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Performance of Hybrid Constructed Wetland System for the Treatment of Secondary Wastewater Effluent under Arid Climate Conditions (Southeastern Algeria): A Laboratory Scale Investigation

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ABSTRACT

Constructed wetland (CWs) systems offer an economical alternative to wastewater (WW) treatment in developing countries. So this study investigated lab-scale hybrid constructed wetlands (HCWs) with plant species *Canna indica* and *Typha latifolia* in mono and mixed culture for removing organic matter and nutrients from municipal wastewater (MWW) under arid climatic conditions. A HCW system consists of a storage tank feeding four series of vertical flow constructed wetlands (VFCWs) followed by horizontal flow-constructed wetlands (HFCWs). The results indicate that the planted beds performed better in removing suspended solids (TSS) (89.93% by *Typha latifolia*), biochemical oxygen demand (BOD5) (95.01% by mixed-culture), chemical oxygen demand (COD) (90.77 by *Typha latifolia*), nitrite (NO_{2-}) (89.99% by mixed-culture), ammonium nitrogen (NH_{4+}) (99.98 % by mixed-culture), and orthophosphate (PO43-) (87.22% by *Typha latifolia*) as compared to the unplanted bed for the same parameters (87.85%, 92.87%, 77.35%, 85.30%, 99.75%, and 80.95%), respectively. The nitrate (NO_{3-}) concentration in the effluent recorded the highest increase in the VFCW unit planted with mixed culture from 0.44 to 0.999 mg/l and decreased in the second stage to 0.588 mg/l at the HCW outlet. The mean values of the testing parameters in different HCW systems were not significant between the mono and mixed culture ($P > 0.05$), with a significant difference ($P < 0.05$) between the VFCWs and HFCWs. The finding of this study demonstrated that Canna indica and *Typha latifolia* have been effective in WW treatment by HCW systems.

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INTRODUCTION

Water pollution and degradation of surface water sources due to sewage discharge have become a global problem in developing countries, especially in dry climate zones (Edokpayi, **2017**). Untreated or inadequately treated WW contains many pollutants: organic material, pathogenic microorganisms, nutrients, and toxic compounds (Mohammed & El Baby, 2016), which cause a variety of adverse effects on health and the environment, requiring adequate treatment and effluent management by efficient systems (Almuktar, 2018). There are several popular technologies for WW treatment in domestic sewage. The Conventional methods of WW treatment are very effective. However, they are expensive and need a lot of energy, making them inappropriate for developing countries (Rajasulochana & Preethy. 2016).

Constructed wetlands (CWs), as an innovative treatment technology particularly for small communities (Stefanakis, 2020), are increasingly used to treat various types of WW (Mahmood et al., 2018) for sustainable management worldwide (Wang, 2017) as a low-cost alternative to municipal, industrial, and agricultural WW treatment (Białowiec, 2014). Surface flow and subsurface flow are two different classifications for CWs. Some subsurface flow CWs are built for VFCW, while others are for HFCW. Various CWs can also be combined into one system to improve water quality. Both arrangements have a demonstrated track record of achieving a respectable level of wastewater treatment efficiency in a large field and pilot-scale research (Waly et al., 2022).

CWs performance is generally limited in nitrogen removal, as there are no ways to balance the conflicting conditions required for organic matter removal, nitrification, and denitrification (Saeed & Sun, 2011). Several studies have shown that a HCW system could be used to treat different types of WW, such as greywater and industrial waste (Franchino et al., 2013; Vymazal, 2014). The efficiency of denitrification in single wetlands is lower than that of hybrid HCW the nitrification and denitrification provided by different types of wetlands (Vymazal & Kröpfelová, 2015). HCWs are a natural solution for WW treatment. The main principle of HCW systems is that they combine various types of CWs placed in series (Šereš et al., 2021). This technique has been widely and successfully used in many countries (Šereš et al., 2021; Fernandez-Fernandez et al., 2020; Rousso et al., 2019). In Algeria, the use of CW systems for WW treatment is limited. To date, only two such stations have been established in Algeria, one of which operates in a VFCW system and the other in an HFCW wastewater garden system (WWG) (Hammadi et al., 2019). In Touggourt, province of Ouargla southern Algeria, the climate is arid with solar radiation all year round; therefore, it is important to choose the plants adapted to the climatic conditions of the study area before their use at the field level in CWs. Compared to wetland studies in many regions, there are relatively few reports of the arid climate. Therefore, this study seeks to highlight the performance of wetlands in the arid climate.

