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Posted Date: 26 February 2026

doi: 10.20944/preprints202602.1248.v1

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Wastewater Treatment Plants as Environmental Barriers in Hyperarid Regions: A Comprehensive Evaluation of their Performance, Groundwater Protection, and Reuse in Agriculture in the Algerian Sahara

Cherif Rezzoug [1,*], Mahdi Belhadj [2], Touhami Merzougui [1] and Abdelhadi Bouchiba [2]

[1] Chemistry and environmental sciences laboratory, University of Tahri Mohamed, Bechar 08000, Algeria
[2] University of Tahri Mohamed, Bechar 08000, Algeria
* Correspondence: cherifrezzoug@yahoo.fr; Tel.: +213550716365

Abstract

Wastewater treatment plants (WWTPs) are increasingly considered a key and importante infrastructure for environmental protection and combating climate change in regions suffering from severe water scarcity. This work aims to provide a comprehensive and integrated evaluation of the performance of WWTPs in arid and hyperarid contexts, based on two representative experiences in the Algerian Sahara. The evaluation is based on an analysis of treatment performance (COD, BOD_5, TSS), operational stability, and the agricultural suitability of the wastewater (electrical conductivity, SAR, RSC), in addition to the indirect effects on groundwater protection. The results show high and stable organic matter removal rates (>85-90%), demonstrating the effectiveness of biological processes under harsh and hostile climatic conditions. Despite this, residual salinity and sodium carbonate remain the two main factors limiting the extent of long-term agricultural reuse, even with effective treatment. The international comparative analysis highlights the systemic nature of this separation in hyperarid environments and seeks to confirm the need to consider wastewater treatment plants as truly integrated environmental barriers.

Keywords: wastewater treatment plants; hyperarid; reuse; salinity; groundwater; climate change

1. Introduction

Water scarcity is a major environmental challenge today, particularly in arid and extremely arid regions, where climate change, population growth, and agricultural intensification are placing increasing pressure on fragile and limited hydrological systems [1,2]. In these contexts, characterized by low and infrequent rainfall (<100 mm/year) and high evaporation rates, the dependence of local communities on deep groundwater exacerbates the salinization crisis, increases nitrate levels, and further degrades fragile oasis ecosystems [3,4]. Therefore, the reuse of treated wastewater is now considered an important factor in integrated water management strategies, effectively contributing to meeting agricultural water needs and also limiting the overexploitation of groundwater aquifers [5,6]. However, in extremely arid environments, compliance with wastewater regulations does not guarantee either agricultural security or environmental sustainability. This is due to limitations related to soil salinity and alkalinity, as well as the low dilution of the receiving environment [7,8].

The evaluation of wastewater treatment plants relies primarily on their conventional treatment performance (COD, BOD_5, TSS), which are basic indicators but insufficient for understanding their overall environmental role in extremely arid contexts, where the challenges include protecting both groundwater and the resilience of agricultural systems to climate change [9,10]. Recent studies in this area have revealed that residual salinity and the ionic composition of wastewater play a key role in limiting the reuse of treated wastewater in agriculture, regardless of the biological efficiency of the treatment [11,12], highlighting the need to emphasize the importance of developing integrated approaches that combine physical, chemical, agricultural, and hydrogeological indicators [13,14]. In this context, reconsidering wastewater treatment plants as genuine environmental barriers helps reduce pressure on fossil aquifers and promote climate adaptation in desert regions, despite the limited number and incomplete nature of experimental studies conducted in extremely arid regions [15,16].

Our study therefore offers a comprehensive evaluation of two wastewater treatment plants in southern Algeria, operating in arid and very arid zones. It combines an analysis of treatment performance, an assessment of the agricultural suitability of the effluents (EC, SAR, RSC), and an analysis of their potential impacts on groundwater and fragile oasis ecosystems. The study's central hypothesis is that, despite increased treatment rates, the sustainability of reuse depends primarily on salinity and hydrogeological constraints, making these plants essential infrastructure for climate change adaptation. Although this study is primarily based on Saharan cases, it aims to identify a set of lessons that can be transferred and applied to wastewater treatment and reuse strategies in hyper-arid environments internationally.

2. Materials and Methods

2.1. Conceptual Framework and Hypothesis

The hypothesis, which is currently being tested, is that in hyper-arid regions, the environmental sustainability of treated water reuse depends more on salinity and hydrogeological constraints than on purification yields alone [17]. Through this assessment, we aim to adopt a comprehensive approach that includes treatment, reuse, agriculture, and groundwater protection—an approach strongly recommended for adapting to water in extreme climates [3,5,13].

