Effects of Treated Municipal Wastewater Irrigation on Soil properties, Switchgrass Biomass Production and Quality under Arid Climate

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Abstract

Ongoing severe drought and increased demand for freshwater by municipal and industrial sectors have reduced the freshwater availability for agriculture in the far west Texas region. The region has enormous potential for developing alternative water sources for a bioenergy crop that requires less water and can grow on saline soils. In addition to improving farm income, this can help in producing 137 billion liters of bio-based transportation fuels goal set by the U.S. Congress by the year 2022. This study evaluated switchgrass (*Panicum virgatum* L.) performance under treated urban wastewater irrigation on salt affected soils amended with gypsum and polymer using soil columns prepared from a salt affected land over six years under greenhouse conditions that mimicked the climatic conditions of the study region. Results indicated that switchgrass produced appreciable biomass even under highly saline and sodic conditions. Qualities of biomass under treated urban wastewater were comparable to that produced under freshwater irrigation. Expectedly, soil salinity increased with time at a greater rate under wastewater irrigation than freshwater. Soil SAR values were below threshold when adequate Ca was available to counter sodicity. In addition irrigation with treated wastewater improved nitrogen and potassium status in the root zone. This can reduce of cost of fertilization and increase farm profitability.

Keywords:

Alamo cultivar, bioenergy feedstock, biomass quality, cellulose, hemicellulose, holocellulose, lignin, Marginal quality water, soil salinity, sodicity, southwest U.S., switchgrass, treated urban wastewater.

1. Introduction

El Paso County is located in the west Texas in USA and it is a part of the extremely arid middle Rio Grande river basin. Agriculture in the region is totally dependent on irrigation water delivered by the Rio Grande Project. It is estimated that about 80% of the cropped area in the Rio Grande project area is affected by varying degrees of salinity (Ghassemi et al., 1995). Middle Rio Grande basin like many arid regions of the world is facing rapid increase in water demands due to rapid population growth (over 2 million people live in the region) and urbanization. Ongoing severe drought and reduced snowpack impacting river flows have resulted in declining freshwater availability. This has restricted river water allocation by the irrigation districts and forced farmers to use brackish groundwater and treated municipal wastewater for meeting irrigation requirements. During some years only 30-60 cm irrigation was made available by the irrigation district in El Paso, mostly supplied in the form of treated municipal water or blended with river water. The cropping pattern in the region is dominated by cotton (*Gossypium hirsutum*), alfalfa (*Medicago sativa*) and pecan (*Carya illinoensis*). Cotton is planted in nearly 50% of the cropped area and requires about 86 cm of irrigation. Both alfalfa and pecan crops require about 153 cm of irrigation and are considered salt sensitive. Since the amount of water supplied by irrigation district was too low to grow even cotton during drought years, almost all of fields were abandoned.

The region has enormous potential for marginal quality water irrigation to produce bioenergy crops for a greater farm returns. For example, only 13% of the 7894 hectare meter of treated urban wastewater in El Paso County in west Texas is reused every year (EPWU, 2011). In addition, far west Texas has about 100,000 hectares of idled or abandoned farmland that can be irrigated with brackish groundwater available in the region for bioenergy crops production. If

1 a suitable bioenergy crop can be produced on these abandoned lands, in addition to improving
2 farm income, it also helps in bridging the huge gap between the mandated Renewable Fuels
3 Standards (RFS2) goal set by the U.S. congress to use at least 137 billion liters of bio-based
4 transportation fuels by 2022 and the current capacity of about 60 billion liters of biobased fuels
5 (USDA, 2015).

6 Switchgrass (*Panicum virgatum* L.) has been identified as a strong candidate for
7 bioenergy production because of its favorable attributes such as ability to grow on different soils
8 under a variety of environmental conditions (McLaughlin et al., 2006). Its many beneficial
9 attributes and wide distribution can make switchgrass a suitable crop for the arid southwest
10 region. Studies have reported that lowland ecotypes have late maturity, thick stems and dense
11 bunch enabling them to better adapt to southern latitudes of the study site (Casler et al., 2007).
12 Among the lowland ecotypes “Alamo” cultivar has been reported to have superior adaptation
13 range spanning numerous USDA hardiness zones (Sanderson et al., 2007; Casler and Vogel,
14 2014). Alamo is well adapted to Texas conditions and limited studies have reported that it is salt
15 tolerant among lowland ecotype cultivars (Kiniry et al., 2012; Liu et al., 2014). However, its
16 performance with marginal quality water irrigation on saline soils under arid conditions is not
17 well studied.