In Touggourt, there is one WWTP. Disregarding the environmental benefits, the MWW treatment plant absorbs only 38% of the WW generated by the inhabitants. 62% goes into the Oued Righ channel (Amiri et al., 2022). This problem has resulted in pollution of the canal water, unpleasant odors spreading in the area, and the massive spread of mosquitoes and harmful insects. In addition, more than 50% of palm trees have died (Benguergoura & Remini, 2014). This situation affects the social life of the population adjacent to the entire Oued Righ channel. Due to the low technical and financial possibilities available in many regions in Algeria, which are manifested in the small number of WWTP as well as in the inability of these plants to absorb the large amounts of water they receive daily, it is now necessary to look for suitable ways to treat WW at the lowest possible cost.

The main goal of this study was to evaluate the treatment efficiency of the lab-scale HCW consisting of vertical and horizontal flow beds for possible use in treating MWW under a dry climate for the first time in the South-east of Algeria, to reach the limits of the Algerian standards. Another objective was to test the effectiveness of two plant species Canna indica and Typha latifolia, in the mono and polyculture on removing pollutants.

MATERIALS AND METHODS

Characteristics of the Experimental Facility

The studied region falls within the hyper-arid climate. The monthly mean air temperature reaches a maximum of 41.6 °C in July and a minimum of 3.4 °C in January. With an average annual precipitation of 60 mm and annual evaporation was 2458 mm (NMO, 2020).

Four parallel HCW systems of identical components and configurations (size and substrates), namely (HCW_0 unplanted), (HCW_1 with Canna indica), (HCW_2 with Typha latifolia), and (HCW_3 with polyculture), were built in the open environment within the WWTP of Touggourt city, Algeria (33° 16’ 00” N and 6° 04’ 00” E). Each system consisted of a VFCW, followed by an HFCW working in series (Figure **1**), fed by a storage tank with a capacity of 0.8 m^3 (See Flow diagram). Three perforated polyvinyl chlorides (PVC) tubes with a diameter of 3 cm and a length of 40 cm were inserted vertically into each VFCW to raise the oxygen concentration in the substrate. Details of the main characteristics of the design are reported in Table 1.

Plant and substrate selection and preparation

The choice of vegetation depends on its availability, adaptation to the local climate and soil type, and tolerance to contaminants in wastewater, characterized by high biomass production

