Eco-Technological Treatment of Domestic Organic Pollution byTypha angustifolia in the Arid Zones of Southern Algeria

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Abstract

The presence of plants in aquatic ecosystems such as lakes, swamps, and ponds is a vital biological phenomenon, as it results from natural physiological processes dependent on the availability of essential elements in nature: water, light, and atmospheric carbon dioxide. These elements are indispensable for the production of organic matter through the process of photosynthesis. However, this process must remain balanced, as excessive nutrient enrichment (eutrophication) can negatively affect the growth of aquatic plants and eventually lead to their decline or death. In our year-long study conducted in 2024, we investigated the capacity of the plant *Narrowleaf cattail* (*Typha angustifolia*) to treat domestic wastewater in the city of Touggourt, southern Algeria. The focus was on organic pollutants, namely Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), and Biological Oxygen Demand over five days (BOD_5). The plant demonstrated remarkable purification efficiencies, which were recorded as follows: 95.23% for TSS, 82.59% for COD, and 85.51% for BOD_5. Consequently, the overall purification rate for organic pollution reached 87.77% a result that reflects the high potential of *Narrowleaf cattail* in reducing such contaminants. In general, the findings clearly demonstrate the effectiveness of this plant species in removing organic and nitrogenous pollutants from domestic wastewater, particularly in arid and semi-arid climatic regions.

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1. Introduction

The treatment of domestic wastewater in plant ponds for the removal of organic pollution mainly depends on the design of the plant ponds, the hydraulic residence time (HRT), and the hydraulic load, as the duration of water retention in the ponds is closely related to the hydraulic load content. The percentage of organic pollutant removal is generally proportional to the contact time. Most often, the performance efficiency of plant ponds is compared to the theoretical residence time assumed during the pond design phase. However, previous studies have shown that this estimated purification yield of organic pollution significantly differs from the actual performance of the plants, as observed in filtration systems implemented in West and Central Africa. The levels of sanitation vary according to different living standards, as they significantly affect the concentrations of organic pollutants. These concentrations are generally low in areas with high living standards (due to high water consumption) and are high and concentrated in areas with modest or medium living standards (due to low water consumption). Here, it is natural to ensure compatibility between organic load, hydraulic load, and residence time in order to achieve clear results in our study, which was conducted throughout 2024 in the city of Touggourt, southern Algeria. For this purpose, and in order to build an experimental station to treat the domestic wastewater of the city of Touggourt using a hydropower-based plant system, we have defined the design parameters based on mathematical equations determined by experimental mathematical methods. This experimental method relies on the loads of organic pollutants assumed to be present at the station's inlet and the removed loads assumed at the outlet of the experimental station, while the rational method is based on the kinetics of decomposition of organic pollutants by the studied plant (*Typha angustifolia*). By combining both methods, we were able to determine the maximum permissible loads at the station's rotor with respect to BOD_5(biological oxygen demand), COD (chemical oxygen demand), and TSS (total suspended solids). We were also able to estimate the theoretical purification efficiency for each organic pollutant, which was not less than 70%. Accordingly, we proposed the establishment of a hybrid treatment station consisting of three basins: two vertical-flow basins and one horizontal subsurface-flow basin. This proposed model for carbon pollution removal in aquaculture is very similar to the piston flow model adopted by many authors, including the International Water Association (IWA) [1][2][3]. It is also important to highlight the ability of this plant's roots to absorb these pollutants through the activity of anaerobic bacteria present at the root level. These microorganisms transform organic and bio-organic compounds into simple sugar substances, which are subsequently utilized for their biological and physiological growth. Is the model we proposed in this experiment capable of removing organic pollutants? What are the purification rates achieved by this plant for these pollutants? Can it be adopted as a final, natural, and environmentally friendly solution? These are the questions we aim to answer through our one-year research study (2024).

2. Materials and Methods

2.1 Plant biotechnology processes and organic pollution treatment

Environmental reclamation relies on one of its fundamental pillars, namely the creation of wetland areas primarily composed of plants in general and green plants in particular. This is because they perform the natural *phytodegradation* of wastewater using an environmentally friendly and optimal technique that aims to replicate natural degradation processes. Through this method, we aim to save energy, reduce costs, and minimize water wastage. It is a method in which two living organisms—plants and bacteria—work together within shallow artificial wet basins filled with used water, whether industrial or domestic. These basins nourish aquatic plants that play a significant role in the natural and ideal reproduction of the wetland environment [4][5][6]. It is a technical system that has been studied and proposed for application [5][6] since the 1980s in Central Europe and the United States of America. In these regions, the system has demonstrated high efficiency in removing pollutants from wastewater in small residential communities by integrating chemical, biological, and physical processes in wet environments. This system effectively removes various pollutants from wastewater, such as Biological Oxygen Demand (BOD_5), Chemical Oxygen Demand (COD), and Total Suspended Solids **(TSS)**. In our study, we will monitor the temporal evolution of the concentrations of these pollutants in domestic wastewater in the Wilaya of Touggourt over the course of the year 2024 (from January to December). Additionally, we will calculate the purification efficiency for each pollutant using the Narrowleaf cattail (Typha angustifolia) plant within a hybrid vertical and horizontal constructed wetland model.

