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Yield response of canola as a biofuel feedstock and soil quality changes under treated urban wastewater irrigation and soil amendment application

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A B S T R A C T

Treated urban wastewater (TWW) is seen as a potential alternative for agricultural irrigation in arid west Texas region, due to scarcity of Freshwater (FW) supplies. However, TWW can potentially cause soil salinization and affect soil quality and crop productivity. Therefore, crops that are salt-tolerant and less water-intensive are needed to sustain agriculture in this region. Canola (*Brassica napus* L.) as an edible oilseed and biodiesel/biofuel crop, is salt-tolerant and relatively less water-intensive than crops that are traditional to this area. This two–year field study evaluated the performance of canola under TWW irrigation in terms of its seed yield potential and seed quality (oil content, oil yield and salt constituents), along with quantifying changes in soil salinity and sodicity. Experimental design included a randomized block split-plot with water quality (FW and TWW) as the main-plot and soil amendment (gypsum + sulfur and no-amendment) as the subplot factor. Results show that TWW application did not significantly affect canola seed yields in any of the two years. On average, seed yields were 1975 kg ha^{-1} across all treatments and years. Seed oil content, oil yield and mineral constituents were also not affected by TWW irrigation. Nevertheless, average seed oil content was 42 % and oil yield was 849 kg ha^{-1}. Other than the effects on soil salinity and sodicity, Gypsum + Sulfur application did not influence canola seed productivity and quality. Changes in soil salinity and sodicity were more prominent under TWW irrigation but the levels were below the thresholds after two years. Gypsum + Sulfur application significantly reduced soil sodicity, especially in TWW irrigated soils. These results highlight that TWW can be successfully used to grow canola as a biofuel feedstock in this arid region while following appropriate soil management practices to alleviate sodicity hazard of TWW in the long-term.

1. Introduction

Global warming and climate change due to anthropogenic activities has resulted in frequent high temperature events and erratic rainfall patterns that has created unprecedented drought conditions across the Southwest United States including the far west Texas (Cook et al., 2015; Woodhouse et al., 2010). Future projections also indicate that drought risks are going to increase in the latter half of the 21st century in the state of Texas (Nielsen-Gammon et al., 2020). Reduced freshwater (FW) availability due to extended drought periods have caused an uncertainty in future FW availability to satisfy needs of both agricultural and municipal sectors. Moreover, increasing FW demand from urban sector due to enormous population growth in these areas has resulted in diversion and reduced allocation of FW for production agriculture. It is therefore prudent that available water resources are efficiently managed to meet both agricultural and municipal requirements. Use of alternative water resources such as treated urban wastewater (TWW) to supplement agricultural irrigation can reduce pressure on FW supplies and help maintain agricultural productivity in this region (Ganjegunte et al., 2018; Dery et al., 2019; Suri et al., 2019; Zhang and Shen, 2019).

El Paso is the largest city in the west Texas region and is home to a population of approximately 800,000. The climate is arid with annual

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evapotranspiration rates far exceeding that of normal precipitation rates (Chaganti et al., 2020). Agricultural irrigation in this region relies largely on Rio Grande river for its FW supplies. The cropping pattern in this area is dominated by water-intensive crops including cotton (*Gossypium hirsutum* L.), pecan (*Carya illinoinensis* L.) and alfalfa (*Medicago sativa* L.). Annual water-requirement for cotton is approximately 0.85 and 1.52 m for pecan and alfalfa. During the periods of drought, reduced FW allocation from Rio Grande river, had forced farmers in the region to abandon lands traditionally under cotton and divert any allocated water to salvage perennial high value cash crops such as pecan (Ganjegunte et al., 2019). El Paso utilities produces an estimated 80 billion liters of TWW annually, of which only 13 % is reused for industrial and commercial landscape irrigation (Chaganti et al., 2020). Thus, there is great potential for diverting this water for supplementing agricultural irrigation.

Treated wastewater is however, known to contain higher total dissolved solids (TDS) or salts (Toze, 2006) that could negatively affect crop performance and increase soil salinity and sodicity, which can result in overall deterioration of soil quality. While cotton is a salt-tolerant crop, it requires large amounts of irrigation water. Therefore, diversifying cropping pattern with crops that are both salt-tolerant and less water-intensive is the need of the hour to ensure long-term viability of agriculture in this region. Growing biofuel crops such as canola (*Brassica napus* L.) can be a suitable alterative as it is considered as salt-tolerant and relatively less water-intensive as it can be grown in winter when the evapotranspiration rates are low (Ashraf and McNeilly, 2004; Hooks et al., 2019; Safavi Fard et al., 2018). Furthermore, growing canola as a biofuel crop on abandoned marginal lands could help generate farm revenue while expanding its acreage into non-traditional areas such as arid southwest. Major advantage of growing canola is that it has an already established market for vegetable oil and other non-food uses such as industrial lubricants, cosmetics, candles etc., in addition to also being extensively developed as a biofuel feedstock, which would ensure farm revenue generation (Katuwal et al., 2018).

Traditional oil seed crops such as brown mustard (*Brassica Juncea* L.), canola, camelina (*Camelina sativa* L.) in addition to soybean (*Glycine max* L.), are increasingly seen as alternative feedstocks for biofuel production including biodiesel (Blackshaw et al., 2011; Hergert et al., 2016; Hossain et al., 2019). Vegetable oil produced from canola seeds, in addition to being edible, is also used for production of industrial quality biodiesel via. the transesterification process utilizing chemical, physical and enzymatic methods (Jang et al., 2012). Biodiesel produced from canola seed oil is considered superior in terms of its quality and is used as a blend in conventional diesel in various proportions (Roy et al., 2013). Canola, along with other oil-seed biofuel stocks is even being explored as a potential resource for producing high quality renewable jet fuel (Gesch et al., 2015; Shi et al., 2019).

Canola is a cool-season crop extensively grown mainly in either winter or spring in central and northern great plains of North America, mostly as a 'rotational' crop (Gesch et al., 2015; Begna and Angadi, 2016). Several studies have explored its performance and seed yield potential under both rainfed and different irrigation regimes (Chen et al., 2015; Gesch et al., 2015; Hergert et al., 2016; Hossain et al., 2019; Pavlista et al., 2016). In a more recent study, Gesch et al. (2019), explored the productivity of several brassica cultivars in the western USA as it is commonly reported that there exists a genotype × environment interaction that affects oil seed production among different cultivars (Gesch et al., 2019; Gunasekera et al., 2006). However, studies evaluating the performance of canola as a biofuel crop in Southwestern U.S are very limited. Also, owing to extreme arid climatic conditions and degraded/marginal soils, performance of canola as a biofuel crop in west Texas (El Paso) region has not been studied yet. Importantly, availability of alternative water supplies in the form of TWW or brackish groundwater for irrigation during winter season in El Paso makes this place suitable for producing winter canola. However, due to wastewater's propensity to increase soil salinity and sodicity, the specific effects of TWW irrigation on agronomic crop performance of canola, it's seed yields and seed quality are largely unknown as the seed yields and seed quality (specifically, seed oil content) are critical for biofuel production.