18 Developing beneficial and economically feasible strategies to utilize these marginal
19 quality waters will benefit the region while providing bioenergy for our growing population.
20 Therefore in this study “Alamo” switchgrass was selected to understand effects of marginal
21 quality treated wastewater irrigation on crop performance and soil salinity/sodicity under
22 greenhouse conditions. The objectives of this study were to evaluate (i) performance of Alamo
23 switchgrass cultivar under marginal quality water irrigation under extremely arid conditions of

far west texas simulated in the greenhouse, and (ii) effects of marginal quality water irrigation on soil salinity and sodicity to develop suitable salinity management practices.

2. Materials and methods

2.1. Study area and experimental design

The experiment was conducted under greenhouse conditions that simulated long-term climate of El Paso County in the far west Texas (Table 1). The long-term annual average values for the study area are: precipitation~ 17 cm; potential evapotranspiration ~194 cm; maximum temperature~ 35.8°C; minimum temperature~ -1.4°C, relative humidity of 48.1%, wind speed of 1.21 m/s and solar radiation 19.78 MJ m⁻² day⁻¹.

Split plot experimental design was used to evaluate the effects of two water qualities (wastewater and freshwater) on three soil treatments (no amendments, gypsum, and polymer) at four soil depths (as repeated measures) replicated three times. Two water qualities consisted of (i) Treated wastewater (TWW) and (ii) freshwater (greenhouse tap water derived from Rio Grande River, used as a control) (Table 2). The source of treated wastewater was the nearby Roberto Bustamante Wastewater treatment plant that receives municipal wastewater. The treatment process consisted of screening, de-gritting, pre-aeration, primary settling, aeration, secondary settling, and disinfection.

A total of 18 soil columns were used to evaluate switchgrass performance in the greenhouse. Soil collected from a nearby abandoned cotton field (35°39'34.6" N & 106°16'9.54" W) at four depths (0-15, 15-30, 30-45 and 45-60 cm) was used to construct 18 columns. As a first step, soil cores were collected from four depths (0-15, 15-30, 30-45 and 45-60 cm) at three random locations in an abandoned salt affected cotton field to determine bulk density (Grossman

and Reinsch, 2002). Then, about 3m x 3m area close to bulk density sampling location was used collect soil samples for constructing soil columns. Soil samples for each of the depths were composited, air dried, sieved through 2 mm and repacked to simulate field bulk densities into pvc tubes that were 46 cm diameter and 60 cm long with a provision of drainage at the bottom. The dominant soil map unit in the field was Harkey silty clay loam (Coarse-silty, mixed (calcareous), thermic Typic Torrifluvents) (USDA-NRCS, 2009).

Soils used to construct columns were either saline (>4 dS/m) or close to being saline and had elevated sodicity at different depths (Table 3). Therefore one of the soil treatments was addition of gypsum. Gypsum is calcium sulfate and adding this to soil increases supply of readily available calcium (Ca^{2+}) to counter sodium (Na^{+}) that is going to be added through the treated wastewater. Additional Ca^{2+} should help soil to maintain its structure and permeability. Soils in the top 60 cm at the abandoned cotton field contained about 10% CaCO_3 and 2.5% Gypsum by weight (USDA-NRCS, 2009). Results from another study in the region indicated that addition of polyacrylamide (PAM) polymer to irrigation water unlocked the native calcium sources in soil and improved its permeability to facilitate leaching of salts (Ganjegunte et al., 2011). Therefore a second treatment, PAM was added, which involved addition of polyacrylamide to both fresh and wastewaters at the rate of 10 ppm only in first irrigation of each year. Effects of gypsum and polymer were compared to results from soil columns that received no-amendments. Gypsum treatment columns received 154 g of gypsum only one time at the beginning of the study. Since gypsum is sparingly soluble in water, to improve its solubility and increase Ca availability, all columns received 25 g of elemental (95% pure) sulfur. In soil elemental sulfur is expected to be converted to sulfuric acid by soil microbes and this in turn increases solubilization of gypsum in soil solution.

