sustainability

Article

Assessing the Efficiency of *Phragmites australis* in Wastewater Treatment as a Natural Approach to Water Quality Improvement

Laid Bouchaala [1], Nabil Charchar [2], Nedjoud Grara [3,*], Ilham Ben Amor [4,5], Soumeia Zeghoud [4,5], Hadia Hemmami [4,5], Moussa Houhamdi [6], Agnieszka Szparaga [7,8,*], Otilia Cristina Murariu [9], Gianluca Caruso [10,†] and Stefano Bellucci [11,†]

[1] Environmental Research Center (CRE), Avenue Boughazi Said, Sidi Amar, Annaba 23001, Algeria; mlbouchaala@gmail.com
[2] Biotechnology Research Center (C.R.Bt), Constantine 25016, Algeria; n.charchar@crbt.dz
[3] Department of Biology, Faculty of Natural and Life Sciences, Earth and Universe Sciences, University 8 Mai 1945, Guelma 24000, Algeria
[4] Department of Process Engineering and Petrochemical, Faculty of Technology, University of El Oued, El Oued 39000, Algeria; ilham-benamor@univ-eloued.dz (I.B.A.); zsoumeia@gmail.com (S.Z.); hemmami.h@gmail.com (H.H.)
[5] Renewable Energy Development Unit in Arid Zones (UDERZA), University of El Oued, P.O. Box 789, El Oued 39000, Algeria
[6] Laboratory of Biology, Water and Environment (LBEE), Faculty SNV-STU, University 8 May 1945 Guelma, P.O. Box 401, Guelma 24000, Algeria; houhamdimoussa@yahoo.fr
[7] Department of Biomedical Engineering, Koszalin University of Technology, Śniadeckich 2, 75-453 Koszalin, Poland
[8] Department of Landscape Management, University of South Bohemia in České Budějovice, Branišovská 1645/31A, 370 05 České Budějovice, Czech Republic
[9] Department of Food Technologies 'Ion Ionescu de la Brad', Iasi University of Life Sciences, 700490 Iasi, Romania; otilia.murariu@iuls.ro
[10] Department of Agricultural Sciences, University of Naples Federico II, Portici, 80055 Naples, Italy; gcaruso@unina.it
[11] Frascati National Laboratories, National Institute for Nuclear Physics (INFN), Frascati, 00044 Rome, Italy; stefano.bellucci@lnf.infn.it
* Correspondence: grara120@yahoo.fr (N.G.); agnieszka.szparaga@tu.koszalin.pl (A.S.)
† These authors contributed equally to this work.

Academic Editor: Mariusz Gusiatin

Received: 26 November 2024
Revised: 14 January 2025
Accepted: 18 January 2025
Published: 29 January 2025

Citation: Bouchaala, L.; Charchar, N.; Grara, N.; Amor, I.B.; Zeghoud, S.; Hemmami, H.; Houhamdi, M.; Szparaga, A.; Murariu, O.C.; Caruso, G.; et al. Assessing the Efficiency of *Phragmites australis* in Wastewater Treatment as a Natural Approach to Water Quality Improvement. *Sustainability* **2025**, *17*, 1102. https://doi.org/10.3390/su17031102

Abstract: The Oued Zénati, a vital waterway in Algeria, faces severe pollution from urban discharges, hospital wastewater, and agricultural activities, threatening both the ecosystem and public health. This pollution is characterized by high nutrient levels, suspended solids, and fecal contamination indicators, jeopardizing biodiversity and human well-being. To explore natural restoration solutions, this study assessed the purification potential of reeds (*Phragmites australis*) found in the Oued Zénati riverbed. Water quality was analyzed at three sites: a non-polluted control site (S1), a wastewater discharge area (S2), and a reed-dense area (S3). Results revealed a significant deterioration in water quality at site S2, with high concentrations of nutrients, suspended solids (SS), and fecal contamination indicators. However, a notable improvement in water quality was observed at site S3, downstream of the reed-dense area, with reductions in fecal coliforms (68.5%), fecal streptococci (92.3%), and phosphates (40.3%), and increased levels of dissolved oxygen (DO). These findings suggest that phytoremediation using *P. australis* could offer a cost-effective, sustainable, and eco-friendly solution for restoring the Oued Zénati. This study recommends establishing phragmifiltration stations, developing artificial wetlands, and enhancing sanitation systems, including hospital wastewater treatment. Public awareness campaigns promoting water and environmental protection are crucial for long-term success. This phytoremediation approach offers economic, ecological, and aesthetic advantages over conventional wastewater treatment techniques.

Keywords: wastewater; pollution; reeds; phytoremediation; water quality parameters; Algeria

1. Introduction

Water pollution is a critical environmental challenge, disproportionately affecting developing countries and arid/semi-arid regions where water resources are limited, and ecosystems are vulnerable [1–3]. Untreated wastewater, intensive agriculture, industrial activities, and fecal contamination degrade water quality, harming human health, biodiversity, and water uses [4,5]. Algeria faces persistent wastewater pollution, with studies showing high levels of organic, nitrogenous, and bacteriological contamination [6,7]; Baziz et al. [8] highlighted significant organic pollution in Boumerdes wastewater, emphasizing the need for treatment.

The Oued Zénati, a vital waterway in the Guelma region, is subjected to significant pollution from various discharges, including urban wastewater, surrounding agricultural activities, and fecal contamination. This pollution has detrimental consequences for the wadi's ecosystem, affecting water quality, biodiversity, and public health [8]. A study by Moussaoui et al. [9] in Ain Sefra, Algeria, investigated the water quality of treated wastewater, highlighting the potential benefits and challenges associated with reusing treated wastewater for irrigation.

Numerous physicochemical and microbiological parameters are impacted by this pollution. High concentrations of nitrates ($NO_3{}^-$) and nitrites ($NO_2{}^-$), often linked to agricultural fertilizers and wastewater discharges, can lead to eutrophication and toxicity in aquatic organisms [10,11]. Organic pollution, microbial activity, and the decomposition of organic matter reduce dissolved oxygen (DO) concentrations, threatening the survival of aquatic organisms and overall ecosystem health [12]. High salinity and electrical conductivity, often associated with soil erosion, runoff, and wastewater discharges, limit water use, particularly for irrigation [13]. Research by Ababsa et al. [14] in eastern Algeria investigated the impact of different wastewater types on soil properties, demonstrating the influence of untreated wastewater on soil health and water infiltration. Suspended solids (SS), stemming from soil erosion and wastewater discharges, reduce light penetration, transport pollutants, and affect aquatic life [15]. Finally, the presence of coliform bacteria, fecal enterococci, and other fecal contamination indicators highlights the public health risks associated with consuming contaminated water. In this respect, it is crucial to understand the spatiotemporal variations in the mentioned parameters and the factors influencing them, such as seasons, hydrological conditions, human activities, and sources of fecal contamination, as well as the identification of contamination sources for effective management [16].

The present study investigates the potential of *Phragmites australis*, a widely distributed and robust wetland plant, for the phytoremediation of wastewater in the Oued Zénati. This species is a promising candidate for wastewater treatment, particularly in arid and semi-arid environments, due to its extensive root system and demonstrated ability to remove various pollutants [17,18]. Its effectiveness stems from several mechanisms: filtration of suspended particles and microorganisms by its dense root mat; biocidal action against pathogenic bacteria through root exudates; competition with undesirable microorganisms for essential nutrients; and enhanced degradation of organic matter facilitated by the rhizosphere microbiome.

Fecal contamination, often linked to inadequate sanitation, untreated wastewater discharges, and insufficient hygiene practices, poses a serious threat to public health. It promotes the spread of waterborne diseases [19,20] and the dissemination of antibiotic resistance [21,22]. A study by Bwire et al. [23] in Uganda demonstrated the presence of contamination in surface and groundwater sources, highlighting the critical need for access to safe drinking water to achieve the UN Sustainable Development Goals. Evaluating this contamination relies on bacterial indicators such as fecal coliforms and *Escherichia coli*, signaling the potential presence of pathogens [24]. Advanced techniques, such as metagenomic sequencing and quantitative polymerase chain reaction (PCR), allow for more precise evaluation and identification of contamination sources, whether human or animal [25].

Several studies have demonstrated the effectiveness of phytoremediation, utilizing aquatic plants like *Phragmites australis*, for wastewater treatment, improving water quality, and reducing fecal contamination [26]. A study by Hammadi et al. [27] in Algeria investigated the effectiveness of phytoremediation for treating wastewater, highlighting its potential to reduce nitrogen pollution and meet Algerian legislative standards. *Phragmites australis* can absorb nutrients and pollutants, promote the development of beneficial microbial communities, improve water oxygenation, and contribute to the removal of pathogenic bacteria and viruses.

In this study, we assessed the *P. australis* potential for Oued Zénati sanitation and fecal contamination reduction by analyzing physicochemical and microbiological parameters upstream and downstream of a reed-dense area. The mentioned work contributes to comparing purification techniques (aerated lagoons and phytoremediation) and identifying optimal solutions [28], given the growing use of phytoremediation in Algeria [29].

2. Materials and Methods

2.1. Study Site

The Oued Zénati, the main waterway in the hydrographic network of the Oued-Zénati municipality in Algeria, crosses the region for over 2 km, receiving water from several minor tributaries [28]. Its valley extends from Constantine to Guelma, collecting water from various wadis and chaâbats on both banks before joining the Oued Bou Hamdane and then the Oued Seybouse (Figure 1) [29]. Its physical and morphometric characteristics, including a watershed area of 592.15 km^2 and a length of 41.30 km, attest to its hydrographic significance (Figure 2).

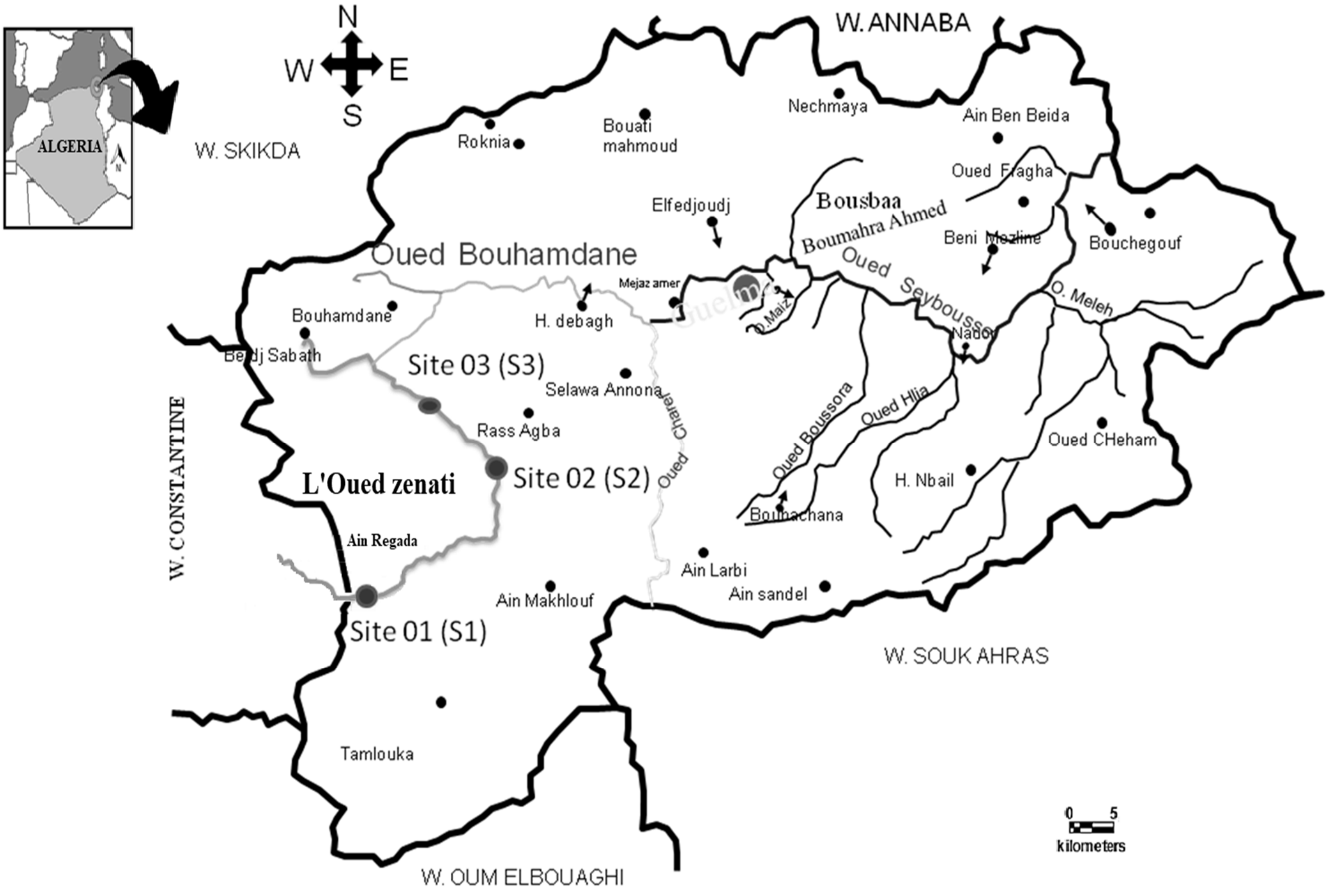

Figure 1. Map showing the geographic location of the Oued Zénati.

