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Efficiency of a biodigester septic tank in sewage treatment and agricultural reuse in forage palm cultivation

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ABSTRACT

This study evaluated the efficiency of a biodigester septic tank (BST) in treating domestic sewage and investigated the effects of reusing treated effluents on forage cactus cultivation. The performance of the BST was observed through the physicochemical and microbiological parameters of the influents and effluents. Forage cactus irrigation was carried out with different proportions of treated domestic sewage effluent (TDWE) and rainwater (RWA): 0:100% (T1), 25:75% (T2), 50:50% (T3), 75:25% (T4), 100:0% (T5) (TDWE:RWA), and Tc (10% RWA). Soil analysis was performed before and after planting to verify the effect of the tested treatments on the soil. Biometric analyses of the crop were performed throughout the growing cycle, in addition to water response indices (WRI). The experimental design was completely randomized with three replicates. The BST demonstrated efficiency in treating domestic sewage, generating effluent of adequate quality for agricultural reuse. Treatment T5, with 100% treated effluent, may have caused nutritional imbalance, since the best crop development was observed in T4 (75% TDWE and 25% RWA), suggesting that dilution favored the agronomic performance of the forage cactus. Therefore, the results demonstrate the technical viability of the BST system effluent as an alternative source of water and nutritional input for forage cactus cultivation.

Keywords: agricultural reuse, cactus, effluent.

Eficiência da fossa séptica biodigestora no tratamento de esgoto e fertirrigação da palma forrageira

RESUMO

Esse estudo avaliou a eficiência de uma fossa séptica biodigestora (FSB) no tratamento de esgoto doméstico e investigou os efeitos do reúso dos efluentes tratados no cultivo da palma forrageira. O desempenho da FSB foi observado por meio de parâmetros físico-químicos e microbiológicos dos afluentes e efluentes. A irrigação da palma foi realizada com diferentes proporções de efluentes de esgoto doméstico tratado (EEDT) e água da chuva (ACH): 0:100%

(T1), 25:75% (T2), 50:50% (T3), 75:25% (T4), 100:0% (T5) (EEDT:ACH) e Tc (10% ACH). Foi realizada análise do solo antes e após o plantio para verificar o efeito dos tratamentos testados no solo. Foram realizadas análises biométricas na cultura ao longo do ciclo de cultivo, além de índices de resposta hídrica (IRH). O delineamento experimental foi inteiramente casualizado com três repetições. A FSB demonstrou eficiência no tratamento de esgoto doméstico, gerando efluente com qualidade adequada para o reúso agrícola. O tratamento T5, com 100% de efluente tratado, pode ter causado desbalanceamento nutricional, uma vez que o melhor desenvolvimento da cultura foi observado no T4 (75% de EEDT e 25% de ACH), sugerindo que a diluição favoreceu o desempenho agronômico da palma. Assim, os resultados evidenciam a viabilidade técnica do efluente do sistema FSB como fonte alternativa de água e insumo nutricional para o cultivo da palma forrageira.

Palavras-chave: cactácea, efluente, reúso agrícola.

1. INTRODUCTION

Water shortages are one of the main limitations to the sustainable development of agriculture in the semiarid region of Northeast Brazil. Characterized by high temperatures and low rainfall, this region faces constant challenges in maintaining agricultural and livestock activities. In this context, forage cactus stands out as a crop strategy, especially during the dry season, due to its tolerance to water deficits, its forage production capacity, and its high water and nutrient content, essential for animal feed (Gomes and Willegaignon, 2021).

Worldwide, forage cactus is cultivated on over one million hectares (ha) for animal feed, with the Brazilian Northeast being the main producing region (IBGE, 2017). In Bahia, approximately 138,000 hectares of forage cactus are cultivated, representing approximately 28% of the entire planted area in the Northeast and the largest cultivated area in the world. The predominant species are the Giant Forage Cactus (*Opuntia fícus-indica*) and the Sweet or Small Forage Cactus (*Nopalea cochenillifera*), which are sources of energy and water for livestock, making them essential for family farmers in the semi-arid region of Bahia (Almeida, 2011; Campos, 2018; Matos, 2020).

Although adapted to the climate conditions of the semiarid region, the productivity of forage cactus is still influenced by the amount and distribution of rainfall. Therefore, water supply, even in reduced volumes, can improve the crop's agronomic performance (Campos *et al.*, 2021).

In this context, the reuse of treated wastewater emerges as an alternative to meet the palm's water demand without compromising the region's scarce water resources. Among the types of reused water, treated domestic sewage effluent is the most widely used, as it not only provides water for irrigation but also provides essential nutrients for plant growth, reducing the need for chemical fertilizers and production costs (Rocha *et al.*, 2023).

According to Moura *et al.* (2020), several technologies have been developed for the treatment and refinement of wastewater for reuse, including adsorption on activated carbon, oxidation with ozone, chlorine dioxide, and hydrogen peroxide, membrane separation processes (microfiltration, ultrafiltration, nanofiltration, and reverse osmosis), reverse electrolysis, ion exchange, distillation, and chemical precipitation. However, these technologies are expensive and often make their adoption unfeasible in rural communities in Northeast Brazil.

