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# Long-term performance of wastewater gardens: follow-up on the status of the wastewater garden in Temacine – Algeria

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## ABSTRACT

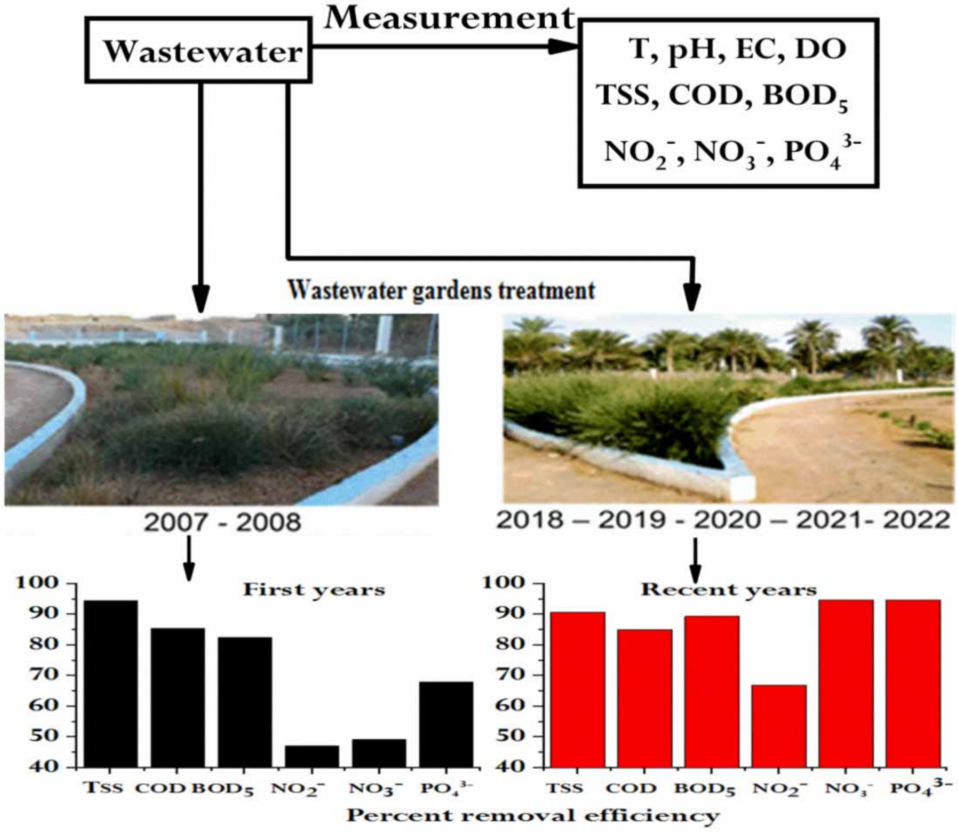
This work investigated the long-term performance of a small wastewater garden (WWG) system for treating municipal wastewater, which has been operating continuously since 2007. The studied system consisted of a horizontal subsurface flow (HFCW) and treated a flow rate of 15 $m^3$/day. Results from 15 years of operation showed that the system has an average removal efficiency of 90.76, 85.12, 89.43, 66.87, 94.74, and 94.74% for total suspended solids (TSS), chemical oxygen demand (COD), biochemical oxygen demand (BOD5), nitrites ($NO_2^-$), nitrates ($NO_3^-$), and orthophosphates ($PO_4^{3-}$), respectively. The high efficiency of the WWG plant was achieved during 2018–2022 compared to the two first years of operation (apart from the TSS). It was noted that the removal of BOD5, $NO_2^-$, $NO_3^-$, and $PO_4^{3-}$ has been improved in the last years of operation. The elimination COD remained relatively consistent between the initial and present period of operation. The finding confirms the high efficiency in the long-term operation of municipal wastewater treatment. Thus, it can serve as a suitable solution for small communities, especially in arid climate areas.

**Key words:** effectiveness, long-term performance, wastewater garden, wastewater treatment

## HIGHLIGHTS

- The papers present results from the long-term performance of wastewater gardens
- The average removal rates of TSS were greater than 90% over 15 years.
- The average removal rates of DCO, $BOD_5$, $NO_2^-$, $NO_3^-$ and $PO_4^{3-}$ showed an ascending trend over 15 years.
- The comparison between the first and recent years of operation shows that WWG is effective in the long run.

## GRAPHICAL ABSTRACT



## 1. INTRODUCTION

Water resources play an important role in all development activities, which depend on the quantity and quality of available water (Tortajada 2020). Population growth leads to larger wastewater volumes with complex compositions (Yildiz 2012). The predominant type of wastewater is municipal wastewater (MWW), characterized by low-strength wastewater and low concentrations of organic matter and suspended solids (Van Lier 2008). Various MWW treatment methods are employed in wastewater treatment technologies, including trickling filters (TF), activated sludge (AS) processes, oxidation ponds (OP), and upflow anaerobic sludge blankets (UASB). These treatment techniques effectively eliminate contaminants in wastewater, ensuring their safe disposal or reuse (Rajagopal *et al.* 2019; Yang *et al.* 2019). Nevertheless, conventional wastewater treatment technologies can have expensive financial implications, and infrastructure requirements that are less feasible for large-scale application in rural areas (Chen *et al.* 2014).