Flood irrigation is the predominant type of irrigation used in the region due to its effectiveness in limiting salts accumulation in the root zone. Bioenergy crops are likely grown with the least amount of irrigation, we considered the amount of about 69 cm as that is irrigation depth currently being used by local farmers to grow forage crops such as sudangrass (*Sorghum bicolor* var. *Sudanese*). Both freshwater and treated wastewater columns were irrigated with 69 cm of respective waters by flood-irrigation. All columns were fertilized with 20:20:20 fertilizer equivalent to 120:120:120 kgs of N:P₂O₅:K₂O per hectare.

2.2 Switchgrass establishment, biomass production and bioenergy quality

In each column, five seeds of the Alamo cultivar of switchgrass were sown 1 cm deep on August 10, 2009. After about eight weeks columns were thinned to leave only one plant per column (mostly in the center). Plants were not harvested in 2009 to ensure good growth and development. Thereafter plants were harvested two times a year (July/Aug and Oct/Nov), leaving 15 cm stubble. Biomass production at each harvest were recorded and sub-samples were sent to Dairy One Laboratory (Madison, WI, USA) for determining forage quality parameters using near infrared reflectance spectroscopy (NIRS). These included crude protein (used to derive N), acid detergent fiber (ADF), neutral detergent fiber (NDF), cellulose, lignin, and ash content. Recent advances in NIRS have made it possible analytically acceptable determination of the above parameters without the need for wet chemistry verifications (Schmer et al., 2012; Guimaraces et al., 2014).

2.3 Irrigation water quality, initial characterization of soils, soil salinity and sodicity

Grab samples of greenhouse tap water and wastewater were collected before the study and regularly (every two months) during the study period. Selected chemical properties of the irrigation water samples such as pH, electrical conductivity (EC), cations (Ca^{2+} , Mg^{2+} , Na^+ , K^+ , NH_4^+), boron, anions (Cl^- , NO_3^- , SO_4^{2-} , PO_4^{3-}) were analyzed as per the standard methods for the examination of waters and wastewaters (APHA, 2005). Biological oxygen demand (BOD) and fecal coliforms are regularly monitored by the wastewater treatment plant to meet the Texas Commission on Environment Quality standards and that data is available for public on request (EPWU, 2011). Table 2 provides data on select parameters of irrigation water quality. No detectable amounts of PO_4^{3-} and heavy metals (As, Cr, Cd, Hg, Se, Pb) were present in the treated wastewater samples. The major concern associated with the TWW irrigation was its elevated salinity (2.6 dS m^{-1}) and sodicity ($\text{SAR} \sim 9.3$).

Baseline as well as at the end of each year (after the November harvest) soil samples were collected from four depths (0-15, 15-30, 30-45 and 45-60 cm) from each of the columns. Samples were air dried, ground to pass through 2 mm sieve and stored for analyses. Sub-samples were used to determine soil texture by using the hydrometer method (Gee and Or, 2002). Processed soil samples were analyzed for saturated paste extract (SPE) electrical conductivity - EC_e (Rhoades, 1996); pH (Thomas, 1996); major cations Na, Ca, and Mg concentrations using inductively coupled plasma spectrometry (Helmke and Sparks, 1996; Suarez, 1996). Sodium adsorption ratio (SAR) of the soil samples were estimated from Ca, Mg, and Na concentrations using the following equation (Essington, 2003):

$$\text{SAR} = \text{Na}^+ / [\text{Ca}^{2+} + \text{Mg}^{2+}]^{0.5} \quad [1]$$

where Ca, Mg, and Na represent millimolar concentrations of the respective ions.

2.4 Data analyses

Treatment effects were evaluated using SPSS (version 24) software with significance level set at $p \leq 0.05$. In addition to treatment effects significant interactions among time, water, soil treatments and depths were also evaluated. After verifying assumptions such as no significant outliers and normality of distribution of data, general linear model with repeated measures ANOVA and post-hoc LSD test were used to determine the significance of treatment effects. Four different depths were treated as repeated measures. Mauchly's test of sphericity was used to test the assumption that the variances of the differences between all combinations of related groups must be equal. When assumptions of sphericity were violated, either Greenhouse-Geisser (when $\epsilon < 0.75$) or Huynh-Feldt (when $\epsilon > 0.75$) corrections were used depending upon eta.

