Agricultural Water Management 247 (2021) 106733

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Research paper

Irrigation with treated wastewater in humid regions: Effects on Nitisols, sugarcane yield and quality

Frédéric Feder[a,b,*,1]

[a] CIRAD, UPR Recyclage et Risque, F-34398 Montpellier, France
[b] Recyclage et Risque, Univ Montpellier, CIRAD, Montpellier, France

ARTICLE INFO

Handling Editor - Dr. Z. Xiying

Keywords:
Réunion
Reuse
Complementary irrigation

ABSTRACT

Treated wastewater (TWW) reuse for crop irrigation has been developing in recent decades in areas hampered by severe water shortages. However, in humid conditions, the agronomic impacts of supplementary irrigation are less and poorly documented. On the island of Réunion, we measured sugarcane yield and quality on a Nitisol over 2 years by providing 2600 mm of TWW or irrigation water (control) as a supplement to the 3500 mm rainfall. Meanwhile, with the same TWW, irrigation water (IW) and rainfall inputs, we monitored leachates and soil under controlled conditions without plants. Sugarcane yield, Brix degree, fiber and sucrose contents were similar between the TWW and control plots each year. The leachate pH and electrical conductivity at 60 cm depth showed marked differences between the TWW and control modalities. Similarly, after a constant increase in chloride, sulfate, potassium and sodium contents, or breakthrough curves for calcium and magnesium, the concentrations of these elements under the TWW modality were stable from 12 pore volumes (PV), except for calcium which was stable from 16 PV. At the end of the experiment, the hydraulic conductivity and organic carbon contents did not show any significant change, while the pH of soils that had received TWW and of the control soil was higher overall than the pH of the initial soil. The dynamics of the major elements in leachates at 65 cm depth were consistent with the input concentrations and the variations in exchangeable base contents in the soil at the end of the experiment. However, potassium and mineral nitrogen had accumulated in the soil profile while there were low concentrations in the leachate. The TWW quality and quantities provided, uptake by plants, competition for adsorption or leaching, and the pedoclimatic context, could therefore: (i) explain the absence of negative agronomic impact, and (ii) highlight the benefits of irrigation with TWW in humid environments to supplement water requirements and fertilize intensive crops.

1. Introduction

Irrigation and organic fertilizer spreading are millennial agricultural practices, contrary to wastewater reuse. The global urban population has been increasing and densifying for more than a hundred years, to the extent that it is now crucial to organize wastewater collection and treatment in sewage treatment plants before its release—mainly into the aquatic environment. Irrigation with treated wastewater (TWW) has long been limited due to the poor treatment efficiency to reduce the omnipresent microbiological risks (Toze, 2006; Pedrero et al., 2010), further aggravated by the TWW salinity and the presence of contaminants such as metallic and organic trace elements (El Moussaoui et al., 2019). In developing countries, irrigation with untreated or barely treated wastewater is sometimes a necessity to meet crop water and nutrient needs despite various risks of contamination (Qadir et al., 2010; Hodomihou et al., 2016). However, irrigation with TWW has been developing in recent decades with the improvement of physicochemical, biological and chemical treatment processes, with clearcut benefits: it is a complementary source of water that reduces pressure on other resources, especially groundwater; it is produced continuously throughout the year; it contains nutrients essential for crops, in turn generating economic benefits for farmers by reducing the need for fertilizers, such as organic waste (Wassenaar et al., 2014). Irrigation with TWW has a positive overall environmental impact, yet it is currently mainly being developed in arid or semiarid regions where water deficits are commonplace (Elgallal et al., 2016).

* Correspondence address: CIRAD, UPR Recyclage et Risque, F-34398 Montpellier, France.
E-mail address: frederic.feder@cirad.fr.
[1] https://orcid.org/0000-0001-8434-5193

https://doi.org/10.1016/j.agwat.2020.106733
Received 3 July 2020; Received in revised form 20 December 2020; Accepted 27 December 2020
0378-3774/

The positive and negative environmental impacts of irrigation with TWW depend on multiple factors, with the main ones being: the TWW quality, the type of soil and crop, the climatic conditions, and the TWW agronomic management modalities. Irrigation with TWW is mainly likely to modify the soil salinity levels (Mohammad and Mazahreh, 2003; Gloaguen et al., 2007; Ayoub et al., 2016; Libutti et al., 2018), pH (Gloaguen et al., 2007; Abegunrin et al., 2016; Ayoub et al., 2016), carbon content (Minhas et al., 2015; Abegunrin et al., 2016; El Moussaoui et al., 2019), hydraulic conductivity (Gloaguen et al., 2007; Bedbabis et al., 2014), exchangeable base contents (Rusan et al., 2007; Abegunrin et al., 2016; Libutti et al., 2018; Elfanssi et al., 2018) and contaminant input (Toze, 2006; Rusan et al., 2007; Singh et al., 2012; El Moussaoui et al., 2019). However, irrigation with TWW affects soils differently. Long-term changes in soil properties also depend on the intrinsic soil characteristics (texture, mineralogy, initial chemical composition, etc.). Tropical soils are particularly vulnerable because they have certain physical (sandy texture, etc.) and chemical (CEC and low carbon content, etc.) characteristics that irrigation with TWW could modify (IUSS working group, 2015). The sustainability of TWW irrigation could thus be assessed by combined monitoring of variations in soil properties and leachates (Gloaguen et al., 2007; Tarchouna et al., 2010). Yet soil solution sampling techniques are still imperfect, especially in the root zone.

Irrigation with TWW is increasingly being implemented in humid environments when annual rainfall is insufficient or very unequally distributed, particularly with regard to water-demanding non-food crops that are not very susceptible to salinity. Irrigation with TWW does not have an impact on crop yields in the short term compared to normal IW and equivalent fertilization (Disciglio et al., 2015; Gonçalves et al., 2017; Libutti et al., 2018; Elfanssi et al., 2018; Chaganti et al., 2020). Yields have been found to increase—sometimes significantly—when TWW irrigation provided additional nutrients and water compared to the control (Sebastian et al., 2009; Leal et al., 2010; Minhas et al., 2015; Elfanssi et al., 2018), whereas yields decrease when there are physical or chemical constraints (Libutti et al., 2018). But these issues can be partially overcome via TWW input management (Toze, 2006; Qadir et al., 2010; Elgallal et al., 2016). In humid environments, high rainfall or the possibility of irrigating crops with good quality water can curb some constraints, especially salinity (Toze, 2006; Qadir et al., 2010), even in the long term (Andrews et al., 2016). In highly arid conditions, irrigation may provide up to 90% of the water needs of sugarcane (*Saccharum* spp.), which makes it impossible to use TWW sustainably. Yet optimal sugarcane yields cannot be achieved without supplementary irrigation in humid tropical environments where rainfall ranges from 2000 to 3000 mm. Irrigation with TWW can therefore provide supplementary water as well as some (or even all) of the nutrients required during the growing season. Sugarcane irrigation with TWW has not been found to decrease yields (Leal et al., 2009), change the industrial characteristics (Braddock and Downs, 2001; Gonçalves et al., 2017), or impact germination and plant physiology (Sebastian et al., 2009). Nitrogen and phosphate leaching has been found to be low (Blum et al., 2013) with little change in soil quality. However, in these studies, the nutrient amounts applied and the volumes of irrigation or rainfall water were not equivalent; this limits the generalization of these results.

Studies on irrigation with TWW have thus mainly been focused on the different environmental risks, yield increases and production quality in arid and subarid environments. The sustainability and pluriannual agronomic impacts of complementary irrigation of sugarcane with TWW as a replacement for normal irrigation and fertilization on Nitisols have yet to be investigated. This study was aimed at assessing whether: (i) water and nutrient inputs via TWW could sustainably replace mineral fertilization associated with conventional irrigation without modifying sugarcane yield or quality, (ii) irrigation with TWW modifies the soil physical and chemical properties, and (iii) the soil solution reaches equilibrium with TWW. We therefore planted a sugarcane crop in an experimental plot and monitored it for 2 years. Meanwhile, we reproduced the same TWW, IW and rainwater inputs in soil columns in order to monitor the dynamics of water and solute fluxes over time, independently of the crop intake.

2. Materials and methods

2.1. Study site in Réunion and the treated wastewater

Réunion is a French island located 800 km east of Madagascar in the southern Indian Ocean region. The main peak of this recent volcanic island (Piton des Neiges, 3070 m ASL) emerged 3 million years ago. The study site in the CIRAD research station is located on the northern slope of Piton des Neiges at 60 m ASL (55°53E; 20°89S). Mean annual rainfall at the station is 2000 mm, with a mean annual temperature of 25 °C. Table 1 gives selected physical and chemical characteristics of the soil. It was classified as a Nitisol (Feder, 2013), including: (i) a surface A horizon (0–30 cm), and (ii) a nitic B horizon (30–150 cm). As defined by IUSS working group WRB (2015), Nitisols are deep, well-drained, red tropical soils with diffuse horizon boundaries and a subsurface horizon with at least 30% clay. A clayey nitic horizon has typical moderate to strong angular blocky structure breaking into polyhedral elements. The TWW used for the experiment was transported from the Saint-Paul sewage treatment plant. This TWW was obtained after primary treatment to remove solid material, a secondary treatment to digest dissolved and suspended organic material as well as nitrogen and phosphorus nutrients, and a tertiary treatment to reduce the pathogenic bacteria count. The average characteristics as well as IW are presented in Table 2. The sodium absorption ratio (SAR) of TWW and IW and the soil exchangeable sodium percentage (ESP) were calculated using the following formulae, where cation concentrations are expressed in mmol l^{-1}:

$$\mathrm{SAR} = \frac{[\mathrm{Na}^+]}{\sqrt{\frac{[\mathrm{Ca}^{2+}] + [\mathrm{Mg}^{2+}]}{2}}} \quad \text{and} \quad ESP = 100\frac{[\mathrm{Na}_{\mathrm{ex.}}]}{\mathrm{CEC}}$$

2.2. Field experiment

The experimental plot (Supporting Information, Feder, 2020) was 40 m long and 30 m wide (corresponding to 20 rows of sugarcane spaced 1.5 m apart). After plantation, eight blocks of 7.5 m (i.e. five rows of sugarcane) by 6 m in length were set up in the center of the plot. Each block was spaced at 5 m distance from the others in the width direction and 3 m distance in the length direction. Four blocks were irrigated with TWW and four control (C) blocks were irrigated with IW. The blocks of each modality were distributed alternately so as not to be side-by-side. Drip irrigation was used and each irrigation line was separate and connected to its own 5 m^3 tank equipped with a solenoid valve with volumetric measurement.