2.2. Study Sites and Climate Constraints

A comparison was conducted between two wastewater treatment plants in southern Algeria (one arid region versus one hyper-arid region), characterized by average rainfall of less than 100 mm/year and a high evaporation rate, in order to isolate the extent of the impact of thermal and saline constraints on the environmental functioning of the two plants [1,2].

Wastewater samples were collected over a monitoring period from January to December 2024. A set of n = 24 composites samples from the two plants was analyzed, representing an average of two samples per month.

Despite the modest sample size (number of composite samples = 24) for both stations, most studies conducted on similar wastewater treatment plants in arid environments similar to our region show that all monthly or seasonal data sets, in addition to appropriate statistical analyses, provide us with sufficient robustness to identify key trends and compare treatment effectiveness [18,19].

2.3. Treatment Performance Indicators

The performance of the treatment process was evaluated using standard wastewater quality criteria [20,21]: Chemical oxygen demand (COD), five-day biological oxygen demand (BOD5), and total suspended solids (TSS) were used. Removal efficiency (η) was calculated using the following formula:

$$\eta(\%) = \frac{C_{in} - C_{out}}{C_{in}} \times 100$$

C_{in} and C_{out} represent the inlet and outlet concentrations, respectively. While these indicators are important and necessary, they are not sufficient on their own to assess the environmental sustainability of the systems studied [9,10].

2.4. Limiting Agronomic Indicators

The suitability of treated effluents for reuse in agriculture was assessed using three critical and effective indicators in arid and hyperarid environments [4,7]:

- Electrical conductivity (EC), an indicator of overall salinity.
- Sodium Adsorption Ratio (SAR), defined by :

$$SAR = \frac{[Na^+]}{\sqrt{([Ca^{2+}] + [Mg^{2+}])/2}}$$

- Residual Sodium Carbonate (RSC), calculated as follows :

$$RSC = ([HCO_3^-] + [CO_3^-]) - ([Ca^{2+}] + [Mg^{2+}])$$

2.5. Integrated Environmental Assessment

The environmental analysis must be based on the capacity of wastewater treatment plants to:
a) minimize the direct discharge of untreated wastewater,
b) reduce water withdrawals from fossil aquifers,
c) mitigate the risks of soil salinization and sodium accumulation.

A wastewater treatment plant is thus considered an element of the coupled water-soil-groundwater system, as it plays an important role as an environmental barrier in the context of climate change, in addition to chronic water stress [6,22].

2.6. Stability Analysis and Statistical Processing

The operational stability of a wastewater treatment plant is assessed using the coefficient of variation (CV), which is defined as follows:

$$CV(\%) = \frac{\sigma}{\mu} \times 100$$

where μ represents the mean and σ the standard deviation of the measured parameters.

A low coefficient of variation can be interpreted as an indicator of operational resilience in harsh climatic conditions [16,23].

Descriptive statistical analyses were performed using Microsoft Excel software (Microsoft Corp., Redmond, USA). Operational stability was assessed using the coefficient of variation (CV), which was calculated as the ratio of the standard deviation to the mean value of each parameter [24].

2.7. Statistical Analyses

To assess the distribution of the data, this study subjected them to statistical analysis, in addition to comparing performance between arid and hyperarid regions and examining the relationships between treated water quality indicators. The normality of these distributions was verified using the Shapiro-Wilk test. Parametric tests were applied when the data followed a normal distribution (pivot value > 0.05) ; otherwise, non-parametric tests were used. Treatment performance (COD, BOD_5, TSS) and agricultural indicators (EC, SAR, RSC) between the two wastewater treatment plants were compared using the independent samples t-test or the Mann-Whitney U test if the assumption of normality was not met. The relationship between agricultural indicators (SAR, RSC) and salinity (EC), and between EC and disposal yields, was assessed using Pearson correlation coefficients (normal data) or Spearman correlation coefficients (non-normal data).

The threshold for statistical significance was set at $\alpha = 0.05$. All analyses were performed using Microsoft Excel with the XLSTAT module (Addinsoft, France).

3. Results

3.1. Comparative Treatment Performance in Arid and Hyper-Arid Conditions

Both plants offer high efficiency in removing organic matter in addition to suspended solids, as the average values exceed 85–90% for COD, BOD_5, and TSS, as shown in Table 1 below. These results

 doi:10.20944/preprints202602.1248.v1

demonstrate the robustness of traditional biological treatment processes, even under extreme climatic conditions, thus confirming what has been observed in similar arid contexts [9,10].

Table 1. Average Treatment Performance of the Studyed Wastewater Treatment Plants.