Given this reality, the biodigester septic tank (BST), developed in 2001 by the Brazilian Agricultural Research Corporation (EMBRAPA), has established itself as a decentralized, low-cost wastewater treatment technology suitable for rural communities. Based on anaerobic digestion (AD), the BST allows for sewage treatment, generating effluent that can be used in agriculture as organic fertilizer (Figueiredo *et al.*, 2019; Moura *et al.*, 2020).

However, daily domestic wastewater production is not always sufficient to fully meet crop water demands. Therefore, the capture and supplemental use of rainwater represents a viable strategy to mitigate this limitation. According to Khan *et al.* (2021), the combined reuse of rainwater and domestic wastewater constitutes a social technology that favors more sustainable agricultural practices, contributing to increased productivity and income per hectare for family farmers, and is therefore a useful strategy for the semiarid region.

Therefore, understanding the composition of effluents generated by anaerobic digestion is crucial to assessing whether they meet the quality standards for agricultural reuse and the nutritional requirements of the crop. This knowledge is essential to ensure proper effluent management, given its importance as a biofertilizer in agriculture. Therefore, this study evaluates the efficiency of a biodigester septic tank (BST) in treating domestic sewage and investigates the effects of reusing treated effluents in forage cactus cultivation.

2. MATERIAL AND METHODS

The biodigester septic tank (BST) installation and the cultivation of forage palm was carried out in the State University of Feira de Santana (UEFS) in the municipality of Feira de Santana – BA (Brazil).

Raw sewage was pumped from a septic tank, which received sewage from a UEFS building, to a 1,000 L reservoir. From this reservoir, the sewage was directed to the BST system, composed of two fermentation modules and a treated effluent storage module, all with an individual capacity of 100 L. The total volume of the system needed to be reduced from 1,000 L to 100 L due to the water table level in the installation area, since, according to Galindo *et al.* (2019), the system must be installed at least 1.5 m above the water table.

After assembling the BST, 1 liter of fresh cattle manure diluted in 1 liter of tap water was added to the first fermentation module to inoculate the system. This operation was performed only in the first month of operation of the BST, aiming to accelerate the initial phase of the organic matter degradation process, since the microorganisms present in the manure aid in the acclimation of the sewage microbiota. From then on, the system received 10 liters of raw domestic sewage daily at 10:00 a.m., maintaining a hydraulic retention time (HRT) of 20 days.

The influents (raw sewage) and treated effluents were monitored by collecting samples for analysis of their physical, chemical, and microbiological characteristics. The first four collections took place between September and January, and the last two were conducted in March and May. This temporal distribution aimed to evaluate the efficiency of the BST under different operating conditions, covering both the dry season (September to November) and the period of less academic activity (December and January), as well as the rainy season (March and May).

The influents were collected at an outlet that preceded the first fermentation module. The effluents were collected in the last reservoir. The samples were then sent to the UEFS Sanitation Laboratory.

The analyses were performed in triplicate, except for the microbiological analyses, which were performed according to the Colilert Enzymatic Chromogenic Substrate method (Covert *et al.*, 1989). Table 1 displays the determined physical-chemical parameters and their respective methods, which are from the Standard Methods for the Examination of Water and Wastewater (APHA *et al.*, 2017). The temperature was measured *in situ*.

The quality of the treated effluents was evaluated based on the parameters established by Resolution nº 75/2010 of the State Water Resources Council (CONERH) (Bahia, 2010), in the water quality guidelines for irrigation proposed by Ayers and Westcot (1987) and in other relevant regulations, with the aim of verifying its suitability for agricultural reuse.

Table 1. Physicochemical parameters evaluated and methods.

Parameters	Unit	Method
pH	-	Electrometric
Temperature	ºC	Digital thermometer
Electrical conductivity	dS m^{-1}	Conductivity meter
Biochemical oxygen demand ($BOD_{5.20}$)	mg L^{-1}	Respirometric
Chemical oxygen demand (COD)		Closed reflux
Total nitrogen (TN)		Kjeldahl in urine
Phosphorus (P)		Ascorbic acid
Potassium (K^+)		Atomic absorption spectrometry

Source: Authors (2023).

The experimental design was completely randomized, with three replicates and six treatments (Table 2). The control treatment (Tc) consisted of applying 10% of the crop's water needs using rainwater. This strategy aimed to provide a minimum irrigation depth for the palm, as the cultivation was carried out in pots, preventing direct absorption of water from the soil. The treated effluent came from the BST, and rainwater was collected at the UEFS. Each treatment was arranged in blocks with three replicates, totaling 18 experimental plots with spacing of 1.5 m x 0.30 m, occupying an area of approximately 9 m². It should be noted that no chemical fertilizers were applied to any of the treatments evaluated.

Table 2. Treatments used in the cultivation of forage palm (*Opuntia ficus-índica* (L.) Mill.).

Treatments	Rainwater (RW)	Effluent (TDWE)
T1	100%	0%
T2	75%	25%
T3	50%	50%
T4	25%	75%
T5	0%	100%
Control treatment (Tc)	10%	0%

Source: Authors (2023).