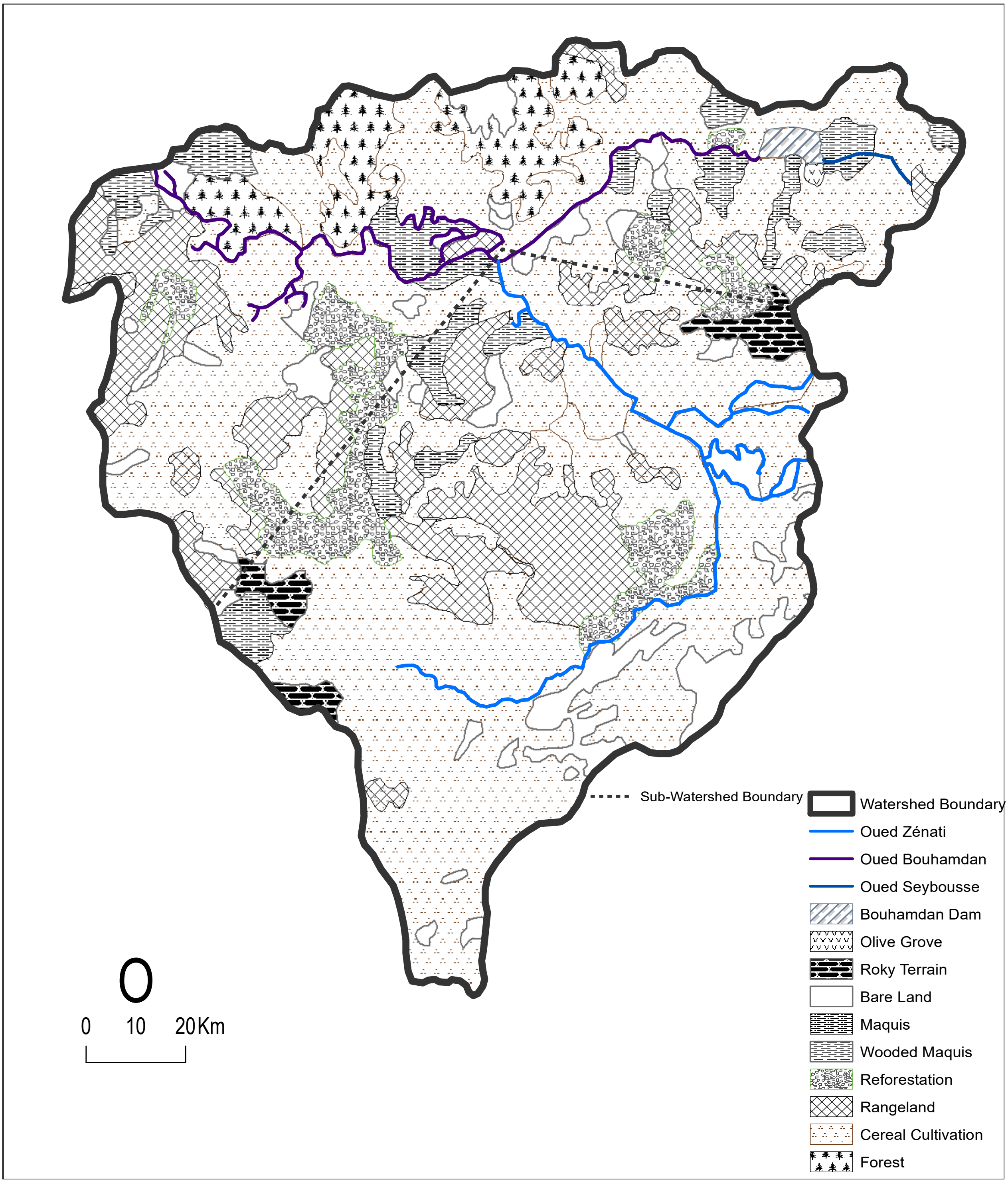

Figure 2. Map showing the vegetation cover of the Oued Zénati sub-watershed.

The Oued Zénati exhibits variable aquatic vegetation, ranging from near total absence upstream to a significant density downstream. The mentioned downstream area is dominated by reeds (*P. australis* Cav.–Trin.), cattails, and bulrushes (Figure 2).

2.2. Sampling Protocol and Analyses

Three sampling sites were established along the Oued Zénati to assess pollution levels and the purification capacity of reeds (*Phragmites australis*):

Site 1 (S1): An upstream control site, devoid of significant anthropogenic pollution sources, located in the Ain Regada commune (Figure 1).

Site 2 (S2): Situated at the outlet of Oued Zénati city, this site is highly impacted by wastewater discharges, representing the area with the most significant anthropogenic pollution (Figure 2). This station is located directly after the outlet of the city of Oued Zenati and its wastewater collection systems, including domestic wastewater from a population exceeding 50.000, and wastewater from more than three public health facilities, several private clinics, and various other industrial and commercial sources. Additionally, the mentioned section of the Oued Zenati is heavily used by residents as a dumping site, with all types of waste directly discharged into the water.

Site 3 (S3): Located 7 km downstream of S2 in the Lama area, this site is characterized by a dense population of reeds (*P. australis*), allowing for the evaluation of their self-purification capacity (Figure 2).

Four seasonal sampling campaigns were conducted at each site. Samples were collected at two depths: 30 cm and 1 m from the bank, following the recommendations of Rodier et al. [30] to ensure representative sampling, a total of 27 samples were collected.

2.2.1. Sample Collection Procedures

Separate sample collection procedures were implemented for physicochemical and bacteriological analyses:

Physicochemical Analyses: Samples (1 L) were collected in pre-cleaned, polyethylene bottles, and rinsed three times in situ with the water to be sampled. Bottles were submerged to a depth of 30 cm, with the neck facing upstream, then hermetically sealed [30]. Samples were immediately placed in a cooler at 4–6 °C for transport to the laboratory (2–3 h).

Bacteriological Analyses: Sterile 250 mL Pyrex glass bottles with screw caps were used for bacteriological sampling. Bottles were completely submerged (30 cm depth) in an inverted position, held by the base, and filled by slowly turning them upright, keeping the opening slightly higher than the bottom and facing upstream. Bottles were tightly capped after sampling and immediately transported to the laboratory in a cooler maintained at 4–6 °C (2–3 h) [30].

2.2.2. Analyses

Physicochemical analyses were conducted according to the following protocols:

Temperature, pH, conductivity, and dissolved oxygen (DO): In situ measurements were obtained using a Inolab 750 wtw portable multiparameter instrument (WTW GmbH, Weilheim, Germany). The instrument was calibrated using WTW calibration solutions according to the manufacturer's instructions before each sampling campaign. The instrument's sensitivity was ± 0.1°C for temperature, ± 0.01 for pH, ±1 µS/cm for conductivity, and ± 0.1 mg/L for dissolved oxygen.

Suspended solids (SS), nitrates (NO_3^-), and orthophosphates (PO_4^{3-}): laboratory spectrophotometric measurements were performed using a HACH Lange DR3900 spectrophotometer (Hach Company, Loveland, CO, USA) and cuvette tests following the manufacturer's protocols.

The bacteriological analyses targeted fecal contamination indicators:

Total coliforms (TC): enumerated using the ISO 9308-2:2012 [31] method (for counting *Escherichia coli* and coliform bacteria). The most probable number (MPN) method, as per ISO 9308-3:1998 [32], was employed using liquid medium inoculation (Purple Bromocresol Lactose Broth, incubation for 24 to 48 h at 37 °C).

Fecal coliforms (FC): enumerated following the same MPN method (ISO 9308-3:1998) and incubation conditions (brilliant green bile broth with a Durham bell, and another tube containing indole-free peptone water then incubated for 24 to 48 h at 44 °C).

Fecal streptococci (FS): were enumerated using the MPN method (ISO 7899-2000 [33]) in EVA Litsky medium at 37 °C for 24 h.

2.3. Statistical Analyses

Statistical analyses were performed using XLSTAT 2016 (version 02.28451, Addinsoft, Paris, France). To investigate the influence of sampling location (S1, S2, S3) on each water quality parameter [Temperature, pH, Electrical conductivity, Salinity, Suspended Solids (SS), Dissolved Oxygen (DO), Phosphate (PO_4^{3-}), Nitrite (NO_2^-), Nitrate (NO_3^-), Ammonium (NH_4^+), Total Coliforms (TC), Fecal Coliforms (FC), and Fecal Streptococci (FS)], a one-way analysis of variance (ANOVA) was conducted. Prior to ANOVA, data normality was checked using the Shapiro–Wilk test ($p < 0.05$). However, instead of removing outliers, each measurement was repeated twice, and the mean of these two measurements was used for all subsequent statistical analyses. The standard deviation was also calculated for each parameter. For parameters that violated the assumption of normality after outlier removal, non-parametric alternatives were considered and applied. Significant differences between sampling locations were determined using a post hoc Tukey's Honestly Significant Difference (HSD) test. To identify relationships among the water quality parameters and to graphically represent the grouping of sampling sites, a Principal Component Analysis (PCA) was performed. Statistical significance for all tests was set at $p < 0.05$.

The primary objective of this study was to evaluate the effectiveness of reeds in reducing pollution in the Oued Zénati. In this respect, we compared water quality upstream and downstream of a reed-dense area. This study also aimed to deepen our understanding of phytoremediation mechanisms, assess its potential as a sustainable sanitation solution for wastewater in arid and semi-arid regions, compare its efficiency with other wastewater treatment techniques, and identify factors influencing its performance. In conclusion, this study offers promising prospects for sustainable water resource management and environmental protection in arid and semi-arid regions, where water pollution and fecal contamination represent significant challenges.

3. Results

The analysis of physicochemical and microbiological parameters of the Oued Zénati water reveals a contrasting picture of water quality between sites S1, S2, and S3, reflecting the impact of upstream pollution and the purifying potential of reeds downstream.

3.1. Physicochemical Parameters (Table 1)

Table 1 shows a broad overview of water quality, demonstrating a general trend of higher mineralization and pollution at S2 compared to S1, and a reduction in pollutant concentrations downstream in the presence of reeds (S3). While pH remains relatively stable across sites, parameters such as temperature, salinity, electrical conductivity, suspended solids, dissolved oxygen, nitrates, nitrites, ammonium, and phosphates exhibit notable variation between the sites. The complete analysis of these individual parameters is addressed in the following sections.

Table 1. Average values and standard deviations of physicochemical parameters at the three sampling sites.