Two annual sugarcane crops were grown consecutively (2010–2012) with the R579 variety. For the two cumulative years, the TWW irrigation modality received 2600 mm of TWW and 3500 mm of rainwater (1900 mm during the first year and 1600 mm during the second year), while the control modality received 2600 mm of IW and 3500 mm of rainwater (Supporting Information, Feder, 2020). Under Reunion Island conditions, in order to achieve a yield of 80 T/ha, the requirements for sugar cane cultivation are, respectively for N, P and K, 200, 55 and 415 kg/ha; these values are similar to recommendations in other situations (Leal et al., 2009; Blum et al., 2013; Ghube et al., 2017). Several parameters (temperature, solar radiation, rainfall, plant cover, soil properties, etc.) influence the crop's water requirements. For Leal et al. (2009), and Braddock and Downs (2001), total crop water requirements are about 2500 mm. Considering the total Nitrogen with Kjedhal method (NTK), $P_{tot.}$ and K concentrations in the TWW (Table 2) and the cumulated volumes of TWW received (Supporting Information, Feder, 2020), the TWW modality received each year and per hectare the

Table 1
Physical and chemical characteristics of the studied soil; standard deviations are in brackets. AEC: anionic exchange capacity; ESP: exchangeable sodium percentage; CBD: citrate-bicarbonate-dithionite; ox.: oxalate.

		0–10 cm		20–30 cm		45–60 cm	
pH_w		6.25	(0.12)	6.16	(0.40)	6.31	(0.20)
pH_{KCl}		4.96	(0.09)	4.89	(0.35)	5.14	(0.12)
$C_{org.}$	g.100 g^{-1}	1.6	(0.17)	1.26	(0.20)	0.48	(0.12)
N total	g kg^{-1}	1.68	(0.11)	1.26	(0.19)	0.39	(0.10)
C/N		12.62	(0.22)	11.83	(0.39)	12.44	(0.87)
N-NO3	mg kg^{-1}	58.0	(1.31)	34.8	(1.22)	5.3	(0.45)
N-NH4	mg kg^{-1}	2.74	(0.91)	1.49	(0.38)	0.54	(0.36)
P_{O-D}	mg kg^{-1}	38.97	(11.83)	15.04	(3.90)	24.71	(17.77)
AEC	$cmol_{(c)}$ kg^{-1}	0.54	(0.1)	0.55	(0.1)	0.9	(0.1)
CEC	$cmol_{(c)}$ kg^{-1}	13.3	(0.41)	12.0	(1.22)	11.5	(1.70)
$Ca_{ex.}$	$cmol_{(c)}$ kg^{-1}	7.37	(0.19)	6.34	(0.88)	5.51	(1.26)
$Mg_{ex.}$	$cmol_{(c)}$ kg^{-1}	3.36	(0.13)	2.89	(0.50)	2.92	(0.87)
$K_{ex.}$	$cmol_{(c)}$ kg^{-1}	0.72	(0.18)	0.13	(0.07)	0.02	(0.01)
$Na_{ex.}$	$cmol_{(c)}$ kg^{-1}	0.14	(0.02)	0.39	(0.10)	0.63	(0.18)
ESP	%	1.05		3.25		5.48	
Clay	g.100 g^{-1}	55.73	(1.34)	56.97	(6.84)	48.93	(7.07)
Fine silts	g.100 g^{-1}	30.42	(0.44)	31.27	(4.45)	35.42	(2.61)
Coarse silts	g.100 g^{-1}	5.23	(0.65)	4.84	(0.71)	7.13	(2.87)
Fine sands	g.100 g^{-1}	3.76	(0.10)	3.79	(0.94)	5.60	(2.25)
Coarse sand	g.100 g^{-1}	4.87	(0.18)	3.14	(1.10)	2.92	(0.95)
Fe(CBD)	g kg^{-1}	76.69	(2.19)	79.03	(0.95)	76.33	(7.37)
Al(CBD)	g kg^{-1}	7.32	(0.19)	7.71	(0.27)	7.25	(0.71)
Si(CBD)	g kg^{-1}	4.52	(0.35)	4.40	(0.34)	4.60	(0.71)
Fe(ox.)	g kg^{-1}	8.21	(0.46)	7.88	(0.62)	6.97	(1.28)
Al(ox.)	g kg^{-1}	3.90	(0.17)	4.14	(0.12)	4.36	(0.22)
Si(ox.)	g kg^{-1}	1.40	(0.04)	1.36	(0.09)	1.49	(0.20)

Table 2
Mean chemical characteristics of the treated wastewater (TWW) and the irrigation water (IW); standard deviations are in brackets. SAR: sodium absorption ratio; EC: electrical conductivity; TSS: total suspended solids; TOC: total organic carbon; COD: chemical oxygen demand; BOD: biochemical oxygen demand.

		TWW		IW	
Cl^-	mg l^{-1}	453.89	(17.89)	4.57	(2.34)
SO_4^{2-}	mg l^{-1}	77.50	(2.41)	0.38	(0.14)
$P_{tot.}$	mg l^{-1}	1.1	(0.5)	0.06	(0.03)
Ca^{2+}	mg l^{-1}	14.23	(6.98)	7.58	(1.44)
Mg^{2+}	mg l^{-1}	25.22	(2.61)	11.54	(4.17)
Na^+	mg l^{-1}	20.03	(2.17)	1.11	(0.2)
K^+	mg l^{-1}	24.36	(2.71)	5.88	(2.18)
NH_4^+	mg l^{-1}	< 0.05		< 0.05	
NO_3^-	mg l^{-1}	7.76	(1.33)	1.90	(0.36)
NO_2^-	mg l^{-1}	0.11	(0.07)	< 0.025	
NTK	mg l^{-1}	4.77	(0.64)	0.18	(0.14)
HCO_3^-	mg l^{-1}	79.00	(4.2)		
pH		7.28	(0.18)	7.65	(0.34)
SAR	mmol l^{-1}	0.74		0.06	
EC	mS cm^{-1}	1.733	(0.043)	0.13	(0.005)
TSS	mg l^{-1}	2.00		< 2.0	
TOC	mg l^{-1} C	4.49	(0.36)	0.3250	(0.03)
COD	mg l^{-1} O_2	37.00	(5.66)	< 30.0	
BOD5	mg l^{-1} O_2	3.00		< 3.0	

following fertilization: 165 kg (N), 30 kg (P) and 315 kg (K); without any complementary fertilization. Each year, at the beginning of the cycle, the control modality received mineral fertilization equivalent to that provided by the TWW modality.

2.3. Soil column experiment

The device consisted of 8 PVC columns 100 cm high (60 cm of which were in the soil) and 20 cm diameter. The soil was reconstituted at the bulk density (BD) measured in the field (BD = 1.30) and in successive 10 cm layers corresponding to the layers sampled in situ. The outlet was protected with a geotextile at the base.

The total volume in each column was 18.84 dm^3. The pore volume ratio (PVR) was calculated for the column by the equation: PVR = 1 − BD/PD (dimensionless), with BD (kg dm^{-3}) corresponding to the bulk density measured in situ and PD (kg dm^{-3}) corresponding to the particle density (PD = 2.7 kg dm^{-3}) for this soil. Applied to the total volume, the calculated pore volume (PV) was then 9.77 dm^3 and corresponded also to 311 mm for the column.

Five columns received 2600 mm of TWW and 3500 mm of rainwater. Three control columns (C) received 2600 mm of IW and 3500 mm of rainwater. The total accumulated amounts of irrigation water (TWW or IR) or rainwater were therefore equivalent in the soil columns and in the field. During the experiments, in order to ensure that the distribution of these different inputs was similar in the two experiments and in order to get closer to the field experiment conditions, each input of ½ PV of TWW or IW was alternated with an input of ½ PV of rainwater. An additional ½ PV rainwater supply was conducted every 2 PV.

2.4. Soil, water and plant analysis

The initial soil analyses were performed on samples collected in situ from the 0–10, 20–30, and 45–60 cm layers. The final soil analyses (at the end of the study) were performed on samples collected in soil columns at the following depths: 0–10, 10–20, 20–30, 30–45, and 45–60 cm. The pH_w (water) and pH_{KCl} (KCl) of the initial and final soils were measured according to the NF ISO 10390 standard at a 1:5 soil/water (or KCl solution 1 M) volume ratio. Total carbon and total nitrogen of the soil samples were analyzed by dry combustion with an element analyser (Thermoquest NC2100 Soil). The content of mineral forms of nitrogen in the soil samples was measured in solution after KCl (1 M) extraction at a soil/water volume ratio of 1:5 (ammonium and nitrate were summed to calculate $N_{min.}$) and assayed by continuous flow colorimetry (Alliance Instruments). We measured the cation exchange capacity (CEC) by the ammonium acetate method at pH 7. The anionic exchange capacity (AEC) of the initial soil was measured on samples collected at 10–20 cm (surface horizon) and 45–60 cm (nitic horizon) depths using the method described by Gillman and Sumpter (1986). We used the recommended analytical procedures (IUSS Working Group WRB, 2015) to measure Al, Si and Fe elements extracted by dithionite-citrate-bicarbonate (DCB) and oxalate (Feder et al., 2018). Extractable Al, Si and Fe were assayed by inductively coupled plasma-atomic emission spectrometry (ICP-AES, Varian Vista spectrometer equipped with a coupled-charge detector device). All samples were analyzed for particle-size distribution analysis by the pipette method using an automated analyser (Texsol 24B instrument) and according to the standard procedure applied to all soils: samples were treated with H_2O_2 to remove organic matter, dispersed with a sodium hexametaphosphate solution, and mechanically shaken (Alary et al., 2013). Coarse sand and fine sand fractions were obtained by sieving; clay, fine silt and coarse silt fractions were obtained by pipetting. The mineralogy of this soil was similar for both horizons. Feder et al. (2015) reported the presence of four iron oxides (magnetite, hematite, maghemite, and goethite), titanium–iron oxides (ilmenite), aluminum oxyhydroxide (gibbsite) and silicates (halloysite, kaolinite, quartz and feldspath). Bulk densities were measured with three 100 cm^3 samples of undisturbed soil collected in the field at three different depths (IUSS Working Group WRB, 2015). The saturated hydraulic conductivity was measured in the field using a permeameter ring (0.4 m diameter) at the soil surface.