The species of forage palm used in this study was *Opuntia fícus-índica* (L.) Mill., known as Gigante, since it is the most cultivated in the semiarid region of Bahia.

Before planting, a soil sample (50 g) was collected from the 0-20cm depth layer using an auger to characterize the physical-chemical attributes and organic matter, in order to evaluate soil fertility (Table 3). The analyses were performed at the Fertilizer, Soil and Environmental Monitoring Analysis Laboratory LTDA.

The rackets were planted whole and individually in 20 L pots, with the aim of allowing greater control over the development of the crop, in an east-west direction, with 40% of their total length buried. Irrigation was performed manually using test tubes. Cultivation was continuous for 230 days, covering the four phenophases of the forage cactus cycle (Lima *et al.*, 2021).

The irrigated depth was calculated based on the reference evapotranspiration (ETo) obtained by the Penman-Monteith method (Allen *et al.*, 1998), using data from the meteorological station installed next to the UEFS, under the responsibility of the National Institute of Meteorology (INMET).

Table 3. Characterize the physical-chemical attributes and organic matter of the soil used in the experiment.

Parameter	Unit	Concentration
pH	-	4.4
Exchangeable acidity		0.2
Potential acidity	$cmol_c\ dm^{-3}$	2.7
Cation exchange capacity		4.3
Organic matter	$g\ kg^{-1}$	12.2
Calcium + Magnesium		1.4
Potassium		45.0
Phosphorus		11.0
Copper	$mg\ dm^{-3}$	0.4
Iron		5.4
Zinc		0.6
Manganese		0.7

Source: Authors (2023).

After obtaining the ETo, crop evapotranspiration (ETc) was quantified using the crop coefficient (Kc). Subsequently, the accumulated irrigation need was quantified using the ETc and precipitation data. Finally, each pot's weekly volume (Vse) of irrigation water received was determined by multiplying the accumulated irrigation need by the pot's surface area.

Biometric measurements were performed monthly on all plants in the experimental area, namely: plant height (PH), plant width (PW), and number of cladodes in order of appearance on the plant (NC_n). After six months the cladodes were counted in the laboratory by their order of appearance, measuring their length (CL), width (CW), and thickness (CT).

Subsequently, the cladodes were weighed individually, and the plant's total green matter (GM) was verified by adding the individual weight of all cladodes. After this procedure, they were dried in a forced circulation oven at 65°C until dry weight stabilized. Then, the percentage of dry matter (DM) of the plants was calculated through the relationship between dry and green matter, determining the biomass of the plants (Queiroz *et al.*, 2015).

Considering the biometric data at the time of collection and the accumulated ETc values for the cycle, the water response indexes (WRI) were calculated. The biometric data of the cladodes, plants, and biomass data provided the morphological indices: Soil Cover Index (SCI), Production Volume Index (PVI), Photosynthetic Area Distribution Index (PADI), and Plant Cladode Distribution Index (PCDI) (Queiroz *et al.*, 2015).

The water response morphological indices were submitted to the Shapiro-Wilk test to verify normality and analysis of variance (ANOVA) to compare the effects of the treatments. Tukey's mean tests were performed at a probability level of 0.05. All statistical analyses were performed using the R Studio program.

3. RESULTS AND DISCUSSIONS

According to Table 4, the pH of the influents ranged from 7.1 to 7.9, within the recommended range for anaerobic digestion, thus favoring the activity of microorganisms responsible for the decomposition of organic matter. This condition is especially favorable for the methanogenic phase of the process, which requires a neutral to slightly alkaline environment. The effluent pH values ranged from 6.5 to 7.6, slightly lower than those observed in the tributaries. This variation suggests the degradation of organic acids, promoted by the activity of methanogenic archaea, which act most efficiently in pH ranges between 6.7 and 7.5 (Amaral *et al.*, 2019). These results indicate that the anaerobic digestion process occurred satisfactorily, with methane production and partial stabilization of the organic matter.

Table 4. Physicochemical characterization in the influents and effluents of the biodigester septic tank (BST) (mean ± standard deviation).

Samples	pH		Temperature (ºC)		Electrical conductivity (dS m $^{-1}$)	
	Influents	Effluents	Influents	Effluents	Influents	Effluents
1	7.8 ± 0.00	7.2 ± 0.00	24	24	2.2 ± 0.03	2.1 ± 0.04
2	7.9 ± 0.00	7.6 ± 0.00	24	24	2.2 ± 0.05	2.1 ± 0.01
3	7.9 ± 0.06	6.5 ± 0.29	27	28	2.2 ± 0.06	2.0 ± 0.06
4	7.1 ± 0.06	6.6 ± 0.15	26	28	2.2 ± 0.03	1.7 ± 0.01
5	7.7 ± 0.00	7.2 ± 0.06	24	24	2.1 ± 0.02	1.7 ± 0.00
6	7.6 ± 0.10	7.3 ± 0.10	26	27	2.3 ± 0.17	1.7 ± 0.00
Average	7.7	7.1	25.2	25.8	2.2	1.9

Source: Authors (2023).

