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How Does Irrigation with Wastewater Affect the Physical Soil Properties and the Root Growth of Sugarcane under Subsurface Drip?

Oswaldo Palma Lopes Sobrinho [1], Leonardo Nazário Silva dos Santos [1], Marconi Batista Teixeira [1], Frederico Antônio Loureiro Soares [1], Ivo Zution Gonçalves [2], Eduardo Augusto Agnellos Barbosa [3], Aline Azevedo Nazário [4], Edson Eiji Matsura [5], Luciana Cristina Vitorino [6,*], Mateus Neri Oliveira Reis [6] and Layara Alexandre Bessa [6]

[1] Laboratório de Hidráulica e Irrigação, Instituto Federal de Educação, Ciência e Tecnologia Goiano, Campus Rio Verde, Rodovia Sul Goiana, Km 01, Rio Verde 75901-970, GO, Brazil; engenheirooswaldopalma@gmail.com (O.P.L.S.); leonardo.nazario@ifes.edu.br (L.N.S.d.S.); marconi.teixeira@ifgoiano.edu.br (M.B.T.); frederico.soares@ifgoiano.edu.br (F.A.L.S.)

[2] Daugherty Water for Food Global Institute, University of Nebraska, Lincoln, NE 68588, USA; ivo.zution@gmail.com

[3] Universidade Estadual de Ponta Grossa, Ponta Grossa 84030-900, PR, Brazil; eaabarbosa@uepg.br

[4] Instituto Adventista de Ensino, Campus Engenheiro Coelho, Engenheiro Coelho 13165-000, SP, Brazil; aline.nazario@acad.unasp.edu.br

[5] Faculdade de Engenharia Agrícola (FEAGRI), Universidade Estadual de Campinas (UNICAMP), Campinas 13083-862, SP, Brazil; matsura@unicamp.br

[6] Laboratório de Metabolismo e Genética da Biodiversidade, Instituto Federal de Educação, Ciência e Tecnologia Goiano, Campus Rio Verde, Rio Verde 75901-970, GO, Brazil; mateursnerioliveira@hotmail.com (M.N.O.R.); layara.bessa@ifgoiano.edu.br (L.A.B.)

* Correspondence: luciana.vitorino@ifgoiano.edu.br

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Abstract: Studies on the development of the root system can provide important information about responses to different management strategies, such as the use of lower quality water, also evaluating the interaction between plants and the physical properties of the soil. This study tested the hypothesis that irrigation with treated sewage effluent (TSE) supplies the water needs of sugarcane plants, increasing root growth and improving the physical properties of the soil. We evaluated the effects of subsurface dripping with TSE or surface reservoir water (SRW) on the root development of first ratoon cane (*Saccharum officinarum* L.) and the physical properties of dystrophic red latosol. Irrigation treatments were applied at 20 and 40 cm and soil properties were evaluated at soil depth layers of 0–20, 20–40, 40–60, and 60–80 cm. We verified that under irrigation with TSE and SRW, shallower soil layers present better porosity, soil aggregation, and aggregate stability conditions, parameters that improve the root system development and plant growth. On the other hand, deeper soil layers have lower macroporosity and higher total clay volume, indicating the possibility of compaction and greater limitations for sugarcane root growth. These results are important for understanding soil quality and provide significant information for agricultural management and for the implementation of sustainable soil conservation practices. This study shows the efficiency of TSE as an alternative water source for sugarcane crops.

Keywords: *Saccharum officinarum* L.; root sampling; lower quality water; irrigation management; water reuse; soil probe

1. Introduction

Sectors involving food and bioenergy production have been under pressure due to increased water consumption demands, with an optimized use of natural resources presupposing the need to create and develop integrated production systems [1] and invest in the use of alternative water sources, such as treated sewage effluent (TSE). This effluent has become a sustainable option for agricultural irrigation, especially when the irrigated areas are located close to urban centers [2]. TSE constitutes one of the main alternative options for expanding water resources in countries suffering from water scarcity, especially since there are enormous amounts of wastewater [3]. In addition to reducing the use of freshwater, the reuse of wastewater contributes to reducing the release of waste into ecosystems and improving the soil, as it can provide nutrients and organic matter [4]. In some cases, TSE can even eliminate the need to supply expensive chemical fertilizers to the soil [5] and therefore has been recognized as an important resource for increasing agricultural production at low costs [6]. However, the risks of reusing wastewater in agriculture cannot be ruled out. Key concerns include health risks, increased salinity, and soil toxicity risks [7]. Thus, other techniques such as the construction of surface water reservoirs have become common in agricultural areas, ensuring productivity [8].

Effluents and wastewater can be introduced into agricultural systems by subsurface dripping. In this technique, water and nutrients are applied directly to the root zone, increasing application uniformity and reducing the total water volume used, the occurrence of invasive plants, and water evaporation in the soil, also reducing mechanical damage to the irrigation system because most of the system is underground [9–11].

Many studies show that the surface drip technique can be efficiently used to cultivate sugarcane [12–14]. Thus, the use of TSE by this technique of irrigation in commercial sugarcane crops has increased the interest of researchers and farmers, as they believed this practice can increase crop productivity and reduce costs with water and fertilizers. Another benefit of this technique is that it can be automated (e.g., using a SCADA System) [15]. Millions of liters of sewage could be used, reducing its spread and exposure in water and in the soil, preserving the quality of surface water intended for human and animal use [2,16,17]. This study tested the hypothesis that irrigation with TSE supplies the water needs of sugarcane plants, increasing root growth and improving the physical properties of the soil.

The evaluations were focused on the root system, as this is the main organ responsible for absorbing water and nutrients [18,19]. This system assists the breathing process, important for sugarcane regrowth and ratoon vigor, improving the transport of water to the leaves and photosynthetic products, which are accumulated and promote rapid leaf expansion and plant growth [20,21].

Thus, it is essential to evaluate root distribution and growth along the soil profile to understand different crop-related processes such as water and nutrient absorption, optimization of the use of natural resources, correct irrigation management, and irrigation efficiency [22–25].

The water content in the soil influences the depth of the root system, highlighting the importance of irrigation management [26]. About 85% of sugarcane roots are in the first 0.5 m of soil depth [27]. However, different mechanisms related to irrigation and fertigation supply can affect this distribution. Thus, the objective of this study was to evaluate the effects of subsurface dripping with TSE or surface reservoir water (SRW) on the root development of first ratoon cane (*Saccharum officinarum* L.) and the physical properties of dystrophic red latosol.

2. Materials and Methods

2.1. Experimental Area and Cultivation Soil

The tests were conducted in the experimental area of the School of Agricultural Engineering (FEAGRI) of the State University of Campinas (UNICAMP), Campinas, SP, Brazil, located at the geographic coordinates latitude 22°53′ S, longitude 47°05′ W, with an average altitude of 620 m. According to Köppen–Geiger [28], the climate is classified as a transition between Cwa (subtropical with dry winter and hot summer) and Cfa (subtropical with hot summers), with an average annual temperature of 22.3 °C, average total annual rainfall of 1425 mm, and average relative air humidity of 62% [29]. Climatic variables were obtained daily from an automatic meteorological station located 100 m away from the experimental area (Figure S1). The soil was classified as dystrophic red latosol by the Brazilian Soil Classification System [30], oxissol (Rhodic Haplustox) by the USDA soil taxonomy [31], and ferralsol [32].

Alternatively, chemical analyses of the planting soil included samples collected only in the 0–0.2 m depth layer, according to the methodologies described by Raij et al. [33], Camargo et al. [34], Teixeira et al. [35], and Meneghetti [36], using four trenches and nine samples per trench. The mean values for these properties are described in Table S1. Additionally, the profile of the dystrophic red latosol was characterized in relation to sodic-saline properties and classification according to the limits established by Richards [37] (Table S2).