TWW were sampled each time the tank was filled. A mean IW sample was obtained by cumulation of 50-ml aliquots that were collected systematically during each irrigation period. The soil solution at the column outlet was cumulated after each input. TWW, IW and soil solution samples were filtered at 0.45 µm and divided into three aliquots. Immediately after sampling, the first untreated aliquot was used for the pH and electrical conductivity (EC) measurements. The pH was measured with an ISFET electrode (Senstron, Hot-line), whilst EC was measured with a standard conductivity cell (WTW, TetraCon 325), and the temperature was adjusted to 25 °C. The two other aliquots were maintained at 4 °C. The second aliquot was acidified with HNO_3 (suprapure) in preparation for assaying the main elements (Ca, Mg, K, Na, $P_{tot.}$) by ICP-AES spectrometry (Varian Vista). The third aliquot was used to quantify chloride, sulfate, nitrate, nitrite and ammonium by continuous flux colorimetry (Alliance Instruments). The total nitrogen content (NTK) of TWW was determined using the Kjeldahl method with a digestion unit B-435 and a distillation unit B324 (Büchi Labortechnik AG, Switzerland). Total organic carbon (TOC) was analyzed using a Shimadzu (Model TOC 5000A) spectrometer. Chemical oxygen demand (COD) and biochemical oxygen demand (BOD) were determined according to standard methods (APHA, 1998). TSS was determined after filtration of the water samples through 0.45 µm pore-size (47 mm dia.) nitrocellulose membranes (Whatman, Maidstone UK) using a vacuum system.

During harvesting, for each block, several sugarcane samples were taken and crushed in a cutting mill. The samples were then pressed in a hydraulic press to extract the juice and the residual content of fibers were weighed. The pressed juice was filtered. The industrial analysis for the juice soluble solids content was measured with a refractometer to determine the degrees Brix (one degree Brix corresponded to 1 g of sucrose in 100 g of solution). The apparent sucrose of the juice (sometimes called Pol) was measured with an automatic saccharimeter (ADS 400).

2.5. Statistical analysis

Origin 2018 (version b9.5.0.193) software was used for the descriptive statistics and to draw box and whisker plots. For each analytical parameter, the mean, median and standard deviation of the measurements were calculated and the Student *t*-test was performed at the 95% confidence level for comparison of means. When the normality was not confirmed, the factors were tested using non-parametric methods, such as the Kruskal–Wallis test.

3. Results

3.1. Effect of wastewater irrigation on sugarcane yield and quality

Sugarcane yields were similar between the TWW and the control plots in the first and second years. The average yield in the four TWW plots was 85 Mg ha^{-1}, with peak yields of 80 and 97 Mg ha^{-1} during the first year of sugarcane cultivation (Fig. 1). The average yield in the four control plots was 88 Mg ha^{-1}, with peak yields of 80 and 94 Mg ha^{-1}. The average yield in the four TWW plots was 109 Mg ha^{-1}, with peak yields of 98 and 117 Mg ha^{-1} during the second year of sugarcane cultivation. The average yield in the four control plots was 114 Mg ha^{-1}, with peak yields of 108 and 120 Mg ha^{-1}. The yield dispersion of the four replicates was always higher for the TWW plots compared to the control plots, but the yield differences were not significant for each year. The first year of sugarcane cultivation showed lower average yields than the second year. In both years, nutrient inputs from TWW or mineral fertilization, irrigation, rainfall and crop duration were similar, but yields in the TWW and control plots increased by 23 and 26 Mg ha^{-1}, respectively, between the first and second year.

The main sugarcane industrial characteristics were similar between the TWW and the control plots in the first and second years. Brix degrees measured postharvest in sugarcane juice were statistically identical when comparing sugarcane from the TWW and control plots for the first and second year (Table 3). Nevertheless, Brix degrees measured at harvest in the second year were significantly lower than in the first year for sugarcane from the TWW and control plots. Sugarcane fiber contents were statistically similar when comparing sugarcane from the TWW and control plots in the first and second years. However, fiber contents were statistically higher in the first year than in the second year for sugarcane from each of the TWW and control plots. Sugarcane sucrose concentrations were statistically similar when comparing sugarcane from the TWW and control plots and between the first and second year. The Brix degree, corresponding to the total sugar, was always higher than the sugarcane sucrose concentration for each year and for each modality. The Brix degree was 23% higher than the sucrose concentration for the TWW and control plots in the first year, but the Brix degree was 21% higher than the sucrose concentration for the TWW modality and 28% higher than the sucrose concentration for the control modality in the second year.

3.2. Solute transfers in soil

At first, we checked whether the experimental setup could closely reproduce flows that occur in the field by measuring the hydraulic conductivity on the column surfaces for each irrigation. These measures ranged from 8.5 10^{-7} m s^{-1} to 1.4 10^{-6} m s^{-1} during the experiment for

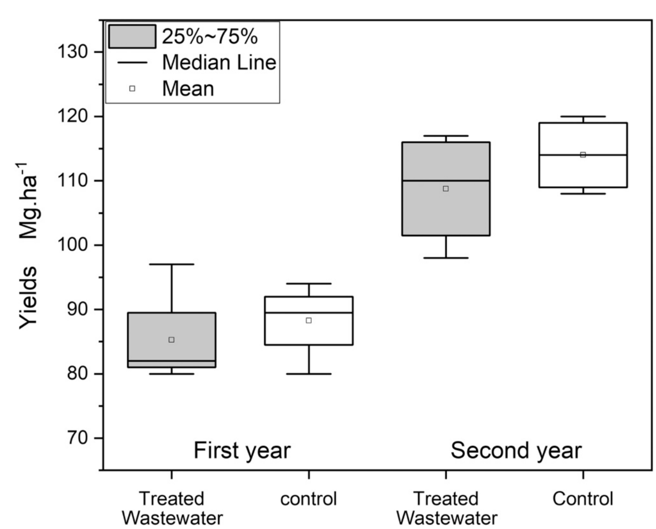

Fig. 1. Box and whisker plot showing, for the 4 blocks, the maximum, minimum, mean, median and quartile yield values (Mg ha^{-1}) for sugarcane crops irrigated with treated wastewater (TWW) or with irrigation water (control) for the first and the second year of the study.

Table 3
Average Brix degree, fiber content and sucrose richness values (four repetitions) in average sugarcane samples for the control (C) modality and the TWW supply modality; standard deviations are in brackets. For each parameter, different letters indicate significant differences ($P < 0.05$).

Sugarcane parameters	Units	First year				Second year			
		Control		Treated waste water		Control		Treated waste water	
Brix	$g.100\ g^{-1}$	21.4	(0.32)[a]	21.7	(0.71)[a]	20.5	(0.75)[b]	20.8	(0.4)[b]
Fiber	$g.100\ g^{-1}$	10.97	(0.03)[c]	11.02	(0.31)[c]	10.2	(0.52)[d]	10.76	(0.49)[d]
Sucrose	$g.100\ g^{-1}$	17.35	(0.35)[e]	17.51	(0.74)[e]	16.02	(0.94)[e]	17.16	(0.54)[e]

all the columns and were in line with the saturated hydraulic conductivity measured in situ with a permeameter ring at saturation: 2.3 10^{-6} m s^{-1}. The column hydraulic properties were similar and close to those of in situ soil. The soil columns could thus accurately replicate the hydrodynamic behavior of in situ soil.

From 4 pore volumes (PV), the electrical conductivity of the leachate at the column outlet was constant and always lower than the average electrical conductivity of the input water (Fig. 2). The average electrical conductivity of the TWW input to the TWW columns was 1.733 mS cm^{-1}. At the TWW column outlets, the leachate electrical conductivity increased linearly from 2 PV and to 4 PV. Then, from 4 PV, the leachate electrical conductivity levelled off at 0.898 mS cm^{-1} (range 4–20 PV). The electrical conductivity of the IW supplied to the control columns was on average 0.130 mS cm^{-1}. At the control column outlets, the leachate electrical conductivity was always constant and averaged 0.07 mS cm^{-1} throughout the experiment. From 3 PV upwards, the electrical conductivity of leachates from the TWW and control columns was always significantly different.

From 3 PV upwards, the leachate pH at the TWW column outlets was always significantly lower than that of the control columns (Fig. 2). The pH of the TWW supplied to the TWW columns averaged 7.28 during the experiment (Table 2). At the TWW column outlets, the leachate pH decreased and then, starting at 3 PV, levelled off between 6 and 6.3. The pH of the IW supplied to the control columns averaged 7.65 during the experiment (Table 2). At the control column outlets, the leachate pH was always constant between 6.4 and 6.7. From 3 PV to the end of the experiment, the pH of the TWW and control columns was always significantly different by about 0.5 units.

From 12 PV upwards, the leachate chloride and sulfate concentrations at the TWW column outlets were similar to the input concentrations, in contrast to the nitrate and phosphate concentrations. All concentrations of chemicals in solution were related to their measured TWW concentration (Fig. 3); a ratio of 1 thus means that the concentration at the outlet was similar to the average supplied TWW concentration. The breakthrough curve for chlorides in the leachate at the TWW outlet showed an almost linear increase between 2 and 6 PV, then reaching a maximum ratio of 1.4 between 6 and 8 PV. Then the ratio was between 0.75 and 0.9 from 12 PV to 20 PV. In addition, the breakthrough curve plotted for the leachate chloride concentrations at the control column outlet showed very little variation, with a ratio of 0.09–3 PV and then the ratio was always below 0.03 from 5 PV upwards. The breakthrough curve for leachate sulfates at the TWW column outlets showed a quasi-linear increase between 4 and 10 PV up to a maximum ratio of 0.87; then this ratio was between 0.87 and 0.74 up to 20 PV. In addition, throughout the experiment, leachate sulfate concentrations at the control column outlet were constant and the ratio ranged from 0.08 to 0.1. On the other hand, leachate nitrate concentrations at the column outlet were always low for the TWW and control columns, with a ratio of less than 0.2 and without significant differences. Phosphate concentrations always had a ratio of less than 0.02, with no significant differences between the TWW and control columns.