The sharper pH reduction observed in the third and fourth collections may be associated with the accumulation of volatile organic acids (VOA), resulting from the intensification of the acidogenic phase. This intensification, in turn, may have been caused by kinetic limitations associated with fluctuations in organic load during academic recess periods, when there is less sewage generation and, therefore, less organic matter input. This imbalance may have favored the predominance of fermentative bacteria, which produce VOA, to the detriment of methanogenic archaea, which are more sensitive to environmental variations (Sun *et al.*, 2021; Kostopoulou *et al.*, 2023).

Effluent temperatures ranged from 24°C to 28°C (Table 4), falling within the mesophilic range (20–45°C), ideal for the activity of microorganisms responsible for anaerobic digestion. This thermal stability favors the performance of the biological process and is in line with expected values for systems such as biodigester septic tanks, depending on location and seasonality (Soares *et al.*, 2016).

The electrical conductivity (EC) of the effluents ranged from 1.7 to 2.1 dS m^{-1} (Table 4), indicating a reduction in salt concentration compared to the influents, possibly associated with a decrease in nitrogen compounds (Table 6), as also observed by Shcherbakov *et al.* (2009). In general, the average pH and EC values of the effluents (Table 4) meet the limits established for water intended for irrigation, according to Ayers and Westcot (1987) and Bahia (2010), corroborating the results obtained by Oliveira (2018). However, the continued use of this effluent must be carefully monitored, especially in soils with low drainage capacity or in salinity-sensitive crops, since, according to Soares *et al.* (2016), EC values above 3.0 dS m^{-1} impose severe restrictions on agricultural reuse.

The average biochemical oxygen demand (BOD) in the influents ranged from 23.0 to 172.5 mg L^{-1}, while in the effluents it ranged from 6.0 to 82.0 mg L^{-1} (Table 5), resulting in an average removal efficiency of 62.2%. This performance is superior to that observed in conventional septic tanks, demonstrating the potential of the biodigester system in stabilizing organic matter, an essential procedure for minimizing the risks of contamination and phytotoxicity when effluents are used in agriculture. However, it is worth noting that the average BOD removal was below the range recommended by Bahia state regulations, which establish minimum efficiencies between 80% and 95%, depending on the socioeconomic profile of the population served (Morais and Santos, 2019).

Table 5. Concentrations of biochemical oxygen demand (BOD), chemical oxygen demand (COD), and thermotolerant coliforms in the influents and effluents of the biodigester septic tank (BST) (mean ± standard deviation).

BOD $_{5.20}$ (mg L^{-1})			
Samples	Influents	Effluents	Removal efficiency (%)
1	135.0 ± 52.99	60.0 ± 14.14	55.6
2	172.5 ± 10.61	82.0 ± 0.00	52.5
3	130.0 ± 0.00	45.0 ± 1.73	65.4
4	125.0 ± 0.00	33.3 ± 2.31	73.3
5	35.0 ± 0.00	6.0 ± 0.00	82.9
6	23.0± 0.00	13.0± 0.00	43.5
Average	103.4	39.9	62.2
COD (mg L^{-1})			
Samples	Influents	Effluents	Removal efficiency (%)
1	317.5 ± 36.4	214.5 ± 31.5	48.0
2	305.4 ± 4.95	152.7 ± 2.40	50.0
3	212.8 ± 24.32	82.5 ± 16.97	61.2
4	85.8 ± 0.00	60.0 ± 2.40	30.1
5	99.5 ± 9.80	56.0 ± 4.00	43.7
6	109.8 ± 0.00	53.2 ± 2.50	51.6
Average	188.5	103.15	47.4
Thermotolerant coliforms (NMP 100mL^{-1})			
Sample	Influents	Effluents	Removal efficiency (%)
1	2.0 x10^{1}	<1.8	91.0
2	2.2x10^{3}	4.5x10^{1}	97.9
3	1.4 x10^{3}	<1.8	99.9
4	2.0 x10^{1}	<1.8	91.0
5	3.3x10^{3}	<1.8	99.9
6	1.7x10^{3}	<1.8	99.9
	Average		96.6

Source: Authors (2023).

Furthermore, throughout the analyzed period, the BOD values of the effluents remained below 100 mg L^{-1}, a limit considered safe for agricultural irrigation, as it does not compromise water absorption by plant roots (Hespanhol, 2002), reinforcing the viability of the agronomic use of the effluent.The average BOD value in the effluents (39.9 mg L^{-1}) was lower than that described by Soares *et al.* (2016), who observed 59.2 mg L^{-1}, suggesting satisfactory performance. Furthermore, in the fifth and sixth collections, the BOD values were below 30 mg L^{-1} (Table 5), meeting the criteria for agricultural reuse.

Regarding chemical oxygen demand (COD), the average values in the influents ranged from 85.8 to 317.5 mg L^{-1}, and in the effluents, from 53.2 to 214.5 mg L^{-1}, with an average removal efficiency of 47.4% (Table 5). This performance was lower than that recorded by Figueiredo *et al.* (2019), who reported an average efficiency of 58.6%. The lower removal observed may be related to the origin of the sewage, already partially treated in a conventional septic tank, which tends to reduce the biodegradable load and, consequently, the efficiency of the BST in subsequent processes.