Modern advancements in wastewater treatment have progressed to tackle diverse pollutants and ecological issues. Despite their persistent popularity owing to their dependable nature, conventional activated sludge (CAS) mechanisms encounter obstacles in eliminating some of the newly identified contaminants (Ávila *et al.* 2014). Membrane bioreactors (MBRs) present enhanced effluent quality and reduced spatial requirements in comparison to CAR$_S$, albeit with increased capital and operational expenditures (Krzeminski *et al.* 2017). Advanced oxidation processes (AOPs) have exhibited potential in decomposing persistent organic substances and pharmaceuticals, with ozonation proving notably efficient (Miklos *et al.* 2018). Anaerobic membrane bioreactors (AMBRs) have garnered interest because of their superpower performance and the opportunity to supply biogas, especially in hotter weather regions (Maaz *et al.* 2019). Nature-based remedies, such as constructed wetlands (CWs), present sustainable options for small-scale purposes and have demonstrated significant effective disposal of pollutants, including microplastics (Justino *et al.* 2023). The selection of a treatment approach is influenced by several factors, such as the characteristics of the influent, regulatory standards, and local circumstances, with hybrid systems frequently offering the most comprehensive resolution (Nishat *et al.* 2023). Therefore, it is important to prioritize cost-effective and efficient alternative technologies for wastewater treatment, particularly in developing regions. In this context, CWs have garnered significant attention as a viable option for wastewater treatment due to their lower cost, reduced operational needs, and minimal maintenance requirements (Cabred *et al.* 2019).

CWs offer a promising solution for treating wastewater in a sustainable and economically feasible manner. CWs are artificial systems that harness a combination of biological, physical, and chemical processes of wastewater treatment (Mojiri *et al.* 2017). They can be classified based on several factors. Firstly, the vegetation type plays a role in classification, with options such as emergent, submerged, floating-leaved, and free-floating plants. Secondly, wetland hydrology distinguishes between free water surface flow and subsurface flow systems. Furthermore, subsurface flow wetlands can be classified based on the flow direction, which can be either vertical or horizontal (Zhang *et al.* 2014). The performance assessment of HFCW demonstrates high effectiveness in removing organic matter and suspended solids (Jamwal *et al.* 2021).

Numerous studies have demonstrated the notable effectiveness of CWs systems cultivated with diverse plant species in arid conditions (Bebba *et al.* 2019; Yahiaoui *et al.* 2020; Zorai *et al.* 2022, 2023). The growth media used in these systems provide physical support for plant growth but also offer additional surfaces for biofilm development, facilitate nutrient adsorption, and enhance sedimentation and filtration of pollutants (Priya & Brighu 2013).

These efficiencies remain consistent throughout the year and are not influenced by seasonal variations or the duration of operation (Vymazal 2011). The HFCW systems have shown high efficiency, which has led to a decrease in the concentration of pollutants over time (Vymazal 2019). Nevertheless, there is a scarcity of comprehensive research focusing on extended performance (exceeding 10 years), with only a handful of studies published, such as the work by Brix *et al.* (2007).

In Algeria, CWs systems are relatively new and have not yet been implemented in Algerian cities and rural areas, Except for three stations built and operated in arid and extremely arid areas. Among these stations, the Temacine wastewater garden (WWG) station is one that we have studied. The present study focused on monitoring the pollutant removal from wastewater using a WWG, planted in *Juncus maritimus*, *Typha angustifolia*, *Cyperus papyrus*, and *Canna indica*. This research aimed to assess the long-term performance of WWG applied to domestic wastewater treatment for a community of about 150 people, focusing on removing organic matter and nutrients, compared to the initial operational phase. The findings enhance comprehension of pollutant removal mechanisms in WWG over an extended period of operation. The performance was assessed over 15 years based on several physicochemical parameters, including temperature, pH, EC, DO, TSS, $BOD_5$, COD, $NO_2^-$, $NO_3^-$, and $PO_4^{3-}$.

Given the lack of widespread use of artificial wetland water treatment technology in Algeria, we find only three such plants in this region and have not yet touched on it in arid areas, this research makes a unique and fundamental contribution. It provides unprecedented data on the efficiency and durability of global water collections under extreme climatic conditions, which is crucial for the improvement and implementation of such technologies in similar environments where water resources are scarce and limited.

## 2. MATERIALS AND METHODS

### 2.1. The study area

Researchers established the first CWs in the country, called the WWG, in the rural community of Temacine, Algeria in 2007 (N 33° 01′ latitude, E 6° 01′ longitude, and elevation 586 m). Their purpose was to create a sustainable solution for developing regions lacking water resources. The WWG was a pilot project completed through cooperation between the government, scientists, and local leaders in Temacine. This arid region provided a challenging setting with extremely hot and dry summers along with powerful winds intensifying the heat. By leveraging natural processes to purify wastewater, the WWG overcame these harsh environmental conditions. In monitoring the performance of this novel system in its initial years, the research aims to demonstrate the enduring potential of WWG for water treatment in remote desert communities in the long term. This study could pave the way for sustainable wastewater management strategies tailored to rural developing regions around the world. Overall, the current study highlights an ecological project in Algeria that held promise as a model for affordable and sustainable wastewater treatment in water-scarce regions.

