



Treated wastewater as an alternative irrigation source for maize production in semiarid regions

Águas residuais tratadas como fonte alternativa de irrigação para a produção de milho em regiões semiáridas

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Using treated wastewater as an alternative irrigation source for maize (*Zea mays* L.) cultivation in semiarid regions is a key strategy for addressing water scarcity and promoting the sustainable reuse of wastewater resources. This study aimed to evaluate the potential of wastewater irrigation for maize production and assess the feasibility of a double-cropping system in the semiarid region of Sergipe, Brazil. Field experiments were conducted at Nossa Senhora das Dores-SE (first irrigated crop) and Nossa Senhora da Glória-SE (second rainfed crop). A randomized complete block design (RCBD) with two replications comprised 17 maize genotypes. Plant height (PH), ear height (EH), and grain yield (GY) were evaluated. Significant differences in grain yield were observed between water regimes, with the highest yield (4336.00 kg/ha) recorded under wastewater irrigation. A significant genotype $\times$ environment interaction was also detected, indicating differential genotypic responses across water regimes. This interaction highlights the potential for selecting specific genotypes with enhanced adaptability to wastewater irrigation, optimizing productivity in water-limited environments. However, PH and EH did not differ significantly between environments. Using of treated wastewater for irrigation improved maize genotypic performance in terms of GY (increased grain yield by 2543.00 kg/ha compared to rainfed conditions) and enabled the establishment of two cropping cycles in the study region. These findings underscore the viability of wastewater irrigation as a sustainable strategy for semiarid agriculture, with implications for targeted genotype selection under specific water conditions.

Keywords: effluent, plant breeding, *Zea mays* L.

O uso de águas residuais tratadas como fonte alternativa de irrigação para o cultivo de milho (*Zea mays* L.) em regiões semiáridas é uma estratégia essencial para mitigar a escassez hídrica e promover o uso sustentável dos recursos hídricos. Objetivou-se avaliar o potencial da irrigação com águas residuais na produção de milho e analisar a viabilidade de um sistema de duplo cultivo na região semiárida de Sergipe, Brasil. Os experimentos foram realizados em Nossa Senhora das Dores-SE (primeira safra irrigada) e Nossa Senhora da Glória-SE (segunda safra em sequeiro). O delineamento experimental foi em blocos casualizados (DBC), com duas repetições e 17 genótipos. Foram avaliadas a altura da planta (AP), altura da espiga (AE) e produtividade de grãos (PG). Observou-se diferença significativa no PG entre os regimes hídricos, com o maior rendimento (4.336,00 kg/ha) registrado sob irrigação com águas residuais. Também houve interação significativa entre genótipo e ambiente, indicando respostas diferenciadas dos genótipos conforme o regime hídrico. Essa interação sugere o potencial de seleção de genótipos adaptados à irrigação com águas residuais, otimizando a produtividade em ambientes com restrição hídrica. No entanto, AP e AE não apresentaram variações significativas entre os ambientes. A irrigação com águas residuais tratadas melhorou a PG do milho, aumentando em 2.543,00 kg/ha em comparação com o cultivo em sequeiro, possibilitando dois ciclos de cultivo na região. Esses resultados demonstram a viabilidade dessa prática como uma estratégia sustentável para a agricultura em regiões semiáridas, contribuindo para a seleção de genótipos adaptados a diferentes condições hídricas.

Palavras-chave: efluente, melhoramento de plantas, *Zea mays* L.

1. INTRODUCTION

Water scarcity is a significant constraint in semiarid regions, directly affecting agricultural productivity and rural livelihoods. Limited water availability reduces crop yields and quality in these areas, challenging food security and economic stability [1]. Climate change further exacerbates this issue by increasing drought frequency and altering precipitation patterns, making rainfall more irregular and unpredictable [2].

Sustainable water management strategies, such as wastewater reuse, desalination, and watershed restoration, are essential to mitigating the impacts of water scarcity on agricultural systems. Using of treated wastewater for irrigation has gained attention as a viable approach to enhance water-use efficiency while supplying essential nutrients and organic matter to the soil. This practice has been shown to improve soil fertility and promote plant growth [3, 4].