Therefore, the objectives of this field study were (i) To evaluate the seed yield potential and seed quality aspects of canola grown for biofuel production on marginal soils with TWW irrigation and (ii) To quantify changes in soil salinity and sodicity overtime after TWW irrigation. We hypothesize that irrigating with TWW increases soil salinity and sodicity and will deteriorate soil quality, which negatively affects canola growth and ultimately reduces seed yields and seed oil content/yield.

2. Materials and methods

2.1. Site and experimental setup

A two-year field study was started in July of 2016 at Texas A&M AgriLife Research Center, El Paso's research farm (31° 39′ 27.31″ N, 106°16′ 8.32″ W) (Fig. 1). The study site is characterized as having an arid climate with an annual average precipitation of 0.169 m and a potential evapotranspiration rate of 1.94 m. Annual temperature ranges from -3.6 °C in winter to 35.8 °C during summer. The dominant soil map unit of the soils at the study site was Saneli Silty Clay loam (clayey over sandy or sandy-skeletal, montmorillonitic calcareous, thermic Vertic Torrifluvents). A split-plot randomized complete block experimental design was used in this study with water type as the main plot factor and amendment application as the subplot actor (Chaganti et al., 2020). Water types consisted of FW and TWW. Amendment application consisted of a combined application of gypsum and elemental sulfur (GS) and a no amendment (control/NA) application. All treatment combinations were replicated three times. There were a total 12 individual experimental plots and each plot measured 5.5 m long and 2.5 m wide.

2.2. Irrigation water and analyses

Freshwater irrigation consisted of regular tap water, which is filtered and disinfected Rio Grande river water. Wastewater was sourced from local municipal wastewater treatment plant (Roberto Bustamante). The wastewater treatment process consisted of screening, de-gritting, pre-aeration, primary settling, aeration, secondary settling and chlorine disinfection. Grab water samples of FW and TWW were collected randomly during each cropping season from their respective sources in 500 mL polyethylene bottles and were stored at 4 °C until further chemical analyses was done in the laboratory. At the time of testing, water samples were initially filtered through a 0.45 m syringe filter and were then analyzed for selected chemical properties including pH, electrical conductivity (EC), cations (calcium-Ca^{2+}, magnesium-Mg^{2+}, sodium-Na^{+}, potassium-K^{+}, ammonium-NH_4^{+}), and anions (chloride-Cl^{-}, nitrate-NO_3^{-}, sulfate-SO_4^{2-}, phosphate-PO_4^{3-}) using methods described by Baird et al. (2017). The pH and EC of water samples were measured on subsamples using a Fisher Scientific Accument XL600 multichannel benchtop meter. Both cations and anions were measured using the ion-exchange chromatography technique on Dionex ICS-1100 chromatography machine. Relevant chemical properties of fresh and wastewater used in this study are presented in Table 1.

2.3. Amendment application

Gypsum ($CaSO_4.2H_2O$) and elemental sulfur (S) were added to respective amended plots at the rates equivalent to 10 and 1 Mg ha^{-1} and were incorporated into the top 0–15 cm soil just before planting. Gypsum was added to counter Na^{+} and its requirement was calculated based on the baseline soil sodicity and Na^{+} that will be added through irrigation waters during the course of the study. Elemental S was added to produce sulfuric acid through a microbially mediated process that in turn would convert insoluble calcite ($CaCO_3$) present in study site soils

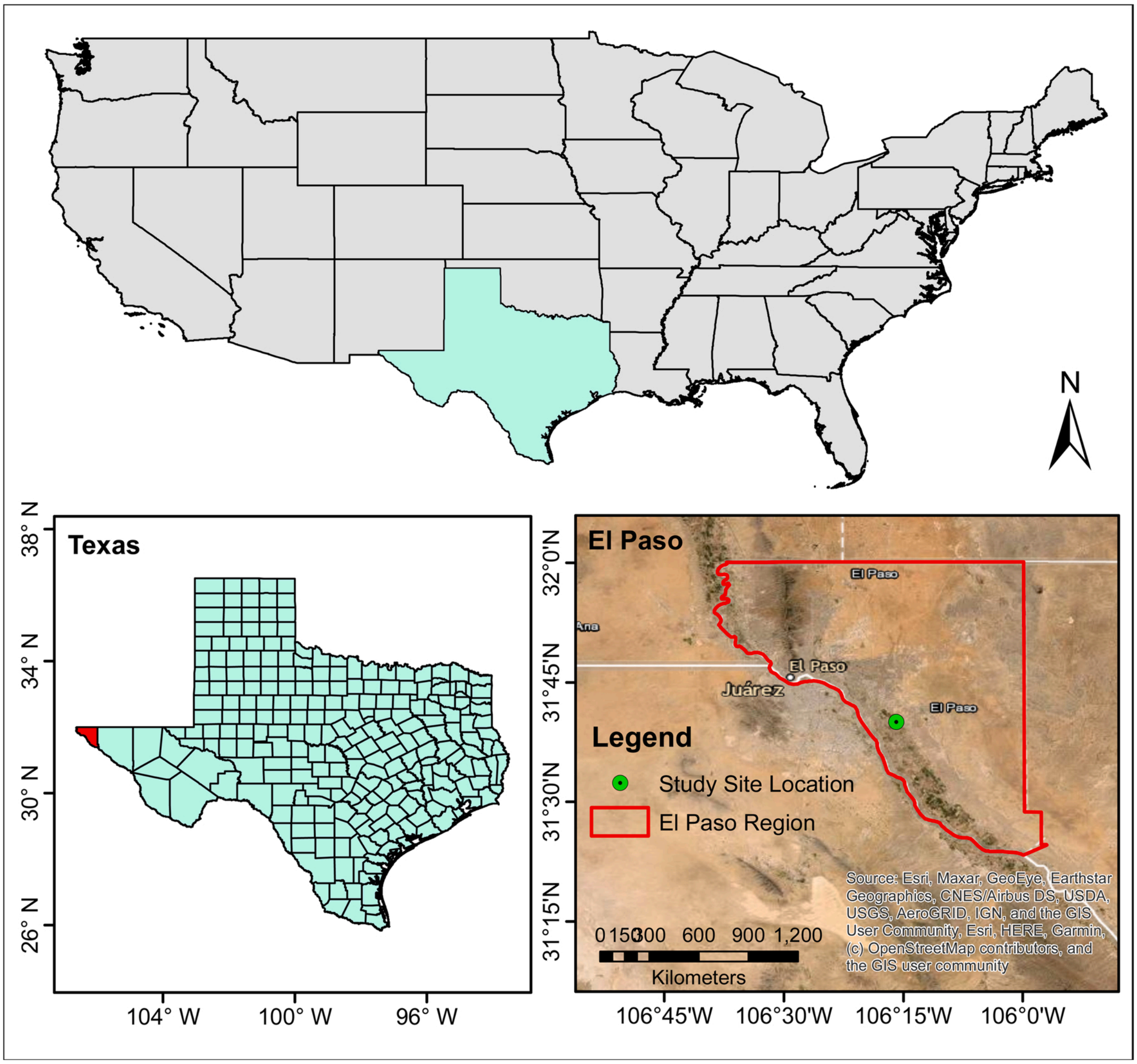

Fig. 1. Illustration of study area in El Paso, TX.