2.2. Experimental Design and Treatments

The field experiment was designed in randomized blocks with a 5 × 4 split-plot structure with three replications, totaling 60 experimental units. The plots had the following irrigation treatment water: non-irrigated (NI), irrigated with TSE at 20 and 40 cm, and irrigated with SRW at 20 and 40 cm, being subdivided into the following soil layers: 0–20, 20–40, 40–60, and 60–80 cm for analysis of soil physical properties and root development in sugarcane plants.

2.3. Cultivation, Planting, and Treatments

The sugarcane variety used was RB86-7515, which has characteristics such as physiological mechanisms that avoid exacerbated water losses when subjected to water deficit, high productivity and sucrose content, tall height, medium tillering with uniform stalks, fast and erect growth, purplish green stem, high density, and easy spread [38,39].

Planting was conducted using a double-row combined spacing system, with two lines spaced 0.4 m apart and 1.4 m between lines, totaling 1.8 m at a depth of 0.3 m (Figure 1). The furrows were opened mechanically with a furrower (Figure 1a,c,d), with 5–6 stalks/stems with an average of three buds each distributed per linear meter. The standard end-to-end technique was used with uniform stalk distribution in the furrows, according to the recommendations by Silva et al. [40] and Rodolfo Junior et al. [41]. A special tool was developed at the FEAGRI/UNICAMP Prototypes Laboratory (Figure 1b) to install the drip tubes at two dripping depths (0.2 and 0.4 m). The installation procedure occurred after sugarcane planting in the center of the double rows (Figure 1c).

The total experimental area was 2430 m^2 (25 plots), and each experimental plot was 97.2 m^2 (5.4 × 18 m), with three replications, with three double rows of sugarcane plants, considering the two lateral as borders, the central one as the useful line, and the final 2 m of each extremity in the longitudinal direction of each plot as the border.

2.4. Fertilization and Irrigation

Fertilization was based on the recommendation proposed by Rossetto et al. [42], with 30, 80, and 80 kg ha^{-1} of N, P_2O_5, and K_2O applied to the plant cane and 120, 40, and 80 kg ha^{-1} of N, P_2O_5, and K_2O applied to first ratoon cane. No planting fertilizer was applied due to the chemical characteristics of the soil.

Fertilization was always manual in the control treatment (NI), 125 days after regrowth, with topdressing between double rows (0.4 m), with full nutrient dosage, applied to plant cane and first ratoon cane. Topdressing fertilization included urea fertilizers as a source of N, monoammonium phosphate (MAP) as a source of P_2O_5, and potassium sulfate as a source of K_2O, at concentrations of 45% N, 9% N, 48% P_2O_5, 15% S, and 48% K_2O, respectively.

The irrigated treatments included mineral fertilizer fertigation according to the nutritional quality of the irrigation water (SRW or TSE), and the nutrients were applied according to the sugarcane absorption rate and as recommended by Haag et al. [43], on a weekly basis. Irrigation was carried out twice a week using a Venturi tube system with MAP, calcium nitrate, and potassium sulfate diluted in a 50 L tank.

Management and treatments included weed control with two manual weeding sessions on the plant cane; three applications of SEMPRA® on the plant cane and two on the first ratoon cane; one application of VELPAR K® WG on the plant cane; two applications of DMA® 806 BR on the plant cane and two on the first ratoon cane; and one application of GLIFOSATO ATANOR® on the first ratoon cane. Phytosanitary control included one application of EVIDENCE® 720WG on the plant cane and two applications of MIREX-S® on the plant cane and on the first ratoon cane for termite and ant control.

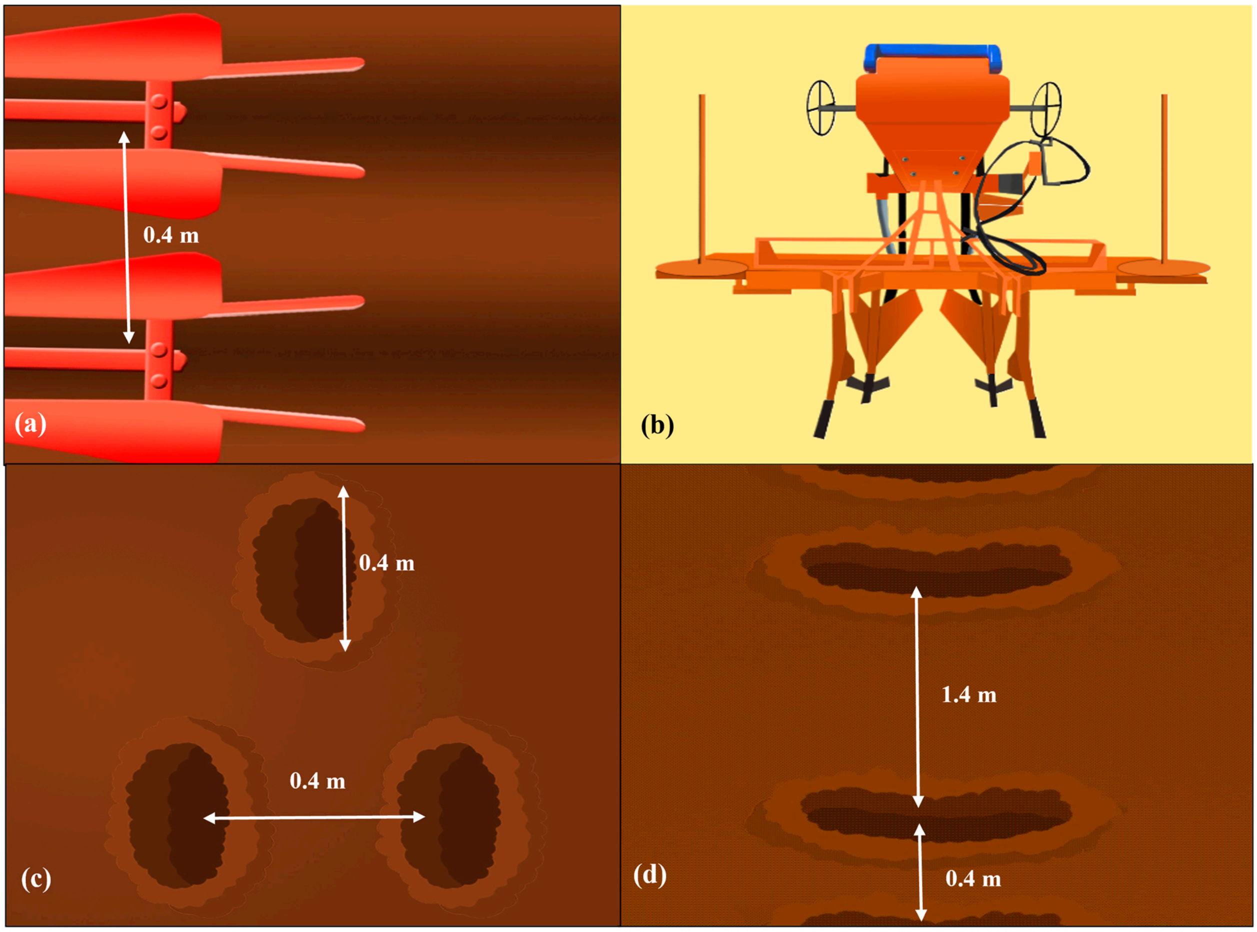

Figure 1. Furrower adjustment for sugarcane planting in double rows of 0.4 m (**a**); tool for installing the drip tube at two depths: 0.2 and 0.4 m (**b**); double-row spacing (**c**); spacing between double rows (**d**).

2.5. Irrigation System and Management

Irrigation was carried out twice a week throughout the two sugarcane cycles, except in the rainy season, when irrigation was suspended and fertigation was maintained. Irrigation was interrupted at the end of the cycle for 45 and 60 days before harvesting in the plant cane and first ratoon cane for plant maturation and sugar accumulation.