### 2.2. Description of the components of the WWG

The WWG (Figure 1(b)) in Temacine, Algeria was designed based on established guidelines for subsurface flow wetlands (Reed *et al.* 1995). The CW covers a 400 $m^2$ crescent-shaped area; the total volume is 260 $m^3$ and the

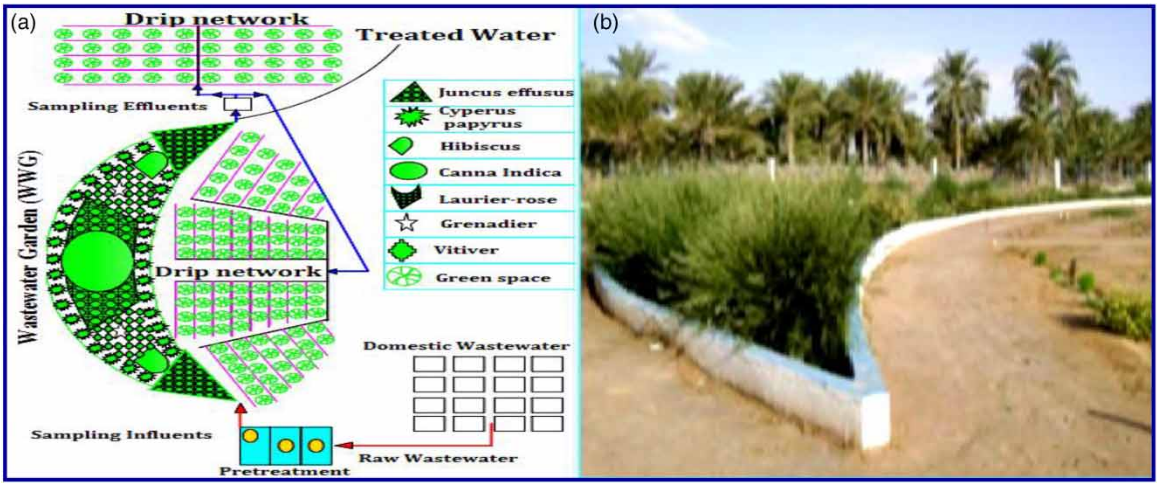


**Figure 1** | General WWG constructed wetlands system scheme.

flow is horizontal subsurface to treat 15 $m^3$/day of wastewater from a population of 150 people. Pretreatment occurs in a 37.5 $m^3$ septic tank (2.5 day retention time), followed by filtration through natural fiber filters before entering the CW. The water depth is 50 cm, covered by substrate contains 60 cm of gravel planted with 941 specimens across 21 wetland plant species tolerant of saturated conditions, including oleander, *Hibiscus*, *Canna*, and *Papyrus*, by integrating wetland processes, with wetland hydrology (soils, microbes, and plants) (Vymazal 2009). The WWG provides primary and secondary treatment of MWW. The sustained performance of the system demonstrates the viability of CWs as an affordable and ecological wastewater treatment solution for water-scarce rural communities. The process flow of the system is as follows: **Municipal wastewater → Primary treatment in septic tank → Gravity flow → Constructed wetland → Gravity flow → Drip irrigation network** (Figure 1(a)).

### 2.3. Water sampling and analysis

Samples were collected on a monthly basis and subsequently analyzed in the laboratory of the water treatment plant in Touggourt Province. Various parameters, including temperature ($T$, °C), pH, electrical conductivity (EC, mS/cm), and dissolved oxygen (DO, mg/L), were measured *in situ* using a portable multimeter instrument model HI9829. Moreover, the standards method (APHA 2012) was used in the analysis of $BOD_5$ (mg/L), COD (mg/L), TSS (mg/L), nitrite ($NO_2^-$, mg/L), nitrate ($NO_3^-$, mg/L), and $PO_4^{3-}$ (mg/L). All samples related to the years mentioned in the study were obtained from the water analysis laboratory in Touggourt Province.

### 2.4. Calculations and statistical analysis

The removal efficiency (RE) of each variable is calculated corresponding to the following equation (Marzec *et al.* 2018).

$$\mathrm{RE}\ (\%) = \frac{C_\mathrm{i} - C_0}{C_\mathrm{i}} \times 100 \tag{1}$$

where $C_\mathrm{i}$ and $C_\mathrm{o}$ are the inlet and outlet concentrations expressed in mg/L, respectively.

We employed a one-way analysis of variance (ANOVA) to assess any notable statistical distinctions in the effectiveness of water treatment between the first and last years. To investigate these differences, an ANOVA test was utilized. Mean comparisons were performed using *Tukey's test* at a significance level of $\alpha = 0.05$. The ANOVA was carried out using the Origin software (2018).