Table 1
Chemical properties of fresh and treated wastewater used in this study (mean ± SE, n = 6).

Measure	Freshwater	Treated Wastewater
EC_w (dS m^{-1})	0.99 ± 0.07	2.12 ± 0.16
pH	7.11 ± 0.08	7.02 ± 0.14
SAR (mmol $l^{-1})^{0.5}$	3.19 ± 0.35	5.98 ± 0.56
Na^+ (mg L^{-1})	153 ± 16.2	288 ± 18.4
K^+ (mg L^{-1})	33.2 ± 16.0	51.9 ± 14.8
NH_4^+ (mg L^{-1})	13.4 ± 8.77	39.2 ± 16.7
Ca^{2+} (mg L^{-1})	94.4 ± 13.8	95.4 ± 14.9
Mg^{2+} (mg L^{-1})	25.3 ± 9.63	22.0 ± 1.19
Cl^- (mg L^{-1})	132 ± 30.7	315 ± 84.1
NO_3^- (mg L^{-1})	8.11 ± 1.44	81.4 ± 19.3
PO_4^{3-} (mg L^{-1})	0.20 ± 0.11	10.1 ± 1.53
SO_4^{2-} (mg L^{-1})	154 ± 21.3	287 ± 46

EC_w: Electrical conductivity of water; SAR: Sodium Adsorption Ratio of water.

(up to 10 % by weight in the upper 75 cm) to a more soluble $CaSO_4.2H_2O$ (gypsum) that would counter Na^+ (see Eqs. 1 & 2 below). Based on this assumption, both the amendments were applied only at the beginning of the experiment to simulate farmers practices as it is a common practice by farmers to apply soil amendments every 2–3 yrs.

$$2S + 3O_2 + 2H_2O \rightarrow 2H_2SO_4 \quad (1)$$

$$H_2SO_4 + H_2O + CaCO_3 \rightarrow CaSO_4.2H_2O + CO_2 \quad (2)$$

2.4. Plot management

Field preparation in each plot included initial disking, manually breaking of large clods, furrow and ridge formation, and demarcation of plots by raised earthen berms (approximately 20 cm in height). Based on the results of the greenhouse salt tolerance studies, DKL-30-42 cultivar was selected for the field experiment. There were 8 rows in each individual experimental plot with an inter-row spacing of 15 cm and intra-row spacing of 10 cm. The final plant density stood at 54 plants m^{-2}, which is close to the recommended planting density (Angadi et al., 2003; Yantai et al., 2016). Seeds were sown in late August-early September in both 2016 and 2017. All plots received a basal application of NPK fertilizer at the rate of 120 kg ha^{-1} of N: P_2O_5: K_2O in the form of granular urea (46–0–0), monoammonium phosphate (MAP; 11–52–0) and sulfate of potash (SOP; 0–0–50). Both fresh and wastewater irrigated plots received approximately 0.68 m of water throughout the cropping season at 3 – 4-week intervals except when there was intermittent rainfall. Herbicides were used prior to germination or after germination and only manual weeding was carried out when weed pressure increased in the plots.

2.5. Soil sampling and analyses

Bulk soil samples were collected randomly from the study site at 0 – 15, 15–30, 30–45, and 45–60 cm depths before the start of the experiment, to quantify their general properties in the study area. Soil collected from each depth was composited, ground, sieved through a 2–mm sieve and was mixed thoroughly to achieve homogeneity. Subsamples of soil at each depth were collected and analyzed for their respective physical and chemical properties as given in Table 2. Soil particle size analysis was conducted using the hydrometer method given in Gavlak et al. (2003) after saturating the soil with 5% sodium hexametaphosphate solution. The cation exchange capacity (CEC) of the soil was estimated on a 5 g sample following the Bower method of Na^+ saturation using 1 M sodium acetate solution with pH adjusted to 8.2, followed by ethanol rinsing and replacing adsorbed Na^+ by NH_4^+ using a 1 M ammonium acetate solution of pH 7.0. Cation exchange capacity was calculated by quantifying the concentration of Na^+ in the 1 M ammonium acetate soil extract (Richards, 1954). Soil salinity (EC_e) and pH were measured on soil saturated paste extracts following the methods given in Richards (1954) using Fisher brand accumet XL600 multichannel benchtop meter (Fisher Scientific, NH). The water-soluble cations (Na^+, K^+, Ca^{2+}, and Mg^{2+}) were analyzed on saturated paste extracts by ion-exchange chromatography (IC) technique on a Dionex ICS-1100 chromatography machine. Sodium adsorption ratio (SAR) of soils was calculated using the equation given by Chaganti et al. (2020) from soluble Na^+, Ca^{2+} and Mg^{2+} concentrations obtained from ion chromatography.

Pre-study (May 2016) and end–of–the–study (April 2018) soil samples were collected from three random locations in each test plot from four depths (0–15, 15–30, 30–45 and 45–60 cm) using a 5-cm diameter soil auger and were composited into a single sample. These composite soil samples were air-dried, mixed and were ground to pass through a 2–mm sieve to achieve uniformity. Pre–study/baseline and end–of–the–study soil samples from all plots were analyzed for soil quality indices including EC_e, pH and SAR using the methods described above.

Table 2
Important physical and chemical properties of soils at depths 0 – 15, 15 – 30, 30 – 45, and 45 – 60 cm (n = 3) (mean ± SE).