Despite this, the average COD values in the effluents are considered adequate for non-potable reuse, allowing the use of these effluents in crop irrigation, as long as aspects such as the nature of the soil, type of crop and frequency of application are considered, in order to avoid negative impacts due to the accumulation of organic matter in the environment.

Regarding thermotolerant coliforms (TerC), the influents presented concentrations between 2.0×10^1 and 3.3×10^3 NMP 100mL^{-1}, while the effluents ranged from <1.8 to 4.5×10^1 NMP 100mL^{-1}, resulting in a high average removal efficiency (96.6%). Sample 2 presented the highest concentration in the effluents (NMP 100mL^{-1}), but all others remained below 1.8 NMP 100mL^{-1}, indicating consistent sanitary performance.

These results are consistent with those reported by Novaes *et al.* (2002), who found a removal of approximately 70% of thermotolerant coliforms in the first fermentation module and the remaining 30% in the second. Similarly, Oliveira *et al.* (2021) observed efficient removal of these microorganisms in biodigester septic tank systems, with an average reduction of 5.09 $\log_{10}$ for *Escherichia coli*, highlighting the potential of this type of system in the microbiological treatment of domestic effluents.

Furthermore, the TerC values in the effluents meet the limits established by CONERH Resolution No. 75/2010 (Bahia, 2010) for agricultural reuse, corroborating Oliveira *et al.* (2021), who concluded that the effluent generated in their study presents adequate quality for subsurface irrigation and for crops grown far from the soil or in highly mechanized systems. Additionally, Torres *et al.* (2019) reported a 99.9% removal of thermotolerant coliforms from the aerial part of plants irrigated with treated effluent after the third day of irrigation suspension, which reinforces the biological safety of the use of treated effluents in agriculture, provided that appropriate management practices are adopted.

The average total nitrogen (TN) concentration in the influents ranged from 74.7 to 149.3 mg L^{-1}, while in the effluents it ranged from 28.0 to 112.0 mg L^{-1}, resulting in an average removal efficiency of 44.2% (Table 6). In the fifth and sixth collections, TN concentrations in the effluents were obtained, with higher removals (62.5% and 66.7%, respectively), indicating that the system may have reached a state of equilibrium in the nitrogen elimination and removal processes. This behavior may be associated with the adequacy of operational factors, such as hydraulic retention time, hydrogen potential, and temperature, which play a fundamental role in stabilizing microbial interactions.

Regarding phosphorus (P), the average concentrations in the influents varied between 8.2 and 19.5 mg L^{-1}, while in the effluents they ranged from 7.9 to 20.8 mg L^{-1}. The removal of P was not very expressive, with an average efficiency of only 4.3%, and an increase in the concentration in the effluents was even observed in the last two samples (Table 6). These results are consistent with those obtained by Figueiredo *et al.* (2019), who reported a similar removal efficiency (6.1%) in similar systems.

The increase in P in the treated effluent can be attributed to its release under anaerobic conditions during the hydrolysis and acidogenesis stages. In these phases, P, previously retained in organic molecules or associated with biomass, is solubilized mainly by the reduction of COD, used as a carbon source for the release of orthophosphate (PO_4^{3-}) (van Haandel *et al.*, 2009; Dai *et al.*, 2021). Furthermore, in the presence of acetic acid, polyphosphate-accumulating organisms (PAOs) assimilate this substrate and degrade their intracellular polyphosphates, releasing PO_4^{3-} into the liquid medium (Xi *et al.*, 2023). In aerobic systems, this PO_4^{3-} could be resorbed by PAOs in the activated sludge and removed with the discharge of the P-rich sludge (Dai *et al.*, 2021). However, in exclusively anaerobic reactors, such as the biodigester septic tank (BST), this mechanism does not occur, which results in higher P concentrations in the effluent.Regarding potassium (K^+), the average values ranged from 13.7 to 85.2 mg L^{-1} in the influents and from 15.6 to 90.9 mg L^{-1} in the effluents. In general, an increase in K^+ concentrations was observed throughout the process, with a final average of 49.2 mg L^{-1} in the effluents, compared to 43.8 mg L^{-1} in the influents, reflecting negative removals in all samples (Table 6).

Table 6. Concentrations of total nitrogen (TN), phosphorus (P), and potassium (K) in the influents and effluents of the biodigester septic tank (BST) (mean ± standard deviation).