Parameter	S1 (Non-Polluted)	S2 (Wastewater Discharges)	S3 (Reeds)
pH	7.58 ± 0.31	7.54 ± 0.31	7.61 ± 0.31
Temperature (°C)	13.1 ± 4.5	17.1 ± 4.5	14.7 ± 4.5
Salinity (Sal)(PSU)	0.52 ± 0.13	0.65 ± 0.13	0.66 ± 0.13

Table 1. *Cont.*

Parameter	S1 (Non-Polluted)	S2 (Wastewater Discharges)	S3 (Reeds)
Electrical conductivity (EC) (µS/cm)	1513 ± 206	1726 ± 206	1632 ± 206
Suspended solids (SS) (mg/L)	181.04 ± 110.38	225.43 ± 110.38	194.25 ± 110.38
Dissolved oxygen (DO) (mg/L)	12.2 ± 5.26	5.7 ± 5.26	12.5 ± 5.26
Nitrates (NO_3^-) (mg/L)	3.69 ± 1.50	2.68 ± 1.50	3.17 ± 1.50
Nitrites (NO_2^-) (mg/L)	0.24 ± 0.22	0.47 ± 0.22	0.26 ± 0.22
Ammonium (NH_4^+) (mg/L)	0.92 ± 0.85	1.47 ± 0.85	1.25 ± 0.85
Phosphates (PO_4^{3-}) (mg/L)	0.73 ± 0.78	1.86 ± 0.78	1.11 ± 0.78

3.1.1. pH

The pH values remain relatively stable at around 7.6 (as shown in Table 1, and illustrated in Figure 3), which corresponds to WHO standards for surface water [34]. This slight alkalinity could be attributed to biological activity, soil composition, and wastewater inputs [6]. However, it is crucial to consider the intricate relationships between pH and other water quality parameters, which can vary depending on the type of aquatic system and the presence of other contaminants [35]. Further analysis is needed to fully understand the factors controlling pH in the Oued Zénati. The statistical analysis did not reveal any significant effect of the station on pH (p-value > 0.05). Furthermore, the Tukey HSD test did not show any significant differences in pH between stations.

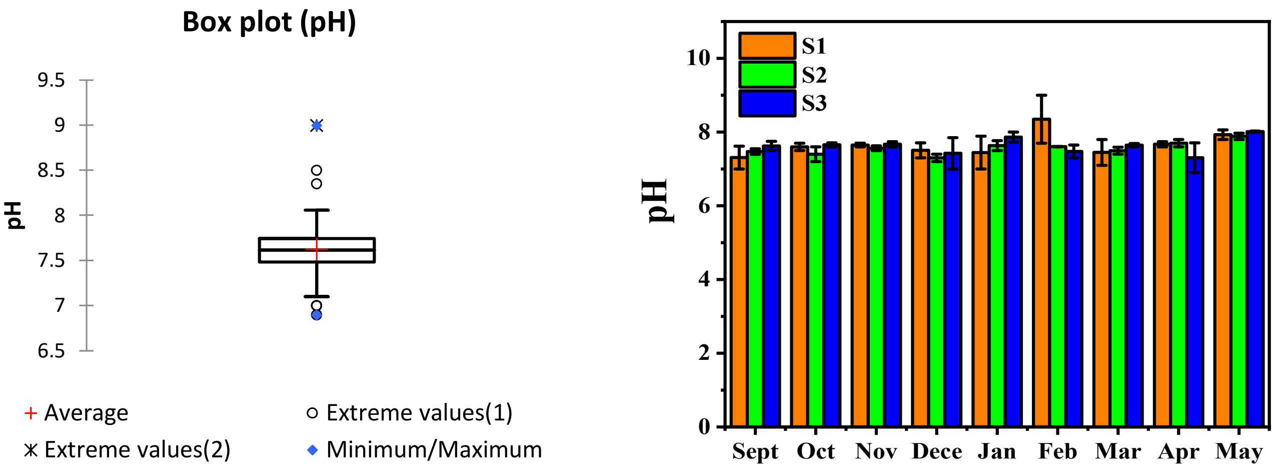

Figure 3. Spatiotemporal variation in pH values of Oued Zénati water. The data represent means and standard deviations calculated from three replicate measurements per sample at each location.

3.1.2. Temperature

Figure 4 shows clear seasonal variations in water temperature, with warmer temperatures during the summer months (24.8 °C) compared to the winter months (9.3 °C). Station S2 (17.1 ± 4.5 °C) exhibits slightly higher temperatures than Station S1 (13.1 °C ± 4.5 °C), possibly due to the influence of wastewater discharges [36].

Statistical analysis (ANOVA) revealed a significant effect of station location on water temperature (p-value < 0.05). The Tukey HSD test indicated that Station S2 has a significantly higher temperature than Station S1 (p-value = 0.003). There is no significant difference between Stations S2 and S3, nor between Stations S3 and S1.

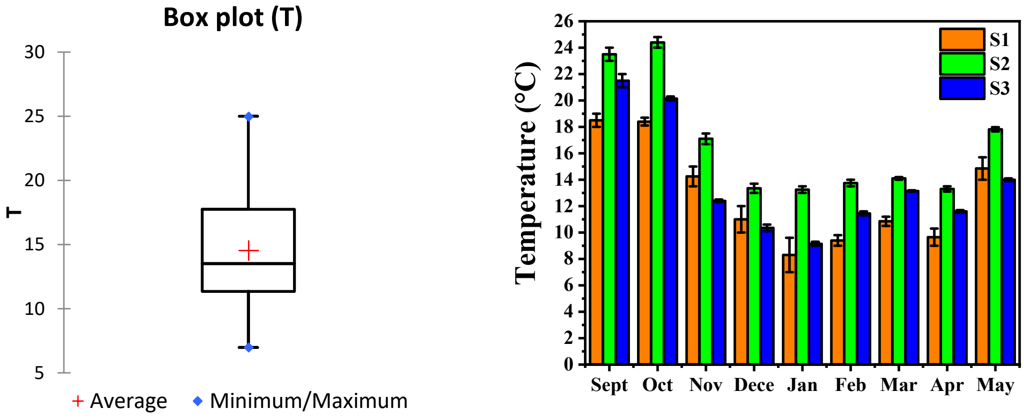

Figure 4. Spatiotemporal variation in temperature (T) of Oued Zénati water. The data represent means and standard deviations calculated from three replicate measurements per sample at each location.

3.1.3. Salinity and Electrical Conductivity (Sal, EC)

Apart from salinity (Figure 5), the elevated values of electrical conductivity (Figure 6) indicate a high degree of mineralization in the water, exacerbated during periods of flooding. This phenomenon mirrors observations in other regions of Algeria, where the dissolution and leaching of surrounding formations contribute to water salinity. Wastewater discharges and soil erosion also contribute to these high concentrations [37].

The median salinity is higher at Station S2 (0.600 PSU) compared to Station S1 (0.500 PSU), indicating greater salinity at Station S2. The median electrical conductivity is higher at Station S2 (1610 µS/cm) compared to Station S1 (1399.25 µS/cm), indicating a higher concentration of dissolved solids at Station S2.

However, average salinity values at the three stations were: 0.52 ± 0.13 PSU (S1), 0.65 ± 0.13 PSU (S2), and 0.66 ± 0.13 PSU (S3). Similarly, average electrical conductivity (EC) values were: 1513 ± 206 µS/cm (S1), 1726 ± 206 µS/cm (S2), and 1632 ± 206 µS/cm (S3).

Statistical analysis reveals a significant effect of station location on both salinity and electrical conductivity (p-value < 0.05). The Tukey HSD test demonstrates that Stations S2 and S3 have significantly higher salinity than Station S1. There is no significant difference between Stations S2 and S3. Similarly, Station S2 has significantly higher electrical conductivity than Station S1. There is no significant difference between Stations S2 and S3, nor between Stations S3 and S1.

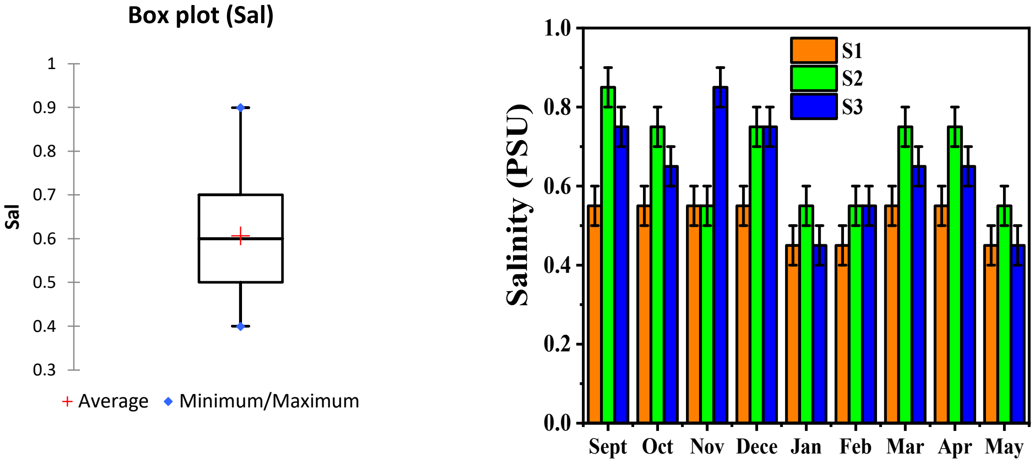

Figure 5. Spatiotemporal variation in salinity (Sal) of Oued Zénati water. The data represent means and standard deviations calculated from three replicate measurements per sample at each location.

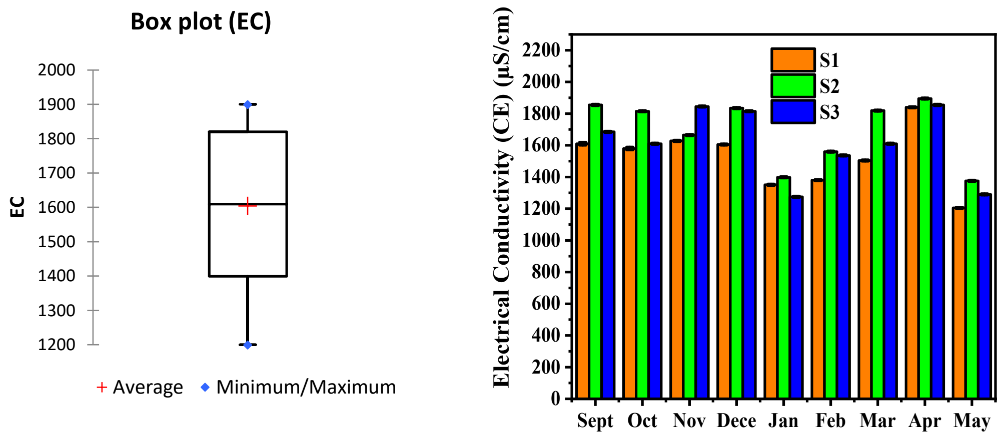

Figure 6. Spatiotemporal variation in electrical conductivity (EC) of Oued Zenati water. The data represent means and standard deviations calculated from three replicate measurements per sample at each location.

3.1.4. Suspended Solids (SS)

Figure 7 illustrates that suspended solids (SS) concentration significantly increases during flood events, reflecting soil erosion and the transport of sediments. These suspended particles can disrupt the aquatic ecosystem and contribute to eutrophication [38].

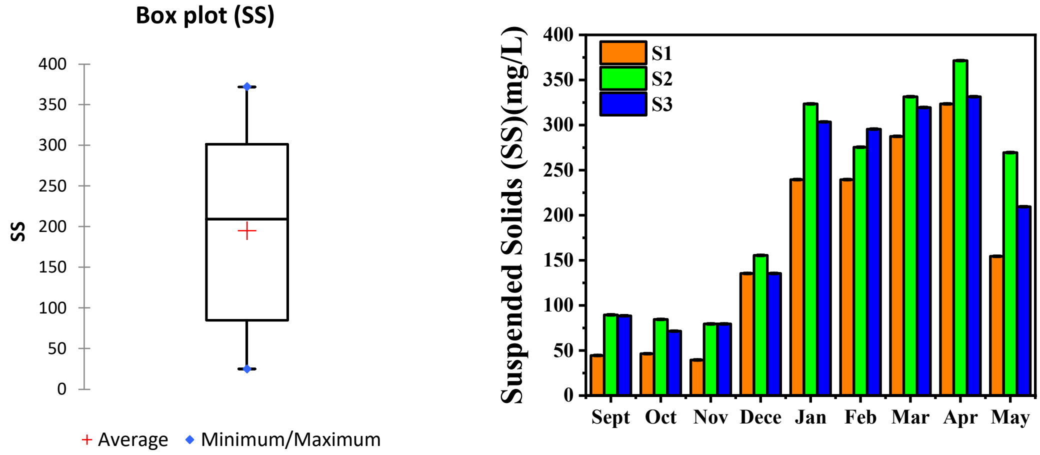

Figure 7. Spatiotemporal variation in suspended solids (SS) in Oued Zénati water. The data represent means and standard deviations calculated from three replicate measurements per sample at each location.