3. RESULTS AND DISCUSSION

3.1 Biomass and bioenergy quality

Biomass production of 'Alamo' switchgrass during the study period ranged from 994 g per column in wastewater-polymer treatment to 154 g per column in freshwater-gypsum treatment (Fig. 1). Biomass production levels did not differ significantly among water quality-soil treatments within any of the 2010-2014 growing seasons. However, water quality and soil treatment differences were significant during 2015 in which freshwater-no soil amendments treatment produced significantly greater biomass than wastewater-no soil amendment treatment. This could be due to increased soil salinity especially towards the end of the study in the 0-30 cm

depth that covers the effective rooting zone of most grasses in the wastewater-no amendment treatment combination.

Significantly differences were observed among the different years for a given water quality and soil treatment combination. In general, biomass productions were higher during first year of irrigation and averaged about 929 g per column across treatments. The biomass production declined until 2013 with an average of 190 g (1143 g m^{-2}) per column before rebounding to 340 g per column (2046 g m^{-2}) in 2015. Average biomass productions for Freshwater-No amendments, Wastewater-No amendments, Freshwater-Gypsum, Wastewater-Gypsum, Freshwater-Polymer, and Wastewater-Polymer treatments during 2010 to 2015 were 325, 321, 267, 306, 311, and 335 g per column or 1956, 1932, 1607, 1841, 1871, and 2016 g m^{-2} respectively. The production estimates are comparable to those reported in the literature for switchgrass under irrigated conditions (Kiniry et al., 2012; Anderson et al., 2015)

Our study results are in contrast to the trend observed in other studies that have evaluated switchgrass performance on non-saline soils under rainfed/unirrigated conditions. The general trend reported for perennial grasses such as switchgrass, which take at least 3 years to mature is lower yields in first two years and higher stabilized yields for years 3 to 5 (Lemus et al., 2002; Varvel et al., 2008; Casler and Vogel, 2014). However, under irrigated conditions studies have reported greater production rates during the first three years, similar to our study results (Kiniry et al., 2012). Our study columns were constructed by using soil collected from abandoned salt affected land. When these soils are irrigated, initially plant responded favorably due to increased moisture and nutrients levels. Over time, as the salinity levels in the root zone increased due to evapo-concentration biomass yield declined but as the plants mature they would have greater

1 tolerance to stress and biomass yield stabilizes during later years. Similar to our study, Burkhard
2 et al. (2015) reported lower biomass production with increasing salinity of irrigation water.

3 Another unexpected result observed in our study was that the lack of response to gypsum
4 treatment. The conventional wisdom is that the application gypsum to counter the sodicity of the
5 soil should produce higher biomass production. This is the practice commonly followed by the
6 growers in the region for other major crops (pecan and alfalfa). However, lack of response to
7 gypsum under freshwater irrigation could be due to the fact that the study area soils already
8 contained significant amounts of native calcium sources such as calcite and gypsum (10 and
9 2.5%, respectively) (USDA-NRCS, 2009; Ganjegunte et al., 2011). However, once the supply of
10 native Ca^{2+} is exhausted (about 3 years as per results), gypsum application may be needed to
11 manage the sodicity of soils (see the discussion under 3.2.3). Greater switchgrass biomass yield
12 for wastewater treatments (e.g. no amendments and polymer) observed in our study could be due
13 to presence of nutrients such as nitrogen that helped in plant growth and greater amounts of
14 divalent cations such as calcium and magnesium compared to freshwater that countered sodium
15 effects and enhanced the efficacy of polymer to improve soil permeability.

16 Six year average biomass production observed in our study was lower than those reported
17 for switchgrass grown under non-saline conditions in other parts of the USA and Texas
18 (McLaughlin et al., 2006; Kiniry et al., 2012). Alamo cultivar produced, on an average 1959 g
19 $\text{m}^{-2} \text{y}^{-1}$ dry matter biomass production during the first three years under irrigated conditions at
20 Gustine, TX (Kiniry et al., 2012). However, results from our study compared well with biomass
21 production of 7 to 10 Mg for two upland ecotype switchgrass cultivars on marginal soils in
22 Ithaca, Nebraska, US (Varvel et al., 2008).

1 In addition to biomass yield, the quality of biomass is important for judging the
2 feasibility of marginal quality waters for bioenergy crop production on salt affected soils. Results
3 of our study indicated that biomass quality did not differ significantly between fresh and
4 wastewater treatments (Fig. 2). Carbohydrates (simple sugars, hemicellulose and cellulose) did
5 not differ significantly between two water qualities and among soil treatments. Our study results
6 are in agreement with the results published in the literature on the switchgrass biomass
7 composition. For example, the mean total hexose ranged from 34.5 to 39.8% while the non-cell
8 wall simple sugars ranged from 3.5 to 6.5% in switchgrass biomass (Schmer et al., 2012).
9 Pentose such as hemicellulose in their study was about 24% and that of lignin was about 11%.
10 As expected, due to elevated salinity, ash content in the biomass in our study was greater than
11 that reported for biomass produced under lower salinity conditions (Pasangulapati et al., 2012).
12 Among different ions, sodium and chloride ions constituted about 40% of ash content (data not
13 presented).