Soil Characteristic	0–15 cm	15–30 cm	30–45 cm	45–60 cm
Sand	38.8 ± 0.16	37.7 ± 0.63	38.9 ± 2.11	36.3 ± 1.38
Silt	35.3 ± 1.83	36.5 ± 0.63	33.6 ± 2.11	41.2 ± 1.38
Clay	25.8 ± 1.67	25.8 ± 0	27.5 ± 0	22.5 ± 0
Texture class	Loam	Loam	Loam	Loam
CEC ($cmol_c$ kg^{-1})	13.1 ± 0.11	11.9 ± 1.92	13 ± 0.71	12.5 ± 0.58
Bulk Density (g cm^{-3})	1.32 ± 0.01	1.39 ± 0.04	ND	ND
Saturated paste extract				
pH	8.37 ± 0.06	8.48 ± 0.03	8.43 ± 0.02	8.38 ± 0.05
EC_e (dS m^{-1})	1.94 ± 0.16	1.66 ± 0.03	1.90 ± 0.02	2.20 ± 0.05
SAR (mmol l^{-1})$^{0.5}$	3.99 ± 0.09	4.05 ± 0.14	4.94 ± 0.20	6.49 ± 0.17
Soluble Na^+ ($mmol_c$ l^{-1})	9.26 ± 0.65	8.21 ± 0.31	10.2 ± 0.36	13.1 ± 0.45
Soluble K^+ ($mmol_c$ l^{-1})	1.19 ± 0.11	0.98 ± 0.02	0.92 ± 0.05	0.67 ± 0.06
Soluble Ca^{2+} ($mmol_c$ l^{-1})	8.47 ± 0.78	6.5 ± 0.07	6.71 ± 0.28	6.22 ± 0.67
Soluble Mg^{2+} ($mmol_c$ l^{-1})	2.38 ± 0.28	1.76 ± 0.03	2.08 ± 0.28	2.06 ± 0.24

CEC: Cation Exchange Capacity of soil; ECe: Electrical conductivity of soil saturated paste extract; SAR: Sodium Adsorption Ratio of soil saturated paste extract. ND: Not Determined.

2.6. Canola harvesting, seed yield and seed quality analyses

At maturity, canola plants were harvested in the month of March and plants were cut at the base. Canola pods from each plant were hand harvested and the seeds were manually separated. A subsample (~20 g) of canola seeds was dried and ground to < 1 mm and was sent to Dairy One forage laboratory (Ithaca, NY, USA) for determining select seed quality parameters by near-infrared reflectance spectroscopy (Xu et al., 2015) and wet digestion methods. These included seed oil content, ash content, and mineral constituents (Na, Ca, Mg, K, and S). Seed oil yield was calculated by multiplying the seed yields with their respective final oil contents.

2.7. Data analyses

All data were subjected to analysis of variance using the General Linear Model (GLM) repeated measures analysis in SPSS (v.26) to determine the significance (at $p \leq 0.05$) of main (water type) and subplot (amendment) factors and their respective interactions. Water type and amendment effects were considered as fixed effects and year was considered as a repeated measure. When soil quality measurements including pH, EC_e and SAR were analyzed, soil sampling depth was also included in the model as a fixed factor. When statistically significant, mean comparisons between treatments were conducted using the Tukey's HSD test at $p \leq 0.05$, unless otherwise stated. To assess the relationship between seed yields and soil quality indices (EC_e and SAR), a linear model was fit using the *lm()* function in R studio. Graphics were generated using the "ggplot2″ package (Wickham, 2016), also in R Studio.

3. Results and discussion

3.1. Seed yield

Canola seed yields across the two years of study ranged from a low of 1724 kg ha^{-1} to a high of 2390 kg ha^{-1} (Table 3). Neither the water type nor the amendment application had any significant effect on canola yields in both the years with no interactions observed. Application of TWW did not cause any seed yield reductions as originally hypothesized due to its potential for soil salinization. Results indicated that soil salinity increased in TWW irrigated soils (Fig. 2b) but rarely exceeded the soil salinity threshold of 4 dS m^{-1} to influence plant productivity.

Table 3
Canola seed yields (mean ± SE) for fresh and wastewater and two amendment treatments in 2017 and 2018 cropping seasons.

Year Water type	Amendment	2017 Yield (kg ha^{-1})	2018
FW	NA	1728 ± 297[a]	1989 ± 413
FW	GS	1725 ± 351	1979 ± 524
TWW	NA	2025 ± 294	2391 ± 230
TWW	GS	2025 ± 135	1933 ± 180
Source		**P > F**	
Year		0.41	
Water type		0.27	
Amendment		0.57	
Year × water type		0.8	
Year × Amendment		0.62	
Water type × Amendment		0.59	
Year × Water type × Amendment		0.63	

[a] Columns or rows with same or no letters indicate that there were no significant differences among treatment means at p < 0.05, Tukey's test. FW: Freshwater; TWW: Treated Wastewater; NA: No Amendment; GS: Gypsum + Sulfur.

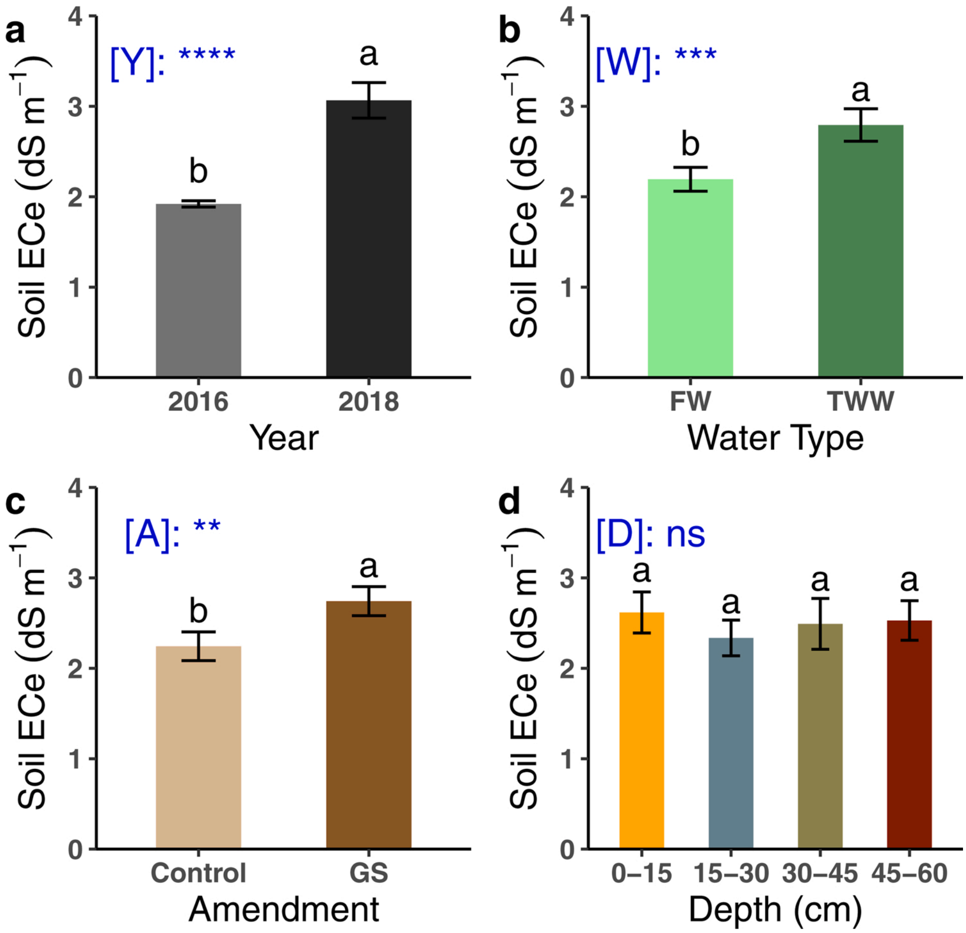

Fig. 2. Changes in soil electrical conductivity (EC_e) (mean ± SE) as affected by (a) time [Y]; (b) water type [W]; (c) soil amendment [A] and (d) depth [D]. Significant effect of factors on soil EC_e is indicated by * at $p < 0.1$, ** at $p < 0.05$, *** at $p < 0.01$, and **** at $p < 0.001$. 'ns' indicates non-significant effects. Significant differences between different levels of each factor are indicated by lower case letters. FW: Freshwater; TWW: Treated Wastewater; Control: No Amendment, NA; GS: Gypsum + Sulfur.

