agronomy

MDPI

Article

Fiber Quality, Yield, and Profitability of Cotton in Response to Supplemental Irrigation with Treated Wastewater and NPK Fertilization

Antonio Flávio Batista de Araújo [1], Eduardo Santos Cavalcante [1], Claudivan Feitosa Lacerda [1,*], Fábio Aquino de Albuquerque [2], Jonnathan Richeds da Silva Sales [1], Fernando Bezerra Lopes [1], Jorge Freire da Silva Ferreira [3], Raimundo Nonato Távora Costa [1], Silvio Carlos Ribeiro Vieira Lima [4], Marlos Alves Bezerra [5] and Hans Raj Gheyi [6]

[1] Agricultural Engineering Department, Federal University of Ceará, Fortaleza 60356-001, Brazil
[2] Embrapa Cotton, Campina Grande 58428-095, Brazil
[3] US Salinity Laboratory, ARS/USDA, Agricultural Water Efficiency and Salinity Research Unit, Riverside, CA 92507, USA
[4] Secretariat of Economic Development and Labor of the State of Ceará, Fortaleza 60811-341, Brazil
[5] Embrapa Tropical Agroindustry, Fortaleza 60511-110, Brazil
[6] Agricultural Engineering Department, Federal University of Campina Grande, Campina Grande 58428-830, Brazil
* Correspondence: cfeitosa@ufc.br

Citation: de Araújo, A.F.B.; Cavalcante, E.S.; Lacerda, C.F.; de Albuquerque, F.A.; da Silva Sales, J.R.; Lopes, F.B.; da Silva Ferreira, J.F.; Costa, R.N.T.; Lima, S.C.R.V.; Bezerra, M.A.; et al. Fiber Quality, Yield, and Profitability of Cotton in Response to Supplemental Irrigation with Treated Wastewater and NPK Fertilization. *Agronomy* **2022**, *12*, 2527. https://doi.org/10.3390/agronomy12102527

Academic Editor: Salvatore Camposeo

Received: 11 August 2022
Accepted: 11 October 2022
Published: 16 October 2022

Abstract: Cotton yield under the rainfed farming system in tropical semi-arid regions is significantly decreased by prolonged dry spells. In this context, supplemental irrigation (SI) with treated wastewater emerges as a strategy for the sustainability of agricultural production besides contributing to the reduction of fertilizer costs. The objective of this research was to evaluate the productivity, photosynthetic parameters, fiber quality, and profitability of cotton cultivation, under supplemental irrigation (SI) with municipal treated wastewater (MTW), with and without mineral fertilization. The treatments consisted of three water scenarios (normal, drought, and severe drought), defined by the historical series of precipitation data of 30 years, and two treatments of supplemental irrigation with MTW, with or without NPK fertilization. SI with treated wastewater increased cotton yield in all three scenarios (normal, drought, and severe drought) by approximately 29%, 255%, and 251%. Longer dry spells in drought and severe drought scenarios increased the volume of SI with MTW, resulting in greater nutrient input to the soil, improved photosynthetic response, higher physical water productivity, reduction in fertilizer costs, and higher farmers' income. Therefore, our results show the importance of using treated wastewater in supplemental irrigation of cotton under scenarios of water scarcity in tropical semi-arid regions.

Keywords: *Gossypium hirsutum* L.; tropical semi-arid; water stress; water reuse; sustainability

1. Introduction

Cotton (*Gossypium hirsutum* L.) is the main raw material for the international textile industry, the most valuable natural fiber, and the second most important oil-seed crop worldwide [1,2]. Cotton yield is affected by edaphoclimatic constraints, genotypes, and crop management practices. Cotton cultivation is predominantly rainfed in most of the producing regions of the world, including Brazil [3,4]. Because of the high crop water demand, the water deficit caused by constant droughts in semi-arid regions is the main factor limiting high yields.

Irrigation is important to guarantee the sustainability of production in regions most susceptible to water deficit, especially when associated with efficient water consumption and economic viability [5–8]. However, cotton has a relatively long cycle and, when grown under full irrigation, it demands large amounts of water [9]. The average irrigation requirement for surface-irrigated cotton is reported to be 6000–7000 m^3 ha^{-1} depending on soil, weather conditions, and seasonal rainfall [10,11]. In the Brazilian semi-arid region, it was determined that the evapotranspiration of cotton (ETc) varied as a function of crop phenology with an average water requirement of 3.8 mm day^{-1} during emergence, 5.0 mm day^{-1} during vegetative growth, 5.9 mm day^{-1} during the reproductive phase, and 5.4 mm day^{-1} during the maturation period [12].

In some parts of the world, as in some cotton producing areas of the United States of America, the irrigation requirement is low or may not be needed, due to the adequate distribution of rainfall during the growing season. However, several producers utilize supplemental irrigation (SI) to minimize drought stress, decrease risk, and improve yield stability across a range of environmental conditions [13]. The requirement for SI is obviously higher in semi-arid regions, due to recurrent droughts and long periods of dry spells, which tend to worsen because of global climate change [14].

Water shortage is one of the main factors that contribute to the reduction of productivity of crops, and the use of alternative sources of water for irrigation is an option to minimize water stress and yield losses [11,13,15]. Besides, frequent droughts in semi-arid regions of the planet and excessive pumping of groundwater to meet the water requirements for irrigated crops have compromised the sustainability of agricultural production systems [16]. These concerns have led fabric manufacturers to adopt environmentally sustainable cotton production technologies to minimize the use of water resources and reduce environmental pollution [11,17].

The possibility of using treated wastewater for irrigation of crops with high water demand such as cotton has been evaluated as a viable alternative to preserve natural water resources while mitigating the effects of water scarcity [18,19], notably for future climate change scenarios. Given the above, municipal treated wastewater (MTW) is a sustainable strategy to increase irrigated cotton areas, save fresh water, and maintain riparian ecosystems stressed by drought and overuse of underground water. Moreover, MTW represents a promising opportunity to meet the cotton crop mineral nutrient demand [19] and to mitigate the current world crisis associated with the high prices of fertilizers.

Cotton farming in the Brazilian semi-arid region, even under adverse edaphic and climatic conditions, has greater profitability when compared to other crops [20]. The main concern for cotton cultivation in semi-arid regions is water scarcity, a determining factor for low productivity rates. In this way, supplemental irrigation in rainfed farming, using the treated wastewater, should become a decisive factor for crop sustainability in semi-arid regions, increasing productivity and improving water use efficiency.

The objective of this research was to evaluate the productivity, fiber quality, and profitability of cotton cultivation in response to supplemental irrigation with treated wastewater, seeking to evaluate the productive and economic sustainability of this crop system under a tropical semi-arid climate. The treatments simulated different water availability scenarios of the rainfed farming system of the Brazilian semiarid region, with and without chemical fertilization.

2. Material and Methods

The experiment was carried out from September to December 2020, in an area adjacent to a municipal wastewater treatment station of CAGECE (Company of Water and Sewerage of the State of Ceará), in the municipality of Russas (4°56′25″ S, 37°58′33″ W, altitude 20.5 m), Ceará, Brazil. Russas (Figure 1) is situated in a low-precipitation region afflicted by prolonged droughts and prone to desertification with a typical vegetation type classified as *Caatinga* ("white forest" or "white vegetation" in Tupi language). The climate of Russas is tropical semi-arid, according to the Köppen's classification, with an average annual rainfall of 745.7 mm and a mean temperature of 27 °C.