14 15 **3.2 Soil chemical properties**

16 Mauchly's test of sphericity results for time, water quality and soil treatments or their
17 interactions were not significant for soil pH, EC_e and SAR indicating that assumption that the
18 variances of the differences between all combinations of related groups were equal and therefore
19 the repeated measures ANOVA results were valid.

20 21 **3.2.1 Soil pH**

22 Soil pH decreased by the end of study period (Fig. 3). Soil pH decreased from 8.9 at 30-
23 45 cm depth in pre-study samples to 6.4 at 0-15 cm depth in freshwater-no amendments during

2015. Solubilization and redistribution of calcium minerals (calcite and gypsum) in the study site soils could have increased divalent cations concentration over time and that in turn could have contributed to lower pH of soil solution. Consequently Soil pH values differed significantly among different water-soil amendment combinations and from one year to another. However, soil pH values were within the range of 6.4 to 8.5 suggesting that neutral salts were dominant. Relatively lower soil pH values for wastewater-gypsum compared to No amendments plots indicated increased Ca ions in the root-zone soil solution (Johnston et al., 2008).

3.2.2 Soil Salinity

Pre-study soil salinity levels were exceeding the threshold EC_e values of 4 dS m^{-1} at 0-15 and 45-60 cm depths (Fig. 4). Application of irrigation water, even the freshwater, to a hitherto unirrigated/abandoned land generally results in the increased salinity because of solubilization of native salts especially in the desert climate such as the study site characterized by high temperature and low precipitation. This was observed in the present study even in soil columns that received freshwater. At the end of the study, salinity of soils at all depths in all water quality-soil treatment combinations had greater EC_e values than 4 dS m^{-1} .

By the end of the study soil salinity was significantly greater for wastewater treatments than that for freshwater. This was expected as wastewater contained higher amounts of dissolved solids than that of freshwater. Most of the salts added by wastewater remained within the soil profile as the amount of water applied was only 34% of potential evapo-transpiration. Increase in soil salinity levels can be attributed to addition (from external sources such as irrigation water), solubilization, transportation, and redistribution of salts within the root zone (Musslewhite et al.,

2009). In all water-soil treatments, salinity levels at deeper depths were greater than the surface depths at the end of the study.

In freshwater-gypsum and freshwater-polymer treatments, salinity levels declined after 2012 especially in effective rootzone (0-30 cm). This could be due to improved soil permeability facilitated by dissolution and transport of native Ca minerals such as calcite and gypsum (in no-amendment treatments and polymer treatments, or added gypsum in gypsum treatments). Dissolution of indigenous calcite is promoted when calcareous soils are irrigated by moderately saline irrigation water (Aydemir and Sonmez, 2008). Native Ca salts dissolution depends on soil solution flow velocity and studies have indicated that low flow velocity facilitated dissolution of native calcite or gypsum (Nadler et al, 1996; Li and Keren, 2008). The slow infiltration rate at the surface and darcy's flux at deeper depths (data not presented), ranging from 0.5 to 2.0 mm h⁻¹ could have increased residence time of moderately saline leaching water which in turn improved cation exchange (between Na on clay with Ca in solution) efficiency and consequently decreased sodicity of soils.

The dominant anions in the soil solution were chlorides, sulfates and nitrates (data not presented). Using the treated wastewater for growing agricultural / bioenergy crops has benefits in addition to providing water for irrigation. Treated wastewater contained essential nutrients such as nitrogen, and potassium. Pre-study nitrate concentration of the soil solution ranged from 269 to 321 mg L⁻¹ in the top 60 cm depth. As a result of treated-wastewater application, at the end of the study period the nitrate concentration in wastewater treatments ranged from 910 mg L⁻¹ in soil solution under wastewater-polymer treatment to 2271 mg L⁻¹ in wastewater-no-amendments treatment (data not presented). Similar to nitrates, potassium concentration in soil increase from an average concentration of about 59 mg L⁻¹ to 140 mg L⁻¹ in freshwater and 195

1 mg L⁻¹ in wastewater irrigated plots in the 0-60 cm soil depth (data not presented). Thus,
2 irrigation with treated wastewater can help farmers in reducing the cost of fertilizing bioenergy
3 crops especially on a marginal land such as the one used in the present study. This can improve
4 farm profitability.