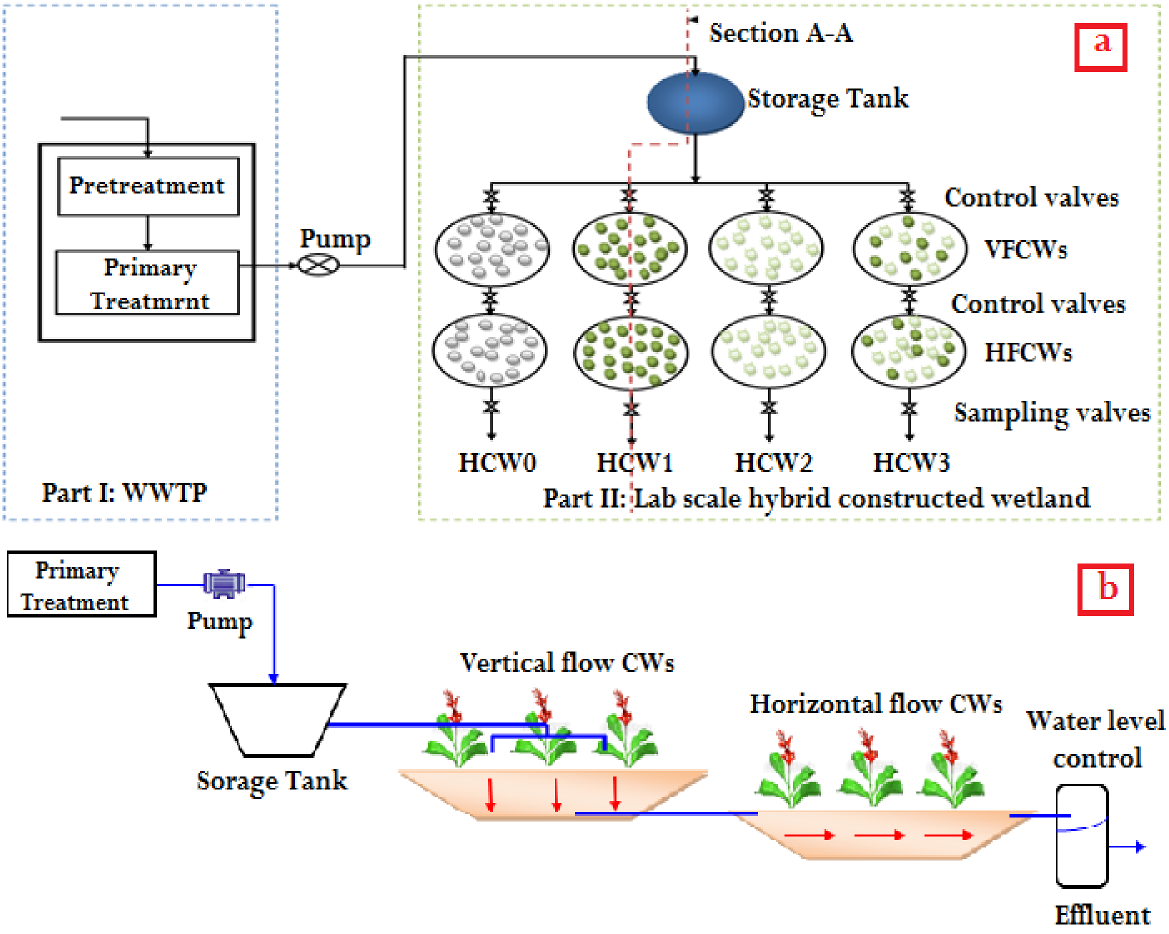


Fig. 1. (a) Layout of the HCWs system, and (b) cross section of the HCW

Table 1. Characteristics of hybrids constructed wetland.

Parameters	Unit	VFCWs and HFCWs
Type of plants	HCW_0	Unplanted
	HCW_1	*Canna indica*
	HCW_2	*Typha latifolia*
	HCW_3	Mixed culture
Shape	/	Circular
Diameter	m	0.70
Surface	m^2	0.35
Volume	m^3	0.06
Height	m	0.25
Layer thickness	m	0.20
Medium (size)	mm	4-25
Filter porosity	%	33
Hydraulic loading rate (HLR)	m/day	0.057
Hydraulic retention time (HRT)	day	05
Plastic connection pipe	cm	3

and rapid growth (Wu et al., 2015; Rahmadyanti & Audina, 2020). The plants used were collected from the WWG in Tamacine, Algeria (33°01’ 19” N, 6° 01’ 22” E). The plant density is 36 species per square meter (Labed, 2015; Kipasika et al., 2016; Bebba et al., 2019). After planting, they were waterlogged for (4) weeks, allowing for the necessary growth of the macrophytes (Lavrnić et al., 2020; Collivignarelli et al., 2020). Choosing the appropriate substrate is among the significant steps during the design and construction of CWs (Wu et al., 2015). Substrate selection is based on previous studies (Labed, 2015; Bebba et al., 2019), as shown in Table 1.

Pre-treatment system

The pretreatment system adopted in the MWW primary treatment of Touggourt city in the WWTP was coarse screening using a derailleur with mechanical bars and aerated sand channels to remove sand, grease, and primary settling (ONA. 2020).

Flow diagram

The diagram of HCW systems built in (VFCW-HFCW) used in this experiment is as follows: MWW → Primary treated sewage ↑ Pump → Storage tank ↓ Gravity ↓ Vertical-flow CW ↓ Gravity → Horizontal-flow CW ↓ Discharge (Figure 1).