The use of wastewater for irrigation is a well-established practice in various agricultural contexts and is recognized as an alternative for water management in regions with water scarcity. This practice is primarily guided by CNRH Resolution N°. 121/2010, which establishes guidelines for the direct non-potable reuse of water in agricultural and forestry applications, and, complementarily, by NBR 13.969/1997 [5] which establishes guidelines for the use of treated effluents.

Maize (*Zea mays* L.) is a key subsistence crop in semiarid regions, and irrigation with treated wastewater has emerged as a promising alternative to sustain its production. Studies indicate that this practice not only helps maintain soil moisture but also provides sufficient nutrients, potentially replacing up to 60 kg of nitrogen per hectare, thus reducing dependency on synthetic fertilizers, according to the amount of nutrients and organic matter of the wastewater [6, 7].

Fertigation with wastewater in corn crops can help supply water and nutrients [8], but requires attention to parameters such as salinity, pH, solids, nutrients, pathogenic microorganisms, and potentially toxic elements, since high concentrations can compromise crop performance and soil quality [9, 10].

Given this context, this study aims to evaluate the feasibility of using treated wastewater as an irrigation source for maize production in semiarid regions and to assess its potential for supporting double-cropping systems under water-limited conditions.

2. MATERIAL AND METHODS

2.1 Obtaining the genetic material

The genotypes were subjected to a complete diallel cross, without reciprocals, during the 2022 growing season at the Experimental Farm of the Federal University of Sergipe (UFS) – Campus of Sertão, located in the municipality of Nossa Senhora da Glória, SE (Table 1). The genotypes were sown at two different times, with a five-day interval between sowings to synchronize pollen availability. The pollination field was structured with two rows of male plants for every four rows of female plants, and pollination was carried out manually.

Table 1: Agronomic traits of the 17 genotypes used in the irrigated and rainfed environments in the 2022 harvest.

Hybrids	
Code	Genetic class
*G1	HS
G2	HS
G3	HS
G4	HS
G5	HE
G6	TC
G7	TC
G8	HE
G9	HE
G10	HE
G11	HE
G12	HE
G13	HE
G14	HS
G15	HS
G16	HS
G17	HS

*G – Genotypes; HS – Simple Hybrid; HE – Experimental Hybrid and TC – Top Cross.

2.2 Experimental design and trial management

The experiment followed a randomized complete block design (RCBD) with two replicates and 17 treatments, including single-cross hybrids, experimental hybrids, varieties, and topcrosses adapted to the region. Each plot consisted of two rows, each four meters long, with a spacing of 0.20 m between plants and 0.70 m between rows.

Two trials were conducted in Sergipe. The first was carried out in the experimental area of the wastewater treatment station in the municipality of Nossa Senhora das Dores (10°12'48.44" S, 37°19'1.68" W, 200 m altitude) under irrigated conditions from February to June (Trial 1). The second was conducted at the Experimental Farm of the Federal University of Sergipe (UFS) – Sertão Campus located in the municipality of Nossa Senhora da Glória (10°13'06" S, 37°25'13" W, 291 m altitude), under rainfed conditions from June to November (Trial 2).

Trial 1 was conducted under a drip irrigation system, using wastewater from the Sewage Treatment Plant (STP) of the Sanitation Company of Sergipe (DESO®) in Nossa Senhora das Dores, whose treatment technology is based on facultative ponds. This system has high efficiency in the removal of organic matter, but lower capacity to remove nutrients, such as nitrogen and phosphorus [11] Irrigation management was carried out daily based on the water balance of the crop. Trial 2 was conducted under rainfed conditions.

Fertilization for both experiments was performed according to soil fertility analysis results (Table 2). Sowing was done manually, and basal fertilization consisted of applying 250 kg/ha of the 06-24-12 formula. For topdressing fertilization, 100 kg/ha of nitrogen was applied as ammonium sulfate between the V4 and V6 growth stages. Crop management practices were carried out as needed for pest and weed control.

Table 2: Chemical analysis of the soil was carried out by the Laboratory of the Technological and Research Institute of the State of Sergipe, for the irrigated and rainfed environments.