Statistical analysis revealed no significant effect of station location on SS concentrations (p-value > 0.05). However, the boxplots (Figure 7) show a higher median SS concentration at Station S2 (209.25 mg/L) compared to Station S1 (84.625 mg/L), suggesting a greater SS concentration at S2. The average concentrations of MES at stations S1, S2, and S3 were 181.04 ± 110.38 mg/L, 225.43 ± 110.38 mg/L and 194.25 ± 110.38 mg/L, respectively.

It is important to note that the lack of a significant station effect on SS might be attributed to the substantial variability in SS concentrations due to hydrological conditions (water flow, floods) and pollution sources. Despite the lack of a significant effect according to ANOVA, it is relevant to highlight the difference observed in the boxplot medians, suggesting a possible trend that warrants further exploration in future studies.

3.1.5. Dissolved Oxygen (DO)

Figure 8 illustrates the spatiotemporal variations in dissolved oxygen (DO) concentrations in Oued Zénati water. As shown in the boxplot, the median DO concentration is significantly higher at station S3 (12.5 mg/L) and S1 (10.1 mg/L) compared to station S2 (5.7 mg/L). The lowest DO levels observed at station S2 likely result from the decomposition of organic matter by bacteria, a consequence of the high pollution levels. The higher level of DO at S3, downstream of the reed-dense area, suggests a purifying effect of the reeds through their oxygen-producing capabilities.

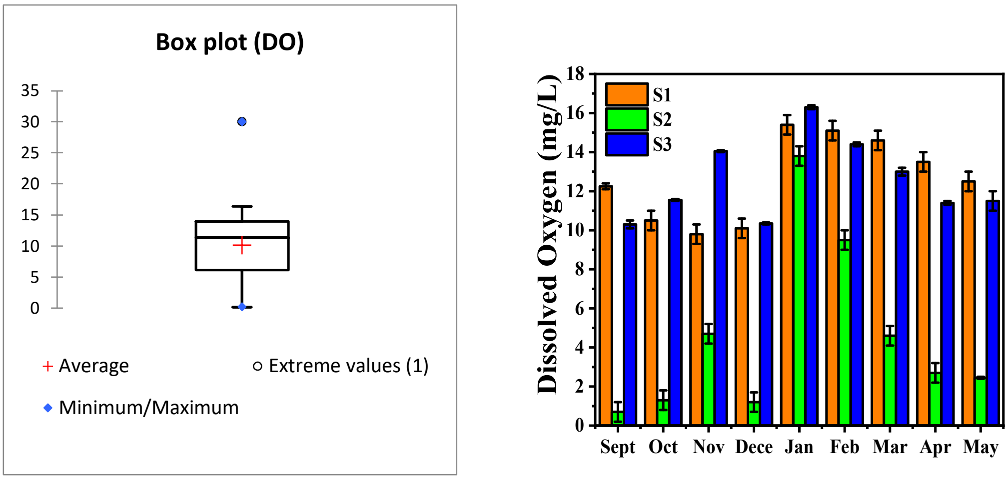

Figure 8. Spatiotemporal variation in dissolved oxygen (DO) in Oued Zenati water. The data represent means and standard deviations calculated from three replicate measurements per sample at each location.

While DO concentrations are also high at station S1, this is more likely due to a lack of organic matter and bacterial activity, rather than a direct purification process, and/or the input of oxygen-rich water by affluents [39]. The average values across all the samples were 12.2 ± 5.26 mg/L at S1, 5.7 ± 5.26 mg/L at S2 and 12.5 ± 5.26 mg/L at S3.

Statistical analysis (ANOVA) revealed a significant effect of station location on DO (p-value < 0.05). The Tukey HSD test indicates that Station S3 has a significantly higher DO concentration compared to Stations S1 and S2, while there is no significant difference between Stations S1 and S2.

3.1.6. Nitrates (NO_3^-)

Figure 9 illustrates the spatiotemporal variations in nitrate (NO_3^-) concentrations in the Oued Zenati water. Nitrate concentrations are higher at station S1 compared to station S2 (Figure 9), which could be attributed to agricultural practices and the use of fertilizers. Wastewater pollution also contributes to elevated nitrate levels. The use of nitrogenous fertilizers and untreated wastewater discharges can lead to eutrophication problems and groundwater contamination [40,41]. The median nitrate concentration, according to boxplots, is higher at Station S2 (2.800 mg/L) compared to Station S1 (2.200 mg/L), although the average value for S1 is actually higher than in S2 with the average concentrations for nitrates being 3.69 ± 1.50 mg/L for S1, 2.68 ± 1.50 mg/L for S2 and 3.17 ± 1.50 mg/L at S3.

Statistical analysis (ANOVA) revealed a significant effect of station location on nitrate levels (p-value < 0.05). The Tukey HSD test indicates that Station S1 has significantly higher nitrate concentrations compared to Station S2. There is no significant difference between Stations S1 and S3, nor between Stations S2 and S3.

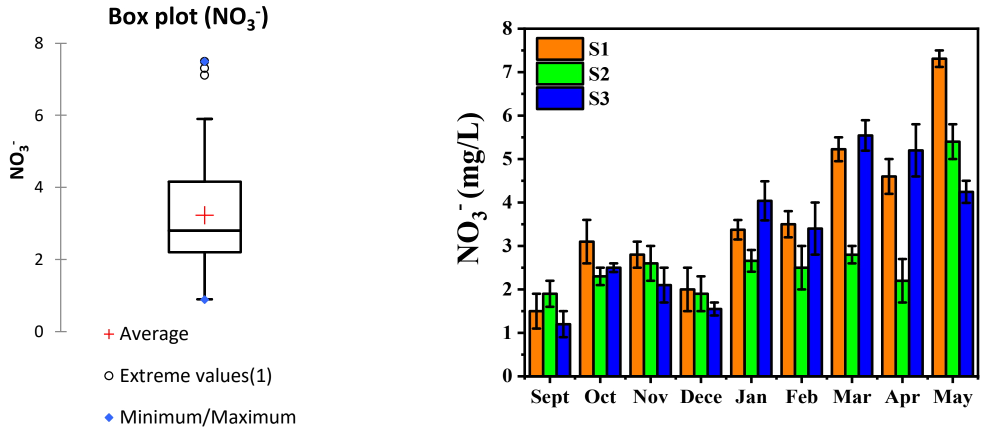

Figure 9. Spatiotemporal variation in nitrate (NO_3^-) concentration in Oued Zénati water. The data represent means and standard deviations calculated from three replicate measurements per sample at each location.

3.1.7. Nitrites (NO_2^-)

Figure 10 presents spatiotemporal variations in nitrite (NO_2^-) concentrations in the Oued Zenati water. Nitrite concentrations follow a similar seasonal pattern to nitrates, with higher concentrations during periods of high-water flow. These levels exceed surface water quality standards [40]. The median nitrite concentration, as shown in your boxplots, is higher at station S2 (0.300 mg/L) than at station S1 (0.230 mg/L), suggesting a higher concentration of nitrites at S2. The average concentrations of nitrites are 0.24 ± 0.22 mg/L at S1, 0.47 ± 0.22 mg/L at S2 and 0.26 ± 0.22 mg/L at S3.

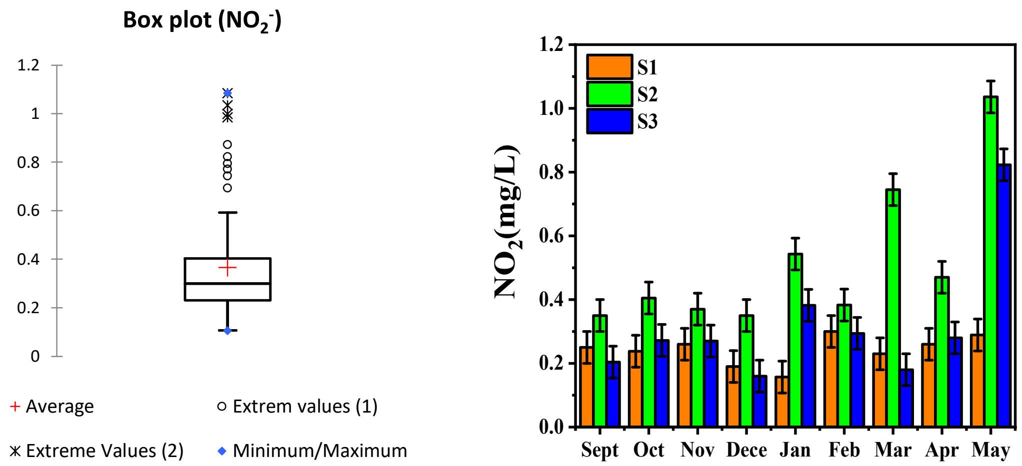

Figure 10. Spatiotemporal variation in nitrite (NO_2^-) concentration in Oued Zénati water. The data represent means and standard deviations calculated from three replicate measurements per sample at each location.

Statistical analysis shows a significant effect of the station on nitrites (p-value < 0.05). The Tukey HSD test reveals that station S2 has significantly higher nitrite concentration than stations S1 and S3. There is no significant difference between stations S1 and S3.

3.1.8. Ammonium (NH_4^+)

Figure 11 shows that ammonium concentrations in the Oued Zenati water fluctuate significantly throughout the year, with higher levels during warmer periods, likely due to increased bacterial activity and the breakdown of organic matter. These concentrations exceed surface water quality standards. Ammonium, at high concentrations, can be toxic to aquatic life and contribute to eutrophication [42]. The median ammonium concentration, according to the boxplots, is higher at S2 (0.742 mg/L) than at S1 (0.366 mg/L), suggesting a higher concentration of ammonium at S2. The average concentrations of ammonium are 0.92 ± 0.85 mg/L at S1, 1.47 ± 0.85 mg/L at S2 and 1.25 ± 0.85 mg/L at S3.

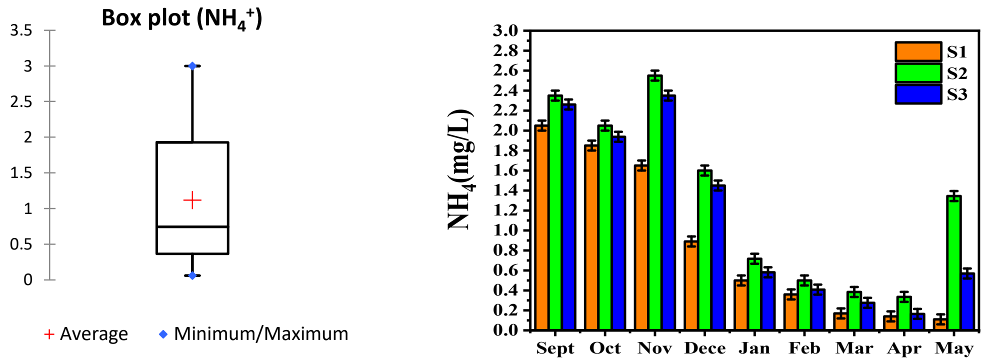

Figure 11. Spatiotemporal variation in ammonium (NH_4^+) concentration in Oued Zenati water. The data represent means and standard deviations calculated from three replicate measurements per sample at each location.

The statistical analysis revealed no significant effect of the station on ammonium concentration (*p*-value > 0.05), suggesting that the station does not have a significant impact. However, the boxplot (Figure 11) shows a higher median ammonium concentration at S2 (0.742 mg/L) than at S1 (0.366 mg/L), suggesting a greater median concentration of ammonium at S2. Furthermore, the principal component analysis (PCA) shows that station S2 is closer to the positive quadrant of the second principal axis (F2), which represents fecal contamination and organic matter.

