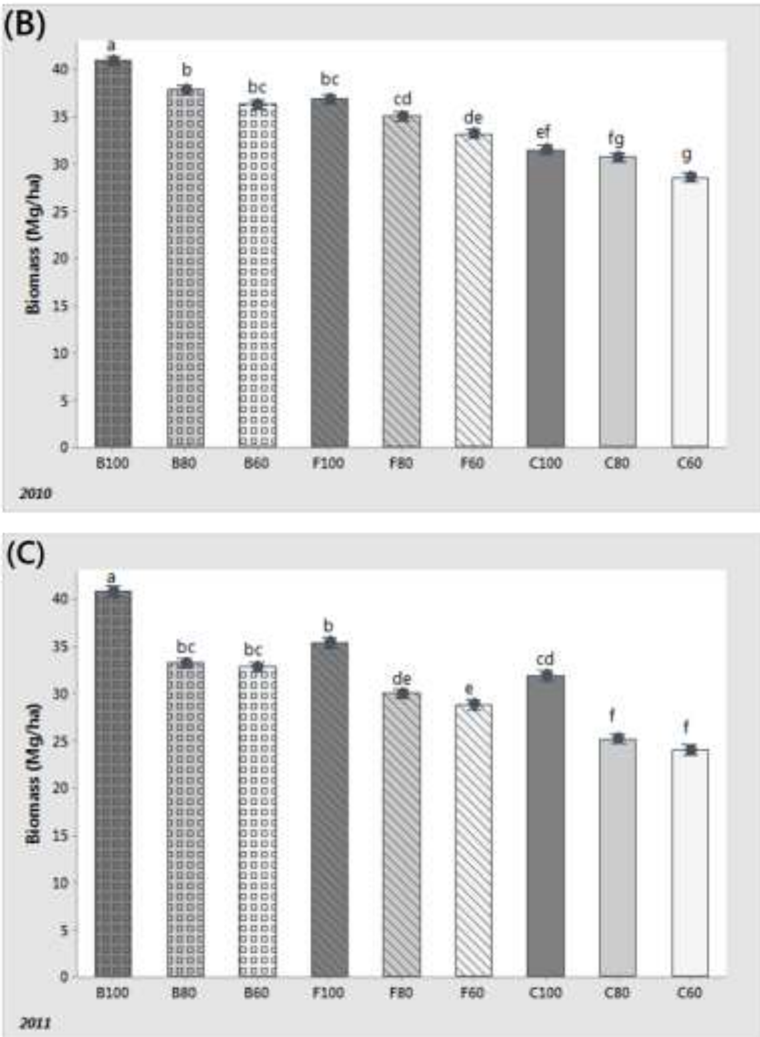

Fig. 3 The data on total dry biomass production of each of the nine treatments, for the years 2010 and 2011

(A) Two-year mean of dry biomass production per treatment (means which do not share common letter(s) are significantly different)

(B) Dry biomass production (Mg/ha) per treatment in the year 2010 (error bars represent ±1SE from the mean; means which do not share common letter(s) are significantly different)

(C) Dry biomass production (Mg/ha) per treatment in the year 2011 (error bars represent ±1SE from the mean; means which do not share common letter(s) are significantly different)

Treatment B80 had a similar dry biomass production with treatments F100 and B60. Additionally, the B60 treatment produced similar biomass production with the F80 treatment. The B60 treatment resulted in similar dry biomass production as the F100 treatment, despite a 31.4% difference in the amount of irrigation water applied. Similarly, the B60 treatment had the same effect on dry biomass production as the F80 treatment, despite an 18.7% difference in the amount of irrigation water applied. Applying 60% and 80% of the crop's water needs through irrigation, combined with the application of biosolids to the soil, resulted in 11.5% and 9.2% more biomass production, respectively, compared to using fertilizer.

The lack of alteration in soil physical properties suggests that the slower release of nutrients from biosolids, compared to the faster release from fertilizers, may be responsible for the findings. Lu et al. (2012) report that dewatered biosolids have greater persistence and slower nutrient release rates, with 50-90% of the nitrogen existing in organic compounds. Moreover, biosolids contain essential micronutrients for plant growth that are not typically present in conventional chemical fertilizers (Epstein 2003).