The subsurface drip irrigation system was installed in the center of the combined double row spacing, at depths of 0.2 and 0.4 m, using DripNet PC AS 16250 (Netafim®) drippers, self-compensating in pressure ranges from 0.4 to 2.4 kgf cm^{-2}, with a flow rate of 1.6 L h^{-1}, spaced 1 m. According to the manufacturer [44], these are labyrinth drippers with extensive water passage sections, which are resistant against obstructions, with a self-cleaning system, and a broad filtration area. They also have a uniform flow with working pressure ranging between 40 and 250 kPa and an anti-siphon system (AS), which prevent the entry of external impurities into the dripper. Anti-vacuum valves were installed at the ends of the lines to prevent the suction of soil particles.

Two system pressurization sets were mounted on the control head: one for SRW and the other for TSE, with individual treatments depending on the irrigation water quality (Figure 2). Before the irrigation system started working with the ends of the lines closed, the drip tapes were washed and then drained by opening the valves to avoid obstructions. Sand filters FA800 (Hidro Solo®) were installed, one for each control head. These were backwashed with potable water after installation and after each irrigation event. In addition, the system was cleaned at the end of each sugarcane cycle using a chlorine and hydrochloric acid solution.

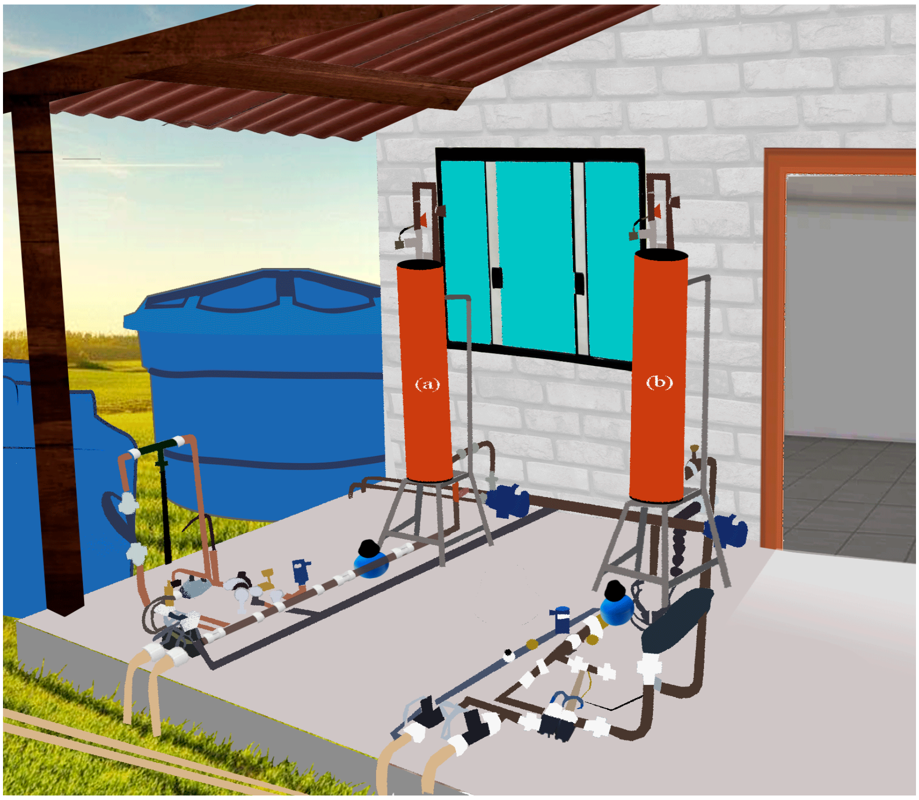

Figure 2. Control head with two irrigation system pressurization sets used to apply irrigation treatments to the sugarcane cultivation: SRW (a); and TSE (b).

Irrigation management was used to maintain soil water content at field capacity in the active region of the root system, based on the soil–water balance and considering the difference between water content in the soil by the Time Domain Reflectometry (TDR), previously calibrated according to Souza et al. [45], and the maximum water storage capacity at 20 kPa (field capacity considering the average soil moisture of 0.35 cm^3 cm^{-3}) at 0–0.2, 0.2–0.4, 0.4–0.6, and 0.6–0.8 m depth layers.

In the plant cane, the soil dimensions for calculating the irrigation depth and dripper flow of 1 L h^{-1} were 0.6 m depth and 0.4 m lane width; the dripper flow of 1.6 L h^{-1} had a bandwidth of 0.5 m with a line length of 18 m (17 m of line + 0.5 m at each line end, which corresponds to the whip connection between the derivation and the drip tube).

The water level applied increased the water content of the soil above the required level throughout the plant cane cycle and after the irrigation events, mainly in treatments with the drip tube installed at a depth of 0.4 m. The quadratic equation proposed by Mestas et al. [46] ($\theta = -0.04805Ka^2 + 2.111Ka + 8.488$) was used in this cycle for TDR calibration and transformation of soil apparent dielectric constant (Ka) data into soil water content before irrigation (θi). Even with high Ka levels, this equation limits the calculation of high humidity, and then the equation designed by Souza et al. [47] ($\theta = 3 \times 10^5$ $Ka^3 - 0.0017$ $Ka^2 + 0.0415$ $Ka - 0.0603$) was used.

The water content increased little in the first layers of the soil, especially in the treatments with a drip tube installed at a depth of 0.4 m. The profile of 0.2–0.8 m was used in first ratoon cane to calculate the irrigation depth of the treatments with water applications at 0.4 m, maintaining the profile of 0–0.6 m for treatments at 0.2 m depth.

2.6. SRW and TSE Quality

SRW from a pond located close to the UNICAMP experimental area (ecological park) and TSE from the different FEAGRI/UNICAMP buildings consisting of domestic and sanitary waste from the laboratories were used for irrigation.

The treatment system consisted of anaerobic reactors measuring 4.19 m^3 compartmentalized by three serial boxes, and the TSE was placed in collection boxes (2.7 m × 1.7 m) with a depth of 0.5 m and a volume of 2.3 m^3 filled with gravel #2 and cultivated with *Canna indica* L. macrophytes, commonly known as Caetê. After treatment, the TSE was pumped and stored in three reservoirs with a capacity of 15 m^3 connected in series, later being used as irrigation water for sugarcane cultivation (Figure S2).

The physical, chemical, and microbiological properties of SRW and TSE were monitored monthly, and the samples were kept in thermal boxes with ice according to the Standard Methods for the Examination of Water and Wastewater [48] and the United States Environmental Protection Agency [49]. These properties were analyzed in the rainy (spring and summer) and in the dry (fall and winter) seasons since nutrient concentrations vary in SRW and TSE according to the volume produced and the occurrence of rain (Table S3).

2.7. Post-Cultivation Evaluation of Soil Physical Properties

The physical properties of the soil were obtained by collecting disturbed and undisturbed soil samples (using a Uhland sampler and metal rings of known volume) in four trenches (replications), at 0–0.2, 0.2–0.4, 0.4–0.6, and 0.6–0.8 m depth. The samples were collected at the end of the first ratoon cane and taken to the FEAGRI/UNICAMP Soil Laboratory for granulometric analyses by the pipette method to obtain the average values of the variables: soil density (SD, g cm^3), particle density (PD, g cm^3), macroporosity (MACRO-P, cm^3 cm^3), microporosity (MICRO-P, cm^3 cm^3), total soil porosity (TP, cm^3 cm^3), weighted average diameter (WAD, mm), aggregate stability index (ASI, %), stable aggregates (SA, %), aggregates > 1 mm (A > 1, %), dispersed clay (DC, g kg^{-1}), total clay (TC, g kg^{-1}), degree of dispersion (DD, %), and degree of flocculation (DF, %), according to the method proposed by Yoder [50], Kiehl [51], Teixeira et al. [35], and Libardi [52].