The maxima of the leachate calcium and magnesium concentrations at the TWW column outlets showed ratios close to 9 and 3, respectively, on the breakthrough curve before becoming identical to the input concentrations. The leachate calcium concentration at the TWW outlet showed an almost linear increase from 2 to 5 PV on the breakthrough curve and then reached a maximum ratio of 8.95 at 8 PV. The ratio then gradually decreased and from 17 PV onwards, while ranging from 0.8 to 1. Furthermore, throughout the experiment, the leachate calcium concentrations at the control column outlet were constant and the ratio ranged from 0.45 to 0.88. The leachate magnesium concentration at the outlet of the TWW columns showed a quasi-linear increase between 2 and 6 PV on the breakthrough curve, then reaching a maximum ratio of 2.86 at 6 PV. The ratio then gradually decreased, and was between 0.69 and 0.9 from 13 PV onwards. Furthermore, throughout the experiment, the magnesium concentrations at the control column outlet were constant and the ratio was between 0.18 and 0.35.

Sodium and potassium leachate concentrations at the outlet of the TWW columns showed the same dynamics but with different maximum ratios. For the leachate sodium concentrations at the TWW outlet,

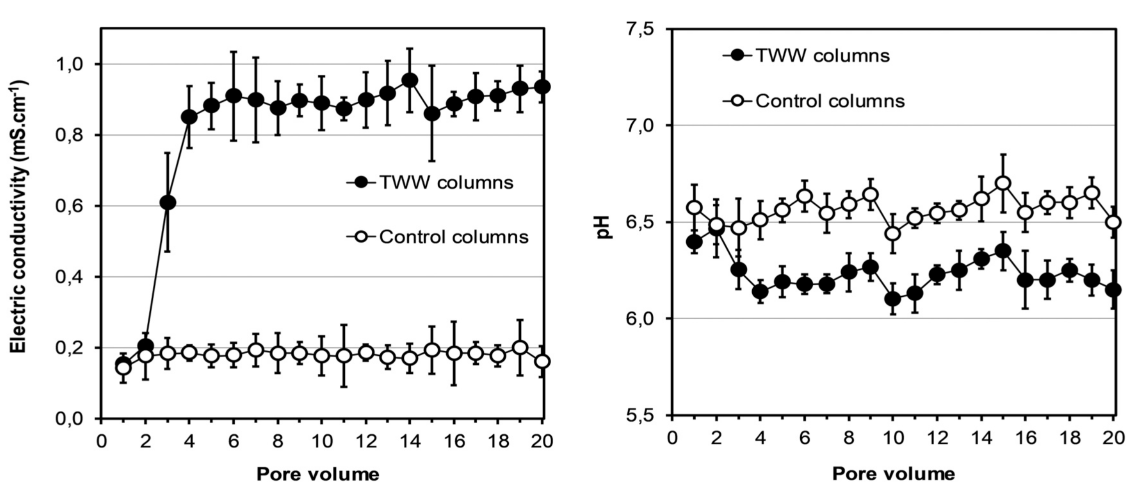

Fig. 2. Leachate electric conductivity and pH at the treated wastewater (TWW) and control (C) column outlets during the experiment. Error bars correspond to repetitions of the five TWW columns or the three control columns.

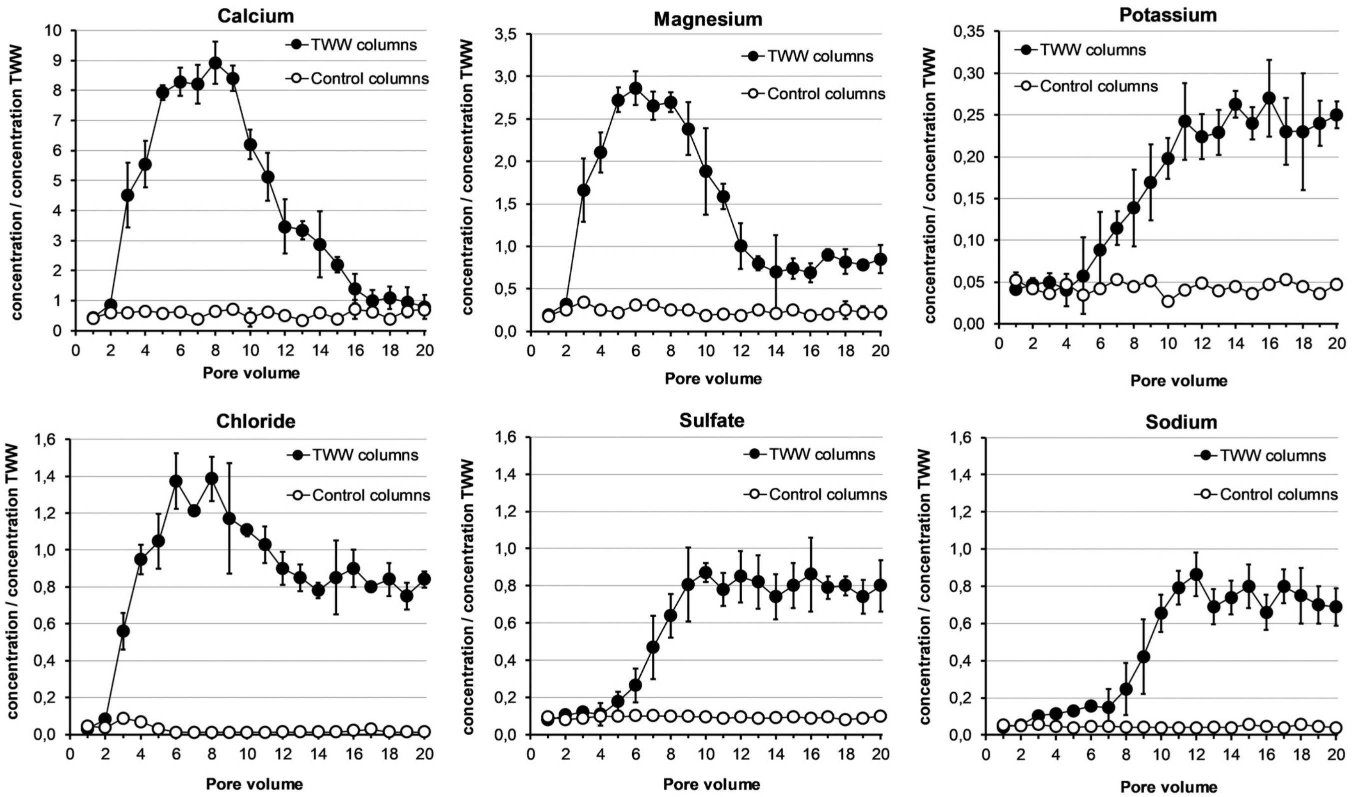

Fig. 3. Leachate anion (chloride and sulfate) and cation (calcium, magnesium, potassium and sodium) concentrations relative to their concentration in treated wastewater (TWW) at the treated wastewater and control (C) column outlets during the experiment. Error bars correspond to repetitions of the five TWW columns or the three C columns.

initially the ratio increased slowly and linearly between 2 and 7 PV and reached a ratio of 0.15. Then, in a second step, the ratio increased linearly from 8 PV to 14 PV and peaked at 0.86 at 12 PV. Then the ratio was between 0.66 and 0.8 from 13 PV to 20 PV. In addition, throughout the experiment, the sodium concentrations in the leachate at the control column outlet were constant and the ratio ranged from 0.04 to 0.06. Otherwise, leachate potassium concentrations at the outlet of the TWW columns reached a maximum ratio of 0.22–0.27 from 11 PV until the end of the experiment. Between 11 and 20 PV, this ratio did not show an increasing trend. Moreover, throughout the experiment, potassium concentrations at the control column outlets were constant and the ratio was between 0.03 and 0.05.

3.3. Exchangeable cations, extractable nitrogen, organic carbon and pH in the soil at the end of the experiment

Exchangeable calcium and sodium concentrations varied substantially when comparing the initial and final soils of the TWW and control