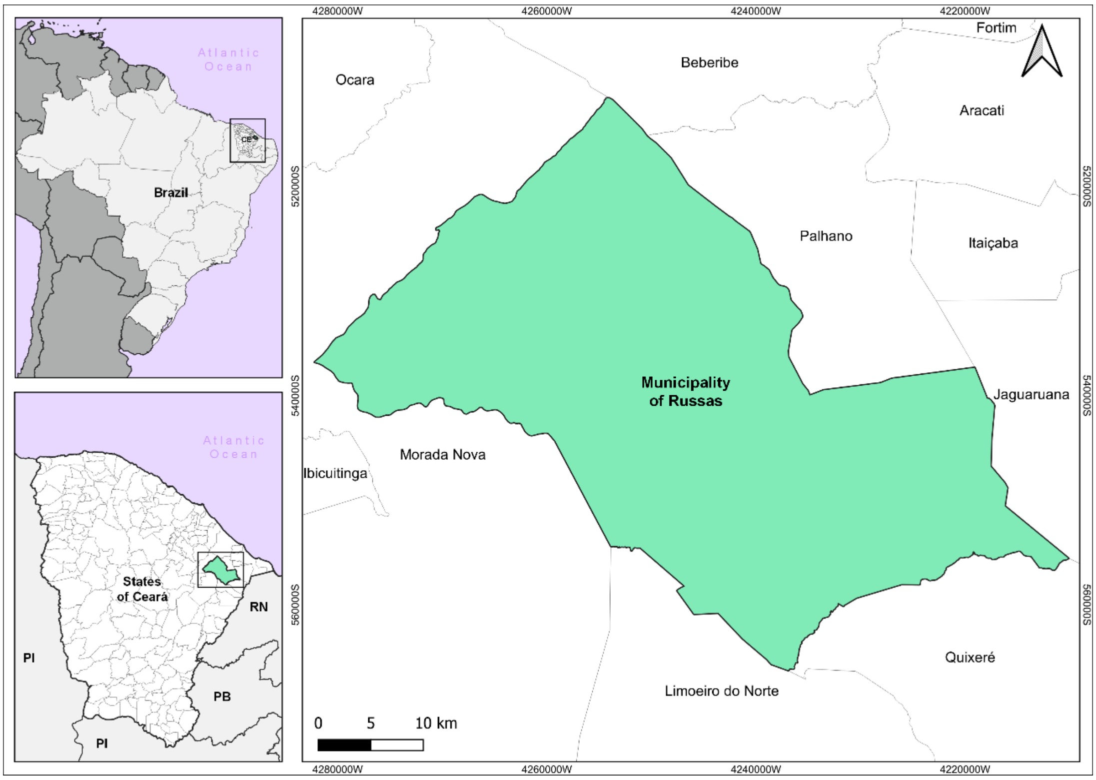

Figure 1. Localization of the municipality of Russas, Ceará, in the northeast of Brazil.

The experimental assay was installed in a randomized complete block design, with treatments arranged in split plots with four replications. Plot experimental design was selected depending on three water scenarios: normal, drought, and severe drought. These scenarios were defined based on a 30-year historical series of precipitation data provided by the Foundation for Meteorology and Water Resources of Ceará (Funceme). This series was defined for the municipality of Russas, Ceará, Brazil, for the rainfed farming season in the region (February to May). The subplots were composed of either the provision or lack of supplemental irrigation with treated wastewater and the sub-subplots by the presence or absence of NPK fertilization. Each experimental unit (sub-subplot) was formed by four rows of plants 4.5 m in length.

Seeds of the cotton cultivar BRS 433, provided by the Secretariat of Economic Development and Labor of the State of Ceará (SEDET), were sown at a spacing of 0.7 × 0.3 m, with two plants per hole. Fertilization was provided by N, P_2O_5, and K_2O applied at doses of 60, 60, and 50 kg ha^{-1}, respectively [21], defined according to soil analysis and regional recommendations for cotton. The chemical analysis of the soil before the experimental setup is presented in Table 1. The determinations were performed according to methodologies recommended by [22]. The soils were classified as Planosol (Alfisol).

Table 1. Chemical analysis of the soil (0–20 cm depth) of the experimental area in the municipality of Russas, Ceará, Brazil.

Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Al^{3+}	S	C	N	OM	P	ESP	pH	ECse
		(cmol$_c$ kg^{-1})					(g kg^{-1})		(mg kg^{-1})	%	-	(dS m^{-1})
12.5	5.7	1.32	0.41	0.1	19.9	0.84	1.08	16.96	53	5	6	0.68

S-sum of cations; OM—organic matter, ESP—exchangeable sodium percentage, ECse—electrical conductivity of the soil saturation extract.

A drip irrigation system was used, consisting of a centrifugal electric pump of 0.5 HP, single-phase current, equipped with double suction with a valve to control the alternate capture of both freshwater and treated wastewater, the first stored in a tank of 2000 L and the second collected in a pre-molded ring well. Irrigation system consisted of a drip tape with a flow rate of 1.6 L h^{-1} and a spacing of 0.3 m between emitters.

The water sources used were from the municipal supply network of the city of Russas (freshwater; FW) available after the municipal wastewater passes through a series of sedimentation and stabilization ponds belonging to the Company of Water and Sewage Treatment of Ceará State (CAGECE). The chemical characteristics of freshwater and MTW (Table 2) were obtained employing methodologies recommended by [23].

Table 2. Chemical analysis of freshwater (FW) and municipal treated wastewater (MTW) in the city of Russas, Ceará, Brazil.

Chemical Analysis	FW	MTW
Ca^{2+} ($mmol_c$ L^{-1})	0.9	2.9
Mg^{2+} ($mmol_c$ L^{-1})	1.8	3.2
Na^{+} ($mmol_c$ L^{-1})	1.6	10.1
K^{+} ($mmol_c$ L^{-1})	0.1	1.4
Cl^{-} ($mmol_c$ L^{-1})	2.6	13
HCO_3^{-} ($mmol_c$ L^{-1})	1.3	4.6
EC (dS m^{-1})	0.38	1.66
P (mg L^{-1})	0.02	10.7
N (mg L^{-1})	12.7	67.2

EC = electrical conductivity of the water, which conveys the water salinity level.

The rainfall simulation was carried out with freshwater, while the supplemental irrigation with water from the stabilization pond (MTW). The total water depths applied during the cotton cycle are shown in Figure 2. According to the historical series of precipitation data, the average for a normal wet-year scenario is 466.2 mm, from February to May (rainy season). For the drought and severe drought scenarios, the average values are 326.2 and 206.2 mm for the same period, reaching average reductions of 30.0% and 55.7%, respectively.

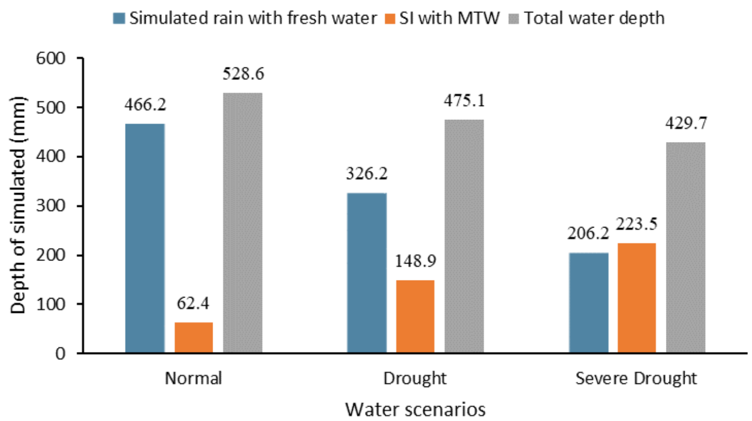

Figure 2. Water depth of simulated rain with freshwater, with supplemental irrigation with municipal treated wastewater (SI with MTW), and the total water depth applied during the cotton cycle.

At 80 days after sowing, the stage that begins with the formation of cotton bolls, the shoots' dry mass and leaf gas exchange parameters were evaluated. Measurements of stomatal conductance (gs, mol m^{-2} s^{-1}) and photosynthesis rate (A, µmol m^{-2} s^{-1}) were performed using a portable Infrared Gas Analyzer (model LI-6400XT, LI-COR, Lincoln, NE, USA), with a light intensity of 1800 µmol m^{-2} s^{-1}. The readings were taken in the morning, between 08:00 and 10:00 a.m., on fully expanded leaves of each plant under ambient conditions of temperature and relative humidity.

After maturation, when reaching the harvest time, two manual harvests were carried out at 106 and 126 days after planting. The following production variables were determined: seed yield (kg ha^{-1}), lint yield (kg ha^{-1}), total yield, and physical water productivity (PWP, kg m^{-3}), obtained by the ratio between the total yield and the total volume of water applied (simulated rain with fresh water plus supplemental irrigation with MTW) in each treatment, according to Equation (1) [24]:

$$\text{PWP} = \frac{\text{Total yield}\left(\text{kg ha}^{-1}\right)}{\text{Total water applied}\ (\text{m}^3\ \text{ha}^{-1})} \quad (1)$$

The efficiency of supplemental irrigation (WUE_{SI}) was estimated by the ratio between the increment in total yield and the volume of water applied in supplemental irrigation, according to Equation (2) [25]:

$$\text{WUE}_{\text{SI}} = \frac{\text{Y}_{\text{SI}} - \text{Y}\left(\text{kg ha}^{-1}\right)}{\text{Suplemental irrigation}\ (\text{m}^3\ \text{ha}^{-1})} \quad (2)$$

where Y_{SI} and Y represent the total yields (seeds plus lint) of plots with and without supplemental irrigation, respectively.