IRRIGATED ENVIRONMENT								
M.O.	pH in H ₂ O	Ca	Mg	H+Al	Al	P	K	Na
	g/dm ³			(cmol/dm ³)			(mg/dm ³)	
11.2	5.82	1.40	0.66	2.03	0.08	2.70	65.7	5.40
RAINFED ENVIRONMENT								
M.O.	pH in H ₂ O	Ca	Mg	H+Al	Al	P	K	Na
	g/dm ³			(cmol/dm ³)			(mg/dm ³)	
15	5.30	2.09	1.63	2.33	0.16	3.70	112	45.7

M.O – Organic Matter; Ca – Calcium; Mg – Magnesium; H+Al – Hydrogen plus aluminum; Al – Aluminum; P – Phosphorus; K – Potassium and Na – Sodium.

2.3 Evaluated traits

Morphological and post-harvest traits were evaluated as follows:

- **Ear height (EH):** The average height of five randomly selected plants per plot, measured from ground level to the insertion of the primary ear, expressed in meters (m).
- **Plant height (PH):** The average height of five randomly selected plants per plot, measured from ground level to the insertion of the flag leaf, expressed in meters (m).
- **Grain yield (GY):** The total weight of grains harvested from the proper plot area, converted to kg/ha and adjusted to 13% moisture, according to the method of Zuber (1942) [12], with results expressed in tons per hectare.

2.4 Statistical Analysis

The data obtained for the analyzed variables were subjected to analysis of variance (ANOVA), and means were grouped using the Tukey test ($p < 0.05$). Statistical analyses were performed using R software [13].

3. RESULTS AND DISCUSSION

3.1 Influence of Wastewater

The technical report includes a detailed analysis of the physicochemical and biological parameters of the treated wastewater in Nossa Senhora das Dores- SE, aiming to assess its feasibility for agricultural reuse. This study was conducted between January 2021 and March 2022, and 16 analyzed samples (Table 3).

Table 3: Results of the wastewater analyses carried out from 01/18/21 to 03/21/22, where the mean, standard deviation, coefficient of variation (CV%), the maximum and minimum values observed, and the maximum values allowed by the standards were evaluated. Sergipe Sanitation Company (DESO®), Nossa Senhora das Dores- SE.

	Average	Detour	CV (%)	Maximum Observed	Observed Minimum	Maximum Amount Allowed	Norm
Free Residual Chlorine	0.87	0.63	72.85	2.00	0.20	Greater than 5mg/L	ABNT 13969/97
Dissolved Oxygen	4.50	1.95	43.40	5.66	0.60	Not less than 5 mg/L	CONAMA N° 357/2005
pH	7.33	0.40	5.40	8.40	6.89	5.00 to 9.00	CONAMA N° 430/2011
Sample Temperature	27.65	2.39	8.65	30.90	23.40	40.00 °C	CONAMA N° 430/2011
Biochemical Oxygen Demand	43.81	32.66	74.55	145.00	16.00	120.00 mg/L	CONAMA N° 430/2011
Chemical Oxygen Demand	107.38	61.45	57.23	246.00	21.00	150 mg/L (domestic) 600 mg/L (sewage service operators' collection system)	Comdema Resolution 34/2012 and Coema Resolution 02/2017
Total Phosphorus	2.05	1.30	63.43	3.60	0.20		
Ammonia Nitrogen	2.97	2.72	91.68	9.47	0.00	20 mg/L	CONAMA N° 430/2011
Oils & Greases	3.96	4.56	115.13	15.70	0.00	100.00	CONAMA N° 430/2011
Sedimentable Solids	0.04	0.09	227.56	0.30	0.00	1.00	CONAMA N° 430/2011
Total Suspended Solids	30.29	17.38	57.37	44.00	0.00	20% efficiency	CONAMA N° 430/2011
Total Solids at 105 °C	511.67	138.90	27.15	710.00	288.00	500 mg/L	CONAMA N° 357/2005
Total sulfide	0.13	0.32	245.63	1.23	0.00	1.00	CONAMA N° 430/2011
Turbidity	35.42	27.81	78.51	82.60	11.20	100NTU	CONAMA N° 357/2005
Thermotolerant coliforms	1.282.971.00	4.422.577.82	344.71	16.000.000.00	23.00		
Total Coliforms	526.783.00	1.323.524.71	251.25	5.000.000.00	2.00		

Physicochemical and microbiological characteristics of the reclaimed wastewater used for irrigation, including mean, standard deviation, coefficient of variation (CV), maximum and minimum observed values, maximum permissible limits, and the corresponding regulatory standard.