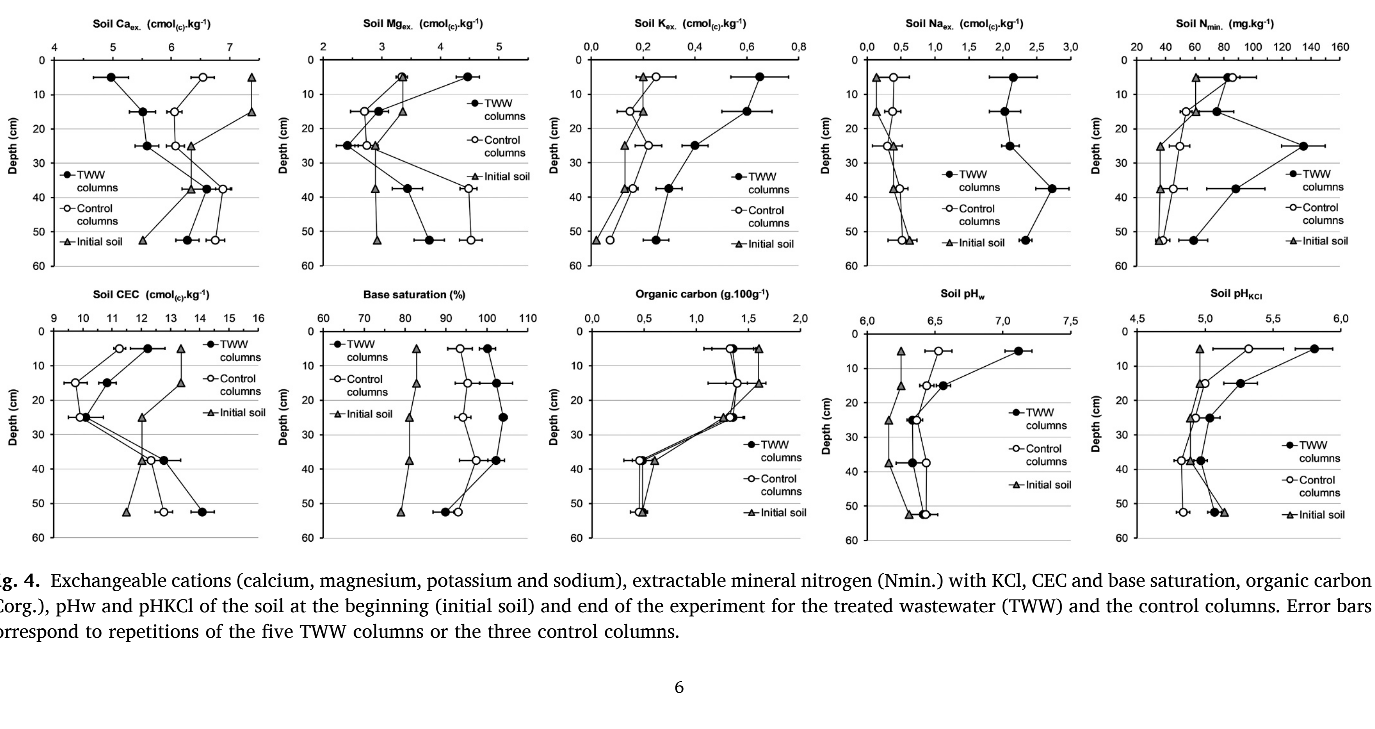

Fig. 4. Exchangeable cations (calcium, magnesium, potassium and sodium), extractable mineral nitrogen (Nmin.) with KCl, CEC and base saturation, organic carbon (Corg.), pHw and pHKCl of the soil at the beginning (initial soil) and end of the experiment for the treated wastewater (TWW) and the control columns. Error bars correspond to repetitions of the five TWW columns or the three control columns.

columns. Exchangeable calcium decreased from 2.4 to 0.9 $cmol_{(c)}$ kg^{-1} in the surface horizon (0–20 cm depth), between the initial and final soils of the TWW and control columns, respectively (Fig. 4). On the other hand, it increased from 0.8 to 1.3 $cmol_{(c)}$ kg^{-1} in the deep horizon (40–60 cm depth), between the initial and final soils of the TWW and control columns, respectively. Exchangeable magnesium increased by 1.1 $cmol_{(c)}$ kg^{-1} in the surface horizon (0–10 cm depth) when comparing the initial and final soils of the TWW columns. However, there was no change in the control columns at this depth. In the deep horizons (35–60 cm depth), the exchangeable magnesium increased by 0.9 and 1.6 $cmol_{(c)}$ kg^{-1} between the initial and final soils of the TWW and control columns, respectively. Exchangeable potassium increased from 0.2 to 0.65 $cmol_{(c)}.kg^{-1}$ in the surface horizon (0–20 cm depth), between the initial and final soils in the TWW columns, while it remained unchanged in the control columns. Similarly, it increased by about 0.2 $cmol_{(c)}$ kg^{-1} in the lower horizon (25–60 cm depth) of the TWW columns. Exchangeable sodium increased from 1.7 to 2.2 $cmol_{(c)}$ kg^{-1} throughout the entire column depth (0–60 cm) when comparing the initial and final soils of the TWW columns. In contrast, there was no change in exchangeable sodium concentration between the initial and final soils in the control columns throughout the full column depth (0–60 cm). The mineral nitrogen—corresponding to the sum of ammonium and nitrate extractable at 1 M KCl—increased from 60 mg kg^{-1} to nearly 80 mg kg^{-1} in the surface horizon (0–20 cm depth) between the initial and final soils in the TWW columns. A similar increase was observed in the surface layer (0–10 cm depth) between the initial and final soils of the control columns. The mineral nitrogen concentration was not modified between the initial and final soils in the control columns between 10 and 60 cm column depth. In contrast, the mineral nitrogen concentration increased significantly between the initial and final soil in the TWW columns from 36 to 135 mg kg^{-1} (20–30 cm), 88 mg kg^{-1} (30–40 cm) and 59 mg kg^{-1} (40–60 cm), respectively. The total CEC followed the same dynamics as the exchangeable calcium concentration. For the surface horizon (0–30 cm depth), CEC decreased by 1–2 $cmol_{(c)}$ kg^{-1} between the initial and final soils in the TWW and control columns, respectively. On the other hand, for the deep horizon (40–60 cm depth), the total CEC increased from 1.2 to 2.5 $cmol_{(c)}$ kg^{-1} between the initial and final soils of the control and TWW columns, respectively. The base saturation rate increased from 5% to 20% throughout the entire column depth (0–60 cm) when comparing the initial and final soils of the TWW and control columns. The increase was always more marked for the final soil of the TWW columns, except for the 50–60 cm depth horizon.

Average organic carbon concentrations did not show significant changes. They decreased by 0.25 g.100 g^{-1} in the surface horizon from 0 to 20 cm depth between the initial and final soils of the TWW and control columns, but not significantly. However, organic carbon concentrations in soils from the TWW and control columns were similar to the initial soil concentrations for the 20–60 cm depth horizons. In addition, for all depths, organic carbon concentrations between the final soil in the TWW and control columns were highly reproducible.

The pH_w and pH_{KCl} of the soils in the TWW and control columns were generally higher than the pH of the initial soil. At the end of the experiment, for all depths, the pH_w of the TWW and control column soils was higher than the pH_w of the original soil by 0.1–0.9 pH units, respectively. The differences in pH_w were most marked for the 0–10 cm layer and gradually decreased for the other depths from 0.1 to 0.4 pH units. At the end of the experiment, the pH_w of the soils in the TWW and control columns was similar for the 20–60 cm depth horizons and was 0.2 pH units higher than in the initial soil.

4. Discussion

4.1. Impact of treated wastewater on sugarcane yield and quality

Sugarcane yields were similar between the TWW and control plots in the first and second year of this study. The nutrients supplied by TWW therefore generated the same yield as obtained with equivalent mineral fertilization in two consecutive years, with equal rainfall and total water supply in the TWW or IW plots. Conversely, Gonçalves et al. (2017) do not observe an increase in sugarcane yield despite the additional nutrient supply by irrigation with TWW compared to the control modality. However, their study was only carried out during one sugarcane crop cycle, which hinders observation of any beneficial effects of the nutrient supply over several cycles. However, with normal IW, sugarcane usually responds well to organic fertilization during the current crop cycle. Yields increase when nitrogen is supplied in mineral form or if it mineralizes quickly (Sebastian et al., 2009; Umesh et al., 2013). Yet Leal et al. (2010) observed an increase in sugarcane yield, which they attribute to the increase in the amount of water supplied with TWW with equal fertilization, as their control modality was not irrigated. But the aim of their study was not to evaluate the effects of short-term TWW irrigation on yield but rather on nitrogen uptake by sugarcane, nitrogen and carbon accumulation in soil and nitrate leaching. In addition, sugarcane yields in the first year of cultivation were always lower in subsequent years due to the need for new root systems to develop (Leal et al., 2010; Gonçalves et al., 2017). Similarly, Braddock and Downs (2001) found a 45% increase in yield when irrigating with TWW but their findings were compared to a non-irrigated modality. These apparent contradictory results for sugarcane are not strictly comparable since the conditions were not identical, especially with regard to fertilization and irrigation management. Moreover, the differences could be attributed to indirect effects of irrigation with TWW on yields, especially when the TWW is too saline or when the soils are sodic (Nelson and Ham, 2000). These depreciation effects are not always observed or measured or are hard to quantify. Finally, in our study, there were two minor differences between the TWW and control modalities despite the identical nutrient intakes in both years. First, sugarcane mineral fertilization was applied during the first month of the crop for the control modality, whereas fertilizers were applied during the plant cycle for 12 months under the TWW modality. This practice is poorly documented, probably because the effects are minor. A main reason is the similarity with the conventional organic fertilization (Piouceau et al., 2020) with solid (sewage sludge, manure, litter, etc.) or liquid products (methanation digestates, slurries, etc.). Secondly, as already observed during fertilization with pig slurry (Feder et al., 2015; Piouceau et al., 2020), a fraction of the nitrogen provided by TWW is organic, thus not assimilable by sugarcane in this chemical form. These forms of nitrogen must therefore be mineralized into bioavailable chemical forms. Finally, since fertilization and irrigation conditions (including rainfall) were similar during the two years of our study, we can attribute the increase in yields between the two years to climatological differences (higher average temperatures and longer and more intense sunshine) as well as to a better installation of the sugarcane root system.

In our study, the rainfall level was 1900 mm during the first year and 1600 mm during the second year, while TWW or IW provided 1300 mm during the first and second year. Complementary irrigation with TWW or IW thus represented 40% and 45% of the total water input (rainfall and irrigation) in the first and second years, respectively. This percentage of complementary irrigation is much lower in more arid situations with two- to tenfold lower rainfall (Gloaguen et al., 2010; Ayoub et al., 2016). Paudel et al. (2018) demonstrated the benefits of alternating TWW inputs with better quality water to limit negative impacts on the soil and improve yields in lemon orchards. Moreover, the hydrodynamic and geochemical properties of Nitisols reduced the negative impact of TWW due to the high clay content (56% in the surface horizon), unlike many other tropical sugarcane soils such as Oxisols (Sebastian et al., 2009; Gloaguen et al., 2010) which have a sandy texture.