The technological quality of cotton fiber was measured through a sample of 20 bolls randomly collected in the middle third of plants in the observation area of the plot. As recommended by [26], the following variables were analyzed: fiber length (UHM, mm), fiber uniformity (UNF, %), short fiber index (SFI, %), and Micronaire index (MIC, µg in^{-1}). The technological variables were determined at the Fibers and Yarns Laboratory of Embrapa Algodão (Campina Grande, Paraiba, Brazil), using HVI (High Volume Instruments) model 900 from Spinlab/Zellweger Uster.

Crop yield, PWP, technological quality of fiber, stomatal conductance (gs), photosynthetic rate (*A*), and shoots dry mass data were submitted to analysis of variance and the means were compared by Tukey's test at 0.05 probability. Statistical analyses were performed using the Sisvar software version 5.6 [27].

Economic analysis was performed using current values (May–July 2022) to estimate gross revenue and costs (fixed, variable, and equipment depreciation), expressed in Brazilian Real (BRL, Brazilian currency). Crop yield data were used to estimate gross revenue using the cotton price (seed plus lint) of 4.67 BRL kg^{-1} (1 BRL = 0.20 USD). For the economic analysis, fixed and variable costs and equipment depreciation were used. Fixed costs for 1.0 ha were used for all treatments with supplemental irrigation. The total fixed cost amount was divided into ten years, as the farmer has the option to finance the agricultural inputs during this period. The farm equipment depreciation was calculated by dividing the investment needed for implementation by the useful life of each piece of equipment, which was estimated as ten years. The final zero residue method at the end of its useful life was used in the calculation.

It was considered that the costs were financed by *Banco do Nordeste do Brasil (BNB)*, using the investment credit line called *Pronaf Mais Alimentos (National Program to Strengthen Family-based Agriculture)*, simulating a ten-year contract with an interest rate of 3% per year with no grace period, seeking to get as close as possible to the reality of the farmer. The calculation of the added value was performed according to the methodology described by [28,29]. The added value of the production systems was obtained for 1.0 ha of production and values are expressed in BRL, according to Equation (3):

$$\text{WUE}_{\text{SI}} = \frac{\text{Y}_{\text{SI}} - \text{Y}\left(\text{kg ha}^{-1}\right)}{\text{Suplemental irrigation}\ (\text{m}^3\ \text{ha}^{-1})} \quad (3)$$

AV: added value

GVP: gross value of production
FC: fixed costs associated with the production system
VC: variable costs associated with the production system, excluding labor
D: depreciation of equipment and facilities

A linear relationship (AV = ax + b) was used to calculate the added value from 2.0 to 5.0 ha, with the ordinate axis being the added value and the abscissa axis represented by the agricultural area. In the linear model, the marginal contribution per unit of equivalent area is represented by "a" and the fixed capital necessary to implement the production system is represented by "b.

The farmers' income for 1.0 ha was estimated, according to Equation (4), with all values expressed in BRL:

$$FI = AV - (I + S + T) \tag{4}$$

FI: farmer's income
AV: added value
I: interest paid to the bank or other financial agent
S: salaries paid to the labor force
T: taxes and tariffs paid to the state in BRL

To calculate the farmer's income from 2.0 to 5.0 ha, linear models were elaborated (FI = ax + b), which describe the variation of farmers' income (FI) in the different treatments concerning the planted agricultural area per unit of work. In this model, the marginal contribution of income concerning the area is represented by "a" and the fixed expenses to implement the system of production is represented by "b".

The level of social reproduction (LSR) of each production unit for a planted area was also accessed. The LSR is related to the income necessary for social reproduction based on the minimum wage, which was adjusted to 1212.00 BRL according to the Provisional Measure of the Federal Government of 2 January 2022. In this case, the LRS value represented in the graph refers to the semiannual (six-month) minimum wage of 7272.00 BRL (US$ 1454.40), considering that in the second semester the farmer will carry out some other activities to obtain his income.

3. Results and Discussion

3.1. Crop Yield, Leaf Gas Exchange, and Water Use Efficiency

Crop yields (total, seed, and lint), physical water productivity (PWP), stomatal conductance (gs), photosynthetic rate (A), and shoots' dry mass were significantly influenced ($p < 0.01$) by the interaction between water scenarios and supplemental irrigation with wastewater (Table 3). The interaction between water scenarios and chemical fertilization exerted a significant influence ($p < 0.05$) only on cotton lint yield. The efficiency of supplemental irrigation (WUE_{SI}) was significantly influenced only by water scenarios ($p < 0.01$).

Supplemental irrigation (SI) with wastewater increased total crop yield in all water scenarios evaluated, when compared to treatments without SI, mainly in drought and severe drought scenarios (Table 4). For the normal, drought, and severe drought scenarios, there were increases in total productivity of 29.1%, 255.4%, and 250.7%, respectively. It is also noted that when there was no supplementary irrigation, the normal water scenario promoted the highest total productivity, with superiorities of 114.0% and 157.5% concerning the drought and severe drought scenarios, respectively. Similar trends were observed for seed and lint yield.

Table 3. Summary of analysis of variance for cotton yields (total, seed, and lint), expressed in kg ha^{-1}, physical water yield (PWP, kg m^{-3}), the efficiency of supplemental irrigation (WUE_{SI}, kg m^{-3}), stomatal conductance (gs, mol m^{-2} s^{-1}), photosynthetic rate (*A*, µmol m^{-2} s^{-1}), and shoots' dry mass (SDM, g) as a function of water scenarios (W), supplemental irrigation (SI) with treated wastewater, and chemical fertilization (F).

Source of Variation	Mean Squares								
	DF	Total Yield	Seed	Lint	PWP	WUE_{SI}	gs	*A*	SDM
Blocks	3	33,928.76 ^{ns}	9493.02 ^{ns}	9467.82 ^{ns}	0.002 ^{ns}	0.348 ^{ns}	0.03 ^{ns}	10.61 ^{ns}	118.98 ^{ns}
W	2	480,087.6 ^{ns}	142,796.9 ^{ns}	100,321.2 ^{ns}	0.007 ^{ns}	1.9713 *	0.13 **	126.59 *	1102.6 *
SI	1	12,505,715 *	4,594,194 **	1,940,268 **	0.563 **	-	0.56 **	467.12 **	9921.6 **
F	1	15,801.3 ^{ns}	5442.8 ^{ns}	2696.5 ^{ns}	0.004 ^{ns}	1.075 ^{ns}	0.004 ^{ns}	0.027 ^{ns}	1.89 ^{ns}
W × SI	2	1,374,153 **	475,923.2 **	232,861.9 **	0.099 **	-	0.045 *	76.11 **	1750.9 **
W × F	2	15,887.51 ^{ns}	46,931.86 ^{ns}	27,359.57 *	0.018 ^{ns}	0.904 ^{ns}	0.002 ^{ns}	0.21 ^{ns}	125.71 ^{ns}
SI × F	1	52,421.57 ^{ns}	19,503.62 ^{ns}	7974.85 ^{ns}	0.017 ^{ns}	-	0.009 ^{ns}	12.89 ^{ns}	22.85 ^{ns}
W × SI × F	2	57,664.91 ^{ns}	27,751.41 ^{ns}	6204.93 ^{ns}	0.014 ^{ns}	-	0.005 ^{ns}	5.47 ^{ns}	151.29 ^{ns}
C.V. (W)%		43.27	39.56	49.36	38.45	48.93	24.07	22.38	31.26
C.V. (SI)%		26.15	24.95	28.28	24.28	-	19.64	13.02	27.73
C.V. (F)%		17.52	18.07	17.03	16.91	54.55	21.06	8.73	17.15

DF—degrees of freedom; CV—coefficient of variation; ns—not-significant; * and ** denote significance at 0.05 or at 0.01 levels, respectively.