## 3. RESULTS AND DISCUSSION

### 3.1. Influent wastewater characteristics

Tables 1 and 2 show the influent and effluent wastewater characteristics for the 2007–2008 and 2018–2022 periods based on spot sampling approximately all month. Temperature, pH, EC, and DO are important

**Table 1** | Mean concentrations (in and out) in the first years of operation, and overall removal efficiency of water quality parameters along the WWG system

| | | First years of operation: Mean (2007 and 2008) | | | | |
|---|---|---|---|---|---|---|
| **Parameters** | **Unit** | **Number of samples** | **In** | **Out** | **RE %** | **Effluent discharge limit JORA** |
| $T$ | °C | 24 | 27.35 | 23.1 | / | 30 |
| pH | / | 24 | 7.61 | 7.99 | / | 6.5–8.5 |
| DO | mg/L | 24 | 0.17 | 0.87 | / | – |
| TSS | mg/L | 24 | 517.89 | 28.42 | 94.60 | 30 |
| COD | mg/L | 24 | 469.19 | 66.20 | 85.38 | 120 |
| $BDO_5$ | mg/L | 24 | 328.99 | 55.92 | 82.49 | 30 |
| $NO_2^-$ | mg/L | 24 | 0.821 | 0.416 | 47.11 | – |
| $NO_3^-$ | mg/L | 24 | 6.27 | 2.10 | 49.28 | 30 |
| $PO_4^{3-}$ | mg/L | 24 | 14.15 | 3.92 | 68.05 | – |

**Table 2** | Mean concentrations (in and out) in the recent years of operation, and overall removal efficiency of water quality parameters along the WWG system ($n = 60$)

| **Months** | **WW** | **$T$ (°C)** | **pH —** | **DO (mg/L)** | **TSS (mg/L)** | **COD (mg/L)** | **$BOO_5$ (mg/L)** | **$NO_2^-$ (mg/L)** | **$NO_3^-$ (mg/L)** | **$PO_4^{3-}$ (mg/L)** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Jan** | **In** | 18.28 | 7.34 | 0.59 | 300.7 | 181.2 | 85 | 0.026 | 3.43 | 3.58 |
| | **Out** | 16.86 | 7.04 | 2.74 | 15.45 | 22.10 | 7.8 | 0.010 | 0.29 | 0.39 |
| **Feb** | **In** | 18.68 | 7.14 | 0.75 | 210.3 | 22.10 | 116 | 0.035 | 0.3 | 4.92 |
| | **Out** | 16.42 | 6.88 | 2.20 | 14.48 | 12.18 | 8 | 0.009 | 0.11 | 0.44 |
| **Mar** | **In** | 19.58 | 7.33 | 0.54 | 202.7 | 169.4 | ND | 0.04 | 0.55 | 2.23 |
| | **Out** | 17.60 | 7.06 | 2.50 | 19.88 | 30.02 | ND | 0.019 | 0.14 | 0.34 |
| **Apr** | **In** | 22.42 | 7.20 | 0.47 | 155.0 | 178.2 | 128 | 0.03 | 0.48 | 5.28 |
| | **Out** | 22.10 | 6.93 | 2.53 | 16.04 | 26.50 | 11.6 | 0.014 | 0.21 | 0.37 |
| **May** | **In** | 23.62 | 7.17 | 0.59 | 158.5 | 174.4 | 117 | 0.035 | 15.5 | 5.28 |
| | **Out** | 22.68 | 7.00 | 2.83 | 20.32 | 30.14 | 9.3 | 0.015 | 1.6 | 0.34 |
| **Jun** | **In** | 24.23 | 7.30 | 0.66 | 117.9 | 197.4 | 113.2 | 0.094 | 12.2 | 7.01 |
| | **Out** | 24.24 | 6.97 | 2.52 | 18.40 | 34.50 | 7.4 | 0.024 | 2.9 | 0.34 |
| **Jul** | **In** | 26.48 | 7.39 | 0.70 | 151.8 | 165.8 | 99 | 0.111 | 22.2 | 0 |
| | **Out** | 24.16 | 6.91 | 2.10 | 13.66 | 33.26 | 12.8 | 0.022 | 3.6 | 0 |
| **Aug** | **In** | 26.60 | 7.30 | 0.36 | 167.7 | 191.4 | 84.2 | 0.054 | 19.7 | 16.1 |
| | **Out** | 23.98 | 6.89 | 2.05 | 15.90 | 38.98 | 14.9 | 0.02 | 0.8 | 0.11 |
| **Sep** | **In** | 23.68 | 7.41 | 0.62 | 178.0 | 193.4 | 78.1 | 0.054 | 0.2 | 18.3 |
| | **Out** | 22.06 | 6.88 | 1.23 | 12.60 | 24.44 | 18.4 | 0.006 | 0.02 | 0.13 |
| **Oct** | **In** | 23.66 | 7.32 | 0.90 | 281.6 | 185.2 | 73 | 0.037 | 32.6 | 19.4 |
| | **Out** | 20.48 | 6.99 | 2.50 | 14.60 | 28.21 | 8.8 | 0.009 | 5.7 | 0.20 |
| **Nov** | **In** | 21.02 | 7.44 | 0.85 | 231.2 | 208.0 | 103.2 | 0.049 | 21.7 | 20.3 |
| | **Out** | 20.48 | 6.98 | 2.35 | 13.34 | 29.22 | 9.4 | 0.007 | 6.7 | 0.109 |
| **Dec** | **In** | 19.74 | 7.36 | 0.33 | 125.4 | 221.8 | 108.4 | 0.052 | 30.5 | 22.5 |
| | **Out** | 17.48 | 6.93 | 2.88 | 17.20 | 17.98 | 8.4 | 0.031 | 5.2 | 0.32 |
| **Mean** | **In** | **22.23** | **7.31** | **0.62** | **190.0** | **184.0** | **92.09** | **0.051** | **13.28** | **10.40** |
| | **Out** | **20.71** | **6.95** | **2.38** | **15.98** | **27.29** | **9.733** | **0.015** | **2.272** | **0.257** |
| | **RE %** | / | / | / | **90.76** | **85.12** | **89.43** | **66.87** | **94.74** | **94.74** |

parameters for pollutant removal. The water temperature at the WWG inlet ranged from 27.35 °C in the first years to 22.23 °C in recent years of operation. The influence of temperature is of great importance in shaping the dynamics of wetland processes, especially with microbial reactions; the optimal environmental conditions supporting the growth of plants and microorganisms typically fall within the temperature range of 20–35 °C (Kadlec & Reddy 2001). In Algeria, the established guideline for wastewater discharge is 30 °C (JORA 2006).