Setting	Arid – Entrance (mg/L)	Arid – Exit (mg/L)	Yield (%)	Hyperarid – Entrance (mg/L)	Hyperarid – Exit (mg/L)	Yield (%)
COD	750 ± 60	85 ± 15	88.7	780 ± 70	75 ± 12	90.4
BOD_5	420 ± 40	42 ± 8	90.0	440 ± 45	40 ± 7	90.9
TSS	310 ± 35	22 ± 5	92.9	330 ± 38	20 ± 4	93.9

The following figure (Figure 1) shows the COD, BOD_5, and TSS removal efficiency for the two treatment plants, comparing performance under arid and hyperarid conditions. COD, BOD_5, and TSS removal efficiencies exceed 85–90% in both climatic contexts, confirming the robustness of the biological processes under heat stress. The lack of a marked difference between arid and hyperarid zones indicates that treatment efficiency is not the primary limiting factor for environmental sustainability.

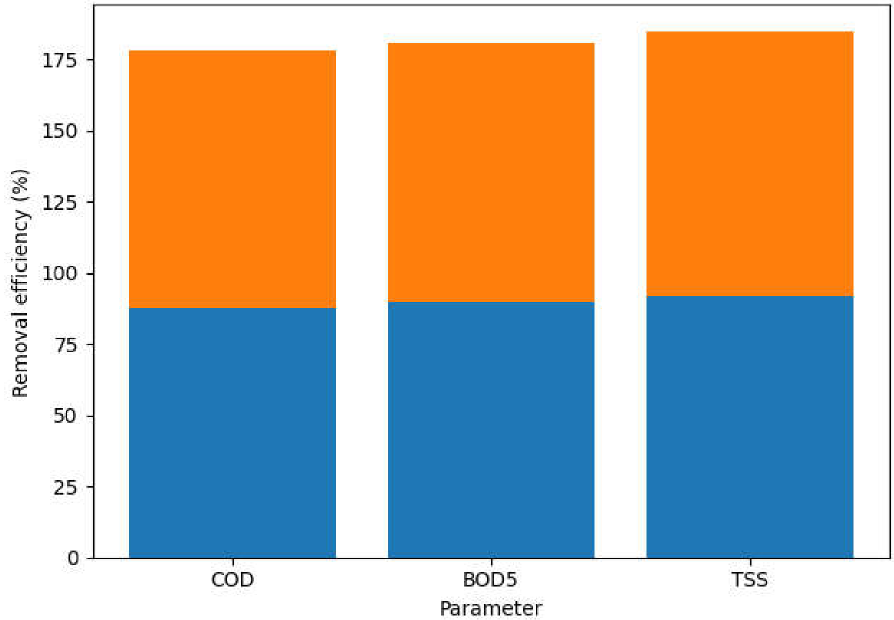

Figure 1. Removal efficiencies of COD, BOD_5 and TSS under arid and hyperarid conditions.

Despite the extremely dry and hot conditions, no significant deterioration in the treatment process was recorded, indicating that the main environmental constraints occur in the stages following biological treatment [25].

3.2. Temporal Stability and Operational Resilience

In general, the coefficients of variation (CV) remain below 20%, demonstrating good operational stability of the wastewater treatment plants, even in a hyperarid environment (Table 2). However, a slight increase in CV was observed for the plant located in the hyperarid zone, which can be explained by increased sensitivity to episodes of extreme heat stress [16,26].

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Table 2. Coefficient of variation (CV, %) of treatment parameters.

Setting	CV – Arid (%)	CV – Hyperarid (%)
COD	14.5	18.2
BOD_5	12.8	16.7
TSS	13.2	17.9

The figure below (Figure 2) shows us the operational stability of wastewater treatment plants via the coefficient of variation (CV) of basic treatment parameters, which allows us to assess their operational flexibility in arid and hyper-arid conditions.