Table 4. Cotton yields (total, seed, and lint), physical water productivity (PWP), the efficiency of supplemental irrigation (WUE_{SI}), stomatal conductance (gs), photosynthesis rate (*A*), and shoots' dry mass as a function of water scenarios, supplemental irrigation (SI) with treated wastewater, and with or without chemical fertilization.

Treatments	Water scenarios		
	Normal	Drought	Severe Drought
		Total yield (kg ha^{-1})	
With SI	1607.4 aA	2067.4 aA	1695.5 aA
Without SI	1244.9 aA	581.7 bB	483.4 bB
		Seed yield (kg ha^{-1})	
With SI	971.7 aA	1236.7 aA	1032.3 aA
Without SI	739.0 aB	340.1 bB	305.4 bB
		Lint yield (kg ha^{-1})	
With SI	635.7 aA	830.8 aA	663.4 aA
Without SI	505.9 aA	241.7 bB	175.9 bB
		Lint yield (kg ha^{-1})	
With chemical fertilization	515.6 aB	551.9 aA	436.8 aA
Without chemical fertilization	626.1 aA	520.6 abA	402.7 bA
		PWP (kg m^{-3})	
With SI	0.43 aA	0.62 aA	0.56 aA
Without SI	0.38 aA	0.33 aB	0.25 aB
		WUE_{SI} (kg m^{-3})	
	1.16 b	1.98 a	1.08 b
		Stomatal conductance (mol m^{-2} s^{-1})	
With SI	0.57 aA	0.51 aA	0.51 aA
Without SI	0.48 aB	0.26 bB	0.21 bB
		Photosynthesis rate (µmol m^{-2} s^{-1})	
With SI	23.72 aA	23.63 aA	22.25 aA
Without SI	22.43 aA	15.72 bB	12.73 bB
		Shoots dry mass (g)	
With SI	58.06 aA	68.64 aA	55.08 aA
Without SI	52.03 aA	21.43 bB	22.06 bB

Means followed by the same lowercase letter in the row and uppercase in the column do not differ statistically from each other by Tukey's test ($p \leq 0.05$).

Low water availability limits the production of photoassimilates and plant development, reducing crop productivity [29,30]. Our results demonstrate the importance of using municipal treated wastewater in supplemental irrigation as it provides water and nutrients throughout the crop cycle providing adequate leaf water status and efficient nutrition, evidencing its agricultural potential to ensure high crop yields [19,31,32].

In treatments without SI, especially in drought and severe drought scenarios, plants were harmed by water scarcity that limits stomatal opening, leaf expansion, photoassimilates production, and plant productivity [25,29]. On the other hand, supplemental irrigation with treated wastewater mitigated the effects of water stress, with more expression in plants that received supplemental wastewater for a longer time, i.e., under the severe drought scenario.

Studying cotton plant responses to water deficit in different growth stages, [26] found an increase in cotton lint yield with increasing irrigation depth applied, under semi-arid conditions, regardless of the growth stage. Irrigation of the cotton crop with municipal treated wastewater showed that the maximum yield of cotton lint was obtained with the combination of 150% irrigation depth and a dose of 100% potassium recommendation [19].

Lint yield was less impacted by the absence of NPK fertilization than by the lack of supplemental irrigation with wastewater (Table 4). Compared to the normal water scenario, reductions in lint productivity of 52% and 65% were observed for the drought and severe drought scenarios, respectively, regardless of the presence or absence of chemical fertilization. However, the lack of fertilization caused reductions of 16.8% and 35.6% in lint productivity under the drought and severe drought scenarios, respectively (Table 4). Limitation of productivity in the scenario of water restrictions (severe drought) can be justified due to low soil moisture content, which significantly affects the absorption and assimilation of nutrients [30].

The use of supplemental irrigation with treated wastewater promoted an increase in physical water productivity (PWP) for all water scenarios studied compared to treatments without SI (Table 4). These increases in PWP for the normal, drought, and severe drought scenarios were 13.1%, 87.9%, and 124.0%, respectively. According to [33], several factors can influence the increase in the efficient use of water, such as an increase in crop yield and a decrease in losses due to evapotranspiration.

The normal scenario resulted in higher crop yields (Table 4). However, the lowest PWP (0.43 kg m^{-3}) was observed in this treatment due to the higher water volume used (simulating rain plus SI). These results corroborate [34], who found that higher water depths have higher yields in herbaceous cotton cultivars, but lower water use efficiency. These same authors obtained higher PWP with a water depth corresponding to 70% of crop evapotranspiration. Even so, the values of PWP obtained in the normal scenario (Table 4) are similar to those reported by [19], using 100% of ETc with municipal treated wastewater (0.49 kg m^{-3}).

Supplemental irrigation with treated wastewater resulted in productivity gains greater than 1.0 kg m^{-3}, values well above those obtained with full irrigation [34]. For the scenario with higher water restriction (severe drought), a lower WUE_{SI} value is observed, which is statistically similar to the treatment with the smallest water restriction (Normal). It is important to emphasize that the former uses the highest SI depth, while the latter presents the smallest increase in cotton yield. The highest WUE_{SI} was observed in the drought scenario, which combined the high increase in cotton yield while using an intermediate depth of supplemental irrigation (Figure 2).

The application of treated wastewater can increase the rate of carbon assimilation, both by reducing water stress and providing mineral nutrients [35,36]. Supplemental irrigation with treated wastewater improved photosynthetic responses and shoot biomass production, especially under drought and severe drought scenarios. Compared to the absence of supplemental irrigation, there were increases of 49.01% and 58.8% in stomatal conductance, 33.5% and 42.8% in photosynthetic rate, and 220.2% and 149.6% in the dry mass of shoot for both drought and severe drought scenarios, respectively (Table 4). On the other hand, photosynthetic responses and shoots biomass production showed similar results for different water scenarios when supplemental irrigation with treated wastewater was used. Plots that did not receive supplemental irrigation suffered from the negative effects of water stress, such as stomatal limitations, reduction in chlorophyll concentration, limited cell elongation, and inhibition of photochemical and enzymatic reactions [25,30].

3.2. Technological Quality of Fiber

All variables related to cotton fiber quality were influenced ($p \leq 0.01$) by supplemental irrigation with treated wastewater (Table 5). Fiber uniformity (UNF) and micronaire index (MIC) were influenced significantly by the interaction between water scenarios and supplemental irrigation with treated wastewater ($p \leq 0.01$).

Table 5. Summary of analysis of variance for fiber length (UHM), fiber uniformity (UNF), short fiber index (SFI), and micronaire index (MIC) of cotton, as a function of water scenarios (W), supplemental irrigation with treated wastewater (SI), and chemical fertilization (F).

Source of Variation	Mean Squares				
	DF	UHM	UNF	SFI	MIC
Blocks	3	0.86 ^{ns}	1.87 ^{ns}	0.67 ^{ns}	0.05 ^{ns}
Water scenarios (W)	2	8.81 ^{ns}	4.32 ^{ns}	1.23 ^{ns}	0.73 ^{ns}
Supplemental irrig. (SI)	1	70.27 **	66.32 **	19.67 **	0.44 **
Fertilization (F)	1	1.66 ^{ns}	5.65 ^{ns}	0.21 ^{ns}	0.02 ^{ns}
W × SI	2	0.73 ^{ns}	0.05 **	0.43 ^{ns}	0.03 **
W × F	2	1.43 ^{ns}	0.28 ^{ns}	0.05 ^{ns}	0.05 ^{ns}
SI × F	1	0.19 ^{ns}	2.19 ^{ns}	0.11 ^{ns}	0.04 ^{ns}
W × SI × F	2	1.44 ^{ns}	5.96 ^{ns}	0.32 ^{ns}	0.01 ^{ns}
With SI		30.18 a	86.01 a	6.94 b	4.83 a
Without SI		27.76 b	83.65 b	8.22 a	4.64 b
C.V (W) (%)		4.67	2.14	16.28	6.56
C.V (SI) (%)		5.51	1.69	14.76	3.99
C.V (F) (%)		3.95	1.53	9.49	4.53

DF—degree of freedom; CV—coefficient of variation; ns—non-significant; ** denote significance at 0.01 levels, respectively. Means followed by the same lowercase letter in the column do not differ statistically from each other by Tukey's test ($p \leq 0.05$).