The pH values (7.61 in the first years and 7.31 in the recent years of operation). The optimal pH required to promote nitrification and denitrification processes is ($7.5 < \text{pH} < 8.0$) (Vymazal 2007), and the presence of the treatment bacteria ($4.0 < \text{PH} < 9.5$) (Gupta *et al.* 2016). Results of the pH values respect the effluent discharge limit in Algeria at 6.5–8.5 (JORA 2006).

During the current investigation, in the influent wastewater, the DO level was measured to be (0.17 mg/L in the first years of operations and 0.62 in the recent years of operations), as illustrated in Tables 1 and 2. The average concentration observed in the initial wastewater specimen was notably minimal due to the DO utilization of organic decomposition and nitrification (Kadlec & Knight 1996). TSS, COD, and $BOD_5$ varied from 517.89, 469.19, and 328.99 mg/L in the first years to 190, 184, and 92.09 mg/L in the recent years, respectively. The coefficients of biodegradation ($COD/BOD_5$) during the study period were 1.42 and 1.99 in the first and recent years, respectively. Consequently, this type of wastewater is easily biodegradable through biological mechanisms (with domestic wastewater K being less than 3) (Metcalf 2003).

### 3.2. First year's RE

The results derived from the initial years of WWG operation (Table 1) showed considerable promise. In 2007, WWG successfully eliminated more than 94% of the TSS, thus exemplifying their efficacy in water purification. This favorable trend continued in 2008, with an even higher elimination rate of 94.4%. The presence of vegetation and substrate in WWG enhances the elimination of TSS through processes such as deposition, interception, and filtration, as highlighted by Herath & Vithanage (2015).

As a result, WWG treatment technology has emerged as a viable and cost-effective option. WWG effectively manages the organic matter disposal, particularly COD and $BOD_5$. In the first years of operation (2007), approximately 85.38% of COD were aptly disposed of appropriately. This encouraging pattern persisted in 2008, with a disposal rate of 82.49%. Concerning $BOD_5$, WWG showcased impressive outcomes. The clearance rate ranged from 94.4 to 87%, further highlighting their effectiveness in eliminating biological contaminants. This affirmative outcome endured in 2008, further underscoring the substantial purifying effect of WWG (Table 1). Oxygen released through plant roots supports aerobic microorganism growth, facilitating the oxidation of organic compounds (Brix & Schierup 1990). Aerobic biodegradation is often the primary pathway through which $BOD_5$ is removed from the upper layers of WWG (Kadlec & Wallace 2008). In deeper or more saturated zones of WWG, anaerobic processes such as fermentation and methanogenesis can occur, contributing to COD reduction (Vymazal 2007). Especially to the breakdown of complex organic matter (Faulwetter *et al.* 2009).

The prescribed threshold for the organic element in the sewage management infrastructure in Algeria has been established at 35 mg/L of TSS, 120 mg/L of COD, and 35 mg/L of $BOD_5$ (JORA 2006). In the initial phases, the mean yearly discharge adhered to the prevailing domestic guidelines.

The WWG displayed a certain degree of efficacy in $NO_2^-$ removal, albeit with relatively lower removal rates when compared to other parameters. In the year 2007, the $NO_2^-$ removal stood at 77%, indicating a moderate level of reduction. This pattern persisted in 2008, with a slightly lower removal rate of 72.6%. As for the $NO_3^-$ removal, the yield was comparatively lower during the same time frame. In 2007, the WWG accomplished a yield of 42.3%, implying a partial decrease in nitrate levels in the water. However, there was an improvement in 2008, with the removal yield reaching 60%. Although the yield of $NO_3^-$ removal remained relatively modest, it signifies progress in the $NO_3^-$ removal concentrations. Nitrogen removal involves ammonia oxidation to $NO_2^-$ by ammonia-oxidizing bacteria and $NO_2^-$ oxidation to $NO_3^-$ by nitrite-oxidizing bacteria (Vymazal 2007). This process converts $NO_3^-$ to nitrogen gas which is then released into the atmosphere. It occurs in anoxic zones of the WWG and is carried out by denitrifying bacteria (Kadlec & Wallace 2008). Wetland plants can assimilate certain amounts of nitrogen, although this route is typically considered less prominent when compared to the role of microbial processes (Brix 1997). The anaerobic ammonium oxidation process can stimulate nitrogen removal in anoxic zones (Zhu *et al.* 2014).