For other types of crops, with identical mineral fertilization conditions, the impact of irrigation with TWW on crop yields compared to normal IW has not been observed in the short term. Irrigation with TWW has been reported to significantly increase *Eucalyptus tereticornis* Sm. biomass production after 10 years (Minhas et al., 2015). Similarly, the fresh weight of alfalfa increased significantly when supplementary fertilization was provided via untreated wastewater, whereas it did not increase with TWW (Elfanssi et al., 2018). In contrast, after 2 years, irrigation with TWW did not significantly increase yields of sorghum (Chaganti et al., 2020), nor of wheat, gram, palak, methi and berseem (Singh et al., 2012). Similarly, irrigation with TWW did not significantly increase tomato yields (Disciglio et al., 2015; Libutti et al., 2018), while it even significantly decreased broccoli yields in two cycles (Libutti et al., 2018). Irrigation of olive trees with TWW did not significantly increase the quantity of olives per tree on a silty-clay soil in northern Jordan, with average annual rainfall of about 275 mm (Ayoub et al., 2016), nor on a sandy-clay-loam soil in Greece, with average annual rainfall of about 750 mm (Bourazanis et al., 2016). In contrast, on sandy soil in central-eastern Tunisia with annual rainfall of about 140–200 mm, Bedbabis et al. (2010) measured higher quantities of olives per tree following irrigation with TWW rather than IW without supplementary fertilization. Chloride concentrations in TWW are high (454 mg l^{-1}) but similar to those measured in other studies. For example, Chaganti et al. (2020) measured chloride concentrations in TWW of 221 mg l^{-1}, El Moussaoui et al. (2019) measured 504 mg l^{-1} for raw wastewater and between 241 and 316 mg l^{-1} for TWW, and Paudel et al. (2018) measured concentrations over several years of 280–343 mg l^{-1}. In all these studies, no toxic effects directly related to these high chloride concentrations were observed on crops.

The main industrial characteristics of sugarcane were similar when we compared sugarcane from the TWW and control plots for the first and second year. However, the Brix degree and fiber content were higher in the second year than in the first year, contrary to the sucrose concentration. As with yields, some industrial characteristics of sugarcane may differ between the first year of cultivation and subsequent years due to new root system development, even under similar irrigation, fertilization and climatic conditions (Leal et al., 2010). Gonçalves et al. (2017) compared the industrial characteristics of sugarcane without irrigation and with two types of irrigation with TWW during a second ratoon. They did not observe any significant differences in Brix degree, yet the fiber content was lower and the sucrose concentration higher for the non-irrigated modality. Braddock and Downs (2001) noted a 12% increase in sucrose concentration when irrigating sugarcane crops with TWW compared to a non-irrigated modality. With normal IW, the industrial characteristics of sugarcane were found to not change under different mineral fertilization conditions, unlike yields (Bokhtiar and Sakurai, 2005; Oliveira et al., 2018), except when additional organic fertilization was applied (Bokhtiar and Sakurai, 2005; Umesh et al., 2013; Ghube et al., 2017).

Irrigation and fertilization do not increase the sugar content of crops, but they increase yields and therefore the amount of sugar per hectare. Sucrose concentrations are measured for other crops, in particular sugarbeet or sweet sorghum. Sugarbeet and sweet sorghum yields were reported to decrease with the IW quality (i.e. higher electrical conductivity) while the Brix degree and sucrose concentrations (Almodares and Sharif, 2007) and all water-soluble carbohydrate concentrations (Chaganti et al., 2020) remained unchanged. On the other hand, alfalfa (*Medicago sativa* L.) accumulated twice as much sugar when irrigated with raw wastewater than with TWW or well water (Elfanssi et al., 2018).

4.2. Changes in soil organic carbon content and soil pH

After irrigation with TWW, soil organic carbon contents vary and depend mainly on the doses applied and the soil-climate conditions. In our study, at the end of the experiment, for the surface layer (0–20 cm depth), we measured a non-significant decrease of 0.25 g.100 g^{-1} in organic carbon content comparatively to the initial soil of TWW and control modalities. Moreover, at the end of the experiment, the TWW and control soils had similar organic carbon contents at all depths. In experiments lasting less than 4 years, many authors have not measured significant changes in organic carbon content when comparing irrigation with TWW and a control modality for sugarcane (Leal et al., 2010), vegetable (Abegunrin et al., 2016; Libutti et al., 2018) and olive (Ayoub et al., 2016) crops. However, Polglase et al. (1995), Gloaguen et al. (2007) and Tarchouna et al. (2010) measured decreases in organic carbon content after irrigation with TWW in forest plantations under semiarid climatic conditions, annual crop fields under humid tropical climatic conditions and in a peach orchard under Mediterranean climatic conditions, respectively. Yet other studies have shown increases in soil organic carbon contents after irrigation with TWW in annual and market gardening crop plots (Singh et al., 2012; Lal et al., 2015), olive orchards (Bedbabis et al., 2014) and fodder crop fields (Elfanssi et al., 2018; El Moussaoui et al., 2019). The inconsistency in long-term wastewater irrigation impacts on soil organic matter has been reported in other studies. Indeed, after 10 years, Minhas et al. (2015) measured increases in organic carbon contents in surface layers receiving TWW compared to normal IW in a *Eucalyptus* plantation. Whereas, after 27 and 48 years, Andrews et al. (2016) did not note any changes when comparing an irrigated modality with TWW and a non-irrigated modality in annual crop fields, grasslands and forests under wet climatic conditions (1000 mm annual precipitation). These a priori contradictory results could be explained by: (i) the nature of organic matter in TWW and its mineralization rate in soils, (ii) the activity of microorganisms that increase with TWW inputs of labile carbon and nitrogen and under favorable soil moisture conditions, (iii) the contrasting climatic conditions and (iv) the soils properties. Indeed, nitisols from Reunion Island have high Corg concentrations that TWW inputs cannot modify in the short term.

Irrigation with TWW increases or decreases the soil and leachate pH depending on the dominant processes that consume or release protons, the duration of irrigation with TWW and its chemical composition. Some studies have revealed minor decreases in soil pH or no significant increase after irrigation with TWW (Mohammad and Mazahreh, 2003; Rusan et al., 2007; Duan et al. 2010; Singh et al., 2012; Ayoub et al., 2016; El Moussaoui et al., 2019; Elfanssi et al., 2018). The short monitoring time, the sandy texture of the soils and the contribution of TWW with very high dissolved organic carbon and total nitrogen contents have frequently been noted. The main processes identified in these studies that decrease soil pH are oxidation of organic compounds and ammonium nitrification. On the contrary, most studies have shown an increase in soil pH under multiple climate, soil and crop conditions (Tarchouna et al., 2010; Andrews et al., 2016; Abegunrin et al., 2016; Libutti et al., 2018). The main reasons identified are: (i) the increase in base cations (mainly calcium, and magnesium) and thus in the alkaline reserve of the soil, (ii) processes that consume protons, or produce hydroxyl ions, such as denitrification, decarboxylation and deamination (organic anions and amino acids), nitrogen mineralization.

4.3. Effect on electrical conductivity, CEC and exchangeable elements

The TWW used in our study was of good quality for irrigation, and the risk of soil salinization and sodisation was low. The electrical conductivity of the leachate at the outlet of columns irrigated with TWW was constant after 4 PV and consistent with the values of the TWW and rainwater supplied at the column inlets. The risk of salinization or alkalinization was low with this TWW since the SAR was less than 1 mmol l^{-1} and the average electrical conductivity was less than 1.75 mS cm^{-1}. These values were five- to tenfold lower than many TWW (Pedrero et al., 2010; Qadir et al., 2010; Ayoub et al., 2016; Libutti et al., 2018; Paudel et al., 2018; Chaganti et al., 2020). At the outlet of the columns receiving TWW, the sodium concentrations were very similar to those at the column inlets. Leal et al. (2009) also measured sodium concentrations in soil solution at different depths that were similar to the TWW concentrations applied and on average fivefold lower on their control plots. After a single crop cycle, Sebastian et al. (2009) and Gonçalves et al. (2017) reported better sugarcane yields with irrigation with TWW and a SAR of 6.9 and 5 mmol l^{-1}, respectively. Leal et al. (2009) observed identical yields with irrigation with TWW and a SAR of 10.3 mmol l^{-1}. Nelson and Ham (2000) measured decreases in sugarcane yields irrigated for several years with groundwater and a SAR of 1.1 mmol l^{-1} and electrical conductivity of 0.28 mS cm^{-1}. However, these yield decreases were correlated with the previously existing soil salinity and particularly with the ESP, and not directly with the IW. A 1% increase in ESP led to a 2.1 Mg ha^{-1} decrease in sugarcane yield (Nelson and Ham, 2000) because soil salinity upset the osmotic balance and the movement of water through plants. In our study, the mean ESP in the soil profile (21.1%) after TWW input was significantly higher than that of the control (4.1%) and initial (3.3%) soils. Leal et al. (2009) measured similar ESP of 18.93% and 5.93%, respectively, for their TWW and control modality at the end of an experiment on an Oxisol. In sandy soils, Tarchouna et al. (2010) also measured a significant increase in ESP up to 42%, but with very high temporal variability related to rainfall and during two dry years where the cumulative rainfall was 600 mm. Paudel et al. (2018) also measured a 2.8–5.9% increase in ESP in irrigated soil after TWW input. Ayoub et al. (2016) measured a significant increase in ESP in the surface horizon of soils receiving TWW (7.6%) and in the subsurface horizon (8.85%) compared to non-irrigated soils (2.1% surface and 2.7% subsurface) and soils irrigated with groundwater (3.7% surface and 4.2% subsurface), between the first and second year of their study. Libutti et al. (2018) measured an increase in exchangeable sodium after the first year of tomato cultivation, but not in subsequent years and with different crops. Elfanssi et al. (2018) measured a significant increase in exchangeable sodium after irrigation with untreated raw water (1.23 $cmol_{(c)}$ kg^{-1}) or TWW (0.32 $cmol_{(c)}$ kg^{-1}) compared to good quality water (0.1 $cmol_{(c)}$ kg^{-1}). The increase in ESP and sodium concentrations in soil solution thus depend on the SAR of the supplied TWW or IW, the evaporation/precipitation balance, and the adsorption/desorption processes. Many tropical soils have a low organic matter content and sandy texture (Diallo et al., 2019), so they have low CEC and are highly sensitive to increases in soil salinization and sodification. We did not observe any negative effects of TWW inputs on the sodium content in the soil or soil solution or on the hydraulic conductivity during our experiment; this could be explained by the TWW quality and the alternation of TWW inputs and rainfalls. In addition, the bivalent cations Calcium and Magnesium initially represent nearly 80% of the total CEC of the nitisols in the study. This helps to reduce the potential negative impacts of monovalent cation inputs, including sodium. Paudel et al. (2018) also observed positive short-term effects (a few months to 2 years) of alternating irrigation with TWW and with good quality water and these authors highlighted the benefits of this irrigation management strategy.