Fiber length (UHM) increased by 8.01% with SI using treated wastewater compared to the treatment without SI (Table 5). The increase in UHM caused by SI with MTW promoted soil enrichment with mineral nutrients, including K and N [31,37]. The increase in soil fertility provided by MTW application possibly favored cell development and, consequently, greater fiber elongation, as previously discussed by [1,19].

Otherwise, the short fiber index (SFI) was about 18.4% higher in the treatment without supplemental irrigation (Table 5) compared to the treatment with SI. This result is similar to that found by [38], who investigated the effect of treated wastewater and nitrogen rates on the fiber quality of herbaceous cotton, concluding that the short fiber index was lower when the crop received irrigation with treated wastewater. The longer the fiber, the better it is for the industry since short fiber produces thicker yarn, while long fiber produces finer yarns used in the manufacture of luxury fabrics with higher commercial value [39].

Supplemental irrigation with treated wastewater promoted an increase in fiber uniformity in all water scenarios, with increments of 4.2%, 2.6%, and 3.7% for the normal, drought, and severe drought scenarios, respectively (Table 6). Supplemental irrigation with treated wastewater also promoted an increase in the micronaire index for the drought and severe drought water regimes, with increments of 5.8% and 5.0%, respectively (Table 6).

Table 6. Fiber uniformity (UNF) and micronaire index (MIC) of cotton, as a function of water scenarios and supplemental irrigation with treated wastewater.

Treatments	Water Scenarios		
	Normal	**Drought**	**Severe Drought**
		UNF-%	
With SI	86.75 aA	85.44 aA	86.19 aA
Without SI	83.28 aB	83.24 aB	83.09 aB
		MIC-μg in^{-1}	
With SI	4.96 aA	4.93 aA	4.61 bA
Without SI	4.88 aA	4.66 bB	4.39 cB

Means followed by the same lowercase letter in the row and uppercase in the column do not differ statistically from each other by Tukey's test ($p \leq 0.05$).

Our results also showed that supplemental irrigation increased both fiber length (Table 5) and fiber uniformity (Table 6) and as a result, most likely reduced the harmful effects of water deficit. In this context, several studies have confirmed that water deficit after flowering and during the fiber elongation stage can compromise fiber length and uniformity, as the physiological and mechanical processes of cell elongation are impaired by water scarcity [19,40,41].

An important feature of the textile industry is the requirement for finer fibers. The micronaire index (MIC) of 3.5 to 4.2 μg in^{-1} allows the fibers to be spun by high-speed rotors in modern spinning equipment. According to the industry classification, MIC values can be included in the following categories: <3.0 (very fine); 3.0–3.9 (fine); 4.0–4.9 (medium); 5.0–5.9 (coarse); >6 μg in^{-1} (very coarse) [42]. The MIC results obtained in our study are in the medium category, superior to the standards required by the textile industry, regardless of the adopted water scenario. Authors reported that adequate values of MIC were obtained with cotton irrigated with treated effluent, 3.46 [19] and 3.90 μg in^{-1} [37], thus contrasting the findings of our study.

3.3. Economic Analysis

A study was carried out on the profit-generating capacity of supplemental irrigation with treated wastewater through indicators of added value and farmer income. Figure 3 shows the variation of the added value as a function of the agricultural area, making it possible to identify the marginal contribution of the different combinations of SI with treated wastewater and mineral fertilization, simulated for normal, drought, and severe drought scenarios.

For the normal water scenario, the highest added value for each hectare of production was found in the treatment with supplemental irrigation with treated wastewater and the treatment with SI without chemical fertilization presented the best result. In general, the treatments studied in the normal water scenario had a similar added value, except the treatment without SI and with NPK fertilization which had the lowest added value, differing from the other treatments.

In the drought and severe drought scenario, supplemental irrigation with treated wastewater increased the added value, with or without the input of fertilizers. In the Drought water scenario, the treatment which obtained the highest added value was with SI and with fertilizer, while in the severe drought scenario, the best result was obtained in the treatment with SI and without fertilizer. It is noted that from the normal to the severe drought scenario, the inclination between the straight lines with and without SI increases considerably, demonstrating that the supplemental irrigation with wastewater increased the added value, especially under water shortage. It is observed that even generating fixed costs with the financing of an irrigation system (fixed costs), the use of SI presents the best economic return.

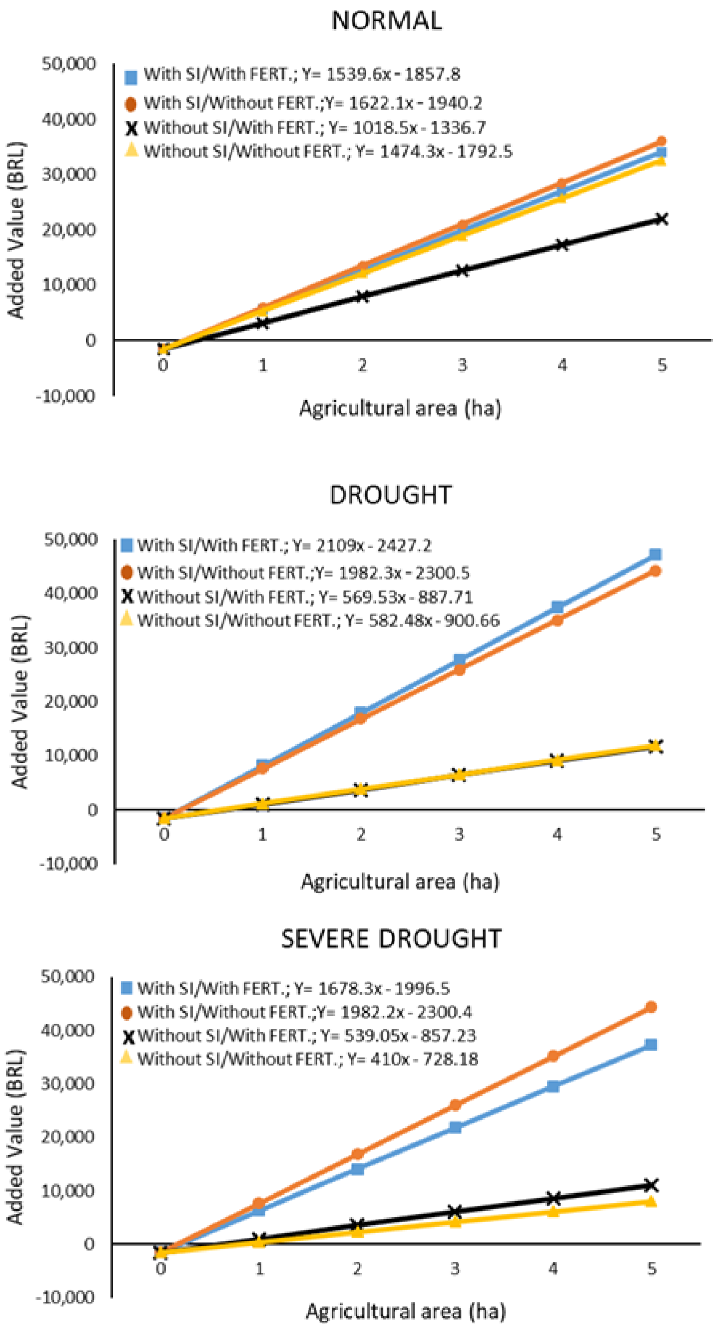

Figure 3. Added value for the different simulated water scenarios, supplemental irrigation (SI) with treated wastewater, and presence and absence of NPK fertilization, as a function of the area cultivated with BRS 433 cotton.

Analyzing the treatments that received fertilization, in general, there were no great differences in the value of production. This demonstrates that, under such conditions, the use of fertilizers must be analyzed to avoid economic losses. Several studies have shown that irrigation with wastewater increases the content of organic matter and the availability of nutrients in the soil [43–45], reducing the variable costs of applying fertilizers. According to [46], treated wastewater can be used for irrigation of corn and cotton, saving fresh water and mineral fertilizers and obtaining the same or better economic results.

Figure 4 shows the farmer's income as a function of the marginal contribution of each water scenario for an agricultural area up to 5.0 hectares. In the normal water scenario, as mentioned above, the treatment with the highest added value was with SI and without mineral fertilization, with supplemental irrigation with treated wastewater starting to be advantageous from 1.7 hectares onwards. In the treatment with SI and with fertilization, the cultivation of cotton is advantageous above 1.8 hectares. For the treatment without SI but with fertilization, the cultivation of cotton is only beneficial from 3.0 hectares.