The phosphate compounds removal, specifically orthophosphates, in the wastewater treatment plant (WWG) during its initial years of operation (2007, 2008) demonstrated a relatively modest performance of 68.05%. The rates of removal suggest an enhancement in reducing the concentrations of phosphate compounds present in the wastewater. $PO_4^{3-}$ can be absorbed by soil particles and WWG media (Vymazal 2007), it is assimilated to a lesser extent by WWG vegetation (Brix 1997), and microorganisms can also incorporate into their biomass (Reddy *et al.* 1999).

### 3.3. Recent year's RE

After 15 years in operation, we have gathered laboratory analyses spanning the most recent 5 years (2018, 2019, 2020, 2021, and 2022) and conducted calculations for the averages of physical and chemical parameters (Table 2). To determine the influence of time on the productivity and effectiveness of the Temacine WWG in this study, we compared these average values with the corresponding means from the initial years of operation.

#### 3.3.1. TSS removal

The findings suggest a substantial impact on numerous studied parameters, as we observed significant discrepancies between the initial and final years of operation. The average RE of TSS (Figure 2) decreased from 94.60% in the first years to 90.76% in the last years of operation ($F = 0.004$; $p < 0.05$). Despite the high effectiveness of TSS removal (95.18, 85.74, 85.74, and 88.92%) throughout 2018–2022, the WWG cannot guarantee a consistent and permanent TSS RE. The results are similar to those reported by Mustafa *et al.* (2009).

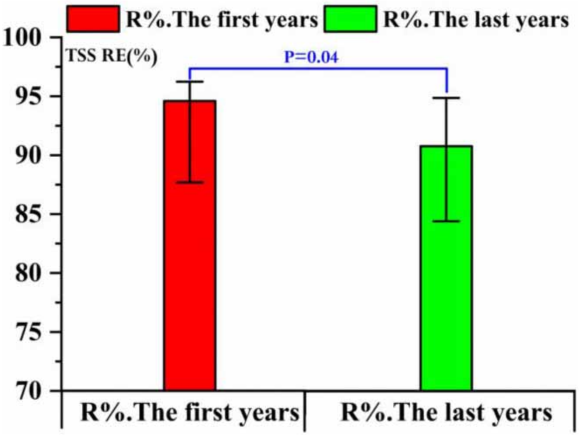


**Figure 2** | Comparison of TSS removal efficiency in the first (2007–2008) and last (2018–2022) years of operation.

One of the most effective processes for eliminating TSS is physical processes, such as sedimentation and filtration, based on aerobic and anaerobic microbial decomposition within the substrate (Avila *et al.* 2014). Due to the deposition of TSS at the bed's bottom, a layer gradually forms and increases in size over time, which enhances the probability of soil media particles settling into the insulating layer (Mucha *et al.* 2017) and becoming captured during sampling (Rahman *et al.* 2022), raising the values of their concentrations. While TSS removal showed only a slight effect, the obtained results remain highly acceptable compared to some previous studies (Singh & Vaishya 2022). Finally, the TSS removal in CWs continues to be affected over time. Moreover, the findings indicate that WWG can adequately meet the regional discharge criteria of 35 mg/L for TSS for a long-term period (JORA 2006).

#### 3.3.2. $BOD_5$ and COD removal

The average RE of $BOD_5$ and COD for the first and last years is shown in Figure 3(a) and 3(b). The efficiency of $BOD_5$ and COD in the first year is 82.49 and 85.38%, respectively. The last efficiency of $BOD_5$ and COD is 89.43 and 85.12%, respectively. In recent years, $BOD_5$ RE has improved ($F = 0.0018$; $p < 0.05$) compared with the first years of operation. On the other hand, there were no significant differences in COD RE ($F = 0.88$; $p > 0.05$) between the first and last years. The results from this study are similar to those reported by Vymazal (2019). However, it is essential to note that the WWG system complies with Algerian standards of 120 mg/L (JORA 2006), indicating its effectiveness in treating wastewater within the context of these guidelines for a long-term period.

The $BOD_5$ removal is due to the presence of various plant species, attributed to oxygen release through their roots, which facilitates the growth of aerobic microorganisms (Haddis *et al.* 2020; Kataki *et al.* 2021). Plants can metabolize some organics, but microbial processes are more essential for organic matter removal (Brix 1997; Stottmeister *et al.* 2003). The efficiency of COD removal in the first year of operation is often lower; the efficiency continues to increase over time and reaches its peak levels in subsequent years due to successive improvements in