The variations in mineral nitrogen (nitrate + ammonium) in solution observed at the column outlets and in the soil at the end of the experiment were consistent with the input concentrations. Tropical soils frequently have an anion exchange capacity that reduces the transfer of nitrates and accumulates them in the soil (Feder et al., 2020). The Nitisols present in this study contained positively charged mineral phases and poorly crystallized phases extractable with oxalate. Hence, between 15 and 50 cm depth, mineral nitrogen extracted with molar KCl accumulated significantly in the TWW columns. Nitrate and ammonium solution concentrations at the outlet were negligible. At 1 m depth, Blum et al. (2013) measured $N_{min.}$ concentrations in solution of 9.3 mg l^{-1} after TWW ($N_{min.}$ = 21 mg l^{-1}) and 6.7 mg l^{-1} without irrigation in an Oxisol cropped with sugarcane. After applying liquid manure on a Nitisol, Feder et al. (2015) measured fivefold lower nitrate concentrations at the maximum of the breakthrough curve at 85 cm depth than input concentrations. Similarly, Duan et al. (2010) measured a significant decrease in nitrate concentrations in soil solution between the beginning and end of their experiment (3 and 0.5 mg kg^{-1} soil, respectively) averaged over the soil profile after a few irrigations with 1000 mm TWW ($N_{min.}$ = 12 mg l^{-1}) over a 1 year period. This confirmed that nitrate and ammonium ions systematically decrease in soil solution because they are taken up by the crop or are adsorbed. Libutti et al. (2018) measured a punctual increase in soil mineral nitrogen in the first year of a tomato crop cycle after TWW irrigation but no significant differences in subsequent years and different crops. Lal et al. (2015) measured a significant increase in soil mineral nitrogen after 8 years of TWW irrigation ($N_{min.}$ = 12.8 mg l^{-1}) on different crops. Following TWW irrigation in our study, mineral nitrogen was thus essentially stored in the soil and remained available to the crop for at least 2 years at a depth within reach of the roots.

The dynamics of the other major elements at the column outlets were consistent with the concentrations supplied at the column inlets and with the variations in exchangeable base contents in the soil at the end of the experiment. Concentrations of calcium, magnesium, chlorides and sulfates at the TWW column outlets reached constant values, with a ratio of close to 0.8. Only potassium did not reach the same concentrations as at the column inlets and continued to accumulate in soils after 20 PV. This accumulation resulted in an increase in exchangeable potassium throughout the soil profile in the TWW columns. However, Libutti et al. (2018) did not measure differences in exchangeable potassium but rather an increase in exchangeable calcium and magnesium for the second crop in the second year of their study. Elfanssi et al. (2018) measured a significant increase in exchangeable calcium, magnesium and potassium after irrigation with untreated raw water (16.33, 2.4 and 8.5 $cmol_{(c)}$ kg^{-1} respectively) or TWW (14.7, 2.2 and 8.1 $cmol_{(c)}$ kg^{-1} respectively) compared to good quality water (14.1, 2.11 and 7 $cmol_{(c)}$ kg^{-1} respectively). Ayoub et al. (2016) measured a significant increase in exchangeable calcium, magnesium and potassium in the surface and subsurface horizons of soils irrigated with TWW compared to non-irrigated soils and soils irrigated with groundwater between the first and second year of their study. Abegunrin et al. (2016) observed disparate results depending on the depth, crop and type of TWW provided. However, the control treatment always showed the lowest calcium, magnesium and exchangeable potassium levels in the surface horizon compared to TWW. In contrast, Tarchouna et al. (2010) measured higher calcium and magnesium concentrations in a modality irrigated with TWW and lower potassium concentrations. These authors explained that high calcium and magnesium levels promote potassium uptake by the plant as well as its desorption and leaching. Thus, in addition to the concentrations of these elements in TWW, their removal by the plant and their competition for adsorption or leaching could explain the differences observed between studies.

4.4. Potential risks to aquifers

The impact of TWW irrigation on groundwater is essentially analyzed by taking into account the chemical elements taken up by the sugar cane, the elements adsorbed on the soil mineral exchange surfaces, leachated with the soil solution or lost by volatilization. Plant uptake was not studied in this study. However, it is well known (Oliveira et al., 2018) and fertilization is calculated a priori to achieve a specific yield for a given soil and plant type (Ghube et al., 2017). Thus, the plant takes up the major chemical elements provided by fertilization (N, P and K) as well as those already present and available in the soil (Piouceau et al., 2020). The calculation of fertilization is a crucial step since fertilizers represent a major cost for the farmer (Wassenaar et al., 2014). However, any chemical elements that are not taken up by the plant are likely to either accumulate in the soil or contaminate groundwater (Qadir et al., 2010). In our study, the flux of chemical elements at the outlet of the soil columns therefore corresponds to the extreme situation when the plant does not intercept any chemical elements (absence of plant, root system still too undeveloped, flux between crop rows, etc.). The chemical analyses of the major elements of the leachates at the soil column outlet and the final measurements of the exchangeable bases present dynamics consistent with the quality of the TWW. The impact of TWW or high-salt irrigation water on groundwater is one of the major potential risks (Toze, 2006). Indeed, to avoid salinisation or sodisation, it is necessary to provide more water than the crop needs to leach the soluble salts and avoid their accumulation in the soil (Elgallal et al. 2016). However, depending on the hydrogeological context, this practice induces two major negative impacts to be avoided, which are an increase in the level of the water table and a progressive increase in its salt concentrations. TWW have a major advantage since they are supplied continuously during the crop cycle. The nutrients supplied are therefore fractionated and the potential losses are reduced. Similarly, nitrogen losses through volatilization are insignificant with TWW compared to applications of organic matter or mineral fertilizer (Bokhtiar and Sakurai, 2005). The risk of groundwater contamination after heavy rainfall events is thus also reduced.

5. Conclusion

Irrigation with TWW is also relevant in humid environmental settings to supplement water and fertilize intensive crops. The percentage of TWW used in the water balance is lower than in arid environmental conditions, which could explain the absence of negative effects on sugarcane crop yields, industrial characteristics and soil properties. We combined two experiments: in a sugarcane field and in the laboratory under the same hydrological conditions, but without the sugarcane crop. The first experiment clearly highlighted the impact of TWW irrigation on sugarcane, while the second provided a more general view of the impact on the soil. Indeed, the apparent contradictions between the studies in terms of changes in pH, organic carbon content and exchangeable base contents could be explained by the variability in element concentrations in the TWW, their uptake by crops, their competition for adsorption or leaching, and the hydric conditions. Short-term impacts of irrigation with TWW were, for example, an increase in pH values compared with the initial value, which results in increased availability of trace elements and heavy metals, and thus reducing the risk of heavy metal uptake by plants. However, a soil pH above 8 reduces the bioavailability of micronutrients to crops and subsequently impacts their growth and development. Soil properties must be monitored in each situation so as to be able to potentially tailor the TWW management conditions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The author would like to thank Sophie Bièque, Géraud Moussard and Didier Baret for their help in collecting field data and for their technical support, David Manley for improving the English in this paper and also three anonymous reviewers for their meaningful contribution to the paper. The author also thank the plant, soil and water analysis laboratory staff (CIRAD, UPR Recyclage et Risque, Saint-Denis, Réunion) for analyses and efficient assistance. This research was funded by *La communauté intercommunale du nord de La Réunion* (CINOR, France), an intercommunal structure involving the cities of Saint-Denis, Sainte-Marie and Sainte-Suzanne (Reuse project). The author declares no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

References

Abegunrin, T.P., Awe, G.O., Idowu, D.O., Adejumobi, M.A., 2016. Impact of wastewater irrigation on soil physico-chemical properties, growth and water use pattern of two indigenous vegetables in southwest Nigeria. Catena 139, 167–178.

Alary, K., Babre, D., Caner, L., Feder, F., Szwarc, M., Naudan, M., Bourgeon, G., 2013. Pretreatment of soil samples rich in short-range-order minerals before particle-size analysis by the pipette method. Pedosphere 23, 20–28.

Almodares, A., Sharif, M.E., 2007. Effects of irrigation water qualities on biomass and sugar contents of sugar beet and sweet sorghum cultivars. J. Environ. Biol. 28, 213–218.

Andrews, D.M., Robb, T., Elliott, H., Watson, J.E., 2016. Impact of long-term wastewater irrigation on the physicochemical properties of humid region soils: "The Living Filter" site case study. Agric. Water Manag. 178, 239–247.

APHA, 1998. Standard Methods for the Examination of Water and Waste Water. American Public Health Association, p. 874.

Ayoub, S., Al-Shdiefat, S., Rawashdeh, H., Bashabsheh, I., 2016. Utilization of reclaimed wastewater for olive irrigation: effect on soil properties, tree growth, yield and oil content. Agric. Water Manag. 176, 163–169.

Bedbabis, S., Ben Rouina, B., Boukhris, M., Ferrara, G., 2014. Effect of irrigation with treated wastewater on soil chemical properties and infiltration rate. J. Environ. Manag. 133, 45–50.

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

Blum, J., Melfi, A.J., Montes, C.R., Gomes, T.M., 2013. Nitrogen and phosphorus leaching in a tropical Brazilian soil cropped with sugarcane and irrigated with treated sewage effluent. Agric. Water Manag. 117, 115–122.

Bokhtiar, S.M., Sakurai, K., 2005. Effects of organic manure and chemical fertilizer on soil fertility and productivity of plant and ratoon crops of sugarcane. Arch. Agron. Soil Sci. 51, 325–334.

Bourazanis, G., Roussos, P.A., Argyrokastritis, I., Kosmas, C., Kerkides, P., 2016. Evaluation of the use of treated municipal waste water on the yield, oil quality, free fatty acids' profile and nutrient levels in olive trees cv Koroneiki, in Greece. Agric. Water Manag. 163, 1–8.