The wet screening technique was used to determine the water ASI [50]. The study considered aggregates with diameters between 2 and 6.35 mm and a set of sieves with 2, 1, 0.5, and 0.125 mm mesh in wet agitation to determine the WAD and ASI properties using Equations (1) and (2).

$$\text{WAD} = \sum_{i=1}^{n} \frac{\text{Mi} \times \text{Di}}{\text{MT}} \quad (1)$$

$$\text{ASI} = \frac{M_T - M_{<0.125}}{M_T} \times 100 \quad (2)$$

where

WAD = weighted average diameter;
ASI = aggregate stability index;
Mi = class i aggregate mass (g);
Di = average class i diameter (mm);
MT = total aggregate mass minus soil water content (g); and
$M_{<0.125}$ = aggregate mass less than 0.125 mm.

Soil DF and DD were determined using Equations (3) and (4).

$$\text{DF} = \frac{(a - b) \times 100}{a} \quad (3)$$

$$\text{DD} = 100 - \text{DF} \quad (4)$$

where

DF = degree of flocculation in dag kg^{-1} (%);
DD = degree of dispersion (%);
a = total clay concentration (g kg^{-1}); and
b = concentration of clay dispersed in water (g kg^{-1}).

2.8. Sugarcane Root System

The roots were sampled after the first ratoon cane harvesting, collected in a 0.6 × 0.8 m mesh using the drip tape installation line as a reference (Figure 3).

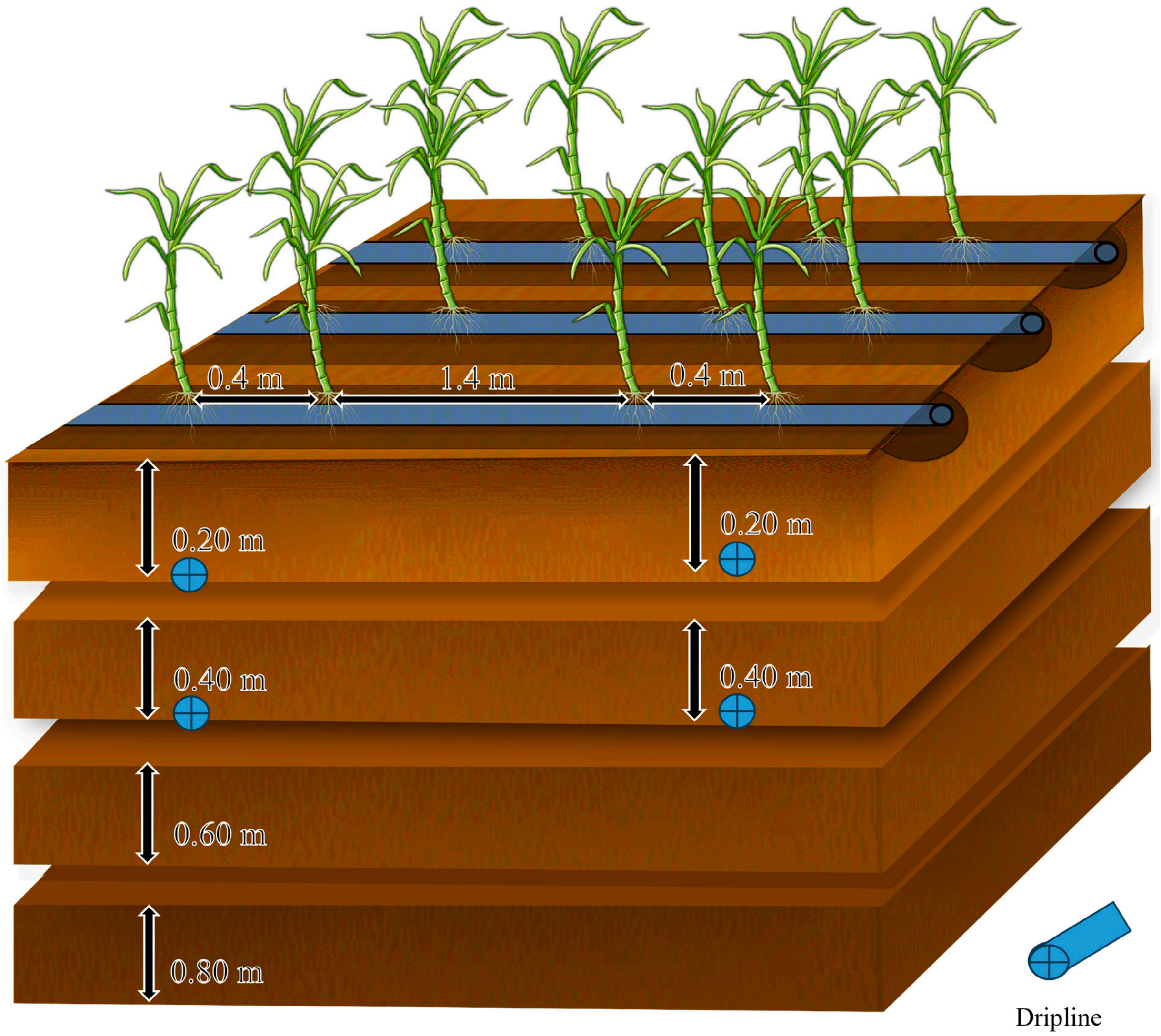

Figure 3. Sugarcane root system sampling points under irrigation treatment with TSE or SRW. The irrigation system was installed at 0.20 and 0.40 m and soil sampling was carried out at 0.2, 0.4, 0.6, and 0.8 m soil depths. The arrows above the soil show the spacing of plants in the rows and between the rows.

The root sampling followed the methodology proposed by Fujiwara et al. [53], using a soil probe with 0.072 m internal diameter and 0.2 m height, with a sampled volume of 0.8143 dm^3. The roots were washed in running water, separated in a 1 mm sieve, and the impurities were removed with tweezers. A table scanner was used to digitize the root images, which were then processed using the Safira® software, version 1.0 [54] to determine the root area (RA, mm^2), root volume (RV, mm^3), and root length (RL, mm).

2.9. Data Analysis

The data were subjected to exploratory analysis, followed by residue analysis and four-way analysis of variance (ANOVA), considering the effects of blocks, soil depth layers, cultivation types, and the interaction between layer depth and irrigation treatment water. In case of significant effects, the "ExpDes.pt" package [55] of the R software version 4.2.2 was used for Tukey's test. The relationship between the different variables was evaluated separately for type of cultivation and soil layer depth using principal component analysis (PCA) with the Tidyverse [56], Factoextra [57], and MVar.pt [58] packages and Pearson's linear correlations. Additionally, clustering analysis and the Mojena test (k = 1.25) verified treatment grouping considering all variables using the Multivariate Analysis package [59].

3. Results

3.1. Univariate Data Analysis

Analysis of variance showed interaction between soil depth layers and irrigation treatment water for the variables of soil density, volume, area, and sugarcane root length. Analyses of cultivation type breakdown within soil depth layers showed a significant effect only at the 0–20 cm layer for sugarcane volume, area, and root length. Soil density showed a significant effect for irrigation treatment water at 20–40 and 40–60 cm (Table 1).

At the 0–20 cm layer, sugarcane root volume and area were improved with $TSE_{(20\ cm)}$, $SRW_{(20\ cm)}$, and NI compared to cultivation with $TSE_{(40\ cm)}$ and $SRW_{(40\ cm)}$. These last two treatments showed no differences between the averages.

Root length was positively affected by irrigation with $TSE_{(20\ cm)}$. These results are better than those with $TSE_{(40\ cm)}$ and $SRW_{(40\ cm)}$. The use of $SRW_{(20\ cm)}$ did not differ from the control treatment but showed values higher than those with $SRW_{(40\ cm)}$.