2.2 Representation of the study area (Touggourt):

The state of Touggourt is located in the southeast of Algeria (650 km from Algiers) at the geographical coordinates of 33.116° north latitude and 6.0783° east longitude. It is a newly established province since 26 November 2019, with an area of approximately 17,428 km² (see Fig.1) (Wikipedia; reddit.com; en.wikipedia.org; elmouchir.caci.dz). Touggourt is characterized by its dry desert climate and hot summers, according to the Koppen classification [7], with an average annual rainfall of approximately 82.45 mm. The temperature can reach up to 51°C in summer, while in the winter months (December–January), it may drop as low as 7°C [8]. Regarding wind patterns, the highest wind speeds are typically recorded during the spring season, from February to May.the

Population of the commune of Touggourt (2008): 39.409 inhabitants (ar.wikipedia.org) and the Population density of the commune in 2008: 182.44 inhabitants /km².The main activity of the population is usually agriculture in the oases, which primarily relies on palm cultivation associated with staple crops, extensive poultry and livestock farming **,** as well as some commercial activities, traditional industries, and light industries.

Fig .1 A map illustrating the geographical location of the city of Touggourt (Micrsoft – Encarta – **2006**) [35]

2.3 Description of the wastewater treatment plant

The wastewater treatment plant for the city of Touggourt is located in the Ben Youssed neighbourhood of the Tebesbest municipality, Touggourt district, on National Road Nº. 16. This plant occupies an area of 5 hectares and was constructed by the Water Resources Directorate of Ouargla Province in 1993. It began operations in late 1993 under the supervision of the National Sanitation Agency, with the aim of purifying the domestic wastewater of the city of Tourgoer. (Fig. 2)

Fig. 2 A satellite image identifying the location of the study area.

The experimental device consisted of three identical plastic boxes, each measuring 50 cm in length, 35 cm in width, and 20 cm in depth. The boxes were filled vertically with three distinct layers of substrate materials.

The first and second boxes were packed with coarse and fine gravel, respectively (Fig 4, panels 1 and 2). The coarse gravel had an average grain size of approximately 0.45 mm, while the fine gravel had a grain size of about 0.20 mm. In both boxes, narrow-leaved cattail (*Typha angustifolia*) was planted as the macrophyte species.

The third box was filled with washed and treated quartz sand, characterized by an effective grain size (D_e) ranging from 0.4 to 0.8 mm and a uniformity coefficient (Uc) ≤ 2 (Fig 4).

The three boxes were hydraulically connected in series using a 50-mm-diameter PVC pipe. Each box was equipped with a control valve to regulate the water transfer after a predetermined hydraulic retention time of 10 days. The overall configuration of the system is illustrated in Fig 4.

Fig. 3 Composition of the experimental setup. A: wastewater samples; B: sand layer sand; C: layer of coarse gravel; D: layer of fine gravel

Fig. 4 Experimental setup. 1: boxe with Typha angustifolia; 2: boxe with Typha angustifolia; 3: device after filling with Typha angustifolia

To treat domestic wastewater, a hybrid constructed wetland system with combined vertical and horizontal flow was employed. As illustrated in (Fig 5), the first and second units were irrigated using vertical flow mode through medium-capacity barrels (50 L per barrel), at a frequency of three irrigation cycles per month. The system then shifted to horizontal flow operation after an approximate retention period of seven days. When the third basin was filled, the water remained in it for an additional three days, resulting in a total hydraulic retention time of 10 days. Subsequently, samples were collected at the outlet of the third basin and transferred to the wastewater treatment laboratory for physicochemical analysis.