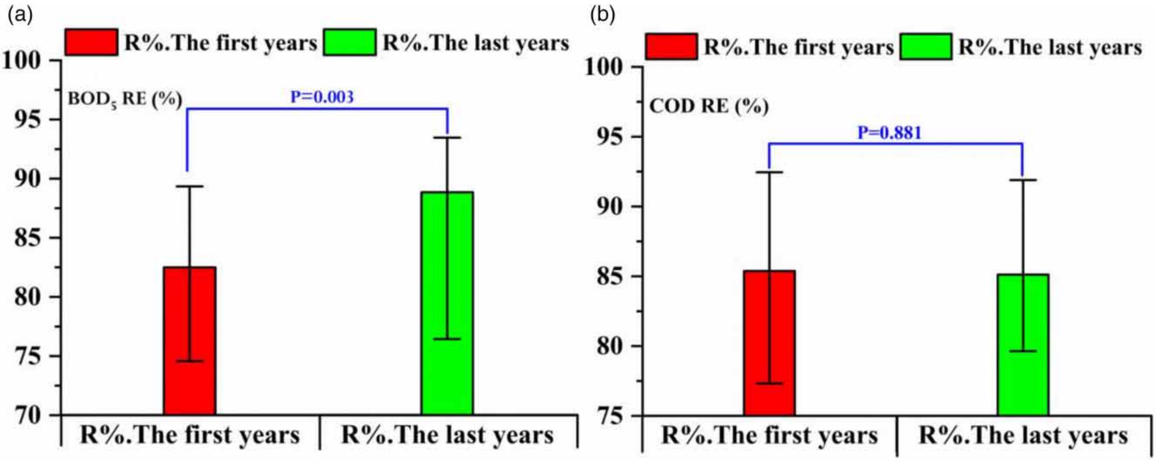


**Figure 3** | Comparison of (a) $BOD_5$ and (b) COD removal efficiency in the first (2007–2008) and last (2018–2022) years of operation.

the system's biology (Stefanakis & Tsihrintzis 2012). The system has demonstrated a consistent COD value from the beginning of its operation. The average values of all measurements are comparable to those obtained in the last years of operation. The results reveal that the trend of COD elimination has remained constant since the first years of operation. The results from this study are similar to those reported by Mucha *et al.* (2017). In contrast, $BOD_5$ showed an increase in removal rates, due to a long period that helped in the deterioration of more resilient organic compounds (Vymazal 2019). For $BOD_5$, the effluent value was within the recommended range (35 mg/L) of the prevailing domestic guidelines (JORA 2006).

### 3.3.3. Nutrients removal ($NO_2^-$, $NO_3^-$, and $PO_4^{3-}$)

The performance of the WWG system in eliminating $NO_2^-$ and $NO_3^-$ is showcased in Figure 4(a) and 4(b). The average removal rate of $NO_2^-$ and $NO_3^-$ throughout the preceding 5 years was 66.87 and 94.74%. In recent years, $NO_2^-$ and $NO_3^-$ RE has improved ($F = 0.0057$; $p < 0.05$) and ($F = 7.89\ 10^{-6}$ $p < 0.05$) compared with the first years of operation, respectively. The average RE of $PO_4^{3-}$ (Figure 5) increased from 68.05% in the first years to 94.74% in the last years of operation ($n = 55$; $F = 8.27\ 10^{-5}$; $p < 0.05$).

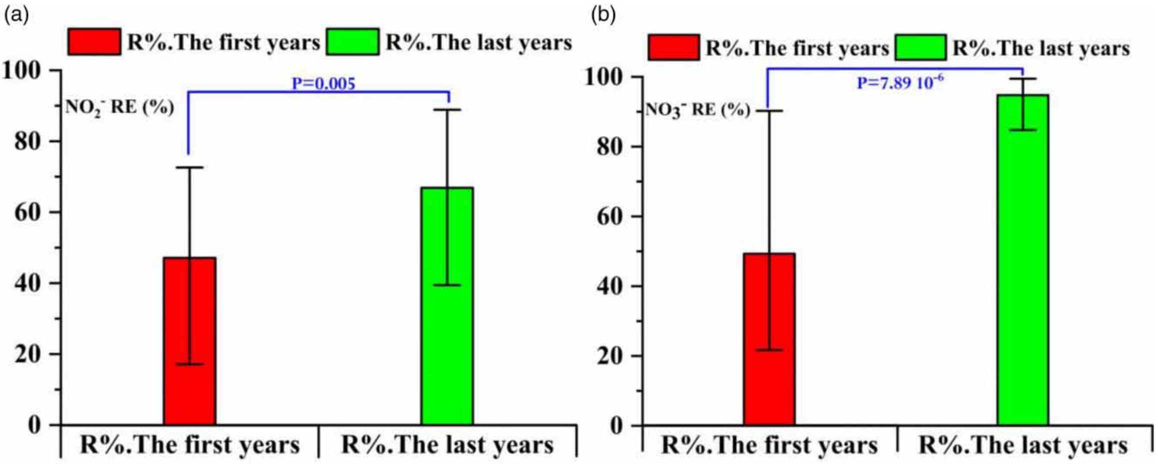


**Figure 4** | Comparison of (a) $NO_2^-$ and (b) $NO_3^-$ removal efficiency in the first (2007–2008) and last (2018–2022) years of operation.

In CWs, most $NH_4^+$ can be converted to $NO_3^-$, leading to elevated $NO_3^-$ levels in treated discharge if denitrification is inadequate (Öövel *et al.* 2007). The decline in the elimination of $NO_3^-$ in the initial years was likely associated with a rapid nitrogen buildup during the initial phase of operation. The removal of $NO_3^-$ is based

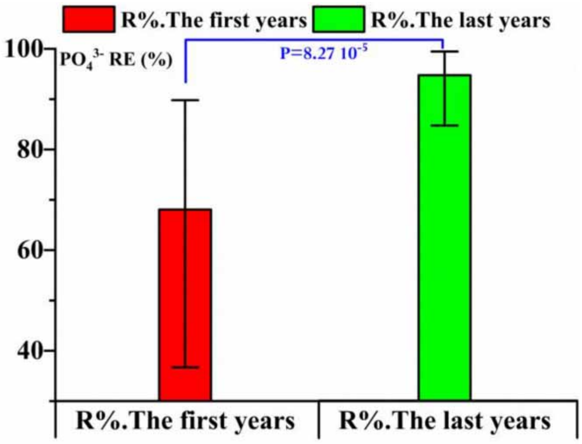


**Figure 5** | Comparison of $PO_4^{3-}$ removal efficiency in the first (2007–2008) and last (2018–2022) years of operation.