Table 1. Soil density, volume, area, and root length of sugarcane under irrigation treatments with TSE or SRW. Evaluations carried out at 0–20, 20–40, 40–60, and 60–80 cm soil depth layers. NI = non-irrigated control treatment.

Irrigation Treatment Water	Soil Depth Layers			
	0–20 cm	20–40 cm	40–60 cm	60–80 cm
	Root volume (mm^3)			
$TSE_{(20\ cm)}$	193.99 ± 129.09 * Aa	100.64 ± 64.36 B	55.48 ± 40.10 BC	37.60 ± 24.86 C
$TSE_{(40\ cm)}$	135.14 ± 53.30 Aab	105.10 ± 89.80 AB	54.27 ± 28.01 BC	29.73 ± 17.39 C
$SRW_{(20\ cm)}$	200.44 ± 84.40 Aa	120.45 ± 74.34 B	59.36 ± 29.35 C	23.15 ± 12.36 C
$SRW_{(40\ cm)}$	74.83 ± 50.30 Bb	85.78 ± 80.15 A	56.70 ± 47.65 AB	21.71 ± 20.45 B
NI	165.98 ± 124.65 Aa	125.28 ± 62.71 A	58.48 ± 38.68 B	44.13 ± 37.21 B
	Root area (mm^2)			
$TSE_{(20\ cm)}$	1842.46 ± 1018.40 Aa	879.18 ± 536.63 B	512.88 ± 337.18 BC	363.24 ± 172.04 C
$TSE_{(40\ cm)}$	1245.77 ± 471.19 Aab	840.35 ± 650.80 AB	500.36 ± 167.42 BC	308.91 ± 173.60 C
$SRW_{(20\ cm)}$	1773.36 ± 663.35 Aa	977.94 ± 484.56 B	510.58 ± 170.11 BC	233.42 ± 84.73 C
$SRW_{(40\ cm)}$	772.18 ± 498.72 Ab	704.20 ± 597.28 A	455.53 ± 363.78 AB	190.30 ± 137.23 B
NI	1602.06 ± 1047.34 Aa	1041.88 ± 403.19 B	501.95 ± 260.11 C	369.97 ± 230.16 C
	Root length (mm)			
$TSE_{(20\ cm)}$	2226.39 ± 1145.07 Aa	994.98 ± 659.46 B	620.75 ± 411.87 B	439.98 ± 197.84 B
$TSE_{(40\ cm)}$	1386.85 ± 577.65 Abc	876.12 ± 657.91 AB	613.05 ± 200.95 B	405.46 ± 237.62 B
$SRW_{(20\ cm)}$	1938.48 ± 757.73 Aab	1052.65 ± 421.39 B	577.84 ± 162.11 BC	302.98 ± 105.19 C
$SRW_{(40\ cm)}$	952.09 ± 567.00 Ac	767.63 ± 578.28 AB	498.72 ± 395.25 AB	222.94 ± 118.72 B
NI	1888.55 ± 1167.21 Aab	1097.96 ± 303.44 B	558.10 ± 272.46 BC	418.46 ± 211.90 C

Table 1. *Cont.*

Irrigation Treatment Water	Soil Depth Layers			
	0–20 cm	**20–40 cm**	**40–60 cm**	**60–80 cm**
		Soil density (g cm^3)		
$TSE_{(20\ cm)}$	1.23 ± 0.09 BC	1.39 ± 0.15 Aa	1.31 ± 0.05 ABa	1.21 ± 0.03 C
$TSE_{(40\ cm)}$	1.28 ± 0.09 AB	1.29 ± 0.12 Aab	1.19 ± 0.06 BCb	1.11 ± 0.03 C
$SRW_{(20\ cm)}$	1.27 ± 0.09 A	1.25 ± 0.12 ABb	1.27 ± 0.06 Aab	1.16 ± 0.06 B
$SRW_{(40\ cm)}$	1.29 ± 0.08 A	1.29 ± 0.16 Aab	1.18 ± 0.08 Bb	1.16 ± 0.07 B
NI	1.27 ± 0.09 AB	1.30 ± 0.12 Aab	1.18 ± 0.08 BCb	1.16 ± 0.06 C

Means followed by the same letter do not differ among themselves by Tukey's test ($p \leq 0.05\%$). Lowercase letters indicate comparison between irrigation treatment water, and uppercase letters indicate comparison between soil depth layers. * Mean values followed by SD.

Soil density at 20–40 cm showed higher values with $TSE_{(20\ cm)}$ than with $SRW_{(20\ cm)}$. In the soil layer of 40–60 cm, $TSE_{(20\ cm)}$ increased soil density more effectively than $TSE_{(40\ cm)}$, $SRW_{(40\ cm)}$, or NI.

The analysis of soil depth layers by type of cultivation showed that the treatments significantly affected all response variables: soil density, volume, area, and root length. Volume and root area with $TSE_{(20\ cm)}$, length and root area with $SRW_{(20\ cm)}$, and root length in the control treatment showed the highest values for the 0–20 cm soil depth layer and the lowest for the 60–80 cm layer, which did not differ from the 40 to 60 cm layer.

$TSE_{(40\ cm)}$ improved sugarcane volume and root area at 0–20 cm. Root volume with $SRW_{(20\ cm)}$ and root area with NI were greater at 0–20 cm, followed by the 20–40 cm layer, with reduced values at 0–40 and 60–80 cm, which showed no differences between themselves. $SRW_{(40\ cm)}$ showed a greater volume of sugarcane roots at 20–40 cm than at 60–80 cm. Root volume in NI was greater at 0–20 and 20–40 cm. The same behavior was observed for soil density with $SRW_{(40\ cm)}$.

The root area with $SRW_{(40\ cm)}$ was higher at 0–20 and 20–40 cm depth. The root area with $SRW_{(40\ cm)}$ was higher at the 0–20 and 20–40 cm depth. With $TSE_{(40\ cm)}$, root length was greater at 0–20 cm than at 40–60 and 60–80 cm. The root length reduced at 60–80 cm using $SRW_{(40\ cm)}$.

The soil density was higher at 20–40 cm than at 0–20 and 60–80 cm with $TSE_{(20\ cm)}$, not differing at 40–60 cm. In cultivation with $TSE_{(40\ cm)}$ and NI, the 20–40 cm soil depth layer showed higher mean density values than the 40–60 and 60–80 cm layers, not differing at 0–20 cm. In cultivation with $SRW_{(20\ cm)}$, the 0–20 and 40–60 cm layers showed higher mean density than the 60–80 cm layer.

Irrigation treatments also affected physical characteristics of the planting soil such as macroporosity, total porosity, weighted average diameter, stable aggregates, aggregate stability index, total clay, degree of flocculation, and degree of dispersion only regarding soil depth layers. Microporosity, particle density, and dispersed clay showed no difference between factors (Table 2).

Thus, particle density was not changed between soil layers, indicating similar clay stability at all depths. There were no differences in soil macroporosity between the 0–20 and 60–80 cm depth layers, which presented higher values than at 20–40 and 40–60 cm.

Total porosity was higher at 0–20 cm than at 20–40 and 40–60 cm, not differing from 60 to 80 cm. Still regarding total porosity, it was similar at 60–80 and 40–60 cm, which showed higher values than at 20–40 cm.

The weighted average diameter was greater at 0–20 cm. Stable aggregates and the degree of dispersion were lower at 60–80 cm than at 0–20 and 20–40 cm. The degree of flocculation was greater at 60–80 cm than at 0–20 and 20–40 cm. However, the degree of dispersion was higher at 0–20 cm.

The aggregate stability index and the percentage of A > 1 were higher at 0–20 and 20–40 cm, and the lowest values were observed at 60–80 cm. The highest stable aggregates and aggregate stability index values at 0–20 cm result in greater resistance to degradation.