Water sampling and analysis

Every month, from January to December 2021, in the WWTP laboratory of Touggourt, influents and effluents from the HCWs pilots were analyzed for physicochemical parameters (Table 1 and Table 4). Laboratory analyses were carried out immediately after sampling to determine temperature (T), dissolved oxygen (DO), potential hydrogen (pH), salinity, and electric conductivity (EC) using a portable multimeter instrument model HI9829. Along with TSS are carried out according to Standard Methods NF T90-105 (AFNOR. 1999). BOD_5 with the 5-day BOD test with OxiTop head gas sensors (OxiTop ® WTW box). COD was measured using the dichromate method following ISO guideline 6060 (ISO. 1989). NH_4^+ and NO_3^- were carried out by ISO guideline 7150 (ISO. 1984). The measurement of NO_2^- was carried out by the method ISO guideline 6777 (ISO. 1984), and PO_4^{3-} was carried out by the ISO guideline 6878 (ISO. 2004).

Calculation and Statistical Analysis

Removal efficiency (RE%) for each variable was calculated by applying the following Equation (1) by comparing influent (C_i) and effluent (C_0) concentrations in WW (Kadlec & Wallace, 2008).

$$Removal\ efficiency\ RE(\%) = \left(\frac{C_i - C_O}{C_i}\right).100 \tag{1}$$

Where C_i and C_0 are the inlet and outlet concentrations expressed in mg/l, respectively.

One-way analysis of variance (ANOVA) was used for all statistical analyses to determine significant statistical differences in the water treatment performance used by VFCWs and HFCWs. An ANOVA test was used, and the level of statistical significance was set at $P \leq 0.05$, with species types and flow types as factors. The analysis of variance (ANOVA) was performed using the Origin Lab software (2018).

RESULTS AND DISCUSSION

Primary treated MWW characterization and quality

The performance of the system was monitored and evaluated during 12 months of operation from January to December 2021. During the experiments, 12 samples were collected for each parameter in MWW and various VFCWs and HFCWs. In this study, MWW was treated using HCW systems operated in vertical and horizontal flow. For example, *Typha latifolia* and *Canna indica* were selected for being superior in nitrogen uptake and organic removal (Sharma et al., 2014; Dias et al., 2020; Pinninti et al., 2021). The average quality characteristics of the primary treated sewage are as follows: T, (28.21±476 °C); DO, (0.37±0.21mg/L); pH, (7.52±0.17); EC, (4.76±0.45 mS/cm); salinity, (2.56±0.32 mg/l), TSS varied from 92 mg/l to 268 mg/l with an average of (156.41±53.07 mg/l). The COD varied between 114 mg/l and 373 mg/l with an average of (232.7±68.91 mg/l), and the BOD_5 values varied between 80 mg/l and 220 mg/l with an average of (124.50±38.85 mg/l). While the nutrient values represented by NH_4^+, NO_2^-, and NO_3^- ranged from (18.6 to 46.4 mg/l, Average 29.70±8.00 mg/l), (0.025 to 0.141 mg/l, Average 0.068±0.033 mg/l) (0.161 to 0.936 mg/l, Average 0.44±0.231 mg/l) respectively. The orthophosphates ranged from 1.19 mg/l to 3.77 mg/l with an average of (2.43±0.65mg/l). The primary treated WW can be considered of medium strength (TSS and BOD_5 concentration, 120–400 mg/l) (Metcalf, 2003). Table 2 provides the average quality characteristics of the primary treated sewage.

The susceptibility to biological treatment is determined by the estimates of the biodegradability of organic pollutants, expressed as the (BOD_5/COD) and (COD/BOD_5) ratios. Table **3** summarizes the ratios (BOD_5/COD) and (COD/BOD_5). The average values of the (BOD_5/COD) and (COD/BOD_5) ratios during the study period were 0.534 and 1.869, respectively. Thus, this type of WW is located in the primary treated WW zone (BOD_5/COD, 0.41 to 0.59) (Cossu et al., 2012) and is considered readily biodegradable by biological processes (Domestic WW K < 3) (Metcalf, 2003).