on denitrification. The effectiveness of nitrite elimination was likely the highest in recent years due to the organic carbon accumulation and facilitated denitrification (Mitsch & Gosselink 2015). The long-term operation of the WWG has significantly reduced wastewater nutrient levels and the risk of nutrient pollution compared to background values. Wetland operations led to significant changes in the structure of microbial communities, which has led to a high disposal of nutrients (Xiong *et al.* 2023). RE is dependent on temperature, with nutrient reaction rates increasing with higher temperatures. The removal rates of nutrients and COD are positively correlated with influent concentration.

The removal of $PO_4^{3-}$ is positively correlated with the hydraulic loading rate (HLR), suggesting that a higher HLR can improve the purification efficiency of $PO_4^{3-}$ (Pu *et al.* 2023). Higher influent concentrations of these pollutants result in higher removal rates in the constructed wetland system. In Temacine WWG, the high $PO_4^{3-}$ removal, could be explained by the plant's uptake or attributed to adsorption on the substrate medium (gravel). In addition, microbial populations residing in submerged roots can also assimilate $PO_4^{3-}$ (Stefanakis 2022).

The results suggested that phosphorus retention in the substrate was the main mechanism for TP removal during the first 3 years of operation (Vohla *et al.* 2007), while plant uptake was the main responsible for phosphorus removal (Shen *et al.* 2022).

### 3.4. Comparison between first and recent years of operation

Based on the previous results (Table 3), a comparison of the WWG system performance between the first and last years of operation can be made:

**Table 3** | Statistical comparison between the first and last years

**Comparison between first and recent years of operation**

| | First years of operation (2007–2008) | Final years of operation (2018–2022) |
|---|---|---|
| TSS | 94.60* | 90.76 |
| COD | 85.00 | 85.12 |
| $BOD_5$ | 82.49 | 89.43* |
| $NO_2^-$ | 47.11 | 69.85* |
| $NO_3^-$ | 67.38% | 82.88* |
| $PO_4^{3-}$ | 68.05% | 97.52* |

Significant difference: $*p < 0.05$.

In summary, while TSS RE declined from the initial operational years, the system demonstrated improved removal rates for $BOD_5$, $NO_2^-$, $NO_3^-$, and $PO_4^{3-}$ in the 2018–2022 periods compared to 2007–2008. The consistency in COD removal over the lifetime of operations also speaks to the sustained performance of the WWG system. The results validate the solution as an effective long-term wastewater treatment method for small communities in arid climates. The functional effectiveness of the sewage treatment system exhibited significant alterations between the early years (2007–2008) and the concluding years (2018–2022) of functioning. Overall TSS elimination capability marginally declined from 94.60 to 90.76% ($p < 0.05$), a phenomenon that might be ascribed to aging infrastructure or variations in influent attributes (Zhang *et al.* 2014). The COD removal exhibited a consistent level, experiencing a slight rise from 85.00 to 85.12%. $BOD_5$ removal improved significantly from 82.49 to 89.43% ($p < 0.05$), suggesting enhanced biological treatment processes over time (Zhu *et al.* 2014).

The most significant enhancements were noted in the nutrient removal, as the efficiency of eliminating $NO_2^-$ increased from 47.11 to 69.85% ($p < 0.05$), $NO_3^-$ removal improved from 67.38 to 82.88% ($p < 0.05$), and $PO_4^{3-}$ removal rate from 68.05 to 97.52% ($p < 0.05$). These improvements in nutrient removal align with the global trend toward more stringent effluent standards and the implementation of advanced nutrient removal technologies. The marked enhancement in $PO_4^{3-}$ removal, in particular, indicates the likely adoption of chemical precipitation or advanced biological phosphorus removal processes (Nguyen *et al.* 2022).

## 4. CONCLUSIONS

These results indicate that WWG plays a key role in removing and improving the overall quality of treated water. Such outcomes are encouraging, and further implementation and research on WWGs can lead to more effective and sustainable water treatment solutions.

The nutrient removal rates are influenced by various factors including WWG-specific conditions, wastewater composition, and operational parameters. Efforts to further optimize the WWG performance of sewage gardens in nitrite and nitrate disposal can lead to improved results over time.

Although the disposal and removal rates for nitrite and nitrate were not as high as those for other substances, the overall positive performance of sewage gardens in treating suspended matter, organic substances, and biological demand for oxygen indicates their potential as effective water treatment solutions. Ongoing research and refinement of sewage garden systems can contribute to enhancing their capability to address a broader range of pollutants, including nitrite and nitrate, to achieve even higher removal rates and further improve water quality.

The WWG in Temacine, Algeria, is a remarkable example of how the nature solutions implementation can address pressing environmental and health challenges. Through the efficient use of plants and natural processes, the project has demonstrated its ability to treat wastewater effectively, conserve water resources, and empower local communities. Despite encountering certain challenges, the garden continues to operate; offering hope for a future where sustainable wastewater management is a reality for all.

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## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

## CONFLICT OF INTEREST

The authors declare there is no conflict.

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