The total clay was higher at 40–60 and 60–80 cm, followed by 20–40 cm, which was higher than 0–20 cm.

Table 2. Particle density (PD), macroporosity (MACRO-P), microporosity (MICRO-P), total soil porosity (TP), weighted average diameter (WAD), aggregate stability index (ASI), stable aggregates (SA), aggregates > 1 mm (A > 1), dispersed clay (DC), total clay (TC), degree of dispersion (DD), and degree of flocculation (DF) in sugarcane cultivation soil under irrigation treatments with TSE or SRW at different soil depth layers (0–20 cm, 20–40 cm, 40–60 cm, and 60–80 cm). NI = non-irrigated control treatment.

Variables	Soil Depth Layers			
	0–20 cm	20–40 cm	40–60 cm	60–80 cm
PD (g cm^3)	2.62 ± 0.13 *	2.63 ± 0.15	2.59 ± 0.21	2.62 ± 0.16
MACRO-P (cm^3 cm^3)	0.13 ± 0.04 a	0.10 ± 0.04 b	0.09 ± 0.03 b	0.12 ± 0.04 a
MICRO-P (cm^3 cm^3)	0.41 ± 0.03	0.41 ± 0.02	0.43 ± 0.03	0.41 ± 0.04
TP (cm^3 cm^3)	0.54 ± 0.03 a	0.51 ± 0.04 c	0.52 ± 0.04 bc	0.53 ± 0.03 ab
WAD (mm)	1.68 ± 0.40 a	1.64 ± 0.51 ab	1.43 ± 0.62 b	1.18 ± 0.45 c
SA (%)	26.80 ± 11.12 a	26.05 ± 13.84 a	23.14 ± 15.96 ab	17.97 ± 10.98 b
A > 1 (%)	47.89 ± 9.84 a	46.87 ± 13.77 a	37.66 ± 17.28 b	29.77 ± 12.73 c
ASI (%)	93.45 ± 2.73 a	92.80 ± 3.76 a	89.06 ± 4.81 b	84.88 ± 5.64 c
DC (g kg^{-1})	382.38 ± 27.34	417.23 ± 25.39	416.83 ± 49.52	376.27 ± 110.86
TC (g kg^{-1})	558.82 ± 29.26 c	587.46 ± 25.81 b	630.20 ± 56.71 a	622.13 ± 26.22 a
DF (%)	31.47 ± 5.00 b	28.91 ± 6.33 b	33.64 ± 7.90 ab	39.56 ± 17.74 a
DD (%)	68.53 ± 5.00 a	71.09 ± 6.30 a	66.36 ± 7.90 ab	60.44 ± 17.73 b

Means followed by the same letter do not differ among themselves by Tukey's test ($p \leq 0.05\%$). Lowercase letters indicate comparison between soil depth layers. * Mean values followed by SD.

No significant differences were found between irrigation treatment water under irrigation for the variables particle density, macroporosity, microporosity, total porosity, weighted average diameter, stable aggregates, aggregate stability index, dispersed clay, total clay, degree of flocculation, and degree of dispersion (Table 3). These results indicate that subsurface drip irrigation with TSE and SRW did not affect the physical properties of the soil used for sugarcane cultivation.

Table 3. Particle density (PD), macroporosity (MACRO-P), microporosity (MICRO-P), total soil porosity (TP), weighted average diameter (WAD), aggregate stability index (ASI), stable aggregates (SA), aggregates > 1 mm (A > 1), dispersed clay (DC), total clay (TC), degree of dispersion (DD), and degree of flocculation (DF) in sugarcane cultivation soil under irrigation treatments with TSE or SRW dripped at 20–40 cm of depth. NI = non-irrigated control treatment.

Variables	Irrigation Treatment Water				
	TSE 20 cm	TSE 40 cm	SRW 20 cm	SRW 40 cm	NI
PD (g cm^3)	2.56 ± 0.18 *	2.65 ± 0.21	2.61 ± 0.10	2.63 ± 0.18	2.64 ± 0.13
MACRO-P (cm^3 cm^3)	0.11 ± 0.03	0.11 ± 0.03	0.12 ± 0.04	0.10 ± 0.04	0.13 ± 0.04
MICRO-P (cm^3 cm^3)	0.42 ± 0.03	0.42 ± 0.02	0.42 ± 0.02	0.42 ± 0.04	0.41 ± 0.05
TP (cm^3 cm^3)	0.52 ± 0.04	0.52 ± 0.03	0.54 ± 0.03	0.52 ± 0.05	0.54 ± 0.03
WAD (mm)	1.55 ± 0.61	1.26 ± 0.25	1.49 ± 0.55	1.52 ± 0.56	1.58 ± 0.61
A > 1 (%)	43.05 ± 17.19	35.03 ± 9.41	41.06 ± 15.80	40.36 ± 15.94	43.24 ± 16.85
SA (%)	24.84 ± 15.42	17.45 ± 5.24	23.72 ± 13.61	25.16 ± 13.70	26.29 ± 15.48
ASI (%)	91.21 ± 5.37	89.31 ± 4.19	90.14 ± 5.89	89.27 ± 6.00	90.29 ± 6.00
DC (g kg^{-1})	406.57 ± 44.04	404.25 ± 90.03	413.56 ± 42.92	381.44 ± 76.34	385.04 ± 67.27
TC (g kg^{-1})	597.97 ± 44.80	603.94 ± 32.91	594.81 ± 69.14	601.35 ± 41.85	600.19 ± 35.93
DF (%)	31.91 ± 6.48	32.89 ± 14.93	30.04 ± 7.48	36.18 ± 13.12	35.95 ± 10.62
DD (%)	68.09 ± 6.47	67.11 ± 14.93	69.96 ± 7.48	63.82 ± 13.12	64.05 ± 10.60

* Mean values followed by SD.

3.2. Pearson Correlation and Multivariate Analysis

Correlation analysis showed that the root development variables were positively correlated regarding irrigation treatment water and soil depth layers, that is, RL was positively correlated with RV and RA (Figure 4a,b). As for soil physical properties, SA was positively correlated with WAD and A > 1 in the two PCAs. TP correlated with MACRO-P for cultivation type, as well as ASI and SD and DD and DC (Figure 4a). At each layer, SD and SA were positively correlated with DD. SA also showed positive correlations with ASI, WAD, and A > 1. ASI, WAD, and A > 1 positively correlate with one another regarding layers (Figure 4b).

Conversely, DF was negatively correlated with DC and DD regarding cultivation type, and with DD, SD, and SA regarding layer level. PD was also positively correlated with SD regarding cultivation and MICRO-P correlated with PD regarding depth layer level. TC was correlated with root biometric variables.