Braddock D., Downs P., 2001. Wastewater irrigation - A strategy for increasing sugarcane production. Proc. Int. Soc. Sugar Cane Technol., 24, 171–173.

Chaganti, V.N., Ganjegunte, G., Niu, G., Ulery, A., Flynn, R., Enciso, J.M., Meki, M.N., Kiniry, J.R., 2020. Effects of treated urban wastewater irrigation on bioenergy sorghum and soil quality. Agric. Water Manag. 228, 105894.

Diallo, F., Masse, D., Diarra, K., Feder, F., 2019. Impact of organic fertilisation on lettuce biomass production according to the cultivation duration in tropical soils. Acta Agric. Scand. Sect. B - Soil Plant Sci. https://doi.org/10.1080/09064710.2019.1702715.

Disciglio, G., Gatta, G., Libutti, A., Gagliardi, A., Carlucci, A., Lops, F., Cibelli, F., Tarantino, A., 2015. Effects of irrigation with treated agro-industrial wastewater on soil chemical characteristics and fungal populations during processing tomato crop cycle. J. Soil Sci. Plant Nutr. 15, 765–780.

Duan, R., Sheppard, C.D., Fedler, C.B., 2010. Short-term effects of wastewater land application on soil chemical properties. Water Air Soil Pollut. 211, 165–176.

Elfanssi, S., Ouazzani, N., Mandi, L., 2018. Soil properties and agro-physiological responses of alfalfa (Medicago sativa L.) irrigated by treated domestic wastewater. Agric. Water Manag. 202, 231–240.

Elgallal, M., Fletcher, L., Evans, B., 2016. Assessment of potential risks associated with chemicals in wastewater used for irrigation in arid and semiarid zones: a review. Agric. Water Manag. 177, 419–431.

Feder, F., 2013. Soil map update: procedure and problems encountered for the island of Réunion. Catena 110, 215–224.

Feder F. 2020: Replication data for: Irrigation with treated wastewater in humid regions: effects on Nitisols, sugarcane yield and quality. ⟨doi:10.18167/DVN1/HFRIGA⟩, CIRAD Dataverse, V1.

Feder, F., Bochu, V., Findeling, A., Doelsch, E., 2015. Repeated pig manure applications modify nitrate and chloride competition and fluxes in a Nitisol. Sci. Total Environ. 511, 238–248.

Feder, F., Oliver, R., Rakotoarisoa, J., Muller, B., Scopel, E., 2020. Geochemical properties of variable charge soil explain the low nitrogen bioavailability. Commun. Soil Sci. Plant Anal. 51 (15), 2022–2037. https://doi.org/10.1080/00103624.2020.1817485.

Feder, F., Trolard, F., Bourrié, G., Klingelhöfer, G., 2018. Quantitative estimation of fougerite green rust in soils and sediments by citrate—bicarbonate kinetic extractions. Soil Syst. 2, 54.

Ghube, N.B., Kadlag, A.D., Kamble, B.M., 2017. Impact of different levels of organic and inorganic fertilizers on growth, yield and quality of preseasonal sugarcane ratoon in Inceptisols. J. Appl. Nat. Sci. 9, 812–820.

Gillman, G.P., Sumpter, E.A., 1986. Modification to the compulsive exchange method for measuring exchange characteristics of soils. Soil Res. 24, 61.

Gloaguen, T.V., Forti, M.-C., Lucas, Y., Montes, C.R., Gonçalves, R.A.B., Herpin, U., Melfi, A.J., 2007. Soil solution chemistry of a Brazilian Oxisol irrigated with treated sewage effluent. Agric. Water Manag. 88, 119–131.

Gloaguen, T.V., Gonçalves, R.A.B., Forti, M.C., Lucas, Y., Montes, C.R., 2010. Irrigation with domestic wastewater: a multivariate analysis of main soil changes. Rev. Bras. Ciência Solo 34, 1427–1434.

Gonçalves, I.Z., Barbosa, E.A.A., Santos, L.N.S., Nazário, A.A., Feitosa, D.R.C., Tuta, N.F., Matsura, E.E., 2017. Water relations and productivity of sugarcane irrigated with domestic wastewater by subsurface drip. Agric. Water Manag. 185, 105–115.

Hodomihou, N.R., Feder, F., Masse, D., Agbossou, E.K., Amadji, G.L., Ndour-Badiane, Y., Doelsch, E., 2016. Diagnostic de contamination des agrosystèmes périurbains de Dakar par les éléments traces métalliques. Biotechnol. Agron. Soc. Environ. 20.

IUSS Working Group WRB, 2015. World Reference Base for Soil Resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. World Reference Base for Soil Resources 2014, update 2015

International soil classification system for naming soils and creating legends for soil maps., World Soil Resources Reports No. 106. FAO, Rome. Rome.
Lal, K., Minhas, P.S., Yadav, R.K., 2015. Long-term impact of wastewater irrigation and nutrient rates II. Nutrient balance, nitrate leaching and soil properties under peri-urban cropping systems. Agric. Water Manag. 156, 110–117.
Leal, R.M.P., Firme, L.P., Herpin, U., da Fonseca, A.F., Montes, C.R., dos Santos Dias, C. T., Melfi, A.J., 2010. Carbon and nitrogen cycling in a tropical Brazilian soil cropped with sugarcane and irrigated with wastewater. Agric. Water Manag. 97, 271–276.
Leal, R.M.P., Herpin, U., Fonseca, A.F. da, Firme, L.P., Montes, C.R., Melfi, A.J., 2009. Sodicity and salinity in a Brazilian Oxisol cultivated with sugarcane irrigated with wastewater. Agric. Water Manag. 96, 307–316.
Libutti, A., Gatta, G., Gagliardi, A., Vergine, P., Pollice, A., Beneduce, L., Disciglio, G., Tarantino, E., 2018. Agro-industrial wastewater reuse for irrigation of a vegetable crop succession under Mediterranean conditions. Agric. Water Manag. 196, 1–14.
Minhas, P.S., Yadav, R.K., Lal, K., Chaturvedi, R.K., 2015. Effect of long-term irrigation with wastewater on growth, biomass production and water use by Eucalyptus (Eucalyptus tereticornis Sm.) planted at variable stocking density. Agric. Water Manag. 152, 151–160.
Mohammad, M.J., Mazahreh, N., 2003. Changes in soil fertility parameters in response to irrigation of forage crops with secondary treated wastewater. Commun. Soil Sci. Plant Anal. 34, 1281–1294.
El Moussaoui, T., Mandi, L., Wahbi, S., Masi, S., Ouazzani, N., 2019. Soil proprieties and alfalfa (*Medicago sativa* L.) responses to sustainable treated urban wastewater reuse. Arch. Agron. Soil Sci. 65, 1900–1912.
Nelson, P.N., Ham, G.J., 2000. Exploring the response of sugar cane to sodic and saline conditions through natural variation in the field. Field Crops Res. 11.
de Oliveira, M.W., Nascif, C., da Silva, V.S.G., Oliveira, T.B.A., Rodrigues, T.C., Gama, K. F.V., de Oliveira, G.C.B., 2018. Biomass yield, nutritional status and industrial quality of sugarcane as a function of nitrogen and potassium fertilization. Aust. J. Crop Sci. 12, 834–840.
Paudel, I., Bar-Tal, A., Levy, G.J., Rotbart, N., Ephrath, J.E., Cohen, S., 2018. Treated wastewater irrigation: soil variables and grapefruit tree performance. Agric. Water Manag. 204, 126–137.
Pedrero, F., Kalavrouziotis, I., Alarcón, J.J., Koukoulakis, P., Asano, T., 2010. Use of treated municipal wastewater in irrigated agriculture—review of some practices in Spain and Greece. Agric. Water Manag. 97, 1233–1241.
Piouceau, J., Panfili, F., Bois, G., Anastase, M., Feder, F., Morel, J., Arfi, V., Dufossé, L., 2020. Bamboo plantations for phytoremediation of pig slurry: plant response and nutrient uptake. Plants 9, 18.
Polglase, P.J., Tompkins, D., Stewart, L.G., Falkiner, R.A., 1995. Mineralization and leaching of nitrogen in an effluent-irrigated pine plantation. J. Environ. Qual. 24, 911–920.
Qadir, M., Wichelns, D., Raschid-Sally, L., McCornick, P.G., Drechsel, P., Bahri, A., Minhas, P.S., 2010. The challenges of wastewater irrigation in developing countries. Agric. Water Manag. 97, 561–568.
Rusan, M.J.M., Hinnawi, S., Rousan, L., 2007. Long term effect of wastewater irrigation of forage crops on soil and plant quality parameters. Desalination 215, 143–152.
Sebastian, S.P., Udayasoorian, C., Jayabalakrishnan, R.M., Parameswari, E., 2009. Performance of sugarcane varieties under organic amendments with poor quality irrigation water. Aust. J. Basic Appl. Sci. 3 (3), 1674–1684, 11.
Singh, P.K., Deshbhratar, P.B., Ramteke, D.S., 2012. Effects of sewage wastewater irrigation on soil properties, crop yield and environment. Agric. Water Manag. 103, 100–104.
Tarchouna, L.G., Merdy, P., Raynaud, M., Pfeifer, H.R., Lucas, Y., 2010. Effects of long-term irrigation with treated wastewater. Part I: evolution of soil physico-chemical properties. Appl. Geochem. 25, 1703–1710.
Toze, S., 2006. Reuse of effluent water—benefits and risks. Agric. Water Manag. 80, 147–159.
Umesh, U.N., Kumar, V., Alam, M., Sinha, S.K., Verma, K., 2013. Integrated effect of organic and inorganic fertilizers on yield, quality parameter and nutrient availability of sugarcane in calcareous soil. Sugar Tech 15, 365–369.
Wassenaar, T., Doelsch, E., Feder, F., Guerrin, F., Paillat, J.-M., Thuriès, L., Saint, Macary, H., 2014. Returning organic residues to agricultural land (RORAL) – fuelling the follow -the- technology approach. Agric. Syst. 124, 60–69.