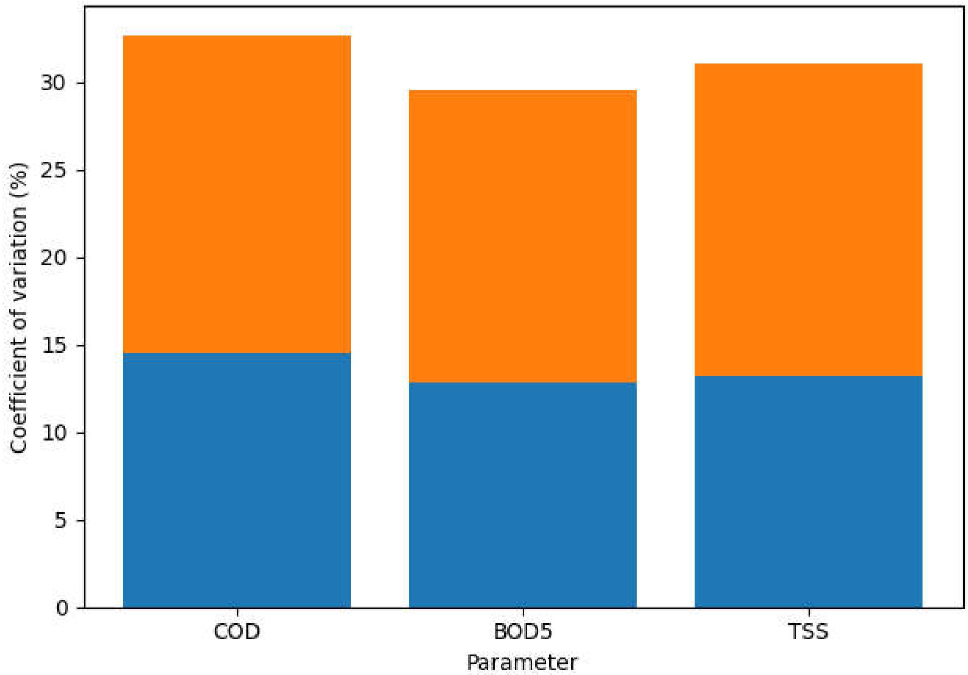

Figure 2. Stability of treatment performance expressed as coefficient of variation (CV).

According to the figure and table above, the average variance coefficients remain below 20% for all parameters, demonstrating operational stability. Furthermore, the higher values observed under hyperarid conditions reflect increased sensitivity to thermal stresses and concentrated loads, without compromising overall operational flexibility. These results confirm that we can maintain the operational flexibility of wastewater treatment plants even in extremely arid environments, provided they are operated correctly [27].

3.3. Saline Constraints and Performance-Sustainability Dissociation

Despite its high treatment performance, it exhibits high levels of electrical conductivity in the treated wastewater, exceeding the recommended thresholds for unrestricted irrigation, particularly in hyperarid environments (Table 3). This dissociation confirms that salinity is the main determinant of environmental sustainability, despite the biological effectiveness of the treatment [3,7].

Table 3. Agronomic indicators of treated effluents.

Indicator	Arid	Hyperarid	FAO threshold
CE (dS/m)	3.1 ± 0.4	4.2 ± 0.5	3.0
SAR	6.5 ± 1.2	8.4 ± 1.5	9.0
RSC (meq/L)	1.2 ± 0.3	2.1 ± 0.4	1.25

The following figure (Figure 3) gives us the range of electrical conductivity levels of treated water, compared to the thresholds recommended by the FAO for irrigation, in order to illustrate the impact of salinity restrictions on agricultural reuse in arid and hyperarid contexts.

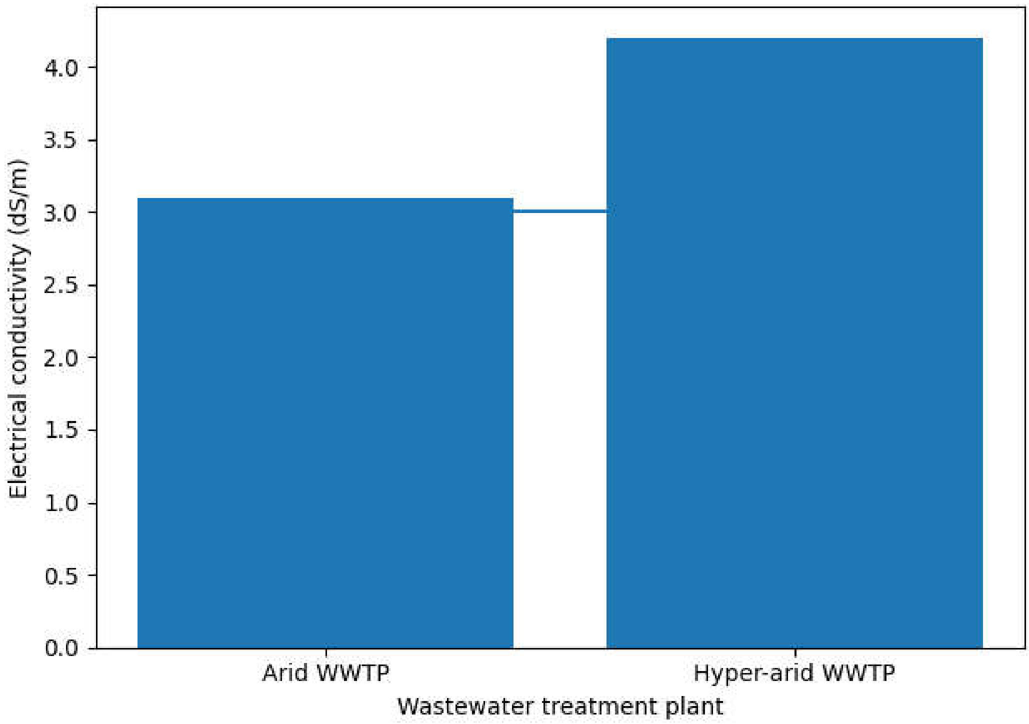

Figure 3. Electrical conductivity of treated effluents compared with FAO irrigation threshold.