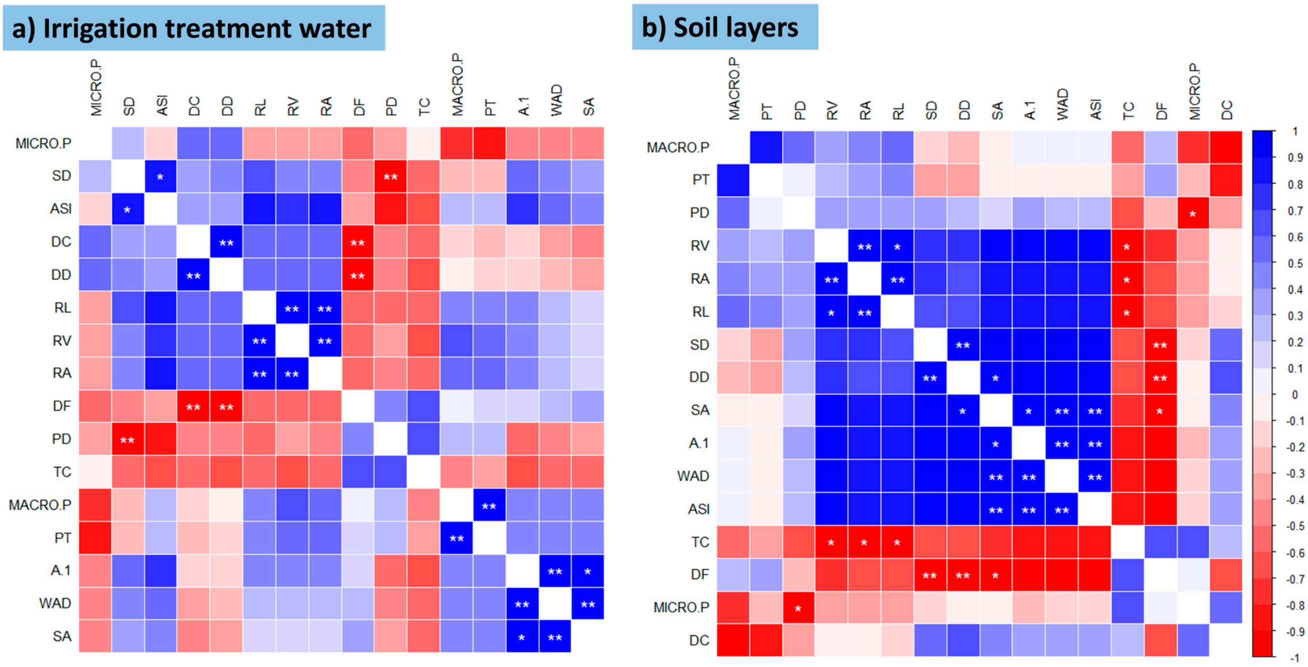

Figure 4. Correlation between variables root volume (RV), root area (RA), root length (RL), soil density (SD), particle density (PD), macroporosity (MACRO-P), microporosity (MICRO-P), total soil porosity (TP), weighted average diameter (WAD), aggregate stability index (ASI), stable aggregates (SA), aggregates > 1mm (A > 1), dispersed clay (DC), total clay (TC), degree of dispersion (DD), and degree of flocculation (DF) in sugarcane cultivation soil under irrigation treatments with TSE or SRW (**a**) at different soil depth layers (0–20 cm, 20–40 cm, 40–60 cm, and 60–80 cm) (**b**). * significant at 5% probability; ** significant at 1% probability.

PCA for irrigation treatment water showed that the first two components jointly explain 76.60% of the total data variation. These components showed that the highest values related to root development (RV, RA, and RL), SD, and ASI are related to irrigation treatments at a depth of 20 cm (Figure 5a), while the highest values for TC and PD are related to SWR at a 40 cm depth.

Analyses at different layers of soil depth showed that the first two components jointly explain 90.70% of the total data variation, with the most significant root development values (RV, RA, and RL) being related to the shallower soil layers (0–20 cm) (Figure 5b).

Thus, the root characteristics and physical properties of the soil showed greater similarity between samples collected at 0–20 and 20–40 cm and between 40–60 and 60–80 cm. The samples collected at 0–20 cm and 20–40 cm showed higher mean RV, RA, RL, PD, WAD, SD, SA, ASI, A > 1, and DD values, and lower mean TC, DF, and MICRO-P values, with the opposite occurring with treatments at 40–60 cm and 60–80 cm.

Cluster analysis revealed three distinct groups among the treatments, which were primarily established by the soil depth criterion (Figure 6). One of the groups was established by the data obtained at 0–20 cm, another by data at the 40–60 and 60–80 cm layers grouped together, and the third group by data collected at the 20–40 cm layer.

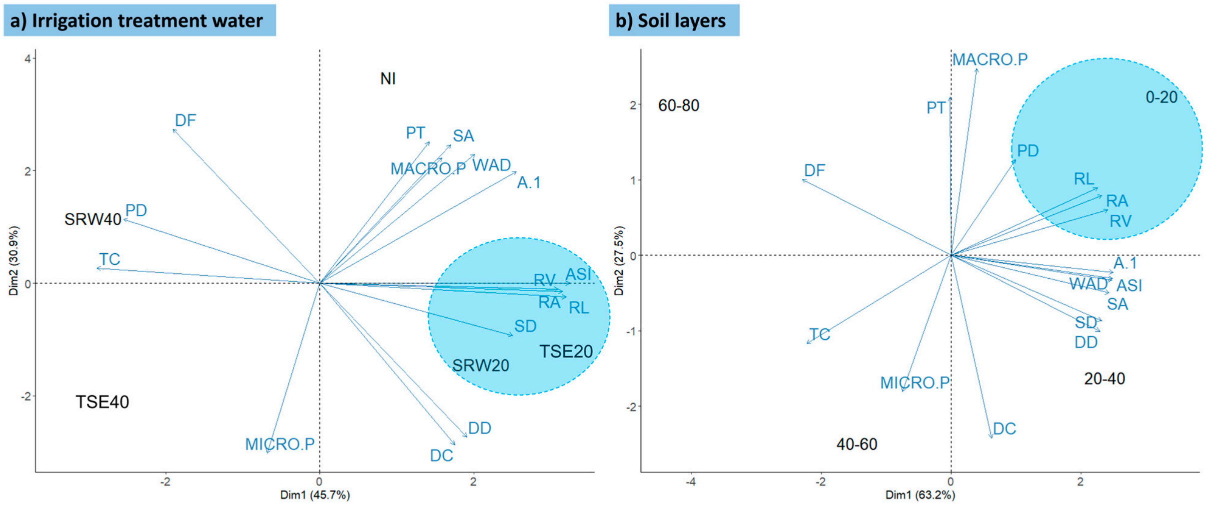

Figure 5. Two-dimensional dispersion of the factorial loading matrix and physical property scores of the soil and root system of sugarcane under irrigation treatments with TSE or SRW dripped at 20–40 cm of depth. NI = non-irrigated control treatment. The analyzed variables were root volume (RV), root area (RA), root length (RL), soil density (SD), particle density (PD), macroporosity (MACRO-P), microporosity (MICRO-P), total soil porosity (TP), weighted average diameter (WAD), aggregate stability index (ASI), stable aggregates (SA), aggregates > 1 mm (A > 1), dispersed clay (DC), total clay (TC), degree of dispersion (DD), and degree of flocculation (DF).

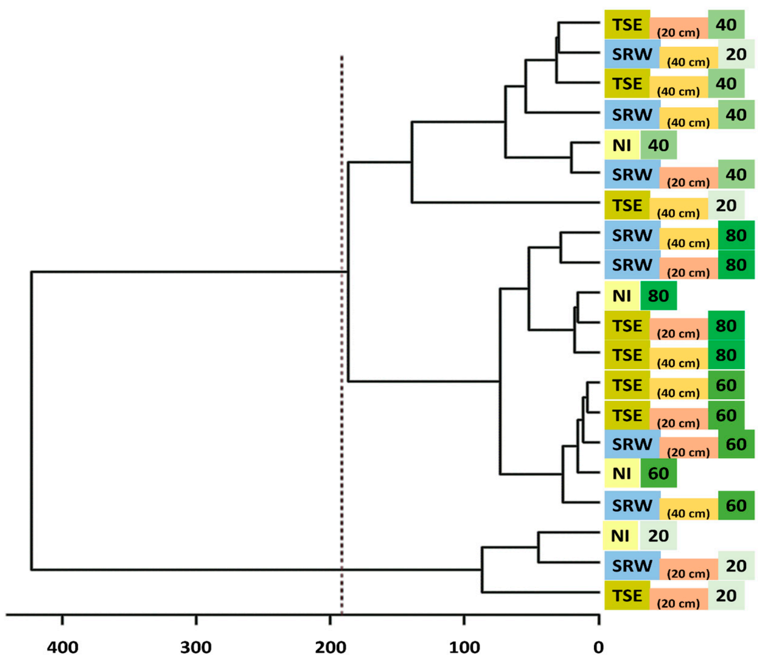

Figure 6. Cluster analysis of sugarcane under irrigation treatments with TSE or SRW dripped at 20–40 cm of depth. NI = non-irrigated control treatment. Soil data at 0–20, 20–40, 40–60, and 60–80 cm.