3.1.9. Phosphates (PO_4^{3-})

Figure 12 shows that phosphate levels remain elevated throughout the year, particularly at Station S2, indicating pollution from urban and agricultural sources. These concentrations significantly exceed surface water quality standards [43]. Phosphorus pollution is a major global concern, contributing to the eutrophication of surface waters, and threatening biodiversity and the availability of potable water [44]. The median phosphate concentration, derived from your boxplots, is higher at Station S2 (1.175 mg/L) compared to Station S1 (0.600 mg/L), indicating a greater concentration of phosphates at S2. The average concentrations for phosphates are 0.73 ± 0.78 mg/L at S1, 1.86 ± 0.78 mg/L at S2 and 1.11 ± 0.78 mg/L at S3.

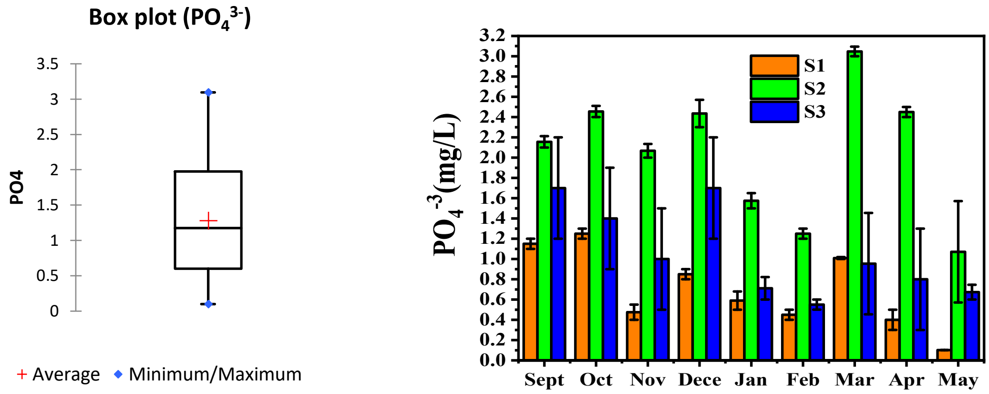

Figure 12. Spatiotemporal variation in phosphate (PO_4^{3-}) concentration in Oued Zenati water. The data represent means and standard deviations calculated from three replicate measurements per sample at each location.

Statistical analysis revealed a significant effect of station location on phosphate levels (p-value < 0.05). The Tukey HSD test indicates that Stations S2 and S3 have significantly higher phosphate concentrations compared to Station S1. Station S2 also has significantly higher phosphate concentrations compared to Station S3.

3.1.10. Microbiological Quality

Bacteriological analyses revealed significant fecal contamination in the Oued Zénati water, with notable spatiotemporal variation (Table 2). Concentrations of total coliforms, fecal coliforms, and fecal streptococci are elevated across all sites, significantly exceeding surface water quality standards, and indicating substantial fecal pollution. The median total coliform count (Figure 13) is higher at S2 (2.5×10^7 MPN 100/mL) compared to S1 (4.5×10^5 MPN 100/mL). The median fecal coliform count (Figure 14) is higher at S2 (9.5×10^5 MPN 100/mL) compared to S1 (2.5×10^4 MPN 100/mL). The median fecal streptococci count (Figure 15) is higher at S2 (2.4×10^4 MPN 100/mL) compared to S1 (1.5×10^3 MPN 100/mL).

Table 2. Average values and standard deviations of microbiological parameters at the three sampling sites.

Parameter	S1 (Non-Polluted)	S2 (Wastewater Discharges)	S3 (Reeds)
Total coliforms (TC) (MPN/100 mL)	$7.7 \times 10^5 \pm 9.9 \times 10^5$	$32 \times 10^6 \pm 18 \times 10^6$	$16 \times 10^6 \pm 12 \times 10^6$
Fecal coliforms (FC) (MPN/100 mL)	$25 \times 10^3 \pm 10^5$	$9.5 \times 10^5 \pm 3 \times 10^5$	$1.5 \times 10^5 \pm 5 \times 10^4$
Fecal streptococci (FS) (MPN/100 mL)	$1.5 \times 10^2 \pm 5 \times 10^2$	$2.4 \times 10^4 \pm 8 \times 10^2$	$3 \times 10^3 \pm 10^3$

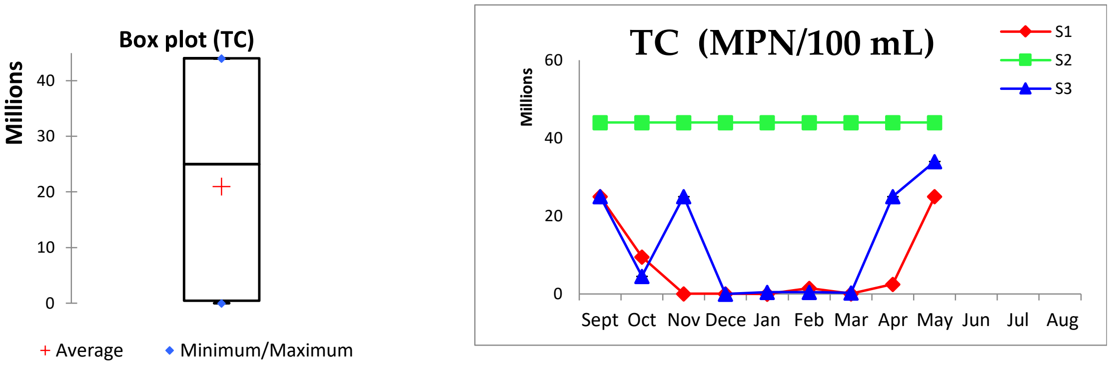

Figure 13. Evolution of the number of total coliforms (TC) in Oued Zénati water. The data represent means and standard deviations calculated from three replicate measurements per sample at each location.

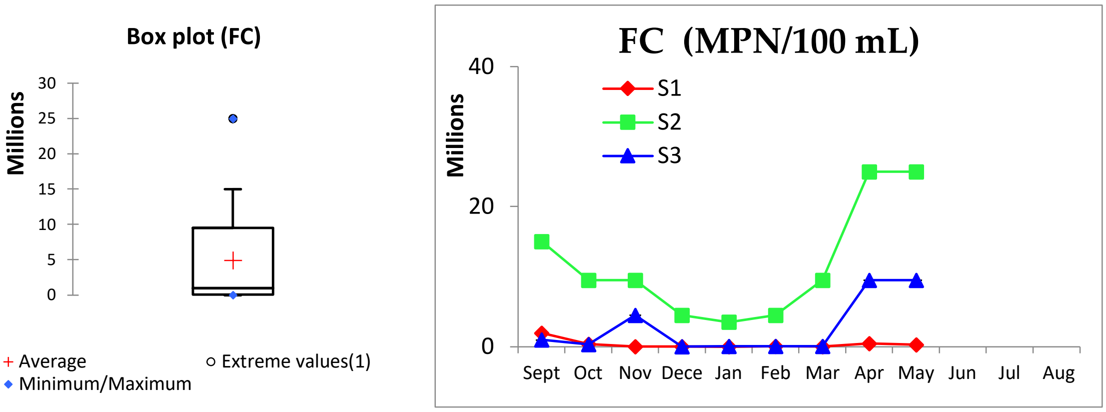

Figure 14. Evolution of the number of fecal coliforms (FC) in Oued Zenati water. The data represent means and standard deviations calculated from three replicate measurements per sample at each location.

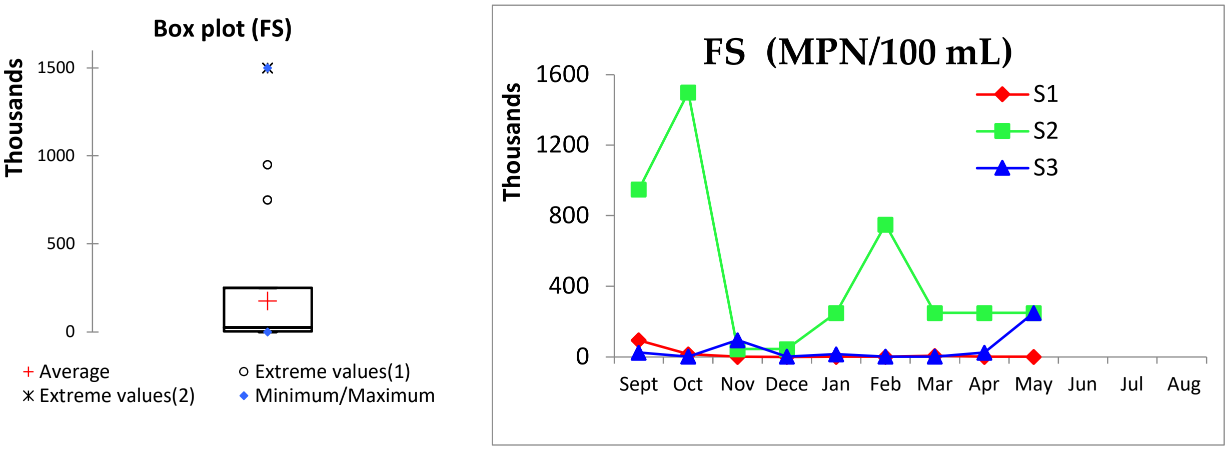

Figure 15. Evolution of the number of fecal streptococci (FS) in Oued Zenati water. The data represent means and standard deviations calculated from three replicate measurements per sample at each location.

Statistical analysis shows a significant effect of station location on total coliforms, fecal coliforms, and fecal streptococci (*p*-value < 0.05). The Tukey HSD test reveals that Station S2 exhibits significantly higher concentrations of total coliforms, fecal coliforms, and fecal streptococci compared to Stations S1 and S3.

3.1.11. ANOVA Analysis

Table 3 clearly demonstrates that station location (S1, S2, S3) has a significant impact on most water quality parameters, except for pH and suspended solids. *p*-values (Pr > F) less than 0.05 indicate that the observed differences are statistically significant.

Table 3. ANOVA results for all study parameters.

Parameter	F	Pr > F	Significant
Temperature	6.075	0.004	Yes
pH	0.877	0.420	No
Salinity (Sal)	13.629	<0.0001	Yes
Electrical conductivity (EC)	4.936	0.010	Yes
Suspended solids (SS)	1.540	0.221	No
Dissolved oxygen (DO)	51.178	<0.0001	Yes
Phosphates (PO_4^{3-})	46.067	<0.0001	Yes
Nitrites (NO_2^-)	14.294	<0.0001	Yes
Nitrates (NO_3^-)	3.295	0.042	Yes
Ammonium (NH_4^+)	2.112	0.128	No
Total coliforms (TC)	112.124	<0.0001	Yes
Fecal coliforms (FC)	37.811	<0.0001	Yes
Fecal streptococci (FS)	24.063	<0.0001	Yes

3.1.12. Principal Component Analysis (PCA)

The PCA graph (Figure 16) represents both the positions of the parameters (the stations and the seasons) and the direction and importance of the variables on the graph. It allows us to simultaneously visualize the relationships between the different stations and seasons and the water quality variables.