We observe that the electrical conductivity of the treated water exceeds the limit recommended by the Food and Agriculture Organization of the United Nations (FAO) for unrestricted irrigation, particularly in arid environments. This finding confirms that residual water salinity remains the main factor limiting the sustainability of treated water reuse in oasis agriculture [28].

Compared to wastewater treatment plants located in arid and hyper-arid environments internationally (Table 4), the wastewater treatment plant in the Timimoun oasis, in southwestern Algeria, achieves a high level of performance in terms of organic matter removal. However, residual salinity, as widely reported in ultra-arid environments, remains the most significant limiting factor for agricultural reuse, further confirming that treatment process efficiency alone is insufficient to guarantee long-term environmental sustainability [3,13,23].

Table 4. Comparative performance of wastewater treatment plants operating in arid and hyperarid regions of selected parts of the world.

Site / Country	Climate type	Treatment process	Influent COD (mg/L)	Effluent COD (mg/L)	COD removal (%)	EC effluent (dS/m)	Agricultural reuse constraint	Main environmental limitation
Timimoun – Algeria (this study)	Hyper-arid	Conventional activated sludge	780 ± 70	75 ± 12	90.4	4.2 ± 0.5	Restricted	High salinity, sodification risk

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Ouargla – Algeria	Hyper-arid	Activated sludge + lagoons	720	90	87.5	3.8	Restricted	Salinity accumulation in soils
Riyadh – Saudi Arabia	Arid	Activated sludge	650	80	87.7	3.5	Controlled	Long-term salinization
Muscat – Oman	Hyper-arid	Conventional biological	700	95	86.4	4.0	Limited	Poor salt removal
Phoenix – USA	Arid	Activated sludge + filtration	580	55	90.5	2.6	Suitable	Groundwater protection priority
Central Australia	Hyper-arid	Waste stabilization ponds	620	110	82.3	4.5	Not recommended	Severe salinity & evaporation

The table above confirms that, in arid and hyperarid environments, high purification rates comparable to international standards cannot guarantee environmental sustainability, as residual salinity of wastewater appears to be a critical and limiting constraint for the long-term agricultural reuse process.

3.4. Agronomic Risks Related to Sodification

The SAR and RSC values indicate an increased risk of sodification at the treatment plant in the hyperarid region, suggesting that long-term reuse without proper management could damage the soil structure of oases [23,29].

The following figure (Figure 4) shows the SAR and RSC values for treated effluents, compared to recommended thresholds, in order to assess the potential risks of soil saponification associated with agricultural reuse in arid and hyperarid environments.

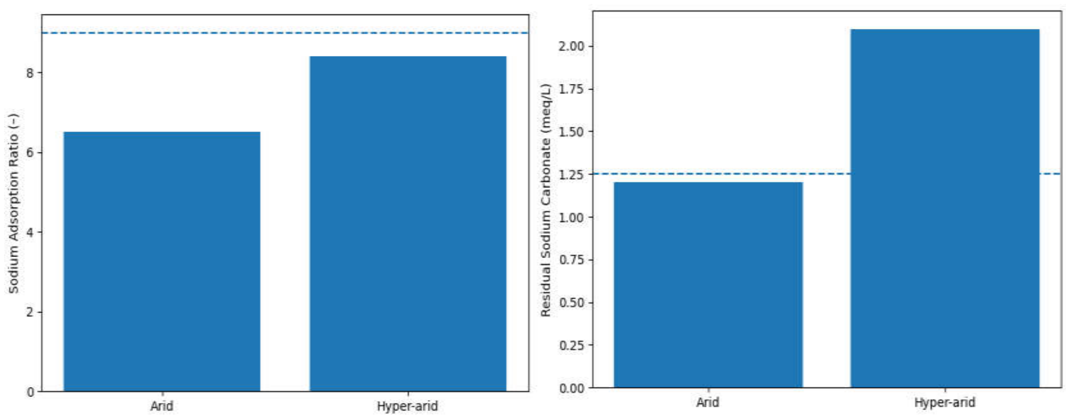

Figure 4. SAR and RSC values of treated effluents compared with FAO thresholds.

Compared to FAO guidelines, sodium absorption values remain below the critical limit, while residual sodium carbonate values exceed or approach the recommended limit under severe drought conditions, indicating a risk of increased soil sodium saturation and deterioration of its structure.

 doi:10.20944/preprints202602.1248.v1

This confirms that long-term agricultural reuse requires appropriate management measures, regardless of high treatment performance [30,31].