Wastewater often contains high levels of phosphorus (P) and nitrogen (N) which, in excessive concentrations, contribute to eutrophication, altering the physical, chemical, and biological properties of the water and making it unfit for consumption or agricultural use [10, 14]. However, when properly treated and managed, these sources can represent relevant agronomic inputs, providing nutrients to the corn crop and positively influencing its productive performance, as observed in hybrids under irrigation with wastewater, in different management with effluents, in the application of sludge from sludge as a source of nutrients and corrective of soil acidity, and improving the fertility of soils cultivated with maize under irrigation with recycled wastewater [8, 15].

Some parameters, such as BOD and total sulfide, may exceed acceptable limits in certain periods, indicating the need for adjustments in effluent treatment and management, which reinforces the importance of continuous monitoring of effluent quality throughout the reuse cycle [16]. Even so, when the treated effluent meets the legal and agronomic criteria, its agricultural use can be viable and sustainable, including in fertigation systems, as long as the risks associated with pathogens, potentially toxic elements, and emerging contaminants are evaluated and kept within acceptable limits, according to CNRH 121/2010 and NBR 13.969/1997 [17, 18].

3.2 Variance Analysis

The analysis of variance revealed significant differences among the evaluated variables, indicating the presence of genetic variability among the studied maize genotypes (Table 4).

Table 4: The mean square of the analysis of variance referring to the traits PH, EH, and GY of the maize genotypes evaluated in irrigated and rainfed environments.

SV	DF	MS		
		PH	EH	GY
Experiment (Blocks)	2	0.018	0.022	504586.5
Genotypes	16	0.013	0.035	1358539.3***
Experiment	1	0.221***	0.698***	6899996.9***
G x E	16	0.010	0.020	703563.7***
Residue	32	0.013	0.025	203963.3

*** Significant at 0.001 significance by the F test.

The results highlight significant differences between experimental conditions, demonstrating that the environment substantially influenced genotype performance. Additionally, the genotype $\times$ environment (G $\times$ E) interaction was significant for GY, suggesting that genotype performance varied across the two experimental conditions. This result indicates that wastewater irrigation can influence genotype development, particularly under rainfed conditions, where this practice may enable a second cropping cycle [19].

Wastewater can contribute to the increase of soil fertility by providing nutrients and organic matter, favoring the growth and development of plants [3, 4]. This effect has been associated with the agronomic potential of effluent reuse, especially in regions subject to water scarcity, where this practice presents itself as a sustainable and efficient alternative for the simultaneous supply of water and nutrients [8, 20]. Thus, the reuse of wastewater emerges as a promising strategy to optimize crop performance, increase agricultural productivity and mitigate the effects of limited water resources [11].

In Figure 1A, the differences observed between the genotypes and the experimental environments show a strong influence of water availability on the expression of productive potential. Under wastewater irrigation, genotypes G17, G14, G2, G4, G13, G12 and G8 showed the highest grain yield values, suggesting that the combination of water supply and additional nutrient input favored the maximization of agronomic performance. This behavior is consistent with the literature, which shows that the reuse of treated effluents can increase productivity by increasing the supply of water and nutrients to plants, especially in environments subject to water deficit [18, 21].