Water temperature, pH, and DO

Mean values and standard deviations of T, pH, and DO for the different treatment units are shown in Table 4. The temperature values of the WW samples range from 21.4 °C to 34.2 °C, with an average value of 28.21 ± 4.76 °C. According to JORA (2006), the temperature values exceeded the Algerian limits for WW (30 °C) in the summer. The abnormal value was due to the high air temperature and the nature of the drinking water (Albian water in the region), which exceeds 55 °C (Tabouche & Achour, 2010). In general, the results indicate that the WW temperature in this study is acceptable. The temperature of water decreased from (28.21± 4.76 °C) to (20.98± 6.63 °C), (21.03 ± 6.81 °C), (20.8±6.48 °C), and (20.88±6.62 °C) in VFCWs, (0), (1), (2), and

Table 2. Mean concentrations with standard deviations, Min and Max of water primary treated sewage quality parameters (n = 12) (values are in mg/l) except for pH, temperature (°C), and EC (mS/cm) between January and December 2021.

Parameter	Initial concentration			Algerian limits for WW
	Mean ± SD	Min	Max	(JORA 2006)
T	28.21±4.76	21.4	34.2	30
pH	7.52±0.17	7.31	7.89	6.5 - 8.5
DO	0.37±0.21	0.09	0.79	/
EC	4.76±0.45	4.04	5.75	3.00
Salinity	2.56±0.32	2.1	3.3	/
TSS	156.41±53.07	92	268	35
COD	232.76±68.91	114	373	120
BDO_5	124.50±38.85	80	220	35
NH_4^+	29.70±8.00	18.6	46.4	/
NO_2^-	0.068±0.033	0.025	0.141	/
NO_3^-	0.44±0.231	0.161	0.936	/
PO_4^{3-}	2.43±0.65	1.19	3.77	02

Table 3. BOD_5/COD and COD/BOD_5 ratios for the primarily treated sewage.

Values	Influent COD (mg/l)	Influent BOD_5 (mg/l)	Ratio	
			BOD_5/COD	K= COD/BOD_5
Min	114	80	0.701	1.425
Max	373	220	0.589	1.695
Average 12 samples	232.76	124.50	0.534	1.869

(3) respectively, and (21.20 ±7.31°C), (20.14±6.38°C), (20.85±7.04 °C), and (20.85±7.10 °C) in HFCWs, (0), (1), (2), and (3) respectively, this is favorable for microbial activity and the removal of nutrients (El fanssi et al., 2019). There was a significant difference ($p < 0.05$) in temperature between the primary treated WW used in unit feeding and the WW treated by VFCWs and HFCWs. While the results recorded in this study were below the limited value of the Algerian standards (JORA. 2006).

The pH is another environmental parameter to characterize water quality. The pH of primary treated WW was (7.52±0.17). The pH of the VFCWs, HFCWs, and unplanted was in an acceptable range of 6.88 to 7.59. A slight decrease in pH occurred due to the metabolism of phosphates and nitrogen compounds and the production of volatile acid produced by acid-forming bacteria, which break down organic matter (Kim et al., **2016**; Sandri & Reis, 2021). The pH in the effluents was below the limit value (6.5 to 8.5) of the Algerian standards (JORA. 2006).

The concentration of DO in the primary treated WW sample was low due to the large consumption of oxygen used in organic decomposition and nitrification (Kadlec & Knight, 1996). And the high concentration in the final effluent due to photosynthesis by plants.

DO increased from (0.37±0.21mg/l) to (2.55±1.55 mg/l), (4.04±1.18 mg/l), (4.14±1.38 mg/l), and (3.50±1.13 mg/l) in VFCWs (1), (2), (3), and (4), respectively. DO slightly decreased in both ($HFCW_1$ with *C.indica* 3.15±1.08mg/l) and ($HFCW_2$ with *T.latifolia* 3.71±1.40 mg/l) due to the lack of oxygen in the HFCW (Rehman et al., 2017). The inlet concentrations of DO differed significantly ($P< 0.05$) compared to the outlet in the VFCWs and HFCWs, due to the transfer of oxygen through the roots, which provides good conditions for the growth rate of microorganisms, organic degradation, nitrification, and bacterial inactivation (Wang et al., 2012). Internal and external flow values were higher during the winter (4.2 mg/l), respectively. It may be due to lower winter temperatures that promote the thawing of oxygen (Zhang, 2010).