Moreover, canola is a salt-tolerant plant with a salinity threshold of 10 dS m^{-1} (Francois, 1994). Since the soil salinity observed in our study (Fig. 2) was less than the canola threshold, it likely did not cause any significant yield reductions. A simple regression analysis revealed that there was no significant relationship between canola seed yields and soil salinity/sodicity (Fig. 3). It was interesting to see that TWW in fact improved seed yields relative to FW irrigation, though not statistically significant. Seed yields were 1855 and 2093 kg ha^{-1} for FW and TWW treatments, respectively. This is most likely due to the fact that TWW generally contains high concentration of nutrients such as nitrogen (N) (Table 1) (Chaganti et al., 2020), which likely increased the soil nutrient status transiently and helped increase seed yields. However, long-term evaluations are needed to gain more insight into the interactions among wastewater irrigation, soil fertility, salinity and plant performance.

On the other hand, application of gypsum and S (GS) did not affect seed yields of canola (Table 3). Application of GS also increased soil salinity (Fig. 2c) after their addition as they add to total dissolved solids (TDS) of soil solution, but results (Fig. 2c) indicated that the EC_e levels in GS treated soils never reached the tolerance threshold of canola. Also, gypsum and elemental S can be significant sources of sulfur, an essential nutrient, and canola was reported to show a positive seed yield response to S fertilization (Ahmad et al., 2011; Jackson, 2000; Malhi et al., 2007, 2005). However, Malhi et al. (2005) suggested that a significant yield response to S can be obtained only when soils are deficient in S. No response to applied S in our study is likely because soils were not deficient in S. Nevertheless, previous studies have reported a wide range of seed yields in canola under both irrigated and rainfed conditions (Gesch et al., 2019, 2015; Hamzei, 2011; Hergert et al., 2016; Hossain et al., 2019; Pavlista et al., 2016). The yields observed in this study are

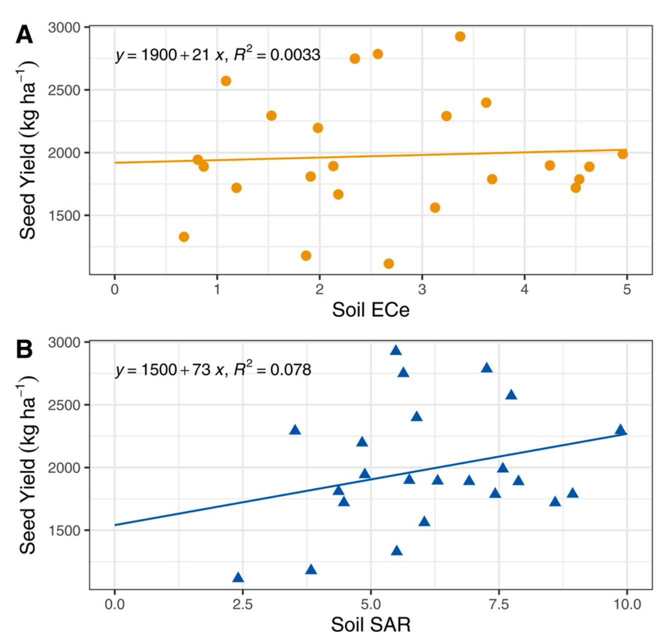

Fig. 3. Linear regressions showing the relationship between (A) soil salinity (EC_e) and (B) soil sodicity (SAR) on canola seed yield. Soil EC_e and SAR data is across all years and treatments and averaged across all four depths.

generally comparable to those reported in some of these studies. For example, Gesch et al. (2019) reported canola (Brassica *napus*) seed yields ranging between 933 to 1474 kg ha^{-1} across multiple environments in western USA. Our results are much closer to those reported by Gesch et al. (2015) where canola seed yields averaged at 2000 kg ha^{-1} for various cultivars of Brassica *napus* sp. across two years in western Minnesota. Furthermore, our results concur with Begna et al. (2017) and Begna and Angadi (2016), who also reported a range of yields when canola was grown as a winter crop in New Mexico under semi-arid conditions. It should be noted that this study is one of its kind to investigate canola growth under arid and marginal soil conditions with TWW irrigation. The results from this study show that canola can be grown on marginal soils under TWW irrigation without any yield compromises and can be a potential biofuel crop as an alternative to traditional crops of this region.

3.2. Seed quality

3.2.1. Seed oil content

Average seed oil content varied between 40.5–42.5 % across all treatments (Table 4). Water type and amendment application did not significantly affect the seed oil content after two-years of study. Respective interactions among treatments were also not statistically significant. Either irrigating with TWW or application of GS did not affect seed oil content. These results contrast our original hypothesis that TWW application would increase soil salinity and negatively affect the seed oil content. Results show that soil salinity did not increase to the extent we originally hypothesized, and the observed EC_e values (Fig. 2) were well below canola's salinity tolerance threshold of 10 dS m^{-1}. This likely did not have any negative affect on seed oil content. These results concur with Francois (1994) and Qasim et al. (2003), who also reported that seed oil content was not affected by increasing soil salinity. Nevertheless, the seed oil content found in this study are within the range or above those reported by some previous studies under non-saline conditions and under different water regimes (Gesch et al., 2019; Hamzei, 2011; Pavlista et al., 2016, 2011; Safavi Fard et al., 2018). For example, our results are very close to those reported by Safavi Fard et al. (2018), who found that seed oil content varied between 41 and 43 %, when canola was grown in winter and spring in Iran. Similarly, Gesch et al. (2019), also found that seed oil content varied between 34–43% among different Brassica *sp.* when grown in multiple environments spanning across the western USA. Furthermore, in a more recent study conducted across different climates in southeastern United States, Tetteh et al. (2019) reported oil contents in the canola seed ranging between 43–48%. On the other hand, Pavlista et al. (2016) reported rather low oil contents (35 %) in spring canola even under full irrigation water application in western Nebraska. Irrespectively, most of the differences in seed oil contents were attributed to the differences between various cultivars of Brassica *spp.* and their response across different environments (Safavi Fard et al., 2018).