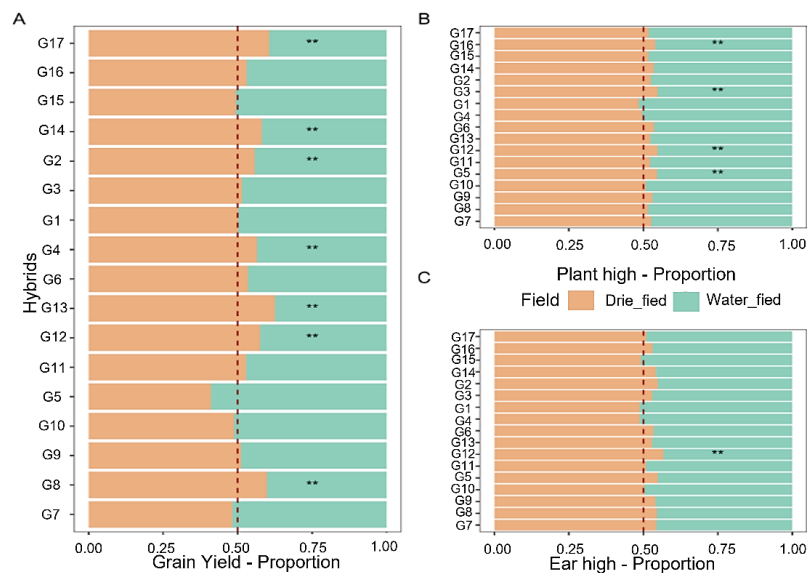


Figure 1. The proportion of variables means that they are across the drie and water field experiments.

The superiority of these genotypes under irrigated conditions indicates that there was a relevant interaction between genetic material and environment, reinforcing the importance of evaluation under multiple conditions for the identification of more responsive and stable genotypes. In corn, studies with wastewater fertigation have shown an increase in dry mass and grain yield, which corroborates the potential of this practice as an agronomic strategy to intensify production in water-restricted agricultural systems [8, 15].

Figures 1B and 1C illustrate the PH and HS distributions, respectively. It is worth noting that the genotypes G16, G3, G12 and G5, in this order, showed more significant increases in PH under irrigation with wastewater. In addition, G12 presented the best performance for HS under irrigation with wastewater. In both cases, the irrigated environment resulted in higher values reinforcing the benefits of wastewater irrigation for plant growth and genotype performance compared to rainfed conditions [8, 10, 22].

The results observed in this study suggest that irrigation with wastewater not only mitigates the effects of water stress, but can also act as a yield promoting factor, depending on the specific response of each genotype performance that remains conditioned to the maintenance of effluent parameters within safe limits over time [15].

Table 5 presents the mean comparison test for GY, PH, and EH across different experimental environments. All analyzed variables showed significant differences, with the irrigated environment outperforming the rainfed system.

Table 5: Tukey's test between the experimental environments for the variables GY, PH and EH.

Experiment	GY	PH	EH
Water field	4336.00 a	2.18 a	1.15 a
Drie field	3699.00 b	1.97 b	1.03 b

Different lowercase letters in the columns indicate a statistical difference by the Tukey test ($P < 0.05$). GY: grain yield; PH: plant height and EH: ear height.

Under irrigated conditions, the average GY was 4336.00 kg/ha whereas in the rainfed environment, it was 3,699 kg/ha. Similarly, the mean PH (2.18 m) and EH (1.15 m) under irrigation were higher than those in the rainfed environment (1.97 m and 1.03 m, respectively). Treatable wastewater can partially replace mineral fertilization in maize cultivation, reducing production costs while providing environmental and agronomic benefits [6, 20]. These findings reinforce the potential of wastewater as an alternative irrigation source, particularly in water-scarce regions. Additionally, wastewater irrigation may enable multiple cropping cycles within the same year, enhancing sustainability and production efficiency [21].

The mean values presented in Table 6 highlight significant differences among genotypes across environments, confirming the statistical significance of these variations. The results underscore the environmental effect on grain GY, PH and EH, as well as the variability in genotype performance.

Table 6. Testing means for the variable GY, PH, and EH between the irrigated and rainfed environments.