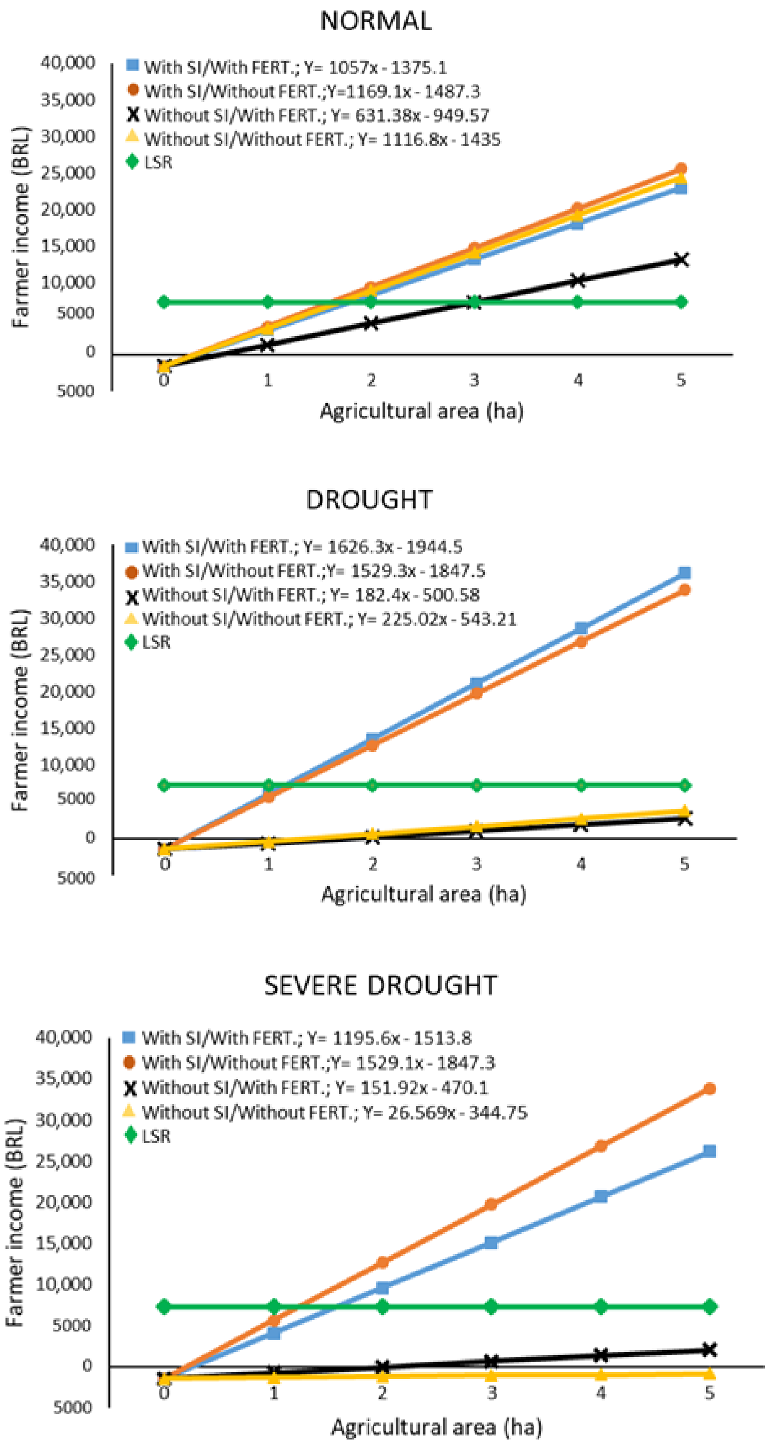

Figure 4. Farmers' income for the different simulated water scenarios, supplemental irrigation (SI with treated wastewater, and the presence or absence of NPK fertilization, as a function of the area cultivated with BRS 433 cotton. The green line indicates the Level of Social Reproduction (LSR).

For the drought water scenario, it is advantageous to cultivate cotton in the treatment with SI and with mineral fertilization from 1.2 hectares, i.e., the level of social reproduction is reached with this cultivated area. In the treatment with supplemental irrigation and without chemical fertilization, cultivation from 1.3 hectares is advantageous. The treatments without SI did not reach the value of the LSR, demonstrating that it is not beneficial to grow cotton in an area smaller than five hectares under severe water restriction. In addition to raising soil moisture, supplemental irrigation with treated wastewater provides nutrients that improve plant growth, reduce the need for fertilizer application, and increase the productivity of soils of low fertility [47].

In the severe drought scenario, the treatment with SI and fertilization reached the level of social reproduction in 1.6 hectares, demonstrating that its cultivation is advantageous from such area. Cotton cultivation with SI and without mineral fertilization reaches LSR with 1.3 hectares. Otherwise, the treatments without SI are not beneficial to grow cotton in an area of up to five hectares under severe drought stress. It was observed that the treatment without both SI and fertilization was negative up to 5 hectares and that the larger the cultivated area, the greater the economic loss to the farmer.

Drought and severe drought treatments that received supplemental irrigation with treated wastewater achieved higher farmer's income when compared to the normal scenario with SI. This can be explained by the higher crop productivity boosted by the higher supply of nutrients found in MTW compared to freshwater (Table 2), also confirmed by other field studies involving treated wastewater and cotton [19]. Supplemental irrigation was carried out during the dry spells, i.e., the drought and severe drought scenarios received a greater number of irrigations and, consequently, received higher depth and input of nutrients to the soil.

The use of alternative sources of water, such as treated and brackish wastewater, can be an important strategy for some productive activities in semi-arid regions, including branches of industry and the agricultural sector [48,49]. Irrigation with treated wastewater is a practice widely used worldwide, especially in arid and semi-arid regions, to alleviate water scarcity in agriculture [50–53]. Supplemental irrigation for cotton is essential, given that its cultivation is predominantly under rainfed conditions in the Brazilian semi-arid region, which is subject to recurrent droughts and the occurrence of long dry spells during the rainy season, which impact the sustainability of agricultural enterprises [14,29]. However, there is a need to assess the environmental risks of using MTW for irrigation, especially in terms of physical, chemical, and microbiological soil quality.

4. Conclusions

Our results show the importance of using treated wastewater in the supplemental irrigation of cotton under scarce-water scenarios in tropical semi-arid regions, as evidenced by improved plant photosynthetic responses, growth, yield, and farmer's estimated profitability. The frequent dry spells during the drought and severe drought scenarios imply greater use of supplemental water depth and, consequently, a greater addition of nutrients, such as N, P, K, Ca, and Mg, to the soil, ensuring higher yields, high water use efficiency, lower fertilizer costs, and higher income for farmers. As an example, under the Severe Drought scenario, the highest income for the farmer was obtained with the use of supplemental irrigation without mineral fertilization. On the other hand, the lack of supplemental irrigation, mainly during the drought and severe drought scenarios caused decreases in cotton lint yield of 52% and 65%, respectively. The use of supplemental irrigation increased cotton productivity in all three scenarios (normal, drought, and severe drought) by approximately 29%, 255%, and 251%, respectively, indicating that even during a normal average wet year the water demands by the cotton crop are not completely satisfied by rainfall. The use of treated wastewater also increased fiber length, uniformity, and short fiber index. The fact that the electrical conductivity of municipal treated wastewater was approximately 2.5-fold higher than the control freshwater did not seem to hinder the growth of cotton plant or crop yield.

It is worth noting that the acceptance of wastewater as an alternative irrigation source requires not only good results in productive and economic terms, but also the certainty that the existence of environmental risks has been thoroughly evaluated. Thus, future studies need to assess the real water potential of wastewater treatment ponds in the Brazilian semi-arid region, as well as the concentrations of emerging contaminants including heavy metals, antibiotics, and microorganisms that may cause environmental damage or health hazards concerns, if the water is used for the production of consumable products, but not so much for cotton. This set of data will add to the knowledge needed for the evaluation of the productive, economic, and environmental sustainability of supplemental irrigation with treated wastewater under a tropical semi-arid climate.