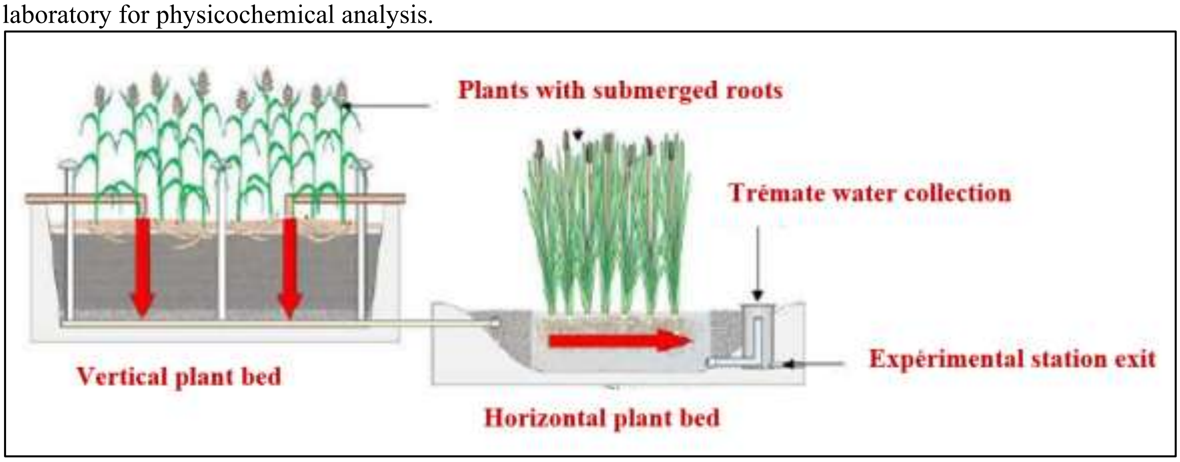

Fig. 5 A treatment pond with varied flow using plants.

Our study is based on a type of plant, Typha angustifolia, characterized by its narrow leaf surface area, which belongs to the following botanical classification (Fig. 6)

Fig. 6 Systematics of the narrow-leaved cattail Typha angustifolia

The specifications and characteristics of the study plant are summarized in Table 1

Table 1 specifications and characteristics of the study plant.

Kingdom	Subkingdom	Division	Class	Subclass	Order	Family	Genus	Species
Plantae	Tracheobionta	Magnoliophyta	Liliopsida	Commelinidae	Typhales	Typhaceae	Typha	angustifolia

As for the physicochemical salinity factors, they were measured using spectrometric devices, each parameter according to the specific device's usage method. The devices are referenced in Table 2.

Table 2 Desired physicochemical parameters.

Indicators	symbol	References	unit
Temperature	T	Direct reading by multi-parameter type HANNA H19829	°C
Acidity	pH	Lecture directe par multi-paramètre de type HANNA H19829	
Suspended matter	TSS	Membrane filtration	mg/L
Chemical Oxygen Demand	(COD)	Thermo reactor AL 125 Aqualitic	mg/L
Biochemical Oxygen Demand	BOD_5	Method with oxytops	mg/L

The study was conducted in the wastewater treatment laboratory at the Touggourt station. We took samples for one year (2024). From January to December. The samples were collected from the main drainage complex at the entrance after primary treatment and at the exit The experimental plant treatment station (WWTP), three times a month after the water has stayed for 10 days in the experimental basins as mentioned above, and they are analyzed immediately in the laboratory. Wastewater samples were stored in a refrigerator maintained at a temperature of 4 °C according to the general guidelines for the preservation and handling of samples [5][6][9]. The quantity of pollutants was determined according to the standard techniques for collecting and analyzing water samples established by the American Public Health Association [10] and Algerian standards [11]**.** We recorded the analysis results in Table 3 by calculating the average concentration value of each pollutant during the research year 2024.

Table 3. Obtained results in the laboratory for the pollutants targeted in the study year (2024).

		January	February	March	April	May	June	July	August	September	October	November	December
T °C	Station entrance	19,40	20,30	22,55	28,00	29,70	32,00	32,01	33,40	31,30	30,10	28,80	20,10
	Station exit	10,20	11,40	15,20	17,20	26,25	31,20	31,00	33,10	27,11	25,10	22,40	12,30
pH	Station entrance	7,80	7,50	8,10	7,90	7,40	7,96	7,70	7,00	7,88	7,60	7,65	7,30
	Station exit	6,70	6,60	6,80	6,48	6,58	6,60	6,85	6,80	6,90	6,70	6,75	6,65
TSS mg/L	Station entrance	510	315,5	610	521	480	581,01	250	230	370	290	234	278
	Station exit	29	17,90	26	28	25	23	12,5	12	24,5	25	26,5	20
(COD) mg/L	Station entrance	250	310	280	200	230	170	235	325	340	330	348	332
	Station exit	40	60	30	44	38	42	40	54	62	55	64	54
BOD_5 mg/L	Station entrance	220	225	228	238	118	178	108	156	211	248	292	236
	Station exit	30	20	36	27	21	34	28	28	36	31	29	36

3.1 Results and discussion

It is worth noting that the average concentrations of pollutants at the inlet of the experimental station (raw wastewater) and at the outlet (treated water) after a 10-day retention time were determined throughout the research period in 2024, in accordance with Equation (1). In addition, the purification rates for each pollutant were calculated over the same period using Equation (2), and the corresponding results are presented in Table 4.

$$\text{Average values} = \frac{\sum pollutant\ concertration\ each\ month}{12} \quad \text{…………………………. Equation 1}$$

$$\text{Purification rates} = \frac{C_{entrance} - C_{exit}}{C_{entrance}} x100 \quad \text{……………………………...... Equation 2}$$

knowing that $C_{entrance}$ is the concentration of the pollutant at the entrance of the experimental station and C_{exit} at its exit.