	Dry field			Water field		
	GY	PH	EH	GY	PH	EH
G1	4768.23 a	2.15 a	1.13 a	4808.50 ab	2.02 a	1.08 a
G15	4425.63 ab	1.98 a	1.18 a	4307.50 ab	2.13 a	1.14 a
G2	4341.67 ab	1.87 a	1.04 a	4588.00 ab	2.27 a	1.17 a
G3	4094.83 ab	2.06 a	0.98 a	5150.00 abc	2.28 a	1.19 a
G7	3884.31 ab	2.19 a	1.12 a	3607.88 cde	2.40 a	1.33 a
G16	3869.82 ab	1.91 a	1.00 a	4367.50 ad	2.24 a	1.11 a
G4	3781.63 ab	2.15 a	1.15 a	4897.50 ad	2.11 a	1.09 a
G9	3738.88 ab	1.99 a	1.01 a	3911.20 ad	2.25 a	1.19 a
G12	3600.37 ab	1.72 a	0.87 a	4881.81 ad	2.09 a	1.14 a
G8	3585.17 ab	2.06 a	1.01 a	5328.81 ab	2.19 a	1.95 a
G17	3518.90 ab	2.09 a	1.07 a	5415.00 a	2.25 a	1.25 a
G10	3485.10 ab	2.00 a	1.02 a	3326.91 de	2.05 a	1.03 a
G6	3375.19 ab	1.82 a	1.00 a	3876.08 ad	2.10 a	1.14 a
G11	3292.11 ab	1.99 a	1.05 a	3694.08 bd	2.18 a	1.09 a
G13	3186.00 ab	1.95 a	1.01 a	5303.27 ab	2.14 a	1.13 a
G14	3069.00 b	1.90 a	1.04 a	4256.00 ad	2.18 a	1.23 a
G5	2872.02 b	1.73 a	0.90 a	1999.34 e	2.08 a	1.09 a

Different lowercase letters in the columns indicate statistical difference by the Tukey test ($P < 0.05$); Equal letters do not differ significantly.

Under rainfed conditions, G1 presented the highest grain yield (4,768.23 kg/ha), indicating agronomic superiority in a water restriction environment, while for genotypes G14 and G5, lower yields were recorded (3,069.00 kg/ha and 2,872.02 kg/ha), respectively. The difference observed between G1 and the lower performing genotypes suggests better adaptation of the material to adverse environmental conditions, a relevant aspect for breeding programs aimed at drought tolerance [18].

Under irrigation conditions, G17 showed the highest grain yield (5,415.00 kg/ha), confirming its agronomic superiority in an environment with greater water and nutritional

availability. The presence of an intermediate group statistically similar to G17 also indicates that there is wide genetic variability for response to the irrigated environment, a pattern already observed in evaluations of genotypes and cultivars under irrigation and effluent reuse [21].

The presence of an intermediate group statistically similar to G17 also indicates wide genetic variability for response to the irrigated environment, reinforcing the importance of genotype x environment interaction in the selection of adapted materials. In this context, the lower performance of G5 shows that irrigation with wastewater does not eliminate the genetic differences between the materials, but reveals which genotypes have the greatest efficiency for irrigated systems with water reuse [8].

Contrary to what was observed for the grouping of PH and HS in this study, some studies have reported statistically significant differences in these traits under irrigation with wastewater in corn, indicating a positive response of vegetative growth to the reuse of treated effluents [8, 18, 23]. These results reinforce that irrigation with wastewater can favor the performance of the corn crop, although the magnitude of the response depends on the genotype, the quality of the effluent and the environmental conditions [11, 21].

Irrigation with treated wastewater has stood out as a promising agronomic strategy for corn crops, especially in environments subject to water limitation, as it simultaneously promotes the supply of water and nutrients essential to plant development [10, 22]. Recent studies indicate that this management can favor the agronomic performance of different genotypes, resulting in increases in grain yield and vegetative traits, such as plant height and ear height.

4. CONCLUSIONS

Using of wastewater as an alternative irrigation strategy highlights its potential to optimize second crop in semiarid agricultural production.

There was genetic variability among the genotypes regarding adaptation to water reuse, indicating materials that are more promising for production systems irrigated with treated effluent.

Wastewater irrigation increased GY by 2543.00 kg/ha compared to rainfed conditions, confirming its viability as a strategy to enhance maize productivity.

5. ACKNOWLEDGMENTS

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