3.2.2. Seed oil yield

Neither the water type nor amendment application affected the net seed oil yields (Table 4) significantly. As seed yields and oil contents were not significantly affected, it is apparent that the oil yields were also not affected by water type and soil amendments. Average seed oil yields ranged between 793 – 978 kg ha^{-1}. Similarly, Gesch et al. (2015), reported an average seed oil yield of 850 kg ha^{-1} across two years of study for various Brassica *napus* cultivars grown in the north central U.S. Katuwal et al. (2018) also reported an average oil yield of 773 kg ha^{-1} under normal irrigated conditions in semi-arid new Mexico. Contrastingly, in a more recent study conducted across different climates in the western U.S., seed oil yields for Brassica *napus* cultivars ranged between 388 and 630 kg ha^{-1} (Gesch et al., 2019), lower than what was found in the current study in the arid region. Most of these differences were generally attributed to alterations in performance of different Brassica cultivars across varying climatic conditions. Nevertheless, our results show that oil yields achieved under arid climatic conditions and irrigated with TWW are comparable to those obtained elsewhere across U.S.

3.2.3. Seed ash and mineral constituents

Seed ash content and percentage of mineral elements (Na, K, Ca, Mg, & S) in the seed are given in Table 4. Irrigating with TWW or GS application did not increase the ash and mineral element concentrations in the seed. Average seed ash contents ranged between 4.51–4.72%. Average percent elemental concentrations of Na, K, Ca, Mg, and S were 0.004, 0.91, 0.35, 0.29, and 0.44, respectively. Since elevated salinity generally translates into increased ash content in biomass/seed, we hypothesized that irrigation with TWW would increase ash content of the seeds. Contrasting to our hypothesis, irrigating with TWW and GS application did not increase seed ash and mineral element concentrations. This can be attributed to the mechanism of higher salt assimilation in the shoot tissue than in the seed (Ashraf and McNeilly, 2004). Unlike canola, ash or mineral constituents are more of a concern in the lignocellulosic biomass feedstocks. This is because higher ash or mineral contents can negatively affect the efficiency of thermo-chemical conversion of biomass into ethanol/biofuel thus increasing the operational costs (Vassilev et al., 2017; Wang et al., 2012). In the case of canola, ash content is not related to seed oil yield as the oil yield is a direct function of seed yields and percent oil content in the seed and therefore is not a likely concern. It is however, possible that ash and mineral constituents may play a significant role when canola seed, after oil extraction, is used as a feed meal ingredient for ruminants (Mejicanos et al., 2016). Nevertheless, the effects of ash and mineral composition of canola seed meal on its feeding value is not within the scope of this study.

3.3. Soil quality indicators

3.3.1. Soil pH

Changes in soil pH as affected by different treatments factors are presented in Fig. 4a-d. Results indicate that soil pH generally decreased significantly across all the depths regardless of water type and amendment application after two years (Fig. 4a). Neither the water type (Fig. 4b) nor the amendment application (Fig. 4c) significantly affected soil pH and there were no significant interactions between various

Table 4
Canola seed quality parameters as affected by two water types and amendment application at the end of the study (2019 data) (mean ± SE).

Water (W)	Amendment (A)	% Oil content	Oil Yield (kg ha^{-1})	% Ash	% K	% Ca	% Mg	% S	% Na
FW	NA	42.4 ± 5.43[a]	798 ± 62.6	4.72 ± 0.58	0.89 ± 0.09	0.37 ± 0.02	0.29 ± 0.01	0.41 ± 0.06	0.005 ± 0.002
FW	GS	41.6 ± 3.39	793 ± 165	4.64 ± 0.49	0.94 ± 0.07	0.37 ± 0.06	0.29 ± 0.02	0.42 ± 0.04	0.003 ± 0.001
TWW	NA	40.5 ± 2.56	978 ± 143	4.63 ± 0.20	0.89 ± 0.05	0.32 ± 0.02	0.29 ± 0.01	0.46 ± 0.02	0.005 ± 0.001
TWW	GS	42.5 ± 1.59	826 ± 102	4.51 ± 0.19	0.90 ± 0.06	0.33 ± 0.02	0.28 ± 0.01	0.47 ± 0.05	0.005 ± 0.001
Source		**P > F**							
W		0.88	0.45	0.81	0.80	0.36	0.48	0.29	0.32
A		0.76	0.40	0.77	0.69	0.99	0.50	0.65	0.43
W x A		0.51	0.43	0.95	0.86	0.92	1.00	0.88	0.31

[a] Means followed by same or no letters in a column are not significantly different from each other at $p \leq 0.05$, Tukey's test. FW: Freshwater; TWW: Treated Wastewater; NA: No Amendment; GS: Gypsum + Sulfur.

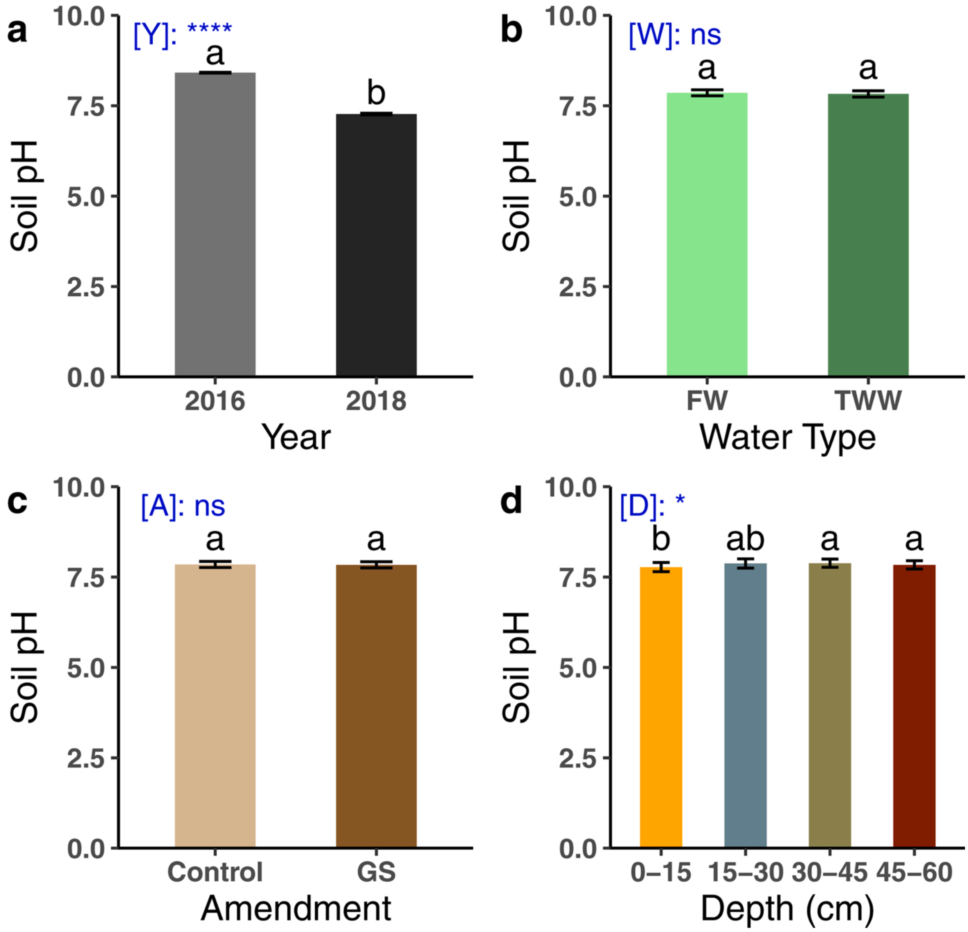

Fig. 4. Changes in soil pH (mean ± SE) as affected by (a) time [Y]; (b) water type [W]; (c) soil amendment [A] and (d) depth [D]. Significant effect of factors on soil pH is indicated by * at $p < 0.1$, ** at $p < 0.05$, *** at $p < 0.01$, and **** at $p < 0.001$. 'ns' indicates non-significant effects. Significant differences between different levels of each factor are indicated by lower case letters. FW: Freshwater; TWW: Treated Wastewater; Control: No Amendment, NA; GS: Gypsum + Sulfur.