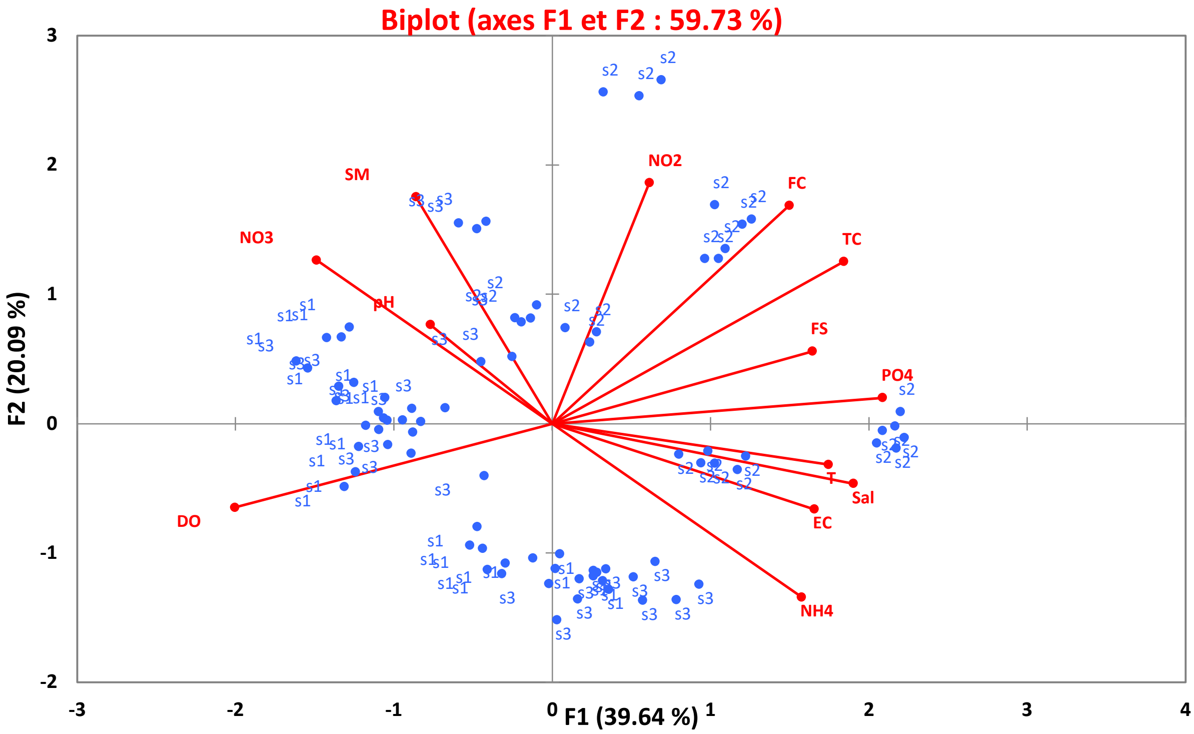

Figure 16. Principal Component Analysis of quality variation in the Oued Zenati water.

Principal components.

- F1 (39.64%). The first principal axis (F1) explains 39.64% of the total variability of the data. It is strongly correlated with salinity, electrical conductivity, temperature, and phosphates. This suggests that F1 mainly represents the mineralization of the water, likely due to soil erosion, runoff, and wastewater inputs. Variables located in the positive quadrant of F1 are positively correlated with this component, signifying that they contribute to the increase in mineralization.
- F2 (20.09%). The second principal axis (F2) explains 20.09% of the total variability. It is strongly correlated with total coliforms, fecal coliforms, and fecal streptococci. This suggests that F2 mainly represents fecal contamination and the presence of organic matter in the water. Variables located in the positive quadrant of F2 are positively correlated with this component, indicating a higher fecal contamination.

Station positions.

- Differences between stations. The graph shows that Stations S1 (non-polluted control zone), S2 (wastewater discharge zone), and S3 (zone with reeds) cluster based on distinct trends. Station S1 is located more at the left of the graph, while Stations S2 and S3 are found at the right. This suggests that there are significant differences in water composition between stations.
- Impact of pollution. Station S1 is positioned more in the negative quadrant of F2, which is consistent with the notion that it is less impacted by fecal contamination and organic matter. Stations S2 and S3 are closer to the positive quadrant of F2, indicating a greater impact of fecal pollution.
- Seasonal influences. It is difficult to distinguish a clear separation of seasons on the graph. Observations from different seasons appear rather scattered, which might suggest that the impact of seasons on water quality is less important than the impact of stations.

Variable vectors.

- Direction and importance of variables. The red vectors indicate the direction and relative importance of each variable on the graph. Variables that are close to each other are highly correlated and evolve together, while variables that are far from each other have a weak correlation.
- Associations between variables. The graph clearly shows that salinity, electrical conductivity, temperature, and phosphates are strongly correlated. Total coliforms, fecal coliforms, and fecal streptococci are also strongly correlated.
- Important variables. The variables that mostly impact the two principal axes, F1 and F2, are salinity, electrical conductivity, phosphates, temperature, total coliforms, fecal coliforms, and fecal streptococci.

General interpretation.

- The PCA analysis suggests that the quality of the Oued Zénati water varies considerably depending on the station. The upstream station (S1) is less impacted by fecal contamination and organic matter, while the downstream stations (S2 and S3) exhibit greater mineralization. Seasonal variations appear less pronounced than differences between stations.

Table 4 shows the correlation between each variable and the first two principal axes (F1 and F2) of the principal component analysis. It allows for an easier visualization of associations between variables.

Table 4. Correlation of variables with principal axes F1 and F2 (PCA).

Variable	F1	F2
Temperature	0.694	−0.126
pH	−0.306	0.305
Salinity (Sal)	0.757	−0.185
Electrical conductivity (EC)	0.659	−0.263
Solid substances (SS)	−0.343	0.698
Dissolved oxygen (DO)	−0.798	−0.258
Phosphate (PO_4^{3-})	0.831	0.080
Nitrite (NO_2^-)	0.244	0.742
Nitrate (NO_3^-)	−0.593	0.503
Ammonium (NH_4^+)	0.627	−0.534
Total coliforms (TC)	0.733	0.499
Fecal coliforms (FC)	0.596	0.672
Fecal streptococci (FS)	0.654	0.223

- F1. The variables salinity, electrical conductivity, temperature, and phosphates are strongly correlated with F1, suggesting that this component represents the mineralization of the water.
- F2. The variables total coliforms, fecal coliforms, fecal streptococci, and ammonium are strongly correlated with F2, suggesting that this component represents fecal contamination and organic matter in the water.

4. Discussion

4.1. Context of Pollution and Study Site

Our results confirm the alarming state of pollution in Oued Zénati, reflecting a widespread issue in Algeria and other regions facing similar water quality challenges [6]. The analysis of the water's physicochemical parameters reveals concerning levels of fecal contamination, particularly at Station S2. This observation aligns with findings from several studies conducted in different contexts [19,45], suggesting that untreated wastewater discharges from urban areas and surrounding agricultural activities are the main sources of contamination. The lack of adequate sanitation infrastructure and insufficient hygiene practices exacerbate the situation, exposing the population to the risk of waterborne infections. The high levels of fecal contamination at S2 are consistent with observations from other studies in Algeria, such as the work of Mamine et al. [46] in Souk Ahras, which revealed the risks associated with using untreated wastewater for irrigation in the Medjerda Wadi, highlighting the urgent need for effective wastewater treatment to protect public health and the environment.

Unfortunately, the Oued Zénati faces intense anthropogenic pressure and suffers from significant pollution. Its function as a sink for urban, hospital, and agricultural discharges, combined with the absence of adequate sanitation systems and the practice of manure spreading, contributes to water contamination by various pollutants, including nitrates (NO_3^-), nitrites (NO_2^-), suspended solids (SS), and fecal contamination indicators [29]. The use of its waters for large-scale irrigation exacerbates health and ecological risks, making its rehabilitation an urgent priority. Pollution by phosphorus, in particular, is a major problem worldwide, with detrimental consequences for water quality and the health of aquatic ecosystems [29]. Eutrophication, one of the most worrying consequences, threatens biodiversity and the availability of potable water.

4.2. Phytoremediation Mechanisms and Effectiveness

The Oued Zénati exhibits variable aquatic vegetation, ranging from near total absence upstream to a significant density downstream. This downstream area is dominated by reeds (*Phragmites australis*), cattails, and bulrushes. This dense vegetation, particularly the reeds, offers a natural self-purification potential through several mechanisms [47]: their dense root system retains suspended particles and microorganisms, their roots secrete biocidal substances that eliminate pathogenic bacteria, they limit the availability of nutrients for undesirable microorganisms, and beneficial microorganisms present in their rhizosphere contribute to the degradation of organic matter. Previous studies have demonstrated the effectiveness of reeds in reducing fecal coliforms, decontaminating wastewater, and eliminating phosphorus, with removal rates reaching 80% to 100% [47]. Phytoremediation, utilizing plants like *P. australis*, is thus a promising solution for wastewater treatment and improving water quality, offering an ecological and economic alternative to conventional treatment methods.

Our results also show high levels of phosphorus, particularly at Station S2. This finding supports the conclusions of several studies demonstrating the global impact of phosphorus pollution on surface water eutrophication and the threat it poses to biodiversity and the availability of potable water [44,48]. Phosphorus pollution can lead to algal blooms, reducing dissolved oxygen (DO) levels and threatening the survival of aquatic organisms [49]. Additionally, certain organophosphorus compounds present in wastewater can be toxic to aquatic fauna and flora [41]. Regarding the reviewer's question about nutrient (nitrogen and phosphorus) content within the plant tissues, this analysis was not conducted in the present study, given the fact that our objectives focused mainly on the potential of the plant to depollute the wastewater, and time and resource constraints prevented additional investigations. The data generated, therefore, do not allow to evaluate their uptake in the studied system. However, this is recommended for future research to gain a deeper understanding of nutrient uptake and utilization within *P. australis*.

The study by Bwire et al. [23] conducted in Uganda demonstrated that surface water and groundwater sources were contaminated and exhibited physicochemical parameters conducive to the propagation of waterborne diseases like cholera. Our results confirm this observation and underscore the need to promote access to safe drinking water in Algeria to achieve the UN Sustainable Development Goals. The effectiveness of natural systems, such as reeds, in removing pollutants from wastewater has also been explored in Algeria. A study by Mamine et al. [50] in Souk Ahras demonstrated the efficiency of *Typha latifolia* in removing organic matter, suspended solids (SS), and nutrients from wastewater. This further highlights the potential of using natural systems for water treatment, particularly in regions facing water scarcity. The significant improvement in water quality observed at station S3, downstream of the reed-dense area, strongly suggests the potential of *Phragmites australis* for phytoremediation in the Oued Zénati. This improvement is especially evident in the significant reduction in fecal coliforms (FC) (68.5%), fecal streptococci (FS) (92.25%), and phosphates (40.3%), coupled with a notable increase in dissolved oxygen (DO) levels. The observed reduction in fecal streptococci at station S3 is likely due to a combination of mechanisms, including the filtration of bacteria by the reed roots and the potential biocidal effects of compounds released by the plant. Further research should investigate this mechanism in more detail.

The study by Elsayed et al. [51], conducted in Egypt, used water quality indices to assess surface water quality and demonstrated that the waters of the Nile Delta were generally suitable for irrigation. However, our results highlight issues of fecal contamination and phosphorus in Oued Zénati, suggesting that using the wadi's water for irrigation could pose health risks to crops and consumers. A study by Gad et al. [52] used water quality indices and multivariate modeling techniques to assess Nile River water quality, finding significant pollution in some areas. These studies, along with that of Gad et al. [53], emphasize the importance of continuous water quality monitoring and the use of innovative techniques to assess risks to human health and the environment. A study by Adesakin et al. [53], conducted in Nigeria, revealed significant bacteriological contamination of domestic water sources, exceeding WHO acceptable limits. Our results confirm the critical importance of addressing bacteriological contamination and highlight the need for water purification and treatment systems before consumption.

Zhang et al. [44] analyzed the presence of opportunistic pathogens in drinking water distribution systems, demonstrating that pathogen concentrations were influenced by physicochemical parameters, particularly residual disinfectant levels. This study emphasizes the importance of maintaining adequate disinfectant levels in drinking water distribution systems to control opportunistic pathogens.

4.3. Future Applications and Recommendations

Bermarce et al. [35] analyzed the relationship between water pH and other physicochemical parameters, showing that this relationship varied depending on the water system. This study highlights the complexity of interactions between physicochemical water parameters and underscores the importance of considering all such parameters when evaluating water quality. Wu et al. [54] examined the reuse of municipal wastewater for irrigation, demonstrating that wastewater treated with membrane technologies (MBR, NF, and RO) met the physicochemical and microbiological quality standards for irrigation. This study emphasizes the importance of membrane technology in wastewater treatment and the potential for reusing treated wastewater for irrigation.

El-Kady et al. [55] investigated the impact of probiotics on water quality, growth, and health of Nile tilapia, showing that probiotics could improve water quality and fish health. This study highlights the potential of probiotics to enhance aquaculture production and water quality.

Hu et al. [56] used metagenomics to analyze microbiome composition in rapid sand filters used for water treatment, demonstrating that microbiome composition varied by water source (surface or groundwater) and played a key role in water purification. This study emphasizes the importance of microbiology in water treatment and the need to understand interactions between microorganisms and water purification processes.