Author Contributions: Conceptualization, A.F.B.d.A., C.F.L., F.B.L. and R.N.T.C.; methodology, A.F.B.d.A., E.S.C., C.F.L., J.R.d.S.S. and F.A.d.A.; investigation, A.F.B.d.A., E.S.C., J.R.d.S.S., M.A.B. and C.F.L.; writing—original draft preparation, A.F.B.d.A., E.S.C., C.F.L., J.R.d.S.S. and H.R.G.; writing—review and editing, F.A.d.A., J.F.d.S.F., S.C.R.V.L., H.R.G., M.A.B. and R.N.T.C.; project administration, C.F.L.; funding acquisition, C.F.L. and S.C.R.V.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the State Development Agency of Ceará (ADECE) and the Foundation for the Support of Scientific and Technological Development of Ceará (FUNCAP), Brazil, Process Number 08126425/2020.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing does not apply to this article.

Acknowledgments: Acknowledgments are due to the State Development Agency of Ceará (ADECE), Secretariat for Economic Development and Labor of Ceará (SEDET), Institute of Technological Education Center (CENTEC), Foundation for the Support of Scientific and Technological Development of Ceará (FUNCAP), and Chief Scientist Program, Brazil, for the financial support provided for this research and award of fellowship to the first author. Acknowledgments are also due to Company of Water and Sewerage of the State of Ceará (CAGECE) for the partnership to carry out this research in the municipality of Russas, Ceará, Brazil.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Guo, K.; Tu, L.; He, Y.; Deng, J.; Wang, M.; Huang, H.; Li, Z.; Zhang, X. Interaction Between Calcium and Potassium Modulates Elongation Rate in Cotton Fiber Cells. *J. Exp. Bot.* **2017**, *68*, 5161–5175. [CrossRef] [PubMed]
2. Abdelraheem, A.; Esmaeili, N.; O'Connell, M.; Zhang, J. Progress and Perspective on Drought and Salt Stress Tolerance in Cotton. *Ind. Crops Prod.* **2019**, *130*, 118–129. [CrossRef]
3. Ferreira, A.C.B.; Borin, A.L.D.C.; Lamas, F.M.; Bogiani, J.C.; Silva, M.A.S.; Silva Filho, J.L.; Staut, L.A. Soil carbon accumulation in cotton production systems in the Brazilian Cerrado. *Acta Scientiarum. Agron.* **2020**, *42*, 1–8. [CrossRef]
4. Santos, A.; Matos, E.S.; Freddi, O.S.; Galbieri, R.; Lal, R. Cotton production systems in the Brazilian Cerrado: The impact of soil attributes on field-scale yield. *Eur. J. Agron.* **2020**, *118*, 126090. [CrossRef]
5. Cetin, O.; Bilgel, L. Effects of different irrigation methods on shedding and yield of cotton. *Agric. Water Manag.* **2002**, *54*, 1–15. [CrossRef]
6. Carvalho, I.R.; Korcelski, C.; Pelissari, G.; Hanus, A.D.; Rosa, G.M. Demanda hídrica das culturas de interesse agronômico. *Enciclopédia Biosf.* **2013**, *9*, 969–985.
7. Uzen, N.; Cetin, O.; Unlu, M. Effects of domestic wastewater treated by anaerobic stabilization on soil pollution, plant nutrition, and cotton crop yield. *Environ. Monit. Assess.* **2016**, *188*, 664. [CrossRef]
8. Multsch, S.; Krol, M.S.; Pahlow, M.; Assunção, A.L.C.; Barretto, A.G.O.P. Assessment of potential implications of agricultural irrigation policy on surface water scarcity in Brazil. *Hydrol. Earth Syst. Sci.* **2020**, *24*, 307–324. [CrossRef]
9. Mekonnen, M.M.; Hoekstra, A.Y. The Green, Blue and Grey Water Footprint of Crops and Derived Crop Products. *Hydrol. Earth Syst. Sci.* **2011**, *15*, 1577–1600. [CrossRef]
10. Roth, G.; Harris, G.; Gillies, M.; Montgomery, J.; Wigginton, D. Water-use efficiency and productivity trends in Australian irrigated cotton: A review. *Crop Pasture Sci.* **2013**, *64*, 1033–1048. [CrossRef]
11. Datta, A.; Ullah, H.; Ferdous, Z.; Santiago-Arenas, R.; Attia, A. Water Management in Cotton. In *Cotton Production*; Jabram, K., Chauhan, B.S., Eds.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2020; pp. 47–60.
12. Bezerra, J.R.C.; Azevedo, P.V.; Silva, B.B.; Dias, J.M. Evapotranspiração e Coeficiente de Cultivo do Algodoeiro BRS-200 Marrom, irrigado. *Rev. Bras. Eng. Agrícola E Ambient.* **2010**, *14*, 625–632. [CrossRef]
13. Raper, T.B.; Pilon, C.; Singh, V.; Snider, J.; Stewart, S.; Byrd, S. Cotton Production in the United States of America: An overview. In *Cotton Production*; Jabram, K., Chauhan, B.S., Eds.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2020; pp. 217–248.