Total nitrogen (mg L^{-1})			
Samples	Influents	Effluents	Removal efficiency (%)
1	140.0 ± 0.00	112.0 ± 0.00	20.0
2	149.3 ± 16.17	98.0 ± 19.80	34.4
3	126.0 ± 19.80	65.3 ± 16.17	48.1
4	84.0 ± 0.00	56.0 ± 0.00	33.3
5	74.7 ± 16.17	28.0 ± 0.00	62.5
6	84.0 ± 0.00	28.0 ± 0.00	66.7
Average	109.7	64.6	44.2
Phosphorus (mg L^{-1})			
Samples	Influents	Effluents	Removal efficiency (%)
1	10.1 ± 0.35	9.7 ± 0.17	4.0
2	8.9 ± 0.10	8.4 ± 0.12	6.0
3	8.6 ± 0.23	8.4 ± 0.07	3.3
4	8.2 ± 0.29	7.9 ± 0.31	3.7
5	19.5 ± 0.50	20.8 ± 0.58	-7.0
6	15.2 ± 0.35	17.3 ± 0.23	-14.0
Average	11.8	12.1	4.3
Potassium (mg L^{-1})			
Samples	Influents	Effluents	Removal efficiency (%)
1	16.3 ± 1.92	16.8 ± 0.74	-3.0
2	15.7 ± 1.87	15.9 ± 0.79	-0.8
3	13.7 ± 0.32	15.6 ± 0.80	-14.0
4	55.4 ± 0.28	68.4 ± 1.71	-19.0
5	85.2 ± 2.26	90.9 ± 2.69	-6.7
6	76.3 ± 3.90	87.8 ± 4.81	-15.0
Average	43.8	49.2	-9.8

Source: Authors (2023).

Potassium K^+ is also released during anaerobic digestion, primarily through microbial cell lysis, which promotes the release of intracellular K^+, normally associated with polyphosphate compounds in microorganisms (Ito *et al.*, 2017; Pereira *et al.*, 2018). The release of P and K^+ is intensified by acetate uptake, which increases with increasing dissolved organic carbon (DOC) concentration. Under these conditions, polyphosphates are degraded, releasing PO_4^{3-} and K^+, used in the production of adenosine triphosphate (ATP), essential for the conversion of volatile fatty acids to polyhydroxyalkanoate (Ito *et al.*, 2017). Therefore, the increase in P and K^+ concentrations in the effluent should not be understood as a system failure, but as a natural consequence of biomass stabilization during the anaerobic digestion process.

This increase can be attributed to the lysis of microbial cells during anaerobic digestion, which promotes the release of intracellular potassium (Pereira *et al.*, 2018). Thus, the increase in K^+ concentration in the effluents does not necessarily represent a system failure, but rather a consequence of the biomass stabilization process itself.

Although the average concentrations of TN, P, and K^+ in the effluents exceeded the recommended limits for agricultural reuse water according to Ayers and Westcot (1987), these nutrients represent the main macronutrients required by plants. Thus, although the use of these effluents requires appropriate management, especially regarding application frequency and soil characteristics, they have great potential as biofertilizers, as discussed by Mayer *et al.* (2021).

Regarding the cultivation of forage cactus with treated domestic effluents (TDWE), Table 7 presents the effects of the application of these effluents on the biometric variables (PH, PW and NCn) and biomass (VM and DM). A statistically significant difference was observed between the treatments for all variables, except for NCn, with treatment T4 presenting the best results.

Table 7. Effect of the use of treated domestic sewage effluents on biometric measurements and biomass of forage palm (*Opuntia fícus-índica* (L.) Mill.).

Treatments	Variables				
	PH	PW	NC_n	GM	DM
	cm		units	g	
Tc	50.000c	18.500d	1.000a	819.600c	48.020b
T1	47.500c	28.500c	1.333a	923.250c	57.535ab
T2	47.500c	18.000d	2.000a	1114.200b	55.675ab
T3	58.000b	35.000b	2.333a	1192.100b	66.810a
T4	64.000a	42.500a	2.333a	1431.650a	67.420a
T5	57.500b	33.000b	2.333a	1557.450a	64.710a
CV (%)	3.328	2.787	27.92	4.253	8.813

Source: Authors (2023).
PH – Plant height, PW – Plant width, NC_n – Number of cladodes according to the order of appearance in the plant, GM – Green mass, and DM – Dry mass. Means followed by the same lowercase letters vertically do not differ statistically from each other by the Tukey test ($p>0.05$).

Plants submitted to treatment T4 presented the highest average height (64cm) and width (42.5cm), demonstrating superior vegetative development compared to the other treatments, followed by plants cultivated in treatments T3 and T5. The greater height and leaf expansion observed in treatments with larger effluent volumes suggest greater nutrient availability, favoring more vigorous plant growth.

Regarding green mass (GM), treatments T4 and T5 also provided the highest accumulations of fresh biomass (1431.65 g and 1557.45 g, respectively), with statistically significant differences compared to the control (Tc) and treatments T1, T2, and T3. These results indicate that the application of TDWE in larger volumes may favor biomass accumulation, possibly due to the continuous supply of essential macronutrients, such as nitrogen, phosphorus, and potassium, elements abundant in the analyzed effluents (Table 6).

Dry mass (DM), in turn, showed higher values in treatments T3, T4, and T5, although there was no statistically significant difference compared to treatments T1, T2, and Tc. This may indicate that, despite the increase in GM, the rate of DM accumulation did not proportionally follow vegetative growth. This behavior may be related to the physiology of the forage cactus, which, as it is a cactus, has around 90% of its mass made up of water, which results in lower proportions of dry matter.