3.5. Indirect Effect on Groundwater Protection

The reuse of treated wastewater helps reduce dependence on fossil aquifers for irrigation [32], thus limiting direct withdrawals and the risks of hydrogeological degradation (Table 5).

Table 5. Indirect Effect of Wastewater Treatment Plants on Groundwater Withdrawals.

Indicator	Before (WWTP)	After (WWTP)
Agricultural levies	High	Moderates
Risk of salinization	High	Reduced
Dependence on fossil fuels	Forte	Attenuated

Figure below (Figure 5) illustrates the impact of treated wastewater reuse on the pressure exerted on aquifers. It also highlights the relative decrease in agricultural withdrawals and indirectly underscores the role of wastewater treatment plants in hydrogeological protection in arid and hyperarid environments [33].

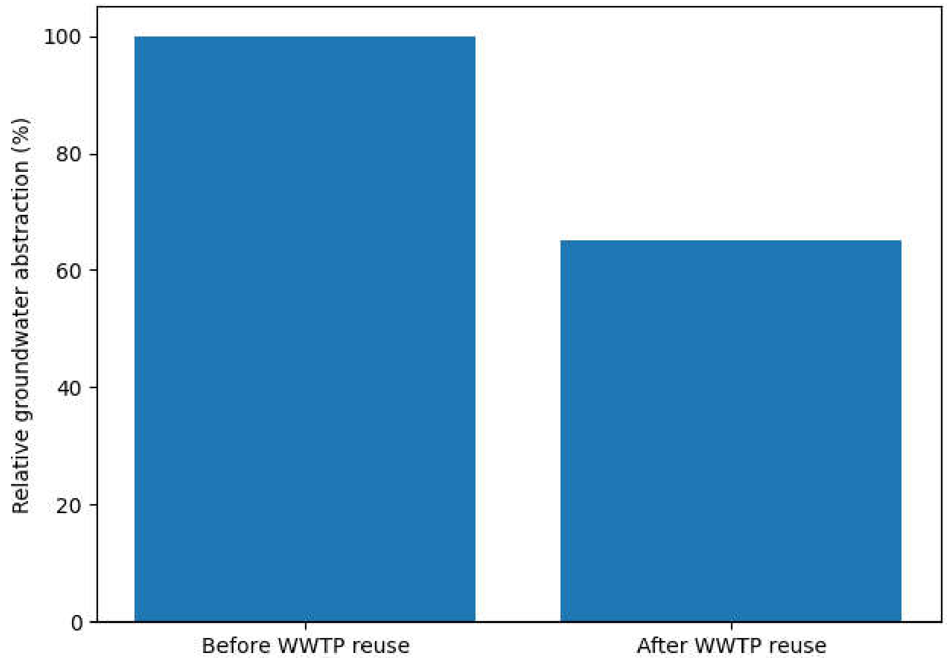

Figure 5. Effect of treated wastewater reuse on groundwater abstraction pressure.

The figure above illustrates a significant decrease in the relative rate of groundwater withdrawal following the reuse of treated wastewater. This water acts as an indirect barrier, effectively preventing the overexploitation of groundwater in arid and hyperarid environments. This is true even when considering the limited reuse of some of these resources in agriculture due to their salinity.

3.6. Integrated Environmental Synthesis

The results are presented within a conceptual framework (Figure 6) illustrating the role of wastewater treatment plants as environmental barriers in hyperarid environments. They confirm that environmental sustainability depends primarily on two key factors – salinity and hydrogeological constraints – and not solely on treatment efficiency.

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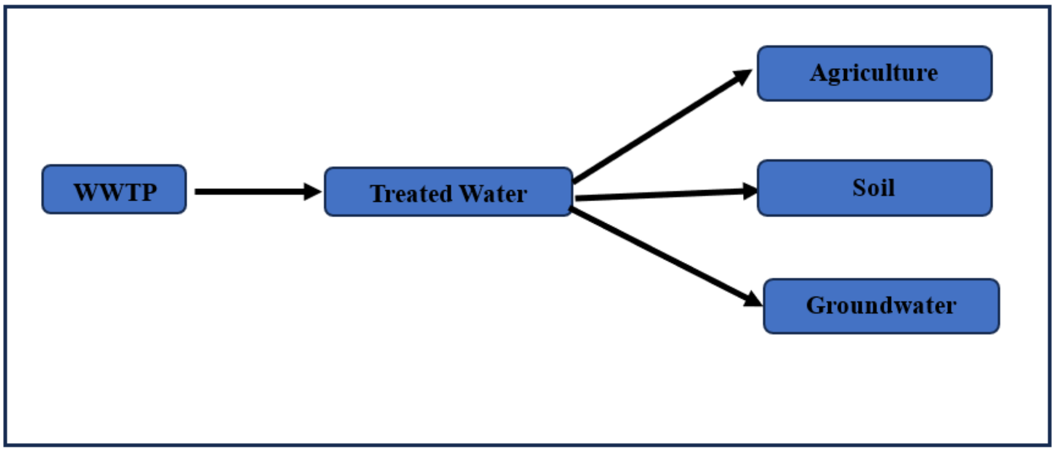

Figure 6. Integrated environmental framework for wastewater treatment plants in hyperarid regions.