Liu et al. [57] evaluated the hydrochemistry of water resources in China's Weibei Plain, analyzing risks associated with high nitrate concentrations in groundwater, which posed significant health risks to residents. This study underscores the importance of controlling nitrate pollution to protect human health.

Yousefi et al. [58] synthesized and characterized Co/Co_3O_4 nanocomposites as efficient photocatalysts for wastewater treatment, showing their potential to decolorize organic dyes and exhibit antibacterial activity. This study highlights the potential of nanomaterials for wastewater treatment and pollution reduction.

Peydayesh et al. [59] investigated the use of lysozyme amyloid fibrils as a bio-flocculant for removing microplastics and natural organic matter from water, demonstrating their effectiveness. This study emphasizes the potential of natural bio-flocculants for water treatment and pollution reduction.

Asadollah et al. [60] compared the performance of machine learning models for predicting water quality indices (WQI), showing that the Extra Tree Regression (ETR) model outperformed traditional models (SVR and DTR). This study highlights the potential of machine learning models to predict water quality and offer insights for water resource management.

The presence of reeds (*P. australis*) downstream of Oued Zénati suggests a positive effect on water quality. The decrease in pollutant concentrations, particularly fecal coliforms and fecal streptococci between sites S2 and S3, indicates a purifying effect of the reeds. This observation aligns with studies that have demonstrated the potential of *P. australis* for heavy metal (Cd, Ni, Pb) accumulation and its contribution to phytostabilization and phytoextraction [61–63]. Regarding the recycling of plants after phytoremediation, several options exist, including composting and biogas production. However, the focus of this research was on evaluating the plants' effectiveness in wastewater treatment, therefore, a discussion of post-harvest plant recycling was beyond the scope of this work, but this aspect represents a promising avenue for future investigation. Furthermore, regarding the reviewer's concern about the absence of summer data, it should be noted that our study period was extended from September to May and this choice was primarily due to laboratory availability and logistics for the collection of data throughout all the seasons. However, to better interpret the data trends, results obtained during May might be seen to offer similar environmental and climatic conditions as summer months. Nonetheless, a more accurate conclusion can be obtained from a study specifically targeted to assess data trends during the summer months, which was beyond the scope of the present study.

5. Conclusions

This purifying effect of reeds could be compared to the various wastewater treatment techniques discussed in the cited studies. Membrane technologies, natural bio-flocculants, multi-functional materials, and photocatalysts are promising water purification approaches. However, phytoremediation using natural plant capabilities offers advantages in terms of cost and sustainability.

Our results underscore the need to implement measures to improve sanitation systems and hygiene practices to reduce fecal contamination. Phytoremediation could be a promising solution for wastewater treatment, but further research is needed to evaluate its effectiveness in the context of Oued Zénati. Continuous water quality monitoring, along with the use of innovative techniques like metagenomics and machine learning models, is essential to identify emerging pollutants and improve water resource management. Further research should focus on optimizing the design and implementation of phragmifiltration systems, investigating the long-term effectiveness and resilience of this approach, and exploring synergies between phytoremediation and other advanced treatment technologies.

The study of Oued Zénati revealed significant water pollution impacting physicochemical and microbiological quality. High concentrations of nutrients, suspended matter, and fecal indicators highlight the impact of untreated wastewater, intensive agriculture, and inadequate sanitation, posing threats to aquatic ecosystems, biodiversity, and public health.

However, this study also demonstrated the purifying potential of *Phragmites australis*, observed downstream of the polluted area. Water quality analysis showed a notable improvement at site S3, with reduced fecal coliforms, fecal streptococci, and phosphates, and increased dissolved oxygen.

Phytoremediation, particularly through phragmifilters, emerges as a promising solution for Oued Zénati sanitation, providing economic, ecological, and aesthetic benefits over conventional methods.

Author Contributions: Conceptualization, L.B., N.C., and M.H.; methodology, L.B., N.C., A.S., I.B.A., M.H., and N.G.; software, L.B., A.S., I.B.A., S.Z., and H.H.; validation N.C., A.S., I.B.A., S.Z., O.C.M., G.C., and S.B.; formal analysis, L.B., A.S., I.B.A., and S.Z.; investigation, N.G., and A.S; data curation, L.B., N.C., M.H., A.S., and I.B.A.; writing—original draft preparation, L.B., A.S., I.B.A., H.H., and N.G.; writing—review and editing, L.B., N.G., N.C., A.S., O.C.M., G.C., and S.B.; supervision, N.G., A.S., I.B.A., and S.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no specific funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data generated during in this study are presented in this paper.

Acknowledgments: First and foremost, we express our sincere gratitude to the General Directorate of Scientific Research and Technological Development (DGRSDT) of the Republic of Algeria for their invaluable support in this research endeavor. We are also deeply indebted to all those who contributed to the completion of this work, including researchers, technicians, and staff. Their collective effort and dedication have been instrumental in achieving the project's goals.

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

References

1. UNESCO World Water Assessment Program. *The United Nations World Water Development Report 2018: Nature-Based Solutions for Water*; UNESCO: Paris, France, 2018; 139p.
2. WHO Teamon Water, Sanitation, Hygiene and Health (WSH). *Progress on Household Drinking Water, Sanitation and Hygiene 2000–2020: Five Years into the SDGs*; WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene (JMP): Geneva, Switzerland, 2020; 162p.
3. Ben Amor, A.; Hemmami, H.; Zeghoud, S.; Ben Amor, I. Strength and limitation of nature-based solutions towards adaptation and mitigation of climate change in developing countries. In *Blue-Green Infrastructure for Sustainable Urban Settlements: Implications for Developing Countries Under Climate Change*; Joshi, P.K., Rao, K.S., Bhadouria, R., Tripathi, S., Singh, R., Eds.; Springer: Cham, Switzerland, 2024; pp. 3–30.
4. Wang, H.; Yang, Q.; Ma, H.; Liang, J. Chemical compositions evolution of groundwater and its pollution characterization due to agricultural activities in Yinchuan plain, northwest China. *Environ. Res.* **2021**, *200*, 111449. [CrossRef] [PubMed]
5. Bouchaala, L.; Charchar, N.; Gherib, A.E. Ressources hydriques: Traitement et reutilisation des eaux usees en Algerie. *Alger. J. Arid Environ.* **2017**, *7*, 84–95. [CrossRef]
6. Burić, D.; Ristić, M.; Ćurčić, S. Wastewater treatment: A review of conventional and advanced methods. *J. Environ. Manag.* **2023**, *336*, 117384.
7. Bouchaala, L.; Charchar, N.; Sahraoui, H.; Gherib, A. Assessment of wastewater biological treatment efficiency and mapping of WWTPs and LTPs in Algeria. *J. Environ. Health Sci. Eng.* **2021**, *19*, 1153–1169. [CrossRef]
8. Baziz, D.; Maazouzi, A.; Lachache, S. Physical-chemical characterisation of the urban wastewater—Case study of the Boumerdes region, North–Algeria. *J. Water Land Dev.* **2022**, *54*, 243–250. [CrossRef]
9. Moussaoui, T.; Derdour, A.; Hosni, A.; Santos, M.; Legua, P.; Pardo-Picazo, M. Assessing the quality of treated wastewater for irrigation: A case study of Ain Sefra wastewater treatment plant. *Sustainability* **2023**, *15*, 11133. [CrossRef]

10. Cardiff, M.; Schachter, L.; Krause, J.; Gotkowitz, M.; Austin, B.C. Quantifying annual nitrogen loss to groundwater via edge-of-field monitoring: Method and application. *Water Resour. Res.* **2022**, *58*, e2021WR031674. [CrossRef]
11. He, S.; Li, Y.; Mu, H.; Zhao, Z.; Wang, J.; Liu, S.; Sun, Z.; Zheng, M. Ammonium concentration determines differential growth of comammox and canonical ammonia-oxidizing prokaryotes in soil microcosms. *ISME J.* **2021**, *15*, 3669–3681. [CrossRef]
12. Ahmed, N.K.; Lin, Q. Dissolved oxygen dynamics and its impacts on the health of aquatic ecosystems. *Ecol. Process.* **2021**, *10*, 1–13.
13. Khedidja, S.; Boudoukha, A. Contribution to the assessment of water quality of some rivers of eastern Algeria: Case of Oued El Hammam (Khenchela). *J. Water Land Dev.* **2019**, *23*, 141–150.
14. Ababsa, N.; Kribaa, M.; Tamrabet, L.; Addad, D.; Hallaire, V.; Ouldjaoui, A. Long-term effects of wastewater reuse on hydro physicals characteristics of grassland grown soil in semi-arid Algeria. *J. King Saud Univ.-Sci.* **2020**, *32*, 1004–1013. [CrossRef]
15. Wang, W.; Wang, S.; Jiang, X.; Zheng, B.; Zhao, L.; Zhang, B.; Chen, J. Differences in fluorescence characteristics and bioavailability of water-soluble organic matter (WSOM) in sediments and suspended solids in Lihu Lake, China. *Environ. Sci. Pollut. Res.* **2018**, *25*, 12648–12662. [CrossRef] [PubMed]
16. Mherzi, N.; Lamchouri, F.; Toufik, H. Assessment of the effects of seasonal changes, urban discharges and leachates on the parasitological and bacteriological qualities of soil and water from Oued Larbaâ (North-eastern, Morocco). *Environ. Monit. Assess.* **2021**, *193*, 628. [CrossRef]
17. Boutin, C.; Bois, J.-S.; Bouvard, V.; Cadic, G.; Dodane, P.H.; Iwema, A.; Lapauze, P.; Lesavre, J.; Pigneur, Y.; Savoye, D.; et al. *Cadre guide pour un Cahier des Clauses Techniques Particulières (CCTP) Filtres Plantés de Roseaux*; Ministère de l'Agriculture, CGGAER/Pôle d'Appui Technique: Paris, France, 2007; 76p.
18. Cherchar, S.; Boutin, C.; Molle, P. Les filtres plantés de roseaux pour l'épuration des eaux usées domestiques en régions méditerranéennes: Etat des lieux. *Sécheresse* **2005**, *16*, 323–330.
19. Assegide, E.; Alamirew, T.; Bayabil, H.; Dile, Y.; Tessema, B.; Zeleke, G. Impacts of surface water quality in the Awash river basin, Ethiopia: A systematic review. *Front. Water* **2022**, *3*, 790900. [CrossRef]
20. Shine, S.; Muhamud, S.; Adanew, S.; Demelash, A.; Abate, M. Prevalence and associated factors of diarrhea among under-five children in Debre Berhan town, Ethiopia 2018: A cross sectional study. *BMC Infect. Dis.* **2020**, *20*, 174. [CrossRef]
21. Dagher, L.A.; Hassan, J.; Kharroubi, S.; Jaafar, H.; Kassem, I. Nationwide assessment of water quality in rivers across Lebanon by quantifying fecal indicators densities and profiling antibiotic resistance of *Escherichia coli*. *Antibiotics* **2021**, *10*, 883. [CrossRef]
22. Karaca, C.; Hüner, T.; Mercimek Takci, H.A. Antibiotic susceptibility profiles of *Escherichia coli* strains and fecal contamination in Orontes river, Turkey. *Int. J. Life Sci. Biotechnol.* **2023**, *6*, 66–76. [CrossRef]
23. Bwire, G.; Sack, D.A.; Kagirita, A.; Obala, T.; Debes, A.K.; Ram, M.; Komakech, H.; George, C.M.; Orach, C.G. The quality of drinking and domestic water from the surface water sources (lakes, rivers, irrigation canals and ponds) and springs in cholera prone communities of Uganda: An analysis of vital physicochemical parameters. *BMC Pub. Health* **2020**, *20*, 1128. [CrossRef]
24. Li, Y.; Zhang, C.; Wang, X.; Liao, X.; Zhong, Q.; Zhou, T.; Gu, F.; Zou, H. Pollutant impacts on bacteria in surface water and sediment: Conventional versus emerging pollutants in Taihu Lake, China. *Environ. Pollut.* **2023**, *323*, 121334. [CrossRef]
25. Brumfield, K.D.; Cotruvo, J.; Shanks, O.C.; Sivaganesan, M.; Hey, J.; Hasan, N.A.; Huq, A.; Colwell, R.R.; Leddy, M.B. Metagenomic sequencing and quantitative real-time PCR for fecal pollution assessment in an urban watershed. *Front. Water* **2021**, *3*, 626849. [CrossRef] [PubMed]
26. Bayuo, J.; Rwiza, M.J.; Choi, J.W.; Njau, K.N.; Mtei, K.M. Recent and sustainable advances in phytoremediation of heavy metals from wastewater using aquatic plant species: Green approach. *J. Environ. Manag.* **2024**, *370*, 122523. [CrossRef] [PubMed]
27. Hammadi, B.; Hadj Seyd, A.; Bebba, A.A. Performance assessment of nitrogen pollution purification by phytodepuration: Case of Temacine pilot station (Algeria). *Int. J. Environ. Sci. Technol.* **2019**, *16*, 6647–6656. [CrossRef]
28. Benchaiba, M. Les risques d'inondations dans le bassin versant de l'oued Seybouse: Exemple du sous bassin versant de l'Oued Zenati. Master's Thesis, Mentouri University, Constantine, Algeria, 2006.
29. Zeghaba, N.; Laraba, A. The principal components analysis (PCA) to evaluate the quality of water of the Bouhamdane river, Guelma (north-east Algerian). *J. Fundam. Appl. Sci.* **2018**, *10*, 383–395.
30. Rodier, J.; Legube, B.; Merlet, N. *L'analyse de l'eau: Eaux Naturelles, Eaux Résiduaires, Eau de Mer*, 9th ed.; Dunod: Malakoff, France, 2009; 1600p.
31. *ISO 9308-2:2012*; Water Quality—Enumeration of Escherichia coli and Coliform Bacteria—Part 2: Most Probable Number Method. ISO: Geneva, Switzerland, 2012.
32. *ISO 9308-3:1998*; Water Quality—Detection and Enumeration of Escherichia coli and Coliform Bacteria—Part 3: Miniaturized Method (Most Probable Number) for the Detection and Enumeration of *E. coli* in Surface and Waste Water. ISO: Geneva, Switzerland, 1998.
33. *ISO 7899-2000*; Water Quality—Detection and Enumeration of Intestinal Enterococci. ISO: Geneva, Switzerland, 2000.
34. Dele-Alimi, T.O.; Ogunlowo, V.; Akpabio, C.A.; Awobode, H.O.; Anumudu, C.I. Physicochemical characteristics and heavy metals levels in surface waters from Aba-lla, Ibadan, Oyo state, Nigeria. *J. Appl. Sci. Environ. Manag.* **2023**, *27*, 1779–1784. [CrossRef]