treatments. On average, soil pH decreased from 8.42 to 7.28 across all four depths overtime. This decrease in pH can be attributed to the acidification processes that occur naturally due to plant root exudates and microbial activity taking place in the rhizosphere region (Pearse et al., 2006; Sun et al., 2019). For example, Pearse et al. (2006) showed that carboxylates released from plant roots can significantly reduce soil pH. Moreover, addition of C through plant roots can stimulate microbial activity, which upon respiring can increase partial pressure of CO_2 within the rhizosphere that can result in the formation of inorganic acids (Abbas et al., 2016). This also likely contributed to the decrease in soil pH overtime. Additionally, dissolution of $CaCO_3$ after S application and in-situ formation of gypsum most likely resulted in an increase in divalent cation (Ca^{2+}) availability in soil solution (Ganjegunte et al., 2017) that could reduce soil solution pH due to the formation of neutral ionic pairs (Essington, 2015). Nevertheless, our results are in line with Chaganti et al. (2020) who also reported a significant reduction in soil pH after two years in biomass sorghum plots irrigated with TWW. Soil pH is a master variable and reduction of soil pH plays an important role in plant nutrient availability, especially in calcareous soils like those seen in this study. On the other hand, soil pH varied with soil depth, with higher pH seen at the lower depths (30–45 and 45–60 cm) relative to surface 0–15 cm soils (Fig. 4d). This could possibly due to higher root density in the surface layers, which likely facilitated higher soil acidification.

3.3.2. Soil salinity

Soil salinity (EC_e) was significantly affected by year (Fig. 2a), water type (Fig. 2b) and amendment (Fig. 2c). Interestingly, soil salinity did not significantly vary between four depths (Fig. 2d). Interactions among year × water type, year × amendment, year × water type × amendment, were significant, respectively ($P < 0.05$). After two years, soil salinity significantly increased regardless of water type and amendment application across all four depths (Fig. 2a). On average, soil salinity increased from 1.92 to 3.07 dS m^{-1}, a 60 % increase relative to pre–study soils. This is an expected result due to the arid climate of this region characterized by high temperatures and low precipitation and irrigation water application not exceeding the evapotranspiration rates. This results in a net accumulation of salts in the root zone as a natural consequence due to inadequate salt leaching (Chaganti et al., 2015). Irrespective of amendment application, irrigating with TWW exacerbated this effect with wastewater irrigated soils having significantly higher soil salinity compared to FW irrigated soils (Fig. 2b). At the end of the second year, TWW treatment had 49 % higher soil EC_e across all depths, relative to FW irrigation treatment. Previous studies have also reported higher soil salinity after TWW irrigation and this effect was attributed to high TDS concentrations commonly found in TWW (Chaganti et al., 2020; Corwin and Bradford, 2008; Elgallal et al., 2016; Ganjegunte et al., 2017).

Regardless of water type, GS plots also had significantly higher soil salinity compared to plots which did not receive any amendment (Fig. 2c). This is because of the gypsum addition as gypsum is in fact a neutral 'salt' and can transiently increase soil salinity by adding Ca^{2+} and SO_4^{2-} ions (Zhao et al., 2020). In addition, solubilization of native salts would have also released Ca^{2+} ions into soil solution thus increasing its electrical conductivity (Ganjegunte et al., 2017). Highest soil EC_e values were observed in the WW–GS combination treatments consistently at all four depths with salinities becoming closer to the 4 dS

m^{-1} threshold. It should however be noted that, salinity increase by Ca salts promotes flocculation by countering Na^+, which results in better soil structure and permeability of the soil (Vance et al., 2004; Johnston et al., 2013; Chaganti et al., 2015). Nevertheless, higher salinity in the WW–GS treatment can be attributed to the cumulative effect of TDS from TWW, gypsum addition and native salt solubilization. On the other hand, soil salinity was generally higher in the 0–15 cm layer compared to the lower depths (Fig. 2d), though the differences were not statistically significant. This is most likely due to the higher accumulation of salts in the top layer as a result of excessive evaporation and relatively less leaching taking place and due to the presence of any insolubilized gypsum that was incorporated into topsoil initially (Cox et al., 2018). More importantly, salinity increases either due to TWW or gypsum application did not cause any significant reductions in seed yields of canola or negatively affected the seed quality. Regression analysis also showed that there was no significant relationship existed between soil EC_e and seed yields (Fig. 3a). These results indicate that canola can be successfully grown on arid soils with TWW irrigation without compromising yield and quality attributes of canola seed.

3.3.3. *Soil sodicity*

The effects of year, water type, amendment and depth were all significant (Fig. 5a-d). Also, statistically significant interactions between year × water type, year × amendment, and amendment × depth were observed ($P < 0.05$). In general, soil SAR increased over time (Fig. 5a) across all four depths and regardless of amendment application and irrigation water type. This is most likely due to the natural addition of Na^+ through irrigation waters that increased concentrations of Na^+ in soil solution. Also, due to the prevalence of the "valence dilution" effect (Chaganti et al., 2020), there was likely an increase in monovalent cation (specifically, Na^+) concentration in soil solution, relative to divalent cations (such as Ca^{2+} and Mg^{2+}), that likely contributed for higher SAR. Across all four depths, average increases in soil SAR were 23 % and 58 %, for FW–NA and WW–NA treatments, respectively, compared to their pre-study levels. It should be noted here that the increase in soil SAR was more in the TWW treatment (Fig. 5b), relative to FW treatment. This is an expected outcome as TWW has higher Na^+ concentrations compared to FW (Table 1) (Assouline et al., 2016; Elgallal et al., 2016; Gharaibeh et al., 2016; Suarez and Gonzalez-Rubio, 2017).