Wastewater treatment plays a key role in linking urban sanitation and agriculture within oases, soils, and groundwater, while simultaneously reducing direct discharges and the depletion of fossil aquifers, as well as the environmental fragility of desert areas [34].

3.7. Results of Statistical Tests

Most treatment performance parameters (COD, BOD_5, TSS) follow a normal distribution ($p > 0.05$) according to the Shapiro-Wilk test. However, some agricultural indicators (EC, RSC) show slightly abnormal distributions. Furthermore, comparisons between stations show that there are no statistically significant differences between COD, BOD_5 and TSS removal rates in arid and extremely arid regions ($p > 0.05$), which helps to confirm that climate does not have a major impact on the efficiency of biological processes. Conversely, statistically significant differences were recorded with regard to electrical conductivity and RSC ($p < 0.05$), with high values recorded in hyperarid regions, which shows that salinity constraints are mainly controlled by the hydroclimatic context rather than by purification performance. Correlation analyses revealed a strong positive correlation between electrical conductivity (EC) and sodium absorption rate (SAR) ($r = 0.72$; $p < 0.01$), as well as between EC and residual desulfurization rate (RDR) ($r = 0.69$; $p < 0.01$). In contrast, no statistically significant correlation was observed between EC and COD removal efficiency ($p > 0.05$).

A summary of the detailed results of statistical tests comparing wastewater treatment plants in arid and extremely arid regions has been compiled in the table below (Table 6).

Table 6. Summary of statistical tests (Arid vs Hyperarid).

Parameter	Test used	p-value (Arid vs. Hyperarid)	Significatif
COD Yield	t-test	0.41	No
BOD_5 Yield	t-test	0.37	No
TSS Yield	t-test	0.33	No
CE	Mann–Whitney	0.018	Yes
SAR	t-test	0.07	No
RSC	Mann–Whitney	0.021	Yes

 doi:10.20944/preprints202602.1248.v1

These results indicate a mismatch between biological efficiency and environmental sustainability, and they confirm the hypothesis that salinity is the main determining factor for agricultural reuse in hyperarid environments.

4. Discussion

4.1. Treatment Robustness and Limitations of an Evaluation Based Solely on Yields

The results obtained show that the two studied treatment plants achieve high and stable productivity in the removal of COD, BOD_5, and TSS, even under hyperarid conditions. This robustness confirms that traditional biological treatment processes can operate effectively even under high heat stress, as has been observed in other arid and desert regions [9,10]. However, the slight difference in performance between arid and hyperarid environments indicates that purification efficiency quickly reaches a stable level, after which it is no longer a reliable indicator of environmental sustainability [35].

This observation aligns with the recent findings of several studies published in various international scientific journals, highlighting that evaluating wastewater treatment plants (WWTPs) based solely on organic yields is insufficient because it tends to mask the critical environmental constraints of regions with harsh climates [36,37]. Therefore, biological treatment performance should be considered a minimum requirement, not an end in itself, particularly in hyperarid regions [38].

4.2. Dissociation Between Biological Efficiency and Environmental Sustainability

One of the key findings of this study is the evident dissociation observed between the high purification performance and the limitations related to the agronomic quality of the effluents. Despite the efficiency of organic matter removal, the recorded values for electrical conductivity, SAR, and RSC indicate the presence of saline and sodium pressures that could compromise the sustainability and quality of oasis soils in the medium and long term. This dissociation has been widely documented in some recent publications, particularly in arid regions where wastewater mineralization is high and may not be significantly affected by traditional biological processes [39,40]. The results obtained also confirm that salinity is the main determining factor for agricultural reuse, regardless of treatment efficiency, which is consistent with global syntheses published by the FAO and cited in various international journals [41,42].

4.3. Agronomic Implications and Long-Term Risks for Oasis Systems

Agricultural indicators show the potential for controlled reuse of treated water, particularly for salt-tolerant crops. However, prolonged use without mitigation measures can exacerbate sodification processes and degrade soil structure in oases. In oasis ecosystems, characterized by low leaching capacity and high evaporation rates, the risks are greater than in semi-arid or temperate regions [43,44].