Table. 4 Mean values of pollutants in raw wastewater at the inlet of the experimental station and in treated water during the year 2024, including the removal efficiency for each parameter**.**

	T °C	pH	TSS mg/L	(COD) mg/L	BOD_5 mg/L
$C_{entrance}$	27,30	7,64	389,12	279,16	204,83
C_{exit}	21,87	6,70	18,54	48,58	29,66
purification rates%			95,23	82,59	85,51

3.1.1 Temporal evolution of temperature:

Fig. 7 illustrates the variation in temperature values over the course of a full year of research. This curve offers a comprehensive representation of the thermal pollutant dynamics, both in the raw wastewater at the inlet of the experimental station and in the treated water at the outlet. It effectively highlights the thermal behaviour of the wastewater before and after treatment, providing valuable insight into the efficiency of the purification process under varying climatic conditions throughout the year.

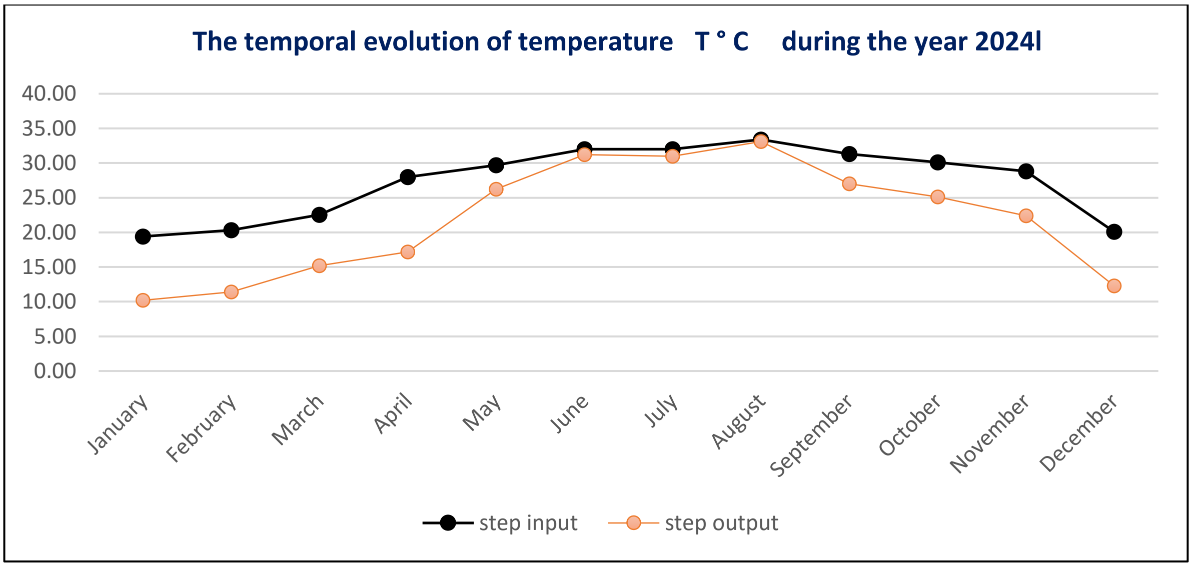

Fig.7 The temporal evolution of temperature T ° C during the year 2024

Through the graphical representation in (Fig. 7), which illustrates the temporal evolution of temperature, it was observed that the temperature of the raw wastewater fluctuated, reaching a maximum value of approximately 33.40 °C in August. This value is considered normal, as the region is characterized by extremely high temperatures during the summer season. The average temperature of the raw water was estimated at 27.30 °C, a value that closely aligns with that reported by Mounia Abouelouafa [16] in northern Morocco, and is slightly lower than the value recorded by B. Hammadi [33] in his study conducted in the Temacine region, Algeria. In fact, the fluctuation in raw wastewater temperature is strongly influenced by variations in ambient air temperature. The temperature of the treated water ranged between a maximum of 33.10 °C in August and a minimum of 10.20 °C in January, with an average temperature of 21.87 °C. This average is well below the maximum allowable temperature limit for wastewater discharge into the environment, which is 30 °C, as set by the World Health Organization (WHO). The increase in both raw and treated water temperatures was clearly associated with seasonal climatic changes, being higher in the hot season and lower in the cold season. The peak temperature of the used water, at 33.40 °C, was recorded in August, which nearly coincided with the maximum temperature of the treated water in the same month (33.20 °C). On the other hand, the lowest temperatures were recorded in the treated water during the winter and spring months, when evaporation, transpiration, and microbial biological activity are reduced due to lower thermal energy levels [12].