35. Benmarce, K.; Zighmi, K.; Hadji, R.; Hamed, Y.; Gentilucci, M.; Barbieri, M.; Pambianchi, G. Integration of GIS and Water-Quality Index for Preliminary Assessment of Groundwater Suitability for Human Consumption and Irrigation in Semi-Arid Region. *Hydrology* **2024**, *11*, 71. [CrossRef]
36. Zhu, S.; Bonacci, O.; Oskoruš, D.; Hadzima-Nyarko, M.; Wu, S. Long term variations of river temperature and the influence of air temperature and river discharge: Case study of Kupa River watershed in Croatia. *J. Hydrol. Hydromech.* **2019**, *67*, 305–313. [CrossRef]
37. Elfanssi, S.; Ouazzani, N.; Latrach, L.; Hejjaj, A.; Mandi, L. Phytoremediation of domestic wastewater using a hybrid constructed wetland in mountainous rural area. *Int. J. Phytoremediat.* **2018**, *20*, 75–87. [CrossRef]
38. Hoshikawa, K.; Fujihara, Y.; Siev, S.; Arai, S.; Nakamura, T.; Fujii, H.; Sok, T.; Yoshimura, C. Characterization of total suspended solid dynamics in a large shallow lake using long-term daily satellite images. *Hydrol. Process.* **2019**, *33*, 2745–2758. [CrossRef]
39. Banerjee, A.; Chakrabarty, M.; Rakshit, N.; Bhowmick, A.R.; Ray, S. Environmental factors as indicators of dissolved oxygen concentration and zooplankton abundance: Deep learning versus traditional regression approach. *Ecol. Indic.* **2019**, *100*, 99–117. [CrossRef]
40. Surdyk, N.; Gourcy, L.; Bault, V. Nitrate transport in the chalk vadose zone in in Picardy (France). *J. Hydrol. Reg. Stud.* **2021**, *37*, 100867. [CrossRef]
41. Bujnovský, R.; Koco, Š.; Cibulka, R.; Vranovská, A.; Vrablíková, D. Nitrate concentration in leachate—Essential information for reducing nitrogen surplus and groundwater pollution from agricultural land in Slovakia. *Water* **2022**, *14*, 1043. [CrossRef]
42. Yan, A.; Guo, X.; Hu, D. Reactive transport of NH4+ in the hyporheic zone from the ground water to the surface water. *Water* **2022**, *14*, 1236. [CrossRef]
43. Ge, X.; Chen, X.; Liu, M.; Wang, C.; Zhang, Y.; Wang, Y.; Tran, H.-T.; Joseph, S.; Zhang, T. Toward a better understanding of phosphorus nonpoint source pollution from soil to water and the application of amendment materials: Research trends. *Water* **2023**, *15*, 1531. [CrossRef]
44. Zhang, H.; Zhou, X.; Lv, X.; Xu, X.; Weng, Q.; Lei, K. Exploration of the factors that influence total phosphorus in surface water and an evaluation of surface water vulnerability based on an advanced algorithm and traditional index method. *J. Environ. Manag.* **2023**, *342*, 118155. [CrossRef]
45. Hasan, M.F.; Nur-E-Alam, M.; Salam, M.A.; Rahman, H.; Paul, S.C.; Rak, A.E.; Ambade, B.; Islam, A.R.M.T. Health risk and water quality assessment of surface water in an urban river of Bangladesh. *Sustainability* **2020**, *13*, 6832. [CrossRef]
46. Mamine, N.; Khaldi, F.; Grara, N. Survey of the physico-chemical and parasitological quality of the wastewaters used in irrigation (Souk Ahras, north-east of Algeria). *Iran. J. Energy Environ.* **2020**, *11*, 79–88.
47. Milke, J.; Gałczyńska, M.; Wróbel, J. The importance of biological and ecological properties of *Phragmites australis* (Cav.) Trin. ex Steud., in phytoremendiation of aquatic ecosystems—The review. *Water* **2020**, *12*, 1770. [CrossRef]
48. Kuwayama, Y.; Olmstead, S.M.; Wietelman, D.C.; Zheng, J. Trends in nutrient-related pollution as a source of potential water quality damages: A case study of Texas, USA. *Sci. Total Environ.* **2020**, *724*, 137962. [CrossRef]
49. Xing, X.; Li, T.; Bi, Z.; Qi, P.; Li, Z.; Chen, Y.; Zhou, H.; Wang, H.; Xu, G.; Chen, C.; et al. Destruction of microbial stability in drinking water distribution systems by trace phosphorus polluted water source. *Chemosphere* **2021**, *275*, 130032. [CrossRef]
50. Mamine, N.; Grara, N.; Khaldi, F. The use of macrophyte *Typha latifolia* filters in the treatment of wastewaters of Medjerda River, in Souk-Ahras city (north-east Algeria). *Stud. Univ. Vasile Goldiş Ser. Ştiinţele Vieţii* **2019**, *29*, 70–81.
51. Elsayed, S.; Hussein, H.; Moghanm, F.S.; Khedher, K.M.; Eid, E.M.; Gad, M. Application of Irrigation Water Quality Indices and Multivariate Statistical Techniques for Surface Water Quality Assessments in the Northern Nile Delta, Egypt. *Water* **2020**, *12*, 3300. [CrossRef]
52. Gad, M.; Elsayed, S.; Moghanm, F.S.; Almarshadi, M.H.; Alshammari, A.S.; Khedher, K.M.; Eid, E.M.; Hussein, H. Combining water quality indices and multivariate modeling to assess surface water quality in the northern Nile delta, Egypt. *Water* **2020**, *12*, 2142. [CrossRef]
53. Adesakin, T.; Oyewale, A.; Bayero, U.; Mohammed, A.; Aduwo, I.; Ahmed, P.; Abubakar, N.; Barje, I. Assessment of bacteriological quality and physico-chemical parameters of domestic water sources in Samaru community, Zaria, Northwest Nigeria. *Heliyon* **2020**, *6*, e04773. [CrossRef]
54. Wu, J.; Zhang, Y.; Wang, J.; Zheng, X.; Chen, Y. Municipal wastewater reclamation and reuse using membrane-based technologies: A review. *Desalin. Water Treat.* **2021**, *224*, 65–82. [CrossRef]
55. Saba, A.O.; Yasin, I.S.M.; Azmai, M.N.A. Meta-analyses indicate that dietary probiotics significantly improve growth, immune response, and disease resistance in tilapia. *Aquac. Int.* **2024**, *32*, 4841–4867. [CrossRef]
56. Hu, W.; Liang, J.; Ju, F.; Wang, Q.; Liu, R.; Bai, Y.; Liu, H.; Qu, J. Metagenomics Unravels Differential Microbiome Composition and Metabolic Potential in Rapid Sand Filters Purifying Surface Water Versus Groundwater. *Environ. Sci. Technol.* **2020**, *54*, 5197–5206. [CrossRef]

57. Liu, J.; Peng, Y.; Li, C.; Gao, Z.; Chen, S. Characterization of the hydrochemistry of water resources of the Weibei Plain, Northern China, as well as an assessment of the risk of high groundwater nitrate levels to human health. *Environ. Pollut.* **2021**, *268*, 115947. [CrossRef]
58. Yousefi, S.R.; Alshamsi, H.A.; Amiri, O.; Salavati-Niasari, M. Synthesis, characterization and application of Co/Co_3O_4 nanocomposites as an effective photocatalyst for discoloration of organic dye contaminants in wastewater and antibacterial properties. *J. Mol. Liquids* **2021**, *337*, 116405. [CrossRef]
59. Peydayesh, M.; Suta, T.; Usuelli, M.; Handschin, S.; Canelli, G.; Bagnani, M.; Mezzenga, R. Sustainable removal of microplastics and natural organic matter from water by coagulation–flocculation with protein amyloid fibrils. *Environ. Sci. Technol.* **2021**, *55*, 8848–8858. [CrossRef]
60. Asadollah, S.; Sharafati, A.; Motta, D.; Yaseen, Z. River water quality index prediction and uncertainty analysis: A comparative study of machine learning models. *J. Environ. Chem. Eng.* **2021**, *9*, 104599. [CrossRef]
61. Fahid, M.; Arslan, M.; Shabir, G.; Younus, S.; Yasmeen, T.; Rizwan, M.; Siddique, K.; Ahmad, S.; Tahseen, R.; Iqbal, S.; et al. *Phragmites australis* in combination with hydrocarbons degrading bacteria is a suitable option for remediation of diesel-contaminated water in floating wetlands. *Chemosphere* **2020**, *240*, 124890. [CrossRef] [PubMed]
62. García-Ávila, F.; Patiño-Chávez, J.; Zhinín-Chimbo, F.; Donoso-Moscoso, S.; Pino, L.; Avilés-Añazco, A. Performance of *Phragmites australis* and *Cyperus papyrus* in the treatment of municipal wastewater by vertical flow subsurface constructed wetlands. *Int. Soil Water Conserv. Res.* **2019**, *7*, 286–296. [CrossRef]
63. Hu, X.; Xu, G.; Zhang, H.; Li, M.; Tu, Y.; Xie, X.; Zhu, Y.; Jiang, L.; Zhu, X.; Ji, X.; et al. Multifunctional β-Cyclodextrin Polymer for Simultaneous Removal of Natural Organic Matter and Organic Micropollutants and Detrimental Microorganisms from Water. *ACS Appl. Mater. Interfaces* **2020**, *12*, 12165–12175. [CrossRef]