These results demonstrate the need to integrate appropriate management strategies, such as mixing with higher-quality water, crop rotation, or the occasional use of targeted tertiary treatments for dissolved salts. Without such measures, the reuse of treated wastewater can lead to negative long-term environmental consequences, even if the treatment meets all recommended standards [35].

4.4. Role of Wastewater Treatment Plants in Groundwater Protection in Hyperarid Environments

In addition to agricultural reuse, the results obtained highlight a significant, often underestimated, environmental benefit: by providing an alternative and sustainable water resource for irrigation and certain local uses, wastewater treatment plants help reduce direct withdrawals and the depletion of non-renewable groundwater, which is often threatened, particularly in hyperarid contexts.

Today, the role of indirect hydrogeological protection is increasingly recognized in recent literature as a key factor in environmental sustainability in desert regions [2,6]. The results obtained in the Algerian desert regions confirm that, even with partial restrictions on agricultural reuse due to salinity, treated wastewater remains an important and key element in maintaining integrated water management.

4.5. Wastewater Treatment Plants as Climate Adaptation Infrastructure

The results obtained from this work support the idea that wastewater treatment plants should be reconsidered as climate change adaptation infrastructure, and not just as wastewater treatment units, particularly in hyperarid regions. By reducing both pollutant discharge and the depletion of fossil aquifers, as well as the vulnerability of oasis ecosystems, wastewater treatment plants play a major role in helping fragile areas withstand climate change, in line with the frameworks proposed by the IPCC and the United Nations [1,2].

This methodological approach also aligns with recent trends in much of the modern literature, which aims to encourage the analysis of water infrastructure through its overall contribution to environmental sustainability, rather than from a purely technological or regulatory perspective [44,45].

4.6. Scope of Results and International Transferability

Although this study focuses on cases observed in the Algerian Sahara, the lessons learned have broader implications, as they can be applied to several similar regions with extremely arid climates and similar constraints, such as the Middle East, parts of Australia, and the Atacama Desert. The observed dissociation between treatment efficiency and environmental sustainability is a strong signal in favor of planning wastewater reuse policies internationally.

4.7. Limitations of the Study and Perspectives

Although the sample size and sampling frequency are sufficient to identify trends and make statistical comparisons, they remain relatively limited. Therefore, certain constraints must be taken into account [46]. In order to better describe the temporal evolution of the treatment process and the quality of wastewater, high-frequency monitoring over long periods, exceeding several years, is necessary. In addition, the study focused its analysis on traditional standards (COD, BOD_5, TSS) as well as on agricultural indicators (EC, SAR, RSC). In order to provide a comprehensive assessment of environmental and health risks, consideration should be given to the future integration of nutrients, trace elements, emerging pollutants and microbiological criteria.

Furthermore, the impact on soils and crops is not effectively assessed by long-term agricultural trials. Conducting field experiments confirms the validity of the identified risks associated with salinization and sodification [47].

The research perspectives encompass all three areas with the aim of reducing salinity, striving to develop management and sustainability strategies (water mixing, irrigation optimization and selection of resilient crops), in addition to integrating and developing modeling and artificial intelligence tools to help improve the operation and sustainability of the station. These visions help to strengthen the role of wastewater treatment plants as essential and important infrastructure for climate change adaptation in extremely arid and hostile environments.

5. Conclusions

This study shows that, even in hyperarid regions, wastewater treatment plants can achieve high and stable performance in removing organic matter, even under severe climatic constraints. Nevertheless, the results confirm that relying solely on biological treatment efficiency is not a sufficient indicator to guarantee environmental sustainability. Residual salinity and the ionic

doi:10.20944/preprints202602.1248.v1

composition of wastewater are the two main determining factors for its long-term agricultural reuse, particularly in fragile oasis ecosystems.

In addition to direct reuse, wastewater treatment plants play a central environmental role by indirectly reducing pressure on fossil aquifers, thus contributing to the preservation of groundwater resources in contexts where aquifer renewal is low. This hydrogeological protection function gives wastewater treatment plants (WWTPs) an important place as strategic infrastructure for environmental conservation ; they are also essential for integrated water management and climate change adaptation in hyper-arid environments.

The results demonstrate the need to reassess sanitation systems using systems approaches that integrate treatment performance, agricultural constraints, and hydrogeological impacts, rather than relying solely on purely regulatory criteria. These visions are directly applicable in similar extremely arid regions facing the same challenges, such as the Middle East, Australia, and the desert regions of South America.

Author Contributions: The first author contributed to the development of the research methodology, supervised data collection, and revised the article. The second author contributed to the simulations and analysis of the results. The third author contributed to drafting the manuscript, formatting the tables. The fourth author was designing the figures. All authors reviewed and approved the final version of the article submitted to you.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data exchange also did not apply.

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

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