3.1.2 Temporal evolution the acidity pH

The variations in pH values of domestic wastewater, both at the inlet and outlet of the experimental station after a 10-day retention time, are illustrated in (Fig. 8).

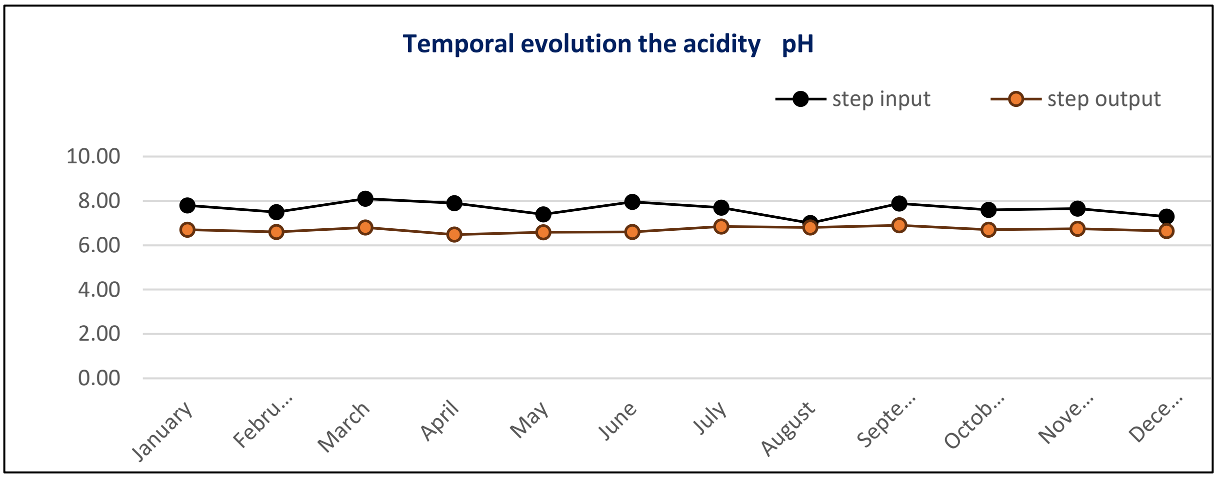

Fig. 8 The temporal evolution of the acid pollutant pH during the year (2024)

We monitored the evolution of pH values in the wastewater before treatment by analyzing the data illustrated in (Fig. 8). The pH values ranged between a maximum of 8.10, recorded in March, and a minimum of 7.00, observed in August. This variation is considered normal, as it remains close to the neutral pH value of 7.00. The average pH of the raw wastewater throughout the 2024 study period was 7.64, a level suitable for bacterial activity involved in the biological degradation of organic matter, indicating a favorable environment for such processes. These values are consistent with those reported by bebba [13]. Regarding the pH values of the treated water using the studied plant species, a slight decrease was observed compared to the raw wastewater, as shown in (Fig. 8). The values fluctuated between a minimum of 6.48, recorded in April, and a maximum of 6.90, noted in September 2024. These values are similar to those obtained by bebba [13]. The average pH of the treated water during the study year reached 6.70, indicating a shift towards a more acidic medium. This acidification is primarily attributed to the oxidation of chemical oxygen demand (COD) and ammonium ions (NH_4^+). The oxidation of COD results in the production of carbon dioxide (CO_2), which dissolves in water to form carbonic acid, thereby lowering the pH. Additionally, the oxidation of ammonium ions (NH_4^+) leads to the acidification of fluvial sediments. Moreover, the root exudates released by plants, such as tannic acid and gallic acid, further contribute to the acidification of the environment, as noted by Vincent with [14].

3.1.3 Temporal evolution the suspended matter (TSS) mg/L

The concentrations of suspended solids exhibit significant variations between the inlet and the outlet of the station. These variations are clearly illustrated in (Fig 9), which depicts the temporal evolution of suspended solids throughout the research period in (2024).