4. Discussion

4.1. Sugarcane Irrigation with TSE and SRW at the Shallowest Layer Improved Root Development but Increased Soil Density

The root surface captures water and nutrients in sugarcane. The crops irrigated with TSE and SRW at a depth of 20 cm provided adequate water levels to the plants, with greater root development (RV and RA), which had a positive impact on water and nutrient absorption by the plants [60–63]. As the effect of TSE and SRW treatments on sugarcane root development was similar, from a water use management point of view, sugarcane irrigation with TSE should be considered. This is because the reuse of sewage water for crop irrigation has proven necessary, due to the scarcity of fresh water and the depletion of groundwater [7]. However, when evaluating the impact of using TSE on public health, given the increase in population exposure to pathogens and heavy metals, both of farmers and consumers, the use of SRW becomes a more advantageous choice. Although we know that irrigation with TSE of agricultural crops destined for the production of biofuels represents a strategic issue, permanent monitoring of areas already irrigated with wastewater is recommended [64,65]. Therefore, new work must be conducted to better understand the advantages and disadvantages of using TSE in agricultural systems.

The root length included the entire root extension, with higher averages being observed in plants irrigated with $TSE_{(20\ cm)}$ compared to TSE and SRW at a depth of 40 cm. This indicates greater root branching and extension, ensuring improved soil use and, consequently, better water and nutrient absorption [66–68]. Well-developed root systems are fundamental for sugarcane adaptation to different environmental conditions, improving survival [69,70].

On the other hand, irrigation provided in the shallowest layer increased soil density and soil compaction, i.e., there was an increased amount of soil mass per unit volume [71–73], hindering root penetration and water movement, affecting sugarcane development [74–77] and long-term water infiltration into the soil [78–80]. However, this negative effect was balanced by better root development in the shallower layers of the soil, ensuring efficient use of soil resources, increasing nutrient and water absorption and resulting in better crop growth and development [81–83]. Some studies relate increased root volume with root system growth and expansion in sugarcane, which provides favorable conditions for crop development and yield [84,85].

Here, we evidenced an improvement in the root development of sugarcane under the effect of TSE. This happens because TSE can contain significant amounts of N, P, and K, increasing soil fertility [86]. However, as these effluents concentrate toxic elements, organic pollution, and saline ions, the continuous use of this resource may incur secondary effects on soil properties [87] and root development. Studies have demonstrated that TSE can significantly reduce soil pH [88], which interferes with the absorption of important nutrients and results in decreased plant growth and loss of productivity.

4.2. TSE and SRW Can Be Used to Irrigate Sugarcane without Affecting Root Formation at Shallower Layers, but We Highlight the Need to Monitor Compaction, Especially at Deeper Layers

The results of this study have agronomic and environmental importance. The use of TSE in irrigation is a water reuse approach that helps reduce water scarcity and water body pollution [89–92]. However, we should carefully consider its potential impact on soil and crops [93,94]. TSE can be more advantageous for sugarcane root development at a shallower depth. Therefore, it is necessary to evaluate possible compaction, as it can be harmful to soil aeration and root growth in the long term. Kadhim et al. [95] state that sewage may contain components that increase the resistance of the soil where they are applied. Similarly, Feitosa et al. [96] demonstrated that sewage components can reduce the void content, increasing particle packing and reducing soil collapsibility. This makes it more compacted. Therefore, monitoring the quality of TSE is important to ensure that it meets appropriate standards for use in agriculture, does not compromise soil quality, and does not represent a risk to human health and to the environment [97–99].

4.3. Sugarcane Irrigation with TSE and SRW Improves Soil Physical Qualities in Shallower Depth Layers, with the Opposite Result in Deeper Layers

Particle density is the mass of solid soil particles per unit volume [100]. The results indicate similar values between the soil layers, with no significant variation between depths. On the other hand, macroporosity refers to the porosity of the soil in relation to the larger spaces between particles, where water and air can be stored and circulate freely [101–106]. Reduced macroporosity related to depth may indicate soil compaction at the layers, affecting the movement of water and air and, consequently, the development of the root system [107–109].

The greater total porosity at the 0–20 cm soil depth layer can be justified due to the greater macroporosity of the surface layer, which allows better water storage and, therefore, greater total porosity [110–112]. This variable is the sum of macroporosity and microporosity and represents soil voids that can store water and air [113–115].

Weighted average diameter is a measure of the average size of soil aggregates [116,117], with the highest average values observed for this variable at 0–20 cm, which indicates that soil aggregates have become larger in the surface layer, resulting in greater soil stability at this layer [118–120].

Stable aggregates represent the soil's resistance to degradation and aggregate breakdown during management [121–123], while the highest degree of flocculation at 60–80 cm indicates greater particle agglomeration. However, the greater degree of dispersion at 0–20 cm means less particle aggregation and greater dispersion. These differences may be related to the chemical and physical properties of the soil at each depth. The degree of flocculation and dispersion refers to the aggregation of soil particles [124,125].

As depth increases, the aggregate stability decreases, which may be related to soil compaction and degradation at deeper layers [126–128]. An increased amount of total clay can be associated with the process of vertical translocation of particles in the soil [129–131], which results in greater amounts of clay negatively correlated with root development at the deeper layers evaluated. A loss of soil quality at increased depths was evidenced by cluster analysis, which defined a group formed by the data collected at 40–60 and 60–80 cm. Thus, soil compaction and physical properties should be monitored in sugarcane cultivation systems to avoid productivity losses due to the physical unsuitability of the soil.

This study offers perspectives for using alternative water sources in sugarcane crops. Given the current moment of constant environmental pressure and future challenges in possible scenarios of global warming and water scarcity, this study proposes the reuse of effluents and wastewater, which are still little used in agriculture, to ensure sugarcane productivity. We expect that this study will help spread this practice and stimulate studies with other alternative sources of water and nutrients.

5. Conclusions

Soil layers irrigated with TSE and SRW can have significantly varied physical properties at different depths, with shallower layers presenting better porosity, soil aggregation, and aggregate stability, which improve sugarcane root development and growth. On the other hand, deeper soil layers have lower macroporosity and higher total clay volume, indicating the possibility of compaction and greater limitations for root growth. These results are important for understanding soil quality and provide significant information for agricultural management and for the implementation of sustainable soil conservation practices. This study shows the efficiency of TSE and SRW as an alternative water source for sugarcane crops.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14040788/s1, Figure S1: Distribution of climate data in the experimental area during the cultivation period of sugarcane under irrigation treatment with TSE or SRW. The data include plant cane (a) and ratoon cane periods (b) and precipitation, humidity, and temperature.; Table S1: Pre-cultivation chemical characterization of a dystrophic red latosol used for sugarcane under irrigation treatments TSE or SRW. Samples collected at 0–0.2 m soil depth.;

Table S2: Pre-cultivation characterization regarding sodic-saline properties and the classification by Richards (1954) of a dystrophic red latosol used for sugarcane under irrigation treatments TSE or SRW. Samples collected at 0–0.2, 0.2–0.4, 0.4–0.6, and 0.6–0.8 m soil depths.; Figure S2: FEAGRI–UNICAMP integrated sewage treatment system used to generate the TSE used to irrigate sugarcane crops.; Table S3: Monthly averages of the properties of TSE and SRW used to irrigate sugarcane crops.

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