Regarding the number of cladodes (NCn), only first-order cladodes were observed, with averages ranging from 1.00 to 2.33 per plant, with no statistically significant differences between treatments. This result can be attributed to the experimental period of 230 days, shorter than the full crop cycle (365 days) (Lima *et al.*, 2021). Studies conducted in soil demonstrate greater emission of higher-order cladodes, favoring plant establishment; for example, Araujo (2023) recorded 4.44 cladodes per plant in the first cycle, while Santos *et al.* (2021) observed 7.00 cladodes in the second cycle. Thus, it is evident that the reduced cultivation time was a determining factor in the lower number of cladodes observed in this study.

Nevertheless, the highest average NCn values were recorded in treatments T3, T4, and T5 (2.33), suggesting a trend toward an increase in the number of cladodes with effluent application. These results corroborate the studies by Lemos *et al.* (2021) and Siqueira (2021), who also identified a direct relationship between effluent application and the increase in the number of cladodes, positively contributing to the productivity of forage forage cactus.

Overall, treatments T4 and T5 performed best in the variables pH, PW, GM, and DM, suggesting that the use of treated domestic effluents can increase forage cactus productivity, mainly due to the greater supply of nutrients essential for plant growth. These results are consistent with those obtained by Lemos *et al.* (2021), who also found that higher effluent doses promoted increases in biometric and biomass variables, mainly attributed to the mineralization of organic matter present in the effluent.

Table 8 presents the morphological indices evaluated in the forage cactus crop irrigated with TDWE. The results indicated significant statistical differences between treatments for the soil cover index (SCI) and production volume index (PVI), with emphasis on the T4 treatment. On the other hand, the photosynthetic area distribution index (PADI) and plant cladode distribution index (PCDI) remained constant at 100% in all treatments, a result attributed to the exclusive presence of first-order cladodes in the analyzed plants.

Table 8. Effect of the use of treated domestic sewage effluents on the morphological indices of forage palm (*Opuntia fícus-índica* (L.) Mill.).

Treatments	Variables			
	SCI	PVI	PADI	PCDI
	%	$m^3\,kg^{-1}$	%	
Tc	1.522d	0.281d	100.000a	100.000a
T1	3.611c	0.532c	100.000a	100.000a
T2	1.440d	0.219d	100.000a	100.000a
T3	5.456b	0.836b	100.000a	100.000a
T4	8.034a	1.341a	100.000a	100.000a
T5	4.843b	0.765b	100.000a	100.000a
CV (%)	5.572	8.768	0.000	0.000

Source: Authors (2023).
SCI – Soil cover index, PVI – Production volume index, PADI – Photosynthetic area distribution index, and PCDI – Plant cladode distribution index. Means followed by the same lowercase letters vertically do not differ statistically by Tukey's test (p>0.05).

Plants irrigated with the treatments containing the highest effluent concentrations (T3, T4, and T5) showed statistically higher SCI and PVI values, with T4 significantly superior to the others. This performance may be associated with the greater nutrient availability in this treatment, enhanced by the combination of effluent with 25% rainwater (Table 2). This may have favored the solubilization, mineralization, and absorption of nutrients by the plants, stimulating lateral growth and leaf expansion.

The SCI represents the crop's ability to cover the soil and is an important indicator in sustainable agricultural systems because it contributes to moisture conservation, erosion reduction, and maintenance of soil microbiota. The average SCI value observed in this study (4.151%) indicates that the adopted management did not provide full coverage of the cultivated area, considering a spacing of 1.50 m x 0.30 m and 18 plants distributed over approximately 9 m². In a similar study, Queiroz *et al.* (2015) observed an average SCI of 32% for an area planted with 60 plants and spacing of 1.60 m x 0.40 m, attributing the low coverage values to the adopted spacing, a factor that may also have influenced the results of this study.

The average PVI value obtained in this study (0.662 m^3 kg^{-1}) indicates that 1.0 kg of dry biomass occupied a volume of 0.662 m^3 in the plant, a value close to that reported by Queiroz *et al.* (2015), who found 0.94 m^3 kg^{-1} when evaluating palm productivity at different irrigation depths. This behavior indicates greater volumetric efficiency of the plant, that is, a more robust and productive structure in terms of biomass, which is essential for animal production systems that use palm as forage.

The lack of variation in PADI and PCDI indices may also be related to the short experimental time (230 days), which prevented the development of higher-order structures, such as second- or third-order cladodes. Thus, the distribution of photosynthetic areas and cladodes in plants remained uniform across treatments. However, the higher SCI and PVI values in T3, T4, and T5 suggest that, with longer cultivation time, these treatments would also tend to show improvements in the other morphological indices.

The water response indices for plant height (WRI_PH) and width (WRI_PW) (Figures 1A and 1B) indicated greater water use efficiency in treatments with higher effluent proportions (T3, T4, and T5). This behavior suggests that the nutrient supply present in the effluents enhanced the vegetative development of forage forage cactus, resulting in greater vertical growth and lateral expansion of the plants.