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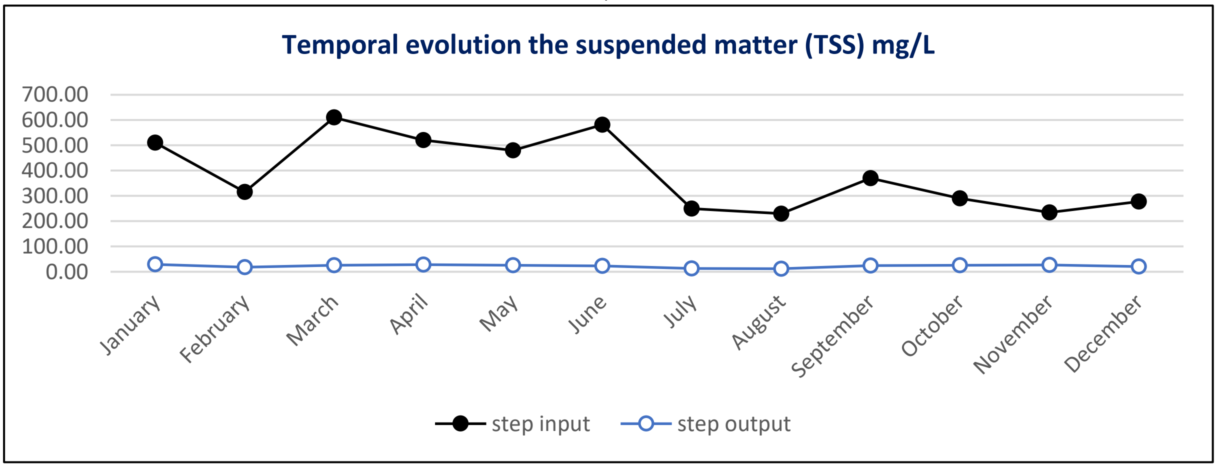

Fig .9 Temporal evolution the suspended matter (TSS)mg/L during the year (2024)

Fig 9 illustrates the variation in suspended solids concentrations in raw water prior to treatment, ranging from a minimum of 230 mg/L in August to a maximum of 610 mg/L in March. The average concentration of suspended solids throughout the study year was 389.12 mg/L. These values are identical to those reported by Hammadi B. [11], and close to those obtained by [15] (Ibrahim Al-Abed.**2017**). They are also comparable to the results recorded by Mounia Abouelouafa [16]. In contrast, the figure shows that the concentration of suspended solids after treatment of the raw water using the study plant decreased significantly, ranging from a maximum of 29 mg/L in January to a minimum of 12 mg/L. The average post-treatment concentration over the year 2024 confirms the plant's effectiveness in removing suspended solids, achieving a purification rate of 96.91%. This rate exceeds the range of 77–91% reported by Benslimane M [17] and Tanner [18]. The high purification efficiency is attributed to the significant reduction in suspended solids concentrations at the outlet of the experimental station after a residence time of 10 days. This decline is Tanner primarily due to physical treatment mechanisms, such as filtration, where coarse suspended particles are trapped within the root network, while fine particles are either retained in filter pores or undergo chemical reactions that reduce their concentration [19] However, the study also revealed that treated water appears more turbid than the raw water prior to treatment. This is explained by the presence of roots and rhizomes, which form channels within the packing materials, allowing some fine suspended particles to pass through and appear in the treated effluent, albeit in very small quantities [20]**.**

3.1.4 Temporal evolution the Chemical Oxygen Demand (COD) mg/L

Fig 10 illustrates the variations in Chemical Oxygen Demand (COD) concentrations throughout the study period (2024) for both the influent and effluent water at the experimental station.

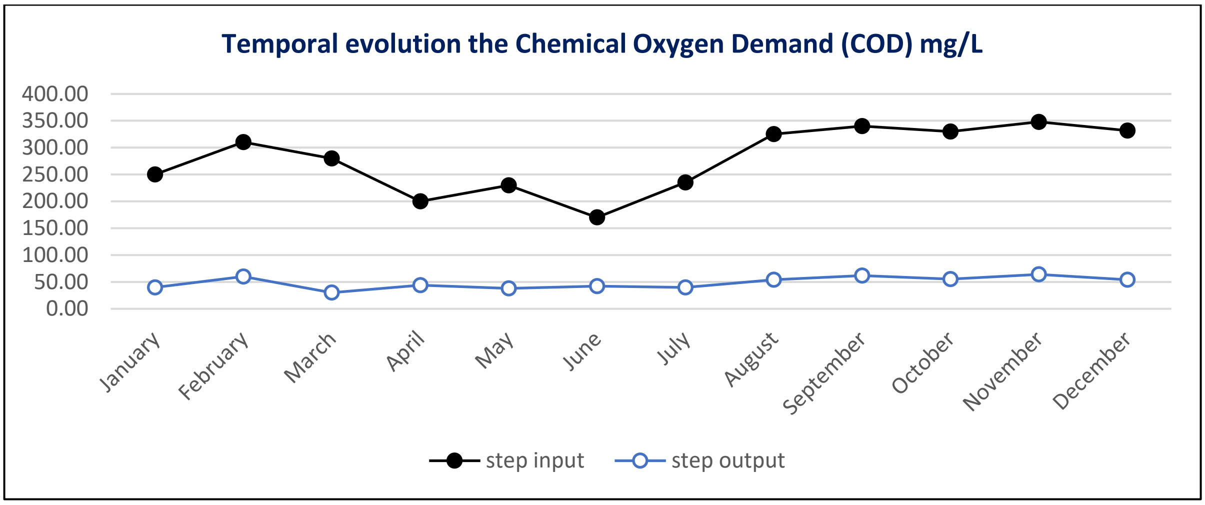

Fig.10 Temporal evolution the Chemical Oxygen Demand (COD) mg/L during the year (2024)