On the other hand, application of gypsum + sulfur significantly reduced soil SAR when compared against unamended soils across all treatments (Fig. 5c). Traditionally, gypsum is used as a common amendment to remediate soil sodicity as it supplies readily available Ca^{2+} to counter Na^+ in soil solution and on soil exchange sites (Oster and Frenkel, 1980). Thus, lower SAR in gypsum treated soils can be attributed to the gypsum solubilization and chemical enrichment of soil solution with Ca^{2+}, which facilitated Na^+ removal from exchanges sites and its subsequent loss through leaching. Relative to baseline levels, soil SAR reductions averaged by 32 & 29 % at 0–15 cm and by 9 & 10 % at 15–30 cm depth for FW-GS and WW-GS treatments, respectively, after two years, where most roots are generally concentrated. Similar reductions in soil SAR after gypsum application were also reported by several other studies (Chaganti et al., 2020, 2015; Dao et al., 2019; Ganjegunte et al., 2017; McKenna et al., 2019; Sundha et al., 2020). Soil SAR significantly increased with increasing depth across all treatment combinations with the highest SAR seen at the 45–60 cm depth (Fig. 5d). This was possibly due to the movement of Na^+ from surface layers into deeper layers because of leaching (Chaganti et al., 2020). Nevertheless, these results indicate that TWW irrigation can increase sodicity hazard

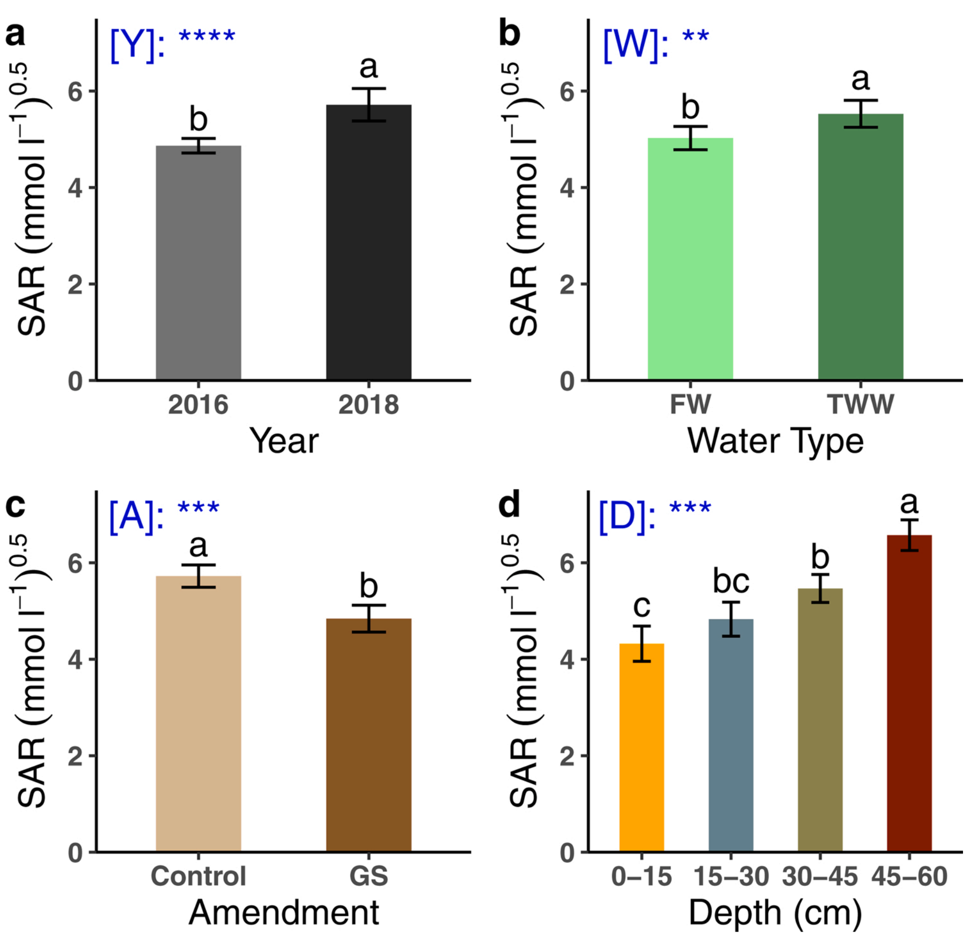

Fig. 5. Changes in soil sodium adsorption ratio (SAR) (mean ± SE) as affected by (a) time [Y]; (b) water type [W]; (c) soil amendment [A] and (d) depth [D]. Significant effect of factors on soil SAR is indicated by * at $p < 0.1$, ** at $p < 0.05$, *** at $p < 0.01$, and **** at $p < 0.001$. 'ns' indicates non-significant effects. Significant differences between different levels of each factor are indicated by lower case letters. FW: Freshwater; TWW: Treated Wastewater; Control: No Amendment, NA; GS: Gypsum + Sulfur.

in arid marginal soils. However, in the presence of soil amendments such as gypsum that can counter Na^+, the extent of soil sodification can be effectively minimized and maintained well below the threshold of 13, above which the effects of high sodium on soil properties become apparent.

4. Conclusions

This field study explored the possibility of using TWW as an irrigation source for growing canola as a biofuel crop and seed yields, along with seed oil yields, were quantified. The results indicate that there were no significant differences in seed yields between FW and TWW irrigation. The results are contrasting to our original hypothesis that TWW could negatively affect crop productivity as it has the potential to increase soil salinity and sodicity. Seed quality parameters relevant to biofuel production including seed oil content and oil yield were also not affected by TWW irrigation. Nevertheless, seed yields and oil content/yields found in our study are well with the normal ranges reported in previous studies under non-arid conditions. Changes in soil quality were more prominent under treated wastewater irrigation with TWW increasing both soil salinity and sodicity relative to FW. Application of gypsum negated this effect and reduced soil SAR significantly to levels close to those seen in baseline soils. These results highlight that TWW can increase soil sodicity overtime and negatively affect soil quality in the absence of gypsum application. Important to note, increase in either soil salinity or sodicity did not negatively affect canola seed productivity and quality, which can be attributed to higher salinity tolerance threshold of canola.

In conclusion, the findings from this study indicate that canola as a biofuel crop, can be successfully grown on arid soils of west Texas with TWW irrigation without any compromises in seed yields and oil content. However, to maintain long-term soil quality and crop productivity, necessary soil management practices must be followed to avoid sodicity hazard associated with TWW application. We believe that these results could have favorable implications in diversifying cropping patterns in this region and help extend acreage of biofuel crops into marginal lands of arid west Texas without competing for food crops in arable lands. More importantly, use of TWW for augmenting agricultural irrigation will help extend FW supplies to more demanding sectors in this region.

CRediT authorship contribution statement

Girisha Ganjegunte and **April Ulery** conceived the idea. **Girisha Ganjegunte** designed and implemented the experiment. **Vijayasatya N. Chaganti** collected and analyzed data, performed statistical analysis, and wrote the manuscript. **Genhua Niu** helped in identifying salt-tolerant cultivar of canola. All authors reviewed the manuscript and provided comments for improvement.

Declaration of Competing Interest

The authors declare that they have no known competing interests.

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