6 **3.2.3 Soil Sodicity**

7 Sodium adsorption Ratio values increased from pre-study to end of study duration (Fig. 5).
8 However, until up to 2014 SAR values were less than or close to the threshold value of 13 in the
9 effective root zone (0-30 cm). This could be due to the reasons discussed earlier, that native Ca
10 release facilitated by polymer or Ca added by gypsum countered the sodicity added by
11 wastewater during the initial years. Significant differences in SAR values were observed among
12 water quality and soil treatment combinations both within a year and among the years. The SAR
13 values of wastewater irrigated soil at all depths were significantly greater than freshwater
14 columns especially during 2013-2015. This could due to exhaustion of Ca sources, either native
15 in soils that received no amendments or gypsum applied. Gypsum treatments received only one
16 application of gypsum largely due to cost concerns. However, results indicated that gypsum
17 application is needed every fourth year.

18 No impairment of permeability was observed in soils that had greater SAR values (SAR
19 >13). This could be due to significant interaction between soil salinity and sodicity that
20 maintained soil permeability (Hillel, 2004) despite high SAR values. This relationship has been
21 expressed as the threshold electrolyte concentration (TEC). The TEC is referred to as the
22 minimum electrolyte concentration required to keep the soil flocculated (Sumner et al., 1998;
23 Chaudhari and Somwanshi, 2004). If the electrolyte concentration in the soil solution can be

maintained at or above the TEC, the soil should remain in a flocculated state at higher SAR levels and maintain good permeability (Suarez et al., 2008). However, if the electrolyte concentration is below the TEC, a highly sodic soil may slake and disperse and soil structure will deteriorate (Shainberg et al, 1981). Irrigating soils with irrigated treated-wastewater in combination with soil amendments may have resulted in soil solution electrolyte concentration levels above TEC required to maintain soil flocculation and permeability. This has important implications for the long-term viability of irrigated agriculture using marginal quality waters under arid conditions. One of major impacts of marginal quality waters is impaired soil permeability due to increase in sodicity of root-zone. Results of this study show that permeability of soils can be maintained under marginal quality waters if the electrolyte concentration of the soil solution can be maintained above TEC while simultaneously considering salinity threshold of the intended crop.

4. Conclusions

The study results indicated that “Alamo” cultivar of switchgrass produced appreciable biomass even under elevated salinity. No significant differences in biomass production between wastewater and freshwater irrigated columns were noticed within a given year. Results indicated that switchgrass biomass production declined with increasing salinity in the root-zone. However, as the salts in the root zone moved to deeper depths after about three years, biomass production increased. Six years average biomass productions for Freshwater-No amendments, Wastewater-No amendments, Freshwater-Gypsum, Wastewater-Gypsum, Freshwater-Polymer, and Wastewater-Polymer treatments were 325, 321, 267, 306, 311, and 335 g per column,

1 respectively. Quality of biomass under treated urban wastewater were comparable to that
2 produced under freshwater irrigation. Irrigation with treated wastewater alone increased salinity
3 of the soil profile. Therefore leaching salts after three years with freshwater or blending marginal
4 quality water with good quality water is advised. Soil sodicity remained under threshold until
5 2012 after initial jump indicating that most of the increase in salinity came from solubilization of
6 Ca salts. However, once the supply of Ca was exhausted in about three years, SAR values
7 increased during 2013 to 2015. This indicated that application of Ca from external sources such
8 as gypsum is necessary every three years. Wastewater improved the fertility of soils by
9 increasing the concentrations of nitrogen and potassium. This can have important implications
10 for the cost of production and farm profitability.

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Figure Captions

Figure 1. Biomass yields (dry weight, g per column) of different treatments during the study period. Lower case letters denote significant differences within water quality-soil treatments within a year and upper case letters denote significant differences among years for the same water quality-soil treatment combination.

Figure 2. Concentrations of (a) Holocellulose (cellulose + hemicellulose, (b) watersoluble carbohydrates, (c) lignin and (d) ash in switchgrass biomass produced under different treatments. Lower case letters denote significant differences within water quality-soil treatments within a year and upper case letters denote significant differences among years for the same water quality-soil treatment combination.