We recorded high levels of chemical oxygen demand (COD) concentrations in the raw domestic wastewater of the city of Touggourt. The concentrations ranged between a maximum of 340 mg/L, recorded in September, and a minimum of 170 mg/L, recorded in June. The average COD concentration in the raw wastewater throughout the monitoring year was 279.16 mg/L. These values are consistent with those reported by Seghairi [21]. Regarding the treated wastewater from the experimental plant, COD concentrations ranged between a maximum of 65 mg/L, observed in November, and a minimum of 40 mg/L, recorded in July, with an average value of 48.58 mg/L over the study period. This corresponds to a purification rate of 82.59%, which is considered excellent when compared to other studies, such as that of Kouakou [22], who reported an 80% removal rate, and significantly higher than the 36% reported by Urbanc-Bercic [23]. The removal efficiency of COD by the plant *Typha angustifolia* was remarkably high, ranging between 75% and 82%. This effectiveness can be attributed to the elevated microbial activity in the planted ponds, particularly the oxidation of organic pollutants. This process is enhanced by the oxygen released at the root level of the plant during photosynthesis. The decrease in COD concentrations from the inlet (raw wastewater) to the outlet (treated effluent) after a 10-day retention time in the three treatment ponds is accompanied by an increase in dissolved oxygen concentrations. This observation highlights the role of oxygen in the decomposition of carbonaceous compounds, leading to a marked reduction in COD levels especially during the first six days of treatment where purification rates ranged between 78% and 89.28%. These values are in line with the findings of Doulaye KONE [24].

3.1.5 Temporal evolution the Biochemical Oxygen Demand (BOD_5) mg/L:

In light of the results presented in Table 3, the changes in the concentration of the biological oxygen demand pollutant (**BOD_5**) were represented at the inlet of the experimental station with raw domestic wastewater from the city of Touggourt, and at its outlet with treated wastewater after a retention time of 10 days in the experimental beds, as illustrated in (Fig. 11).

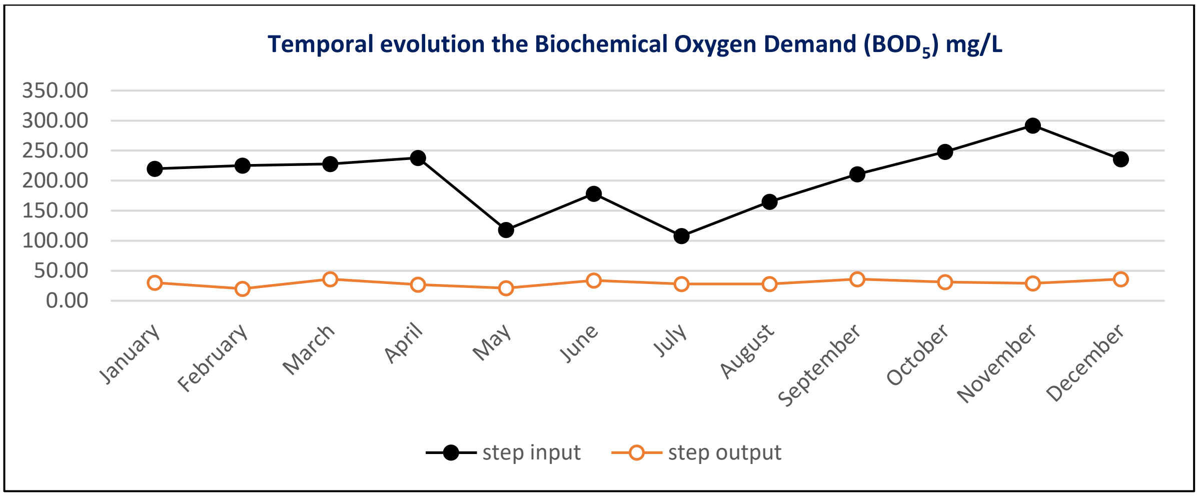

Fig.11 Temporal evolution the Biochemical Oxygen Demand (BOD_5) mg/L during the year (2024)