Electrical Conductivity and Salinity

The conductivity of the untreated WW samples was in the range of 4.04 to 5.75 mS/cm. The mean conductivity was (4.76±0.45 mS/cm) (Table **2**). However, the effluent values were higher in all VFCW and HFCW systems. The average values were (7.42±1.51 mS/cm), (9.45±2.48 mS/cm), (10.48±2.99 mS/cm) and (10.83±4.55 mS/cm) for VFCW, (0), (1), (2), and (3), respectively. In contrast, the average values in the HFCW, (0), (1), (2), and (3) were (9.95±4.31 mS/cm), (11.16±3.46 mS/cm), (16.86±8.41 mS/cm), and (17.54±9.31 mS/cm), respectively (Table 4). The values in horizontal systems were more significant than in vertical ones. The increase in all units could be due to the evapotranspiration of plants and the phenomenon of the dissolution of salts (Chen et al., 2017).

On the other hand, the average influent salinity was (2.56±0.32 mg/l) (Table 2). This salinity increased significantly at the outlet of the VFCWs systems were (4.42±0.84 mg/l), (5.80±1.48 mg/l), (6.22±1.47 mg/l), and (6.35±2.31 mg/l) for VFCWs, (0), (1), (2), and (3) respectively, and (5.80±1.80), (6.50±2.19), (10.48±5.23), and (10.80±5.81 mg/l) for HFCWs, (0), (1), (2), and (3) respectively (Table 4). Salinity follows conductivity, due to extremely arid climatic conditions that cause very high evaporation, which in turn raises salinity concentrations (Gouaidia et al., 2012).

Visual observations of the plant color, height, leaf density, and mortality show that *Canna indica* and *Typha latifolia* have adapted to increasing salinity (Chyan, 2017). The results exceed the limit values (> 3.00 mS/cm) recommended by the Algerian standards (JORA. 2006).

Removal of TSS

Figure 2. shows a comparison of the elimination of TSS in HCW systems. The influent TSS concentration was (156.41±53.07 mg/l), and the mean overall removal efficiencies of TSS were (87.85±19.17 %), (89.05±19.29 %), (89.93±17.04 %), and (88.55±23.15 %) for the HCW systems (0), (1), (2), and (3), respectively. That is comparable to the removals reported by Zurita & John (2014) and Lavric et al. (2020). No significant differences (P>0.05) between the different HCWs in TSS removal and between the unplanted control and other cultivated beds. That is due to the removal of solids from the influent by the physical processes of filtration and sedimentation (Stefanakis et al., 2014).

In comparison between the VFCWs and HFCWs series, the mean TSS removal efficiency of VFCWs (0), (1), (2), (3) was higher than the mean TSS removal efficiency of HFCW (0), (1), (2), (3), (>40.0 %), (>58.0 %), (>45.0 %), and (>60.0%), respectively. The removal efficiencies of the first-stage VFCWs were significantly higher (P<0.05) than the second-stage HFCWs, this is due to the removal of TSS takes place in the pretreatment and the first phase of HCWs (Vymazal & Kröpfelova, 2011; Avila et al., 2015; Fernandez-Fernandez et al., 2020).

Generally, we observe a high removal efficiency of HCWs with the Typha latifolia plant (89.93±4.91%) from MWW. There was no temperature impact on the removal efficiency of TSS in all analyzed units, and the TSS concentrations in the effluents were below the limit value of the Algerian standards (JORA. 2006).

Removal of COD

As seen in Figure **3** below, the influent COD concentration was in the range of 114–373 mg/l, with a mean value of (232.7±68.91 mg/l), while effluent COD after treatment in the VFCW series (0), (1), (2), (3) (66.56±11.95 mg/l), (71.34±10.83 mg/l), (68.11±14.00 mg/l), and (69.62±13.24 mg/l), respectively. In the HFCW series (0), (1), (2), (3), were (33.54±16.68 mg/l), (31.81±17.77

Table 4. Mean concentrations, (±s.d.), and overall removal efficiency of water quality parameters along the HCWs system (values are in mg/l) except for pH, temperature (°C), EC (mS/cm), and Efficiency (%), between January and December 2021.