Figure 3. Changes in soil pH during the study period. Error bars indicate standard deviation.

Figure 4. Changes in soil salinity (measured as EC_e , $dS\ m^{-1}$) during study period. Error bars indicate standard deviation.

Figure 5. Changes in soil sodicity (SAR, $mmol^{1/2}\ L^{-1/2}$) during study period. Error bars indicate standard deviation.

1 **Table 1: Long-term climatic data for the study area**

Month	Max Temp. °C	Min Temp. °C	Avg Temp. C	Relative Humidity %	Precipitation cm	Potential Evapo- Transpiration cm day ⁻¹
Jan	15.7	-3.2	6.2	53.3	0.711	0.234
Feb	17.7	-1.4	8.2	47.0	0.889	0.368
Mar	21.3	2.0	11.7	39.6	0.711	0.521
Apr	26.6	6.9	16.8	37.6	0.483	0.671
May	31.4	11.0	21.2	38.4	0.508	0.759
June	35.8	16.2	26.0	40.2	1.473	0.833
July	35.4	19.1	27.3	51.9	3.505	0.744
Aug	34.4	17.6	24.9	55.5	3.353	0.699
Sep	31.9	13.6	22.8	55.1	2.667	0.592
Oct.	27.1	6.8	16.9	53.4	1.346	0.442
Nov	20.0	0.4	10.2	51.3	0.610	0.300
Dec	15.4	-3.4	6.1	54.9	0.660	0.201
Annual				48.1	16.916	193.751

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Table 2. Selected chemical properties of the irrigation waters used in the study.

Parameters	Tap water	Treated Wastewater
Electrical Conductivity EC_e ($dS\ m^{-1}$)	1.4 ± 0.4	2.6 ± 0.3
pH	7.1 ± 0.4	7.3 ± 0.4
SAR ($mmol^{1/2}\ L^{-1/2}$)	4 ± 1	9.3 ± 0.4
Ca ($mg\ L^{-1}$)	54 ± 21	66 ± 10
Mg ($mg\ L^{-1}$)	13 ± 4	17 ± 4
Na ($mg\ L^{-1}$)	127 ± 14	328 ± 14
K ($mg\ L^{-1}$)	12 ± 2	32 ± 5
B ($mg\ L^{-1}$)	0.08 ± 0.10	0.26 ± 0.13
Cl ($mg\ L^{-1}$)	164 ± 93	465 ± 22
NH ₄ ($mg\ L^{-1}$)	-	3.86 ± 2.39
NO ₃ ($mg\ L^{-1}$)	6 ± 3	18.1 ± 5.1
SO ₄ ($mg\ L^{-1}$)	101 ± 51	201 ± 33
BOD 5 ($mg\ L^{-1}$)	-	3.22 ± 0.86
Fecal Coliform (CFU/100 mL)	-	3.29 ± 2.62

1 **Table 3:** Pre experiment soil physical and chemical properties

	Soil Depth			
	0-15 cm	15-30 cm	30-45 cm	45-60 cm
Sand (%)	40±2	31±6	30±3	36±6
Silt (%)	33±1	37±5	39±4	36±4
Clay (%)	27±1	32±1	31±2	28±3
Texture	Clay Loam	Clay Loam	Clay Loam	Clay Loam
Bulk Density (Mg m ⁻³)	1.34±0.02	1.48±0.05	1.42±0.04	1.36±0.01
EC _e	4.09±0.10	3.68±0.04	3.66±0.04	4.51±0.06
pH	8.61±0.01	8.88±0.02	8.91±0.04	8.40±0.01
Sodium Adsorption Ratio (mmol ^{1/2} L ^{-1/2})	3.2±0.6	3.2±0.1	8.3±5.6	11.4±6.0
Organic Carbon (%)	0.90±0.10	0.88±0.09	0.68±0.02	0.61±0.03
Olsen P expressed as P ₂ O ₅ (kg ha ⁻¹)	1.98 ± 0.23	2.44 ± 0.31	1.85 ± 0.29	1.92 ± 0.28
Total Kjeldahl Nitrogen (%)	0.081±0.010	0.050±0.004	0.047±0.006	0.032±0.002

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Fig. 1

Fig. 2

Fig. 2

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Fig. 4

Fig. 5