Typically, subsurface horizontal flow systems provide high removal rates in reducing organic matter, including biochemical oxygen demand (BOD_5) [25] [26]. In this study, the highest recorded concentration of BOD_5 in raw wastewater was 292 mg/L, observed in November, compared to a concentration of 29 mg/L in the treated effluent, resulting in a purification efficiency of 90.06%. This rate exceeds the 58% efficiency reported by Cristina S. C with al. in their study conducted in Portugal. Additionally, in July 2024, the influent BOD_5 concentration was 108 mg/L, while the treated effluent recorded a concentration of 28 mg/L, yielding a purification efficiency of 74.07%. This percentage is considered remarkably high when compared to results obtained by other researchers such as [27] [28] (. In fact, the reduction of BOD_5 concentrations through the use of aquatic plants is part of the broader strategy of treating organic pollution, which includes suspended solids, BOD_5, COD. Both natural and artificial systems that utilize such technologies have demonstrated excellent efficiency in removing carbon-based pollutants, particularly BOD_5, achieving purification rates of up to 90% [29] [30] [31] [32] [1]. These promising results have encouraged further research in this field. Accordingly, our study confirmed the findings of previous researchers. The purification efficiencies of BOD_5 in our experiment using *Typha angustifolia* over a full year in 2024 ranged from 74.07% to 91.11%, with an average efficiency of 85.91% throughout the study period.

4 Conclusion

Environmental protection represents one of the major strategic objectives pursued by the Algerian state, particularly the preservation of groundwater and surface water resources. One of the main causes of water pollution is the discharge of untreated wastewater into the environment. To address this issue, Algeria has established a large number of wastewater treatment plants across various provinces, reaching approximately 940 stations employing different technologies by 2024. However, these facilities present several limitations, particularly financial constraints related to their construction, operation, and maintenance.In response to these challenges, this study explores the use of low-cost ecological treatment systems based on natural resources. An experimental pilot plant was therefore established in Touggourt alongside the conventional activated sludge treatment plant, with the aim of evaluating the capacity of the macrophyte Typha angustifolia to remove organic pollutants from domestic wastewater. The results obtained during a one-year monitoring period (2024) demonstrated promising treatment performance. Concerning the physico-chemical parameters, water temperature decreased from 27.30 °C at the inlet to 21.37 °C at the outlet, remaining below the 30 °C limit recommended by the World Health Organization (WHO) and adopted in Algerian standards. This temperature range is also favorable for bacterial activity, as reported by Ford et al. [36](1980) and Jianlong [35] and Ning (2004). Similarly, pH values varied from 7.64 in raw wastewater to 6.70 in treated water, remaining within the optimal range for microbial activity and consistent with the recommendations of Josserand (1983) [34] and Algerian discharge standards.Regarding organic pollution indicators, significant reductions were observed. The concentration of Total Suspended Solids (TSS) decreased from 389.12 mg L^{-1} to 18.54 mg L^{-1}, corresponding to a removal efficiency of 95.83 %. The Chemical Oxygen Demand (COD) decreased from 279.16 mg L^{-1} to 48.50 mg L^{-1}, with a removal rate of 82.62 %, while Biochemical Oxygen Demand (BOD_5) declined from 204.83 mg L^{-1} to 29.66 mg L^{-1}, achieving a removal efficiency of 85.51 %.These results indicate that the reduction of carbonaceous pollution is not primarily governed by oxidation–reduction processes or oxygen supply within the ponds. Instead, pollutant removal is mainly associated with the filtration and sedimentation processes occurring within the plant root system, while algae and microorganisms contribute significantly to the degradation of organic matter during the hydraulic residence time within the system. Based on these findings, several recommendations can be proposed. Increasing the surface area of the treatment ponds could enhance purification efficiency, while increasing pond depth beyond the 70 cm commonly recommended in previous studies may improve dissolved oxygen (DO) availability and aeration conditions, thereby supporting aerobic degradation processes. Moreover, greater pond depth may enhance nitrogen retention, which is essential for plant growth and chlorophyll synthesis.

Overall, the study demonstrates that the vertical–horizontal hybrid constructed wetland system represents an effective and sustainable approach for domestic wastewater treatment. The vertical flow filter promotes aerobic conditions that enhance nitrification and organic matter removal, whereas the horizontal flow filter provides quasi-anaerobic conditions favorable for denitrification and nitrogen removal. The system also exhibited stable performance in the removal of suspended solids under varying hydraulic and organic loads, while maintaining low energy and operational requirements due to its reliance on natural plant–microorganism interactions. Despite certain limitations, including greater land requirements, potential filter media clogging, and relatively high initial construction costs, the vertical–horizontal hybrid system remains a promising and sustainable solution for wastewater treatment, particularly in rural and peri-urban areas.

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