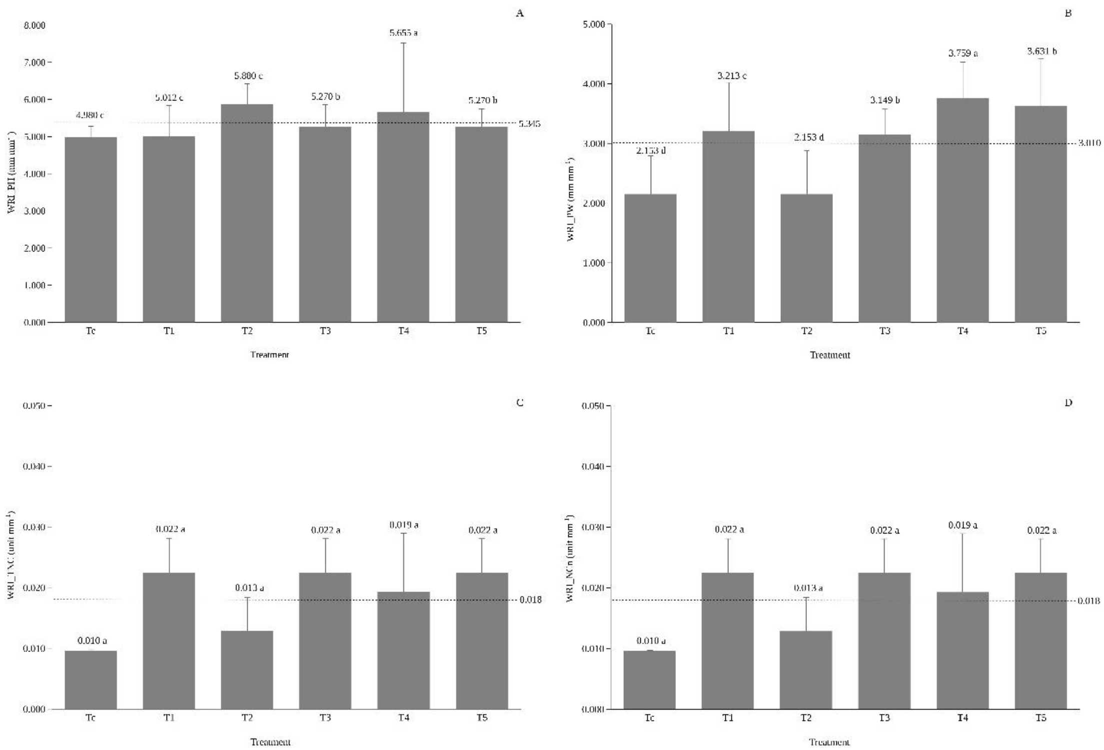

Figure 1. Water response indices (WRI): WRI_PH – Plant height (A); WRI_PW – Plant width (B); WRI_TNC – Average total number of cladodes per plant (C); and WRI_NCn – Number of cladodes per order (D) of forage palm (*Opuntia ficus-índica* (L.) Mill.), under different treatments. Averages followed by the same lowercase letters vertically do not differ statistically by the Tukey's test (p>0.05).

Source: Authors (2023).

Similarly, the water response indices related to the average total number of cladodes per plant (WRI_TNC) and the number of cladodes per order (WRI_NCn) (Figures 1C and 1D) showed the same pattern, with an average of 0.018 units mm^{-1}. This result is due to the exclusive presence of first-order cladodes, which indicates that the 230 day experimental cycle may have been insufficient for the emergence of higher-order structures, generally observed in more advanced stages of crop development.

The control treatment (Tc), irrigated with only 10% rainwater, demonstrated good performance in terms of water response, with results similar to those observed in T2. This observation highlights the effectiveness of the adaptive mechanisms of forage cactus under water-restricted conditions, highlighting its efficiency in conserving and utilizing available water, a relevant characteristic in semiarid regions.

However, the best results were observed in treatments with higher effluent content, especially T4. This performance demonstrates that the supply of macro and micronutrients by effluents contributes to the physiological and morphological development of the crop. Thus, in addition to constituting a water source, effluents also provide complementary nutrients, favoring increased productivity and the structural development of plants.

The results obtained in this study are consistent with those of Torres *et al.* (2019) and Lemos *et al.* (2021), who observed that plants irrigated with effluents developed faster than those irrigated with drinking water, with increases of up to 36% in height and approximately 153% in dry mass. Furthermore, a 29% increase in fresh matter was observed, demonstrating the importance of using effluents as an alternative source of water and nutrients, promoting plant biomass gains, especially in agricultural systems with water and economic limitations.

4. CONCLUSION

The biodigester septic tank (BST) demonstrated efficiency in treating domestic sewage, improving the physical, chemical, and microbiological parameters of the effluents. Despite the high nutrient concentrations, the effluents met the quality criteria for agricultural reuse, containing nitrogen, phosphorus, and potassium levels that can meet the nutritional needs of forage cactus (*Opuntia ficus-indica* (L.) Mill.).

Treatment T5, with 100% treated effluent, may have caused nutritional imbalance, since the best crop development was observed in T4 (75% TDWE and 25% RWA), suggesting that dilution favored the agronomic performance of the forage cactus. Therefore, the results demonstrate the technical viability of the BST system effluent as an alternative source of water and nutritional input for forage cactus cultivation.

5. DATA AVAILABILITY STATEMENT

Data availability not informed.

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