14. Marengo, J.A.; Torres, R.R.; Alves, L.M. Drought in northeast Brazil: Past, present and future. *Theor. Appl. Climatol.* **2017**, *129*, 1189–1200. [CrossRef]
15. Gonçalves, I.Z.; Barbosa, E.A.A.; Santos, L.N.S.; Nazario, A.A.; Feitosa, D.R.C.; Tuta, N.F.; Matsura, E.E. Nutritional balance and Production of Sugarcane Irrigated with Treated Wastewater through Subsurface Drip. *Irrig. Sci.* **2019**, *37*, 207–217. [CrossRef]
16. Jasechko, S.; Perrone, D. Global Groundwater Wells at Risk of Running dry. *Science* **2021**, *372*, 418–421. [CrossRef] [PubMed]
17. Chen, L.; Wang, L.; Wu, X.; Ding, X. A Process-Level Water Conservation and Pollution Control Performance Evaluation Tool of Cleaner Production Technology in Textile Industry. *J. Clean. Prod.* **2017**, *143*, 1137–1143. [CrossRef]
18. Feitosa, E.O.; Lopes, F.B.; Andrade, E.M.; Magalhães, A.C.M.; Freitas, C.A.S. Environmental impact of different agricultural production systems. *Rev. Ciência Agronômica* **2021**, *52*, 1–9.
19. Lima, B.L.C.; Silva, Ê.F.F.; Zonta, J.H.; Cordão Terceiro Neto, C.P.; Lacerda, C.F.; Ferreira, J.F.S.; Cruz, F.J.R. Irrigation with wastewater and K fertilization ensure the yield and quality of colored cotton in a semiarid climate. *Agronomy* **2021**, *11*, 2370. [CrossRef]
20. Etene, Escritório Técnico de Estudos Econômicos do Nordeste. Algodão: Produção e.mercado. Banco do Nordeste. Fortaleza, Ano 6, nº 166. 2021. Available online: https://www.bnb.gov.br/s482-dspace/bitstream/123456789/808/1/2021_CDS_166.pdf (accessed on 12 June 2022).
21. Fernandes, F.H.F.; Aquino, A.B.; Aquino, B.F.; Holanda, F.J.M.; Freire, J.M.; Crisostomo, L.A.; Costa, R.I.; Uchoa, S.C.P.; Fernandes, V.L.B. *Recomendações De Adubação E Calagem Para O Estado Do Ceara*; Editora ABC: Fortaleza, Brazil, 1993; p. 247.
22. Teixeira, P.C.; Donagemma, G.K.; Fontana, A.; Teixeira, W.G. *Manual de Métodos de Análise de Solo*, 3rd ed.; Embrapa: Brasilia, Brazil, 2017; p. 574.
23. Eaton, A.D.; Clesceri, L.S.; Rice, E.W.; Baird, R.B. *Standard Methods for the Examination of Water and Wasterwater*, 23rd ed.; American Public Health Association: Washington, DC, USA, 2017; p. 1504.
24. Frizzone, J.A.; Lima, S.C.R.V.; Lacerda, C.F.; Mateos, L. Socio-economic indexes for water use in irrigation in a representative basin of the tropical semiarid region. *Water* **2021**, *13*, 2643. [CrossRef]
25. Cavalcante, E.S.; Lacerda, C.F.; Mesquita, R.O.; Melo, A.S.; Ferreira, J.F.S.; Teixeira, A.S.; Lima, S.C.R.V.; Sales, J.R.S.; Silva, J.S.; Gheyi, H.R. Supplemental irrigation with brackish water improves carbon assimilation and water use efficiency in maize under tropical dryland conditions. *Agriculture* **2022**, *12*, 544. [CrossRef]
26. Zonta, J.H.; Bezerra, J.R.C.; Sofiatti, V.; Farias, F.J.C.; Carvalho, L.P. Efeito da irrigação no rendimento e qualidade de fibras em cultivares de algodoeiro herbáceo. *Rev. Caatinga* **2015**, *28*, 52–62. [CrossRef]
27. Ferreira, D.F. Sisvar: A computer analysis system to fixed effects split plot type designs. *Rev. Bras. Biom.* **2019**, *37*, 529–535. [CrossRef]
28. Silva Neto, B.; Dezen, M.; Santos, P.E. O conceito de reprodução social na análise de unidades de produção agropecuária. *Teor. E Evid. Econ.* **2009**, *32*, 87–108. Available online: http://seer.upf.br/index.php/rtee/article/view/4747/3181 (accessed on 20 February 2022).
29. Cavalcante, E.S.; Lacerda, C.F.; Costa, R.N.T.; Gheyi, H.R.; Pinho, L.L.; Bezerra, F.M.S.; Oliveira, A.C.; Canjá, J.F. Supplemental irrigation using brackish water on maize in tropical semi-arid regions of Brazil: Yield and economic analysis. *Sci. Agric.* **2021**, *78*, e20200151. [CrossRef]
30. Taiz, L.; Zeiger, E.; Møller, I.M.; Murphy, A. *Fisiologia e Desenvolvimento Vegetal*; Artmed Editora: Porto Alegre, Brazil, 2017; p. 888.
31. Alikhasi, M.; Kouchakzadeh, M.; Baniani, E. The Effect of Treated Municipal Wastewater Irrigation in Non-Agricultural Soil on Cotton Plant. *J. Agric. Sci. Technol.* **2012**, *14*, 1357–1364.
32. Dehghanisanij, H.; Emani, S.; Khasheisiuki, A. Functional properties of irrigated cotton under urban treated wastewater using an intelligent method. *Appl. Water Sci.* **2022**, *12*, 66. [CrossRef]
33. Karam, F.; Lahoud, R.; Masaad, R.; Daccache, A.; Mounzer, O.; Rouphael, Y. Water Use and Lint Yield Response of Drip Irrigated Cotton to the Length of Irrigation Season. *Agric. Water Manag.* **2006**, *85*, 287–295. [CrossRef]
34. Zonta, J.H.; Bezerra, J.R.C.; Sofiatti, V.; Brandão, Z.N. Yield of cotton cultivars under different irrigation depths in the Brazilian semi-arid region. *Revista Brasileira Engenharia Agrícola Ambiental* **2015**, *19*, 748–754. [CrossRef]
35. Lima, B.L.C.; Silva, Ê.F.F.; Santos, H.R.B.; Souza, E.R. Potassium fertilization and irrigation with treated wastewater on gas exchange of colored cotton. *Revista Brasileira Engenharia Agrícola Ambiental* **2018**, *22*, 741–746. [CrossRef]
36. Oliveira, A.C.; Araujo, A.F.B.; Lacerda, C.F.; Canjá, J.F.; Pinho, L.L.; Sousa, N.I.G. Influência da irrigação suplementar com águas residuárias sobre as trocas gasosas foliares do algodoeiro. *Irriga* **2020**, *25*, 677–682. [CrossRef]
37. Santos, S.R.; Soares, A.A.; Kondo, M.K.; Matos, A.T.; Maia, V.M. Indicadores de produção e qualidade da fibra do algodoeiro fertirrigado com água residuária sanitária. *Eng. Agrícola* **2016**, *36*, 525–536. [CrossRef]
38. Azevedo, M.R.Q.A.; König, A.; Beltrão, N.E.; Ceballos, B.S.O.; Azevedo, C.A.V.; Tavares, T.L. Características tecnológicas da fibra do algodão herbáceo sob efeito de adubação nitrogenada e irrigação com água residuárias tratada. *Rev. Bras. Eng. Agrícola Ambient.* **2005**, *9*, 202–206. [CrossRef]
39. Carvalho, L.P. *Brasil Poderá Produzir Algodão de Fibra Longa Para Tecidos de Luxo*; Embrapa Algodão: Campina Grande, Brazil, 2015. Available online: https://www.embrapa.br/busca-de-noticias/-/noticia/3272256/ (accessed on 21 June 2022).
40. Papastylianou, P.T.; Argyrokastritis, I.G. Effect of Limited Drip Irrigation Regime on Yield, Yield Components, and Fiber Quality of Cotton under Mediterranean Conditions. *Agric. Water Manag.* **2014**, *142*, 127–134. [CrossRef]

41. Zhang, D.; Luo, Z.; Liu, S.; Li, W.; Tang, W.; Dong, H. Effects of deficit Irrigation and Plant Density on the growth, Yield and fiber quality of irrigated cotton. *Field Crops. Res.* **2016**, *197*, 1–9. [CrossRef]
42. Santana, J.C.F.; Wanderley, M.J.R.; Beltrão, N.E.M.; Azevedo, D.M.P.; Leão, A.B.; Vieira, D.J. Características da Fibra e do Fio do Algodão. In *O Agronegócio do Algodão no Brasil*; Beltrão, N.E.M., Azevedo, D.M.P., Eds.; Embrapa Informação Tecnológica: Brasília, Brazil, 2008; pp. 1099–1120.
43. Kiziloglu, F.; Tuean, M.; Sahin, U.; Angin, I.; Anapali, O.; Okuroglu, M. Effects of wastewater irrigation on soil and cabbage-plant (*Brassica olereacea* var. capitate cv. Yavola-1) chemical properties. *J. Plant Nutr. Soil Sci.* **2007**, *170*, 166–172. [CrossRef]
44. Jueschke, E.; Marschner, B.; Tarchitzky, J.; Chen, Y. Effects of treated wastewater irrigation on the dissolved and soil organic carbon in Israeli soils. *Water Sci. Technol.* **2008**, *57*, 727–733. [CrossRef]
45. Mañas, P.; Castro, E.; Heras, J.L. Irrigation with treated wastewater: Effects on soil, lettuce (*Lactuca sativa*) crop and dynamics of microorganisms. *J. Environ. Sci. Health* **2009**, *44*, 1261–1273. [CrossRef]
46. Tsadilas, C.D.; Vakalls, P.S. Economic benefit from irrigation of cotton and corn with treated wastewater. *Water Sci. Technol.* **2003**, *3*, 223–229. [CrossRef]
47. Gatica, J.; Cytryn, E. Impact of treated wastewater irrigation on antibiotic resistance in the soil microbiome. *Environ. Sci. Pollut. Res.* **2013**, *20*, 3529–3538. [CrossRef]
48. Neiva, T.S. Potencial de reuso na agricultura da água residuária da estação de tratamento limoeiro. *Rev. Eletrônica Gestão Tecnol. Ambient.* **2015**, *2*, 1–75. [CrossRef]
49. Medeiros, S.S.; Soares, A.A.; Ferreira, P.A.; Neves, J.C.L.; Matos, A.T.; Souza, J.A.A. Utilização de água residuária de origem doméstica na agricultura: Estudo das alterações químicas do solo. *Revista Brasileira Engenharia Agrícola Ambiental* **2005**, *9*, 603–612. [CrossRef]
50. Siebe, C. Heavy metal availability to plants in soils irrigated with wastewater from Mexico City. *Water Sci. Technol.* **1995**, *32*, 29–34. [CrossRef]
51. Jimenez, B.; Chávez, A. Quality assessment of an aquifer recharged with wastewater for its potential use as drinking source: "El Mezquital Valley" case. *Water Sci. Technol.* **2004**, *50*, 269–276. [CrossRef]
52. Elifantz, H.; Kautsky, L.; Mor-Yosef, M.; Tarchitzky, J.; Bar-Tal, A.; Chen, Y.N. Microbial activity and organic matter dynamics during 4 years of irrigation with treated wastewater. *Microb. Ecol.* **2011**, *62*, 973–981. [CrossRef] [PubMed]
53. Frenk, S.; Hadar, Y.; Minz, D. Resilience of soil bacterial community to irrigation with water of different qualities under Mediterranean climate. *Environ. Microbiol.* **2014**, *16*, 559–569. [CrossRef] [PubMed]