In a study conducted on heavy alluvial clay loam soil in Australia, Pu et al. (2008) reported similar results showing an increase in biomass production with the addition of biosolids compared to fertilizer. The treatments in which biosolids were applied produced 16.6% more biomass of forage sorghum (variety not stated) than the fertilizer treatments. Other studies using organic amendments, such as compost, have also reported higher yields of sorghum compared to fertilizer alone (Cifuentes et al. 2016). In addition, several reports have shown similar results regarding the dry biomass production of fertilized treatments (Curt et al. 1995; Cosentino et al. 2012). Other studies have found that sweet sorghum yield was strongly influenced by the amount of water supplied, rather than the nitrogen level resulting from inorganic fertilization (Cosentino et al. 2012). Further investigation especially in the specific variety used in this study could provide additional insights.

Water Use Efficiency (WUE)

The data on WUE under the nine treatments, for the years 2010, 2011, and the two-year mean are presented in Table 2.

Table 2 Water use efficiency per treatment and year, as well as the two-year mean

	Water Use Efficiency (kg/m^3)			
Treatment	**Year 2010**	**Year 2011**	**Two-year mean**	
B60	10.94 ±0.11	9.62 ±0.20	10.28 ±0.74	**a**
F60	9.99 ±0.04	8.45 ±0.13	9.22 ±0.85	**b**
B80	9.41 ±0.29	8.18 ±0.06	8.80 ±0.70	**bc**
B100	8.66 ±0.36	8.68 ±0.26	8.67 ±0.28	**bc**
F80	8.72 ±0.30	7.39 ±0.18	8.05 ±0.74	**cd**
C60	8.60 ±0.06	7.04 ±0.16	7.82 ±0.86	**d**
F100	7.80 ±0.17	7.53 ±0.38	7.66 ±0.30	**de**
C80	7.63 ±0.19	6.21 ±0.13	6.92 ±0.79	**ef**
C100	6.65 ±0.19	6.78 ±0.23	6.72 ±0.20	**f**

Means which do not share common letter(s) are significantly different

As presented in Table 2, the WUE in 2010 ranged from 6.6 ±0.2 kg/m3 to 10.9 ±0.1 kg/m3, while in 2011 it ranged from 6.2 ±0.1 kg/m3 to 9.6 ±0.2 kg/m3, with the B60 treatment having the highest values. In contrast to 2010, statistical analysis showed no significant differences among the B80, B100, and F60 treatments in 2011. Over the two-year research period, the B60 treatment demonstrated the highest water use efficiency, while treatments receiving greater amounts of water had lower WUE values. The statistical analysis was performed considering the year as a random effect. There was also no statistically significant difference in WUE among the treatments B80, B100, and F60. Additionally, treatment B80 had similar WUE values with treatments B100 and F80.

The crop used 97.28 L of water to yield 1 kg of sorghum dry biomass in the B60 treatment, 113.64 L in the B80 treatment, and 115.34 L in the B100 treatment. In contrast, for the yield of 1 kg of dry biomass of sorghum, the crop used 108.46 L in the F60 treatment, 124.23 L in the F80 treatment, and 130.55 L in the F100 treatment.

When irrigated with water equal to 60% of the crop's water needs, applying biosolids to soil resulted in an 11.5% increase in WUE compared to fertilizer application. Similarly, under irrigation with water equal to 80% of the crop's water needs, applying biosolids to soil resulted in a 9.3% increase in WUE compared to fertilizer application.

When biosolids were applied to soil along with irrigation water equal to 60% of the crop's water needs, there was a 34.2% increase in WUE compared to fertilizer application with irrigation water equal to 100% of the crop's water needs. The difference in the amount of irrigation water used in this case was 31.4%. It could be inferred that sorghum has the potential to make more efficient use of moisture and limit yield loss until water supply restrictions become severe, thereby enhancing WUE (Sher et al. 2013).

Conclusion

The findings of this study suggest that biosolids can be a viable alternative to inorganic fertilizers for energy crops. The application of biosolids with reduced irrigation had comparable effects on plant height and dry biomass production as inorganic fertilization with increased irrigation. Moreover, the use of biosolids resulted in higher water use efficiency compared to inorganic fertilization under increased irrigation. The observed water savings of over 30% further support the use of biosolids as an eco-friendly and sustainable solution for enhancing crop productivity while conserving water resources, which is particularly important in regions with limited water resources. However, further investigations on the specific variety of sweet sorghum are needed to fully understand the potential benefits of biosolid application under different irrigation regimes.

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Compliance with ethical standards

Conflict of interest The authors declare that there are no conflicts of interest associated with this study.

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