Systems	Parameters	VFCWs		HFCWs		RE (%)
		Effluent conc.± SD	**RE (%)**	**Effluent conc.± SD**	**RE (%)**	
Zero (0) Unplanted	T	20.98±6.63	/	21.20±7.31	/	/
	pH	7.59±0.48	/	7.50±0.28	/	/
	EC	7.42±1.51	/	9.95±4.31	/	/
	DO	2.55±1.55	/	3.21±0.77	/	/
	Salinity	4.42±0.84	/	5.80±1.80	/	/
	TSS	29.75±13.92	79.57	18.08±9.37	39.47	87.85
	COD	73.55±22.35	66.56	48.92±19.25	33.54	77.35
	BDO_5	18.58±11.53	84.03	8.33±5.63	56.00	92.87
	NH_4^+	14.97±10.83	49.43	0.057±0.117	83.03	99.75
	NO_2^-	0.020±0.014	68.16	0.009±0.008	50.45	85.30
	NO_3^-	0.749±0.432	- 87.10	0.361±0.201	45.55	5.58
	PO_4^{3-}	1.281±0.595	47.50	0.482±0.259	61.68	80.95
One (1) Mono-C.indica	T	21.03±6.81	/	20.14±6.38	/	/
	pH	6.88±0.24	/	7.22±0.34	/	/
	EC	9.45±2.48	/	11.16±3.48	/	
	DO	4.04±1.18	/	3.15±1.08	/	/
	Salinity	5.80±1.47	/	6.50±2.19	/	/
	TSS	23.25±8.23	83.54	16.08±8.15	25.15	89.05
	COD	62.90±21.92	71.34	42.68±17.97	31.81	81.86
	BDO_5	14.50±9.96	87.96	6.58±4.07	48.03	94.28
	NH_4^+	0.932±1.42	96.57	0.0226±0.065	70.98	99.91
	NO_2^-	0.017±0.010	69.34	0.008±0.006	44.77	86.65
	NO_3^-	0.762±0.344	- 97.46	0.383±0.253	47.81	- 6.56
	PO_4^{3-}	0.742±0.431	69.67	0.347±0.261	55.01	86.68
Two (2) Mono-T. latifolia	T	20.80±6.48	/	20.85±7.04	/	/
	pH	6.91±0.25	/	7.03±0.33	/	/
	EC	10.48±2.99	/	16.86±8.41	/	
	DO	4.14±1.38	/	3.71±1.40	/	/
	Salinity	6.22±1.47	/	10.48±5.23	/	/
	TSS	25.83±12.43	82.36	14.83±6.83	36.74	89.93
	COD	69.60±27.30	68.11	39.27±11.48	40.26	90.77
	BDO_5	13.75±7.39	88.31	6.91±4.35	49.23	94.13
	NH_4^+	0.615±0.783	97.93	0.0266±0.065	63.57	99.90
	NO_2^-	0.019±0.012	67.97	0.007±0.006	60.80	88.60
	NO_3^-	0.850±0.451	- 114.17	0.606±0.361	34.99	- 47.04
	PO_4^{3-}	0.809±0.536	68.03	0.333±0.209	55.45	87.22
Three (3) Mixed-culture	T	20.88±6.62	/	20.85±7.10	/	/
	pH	6.93±0.22	/	7.01±0.27	/	/
	EC	10.83±4.55	/	17.54±9.31	/	
	DO	3.50±1.13	/	3.84±1.31	/	/
	Salinity	6.35±2.31	/	10.80±5.81	/	/
	TSS	22.25±9.94	83.98	16.50±9.00	23.32	88.55
	COD	66.09±24.98	69.62	35.98±19.18	46.24	83.21
	BDO_5	12.33±6.58	89.80	6.16±3.63	51.12	95.01
	NH_4^+	0.383±0.472	98.69	0.005±0.013	61.84	99.98
	NO_2^-	0.018±0.012	69.22	0.006±0.004	52.28	89.99
	NO_3^-	0.998±0.829	- 170.20	0.588±0.507	46.96	- 32.07
	PO_4^{3-}	0.762±0.490	69.23	0.363±0.268	50.94	86.17

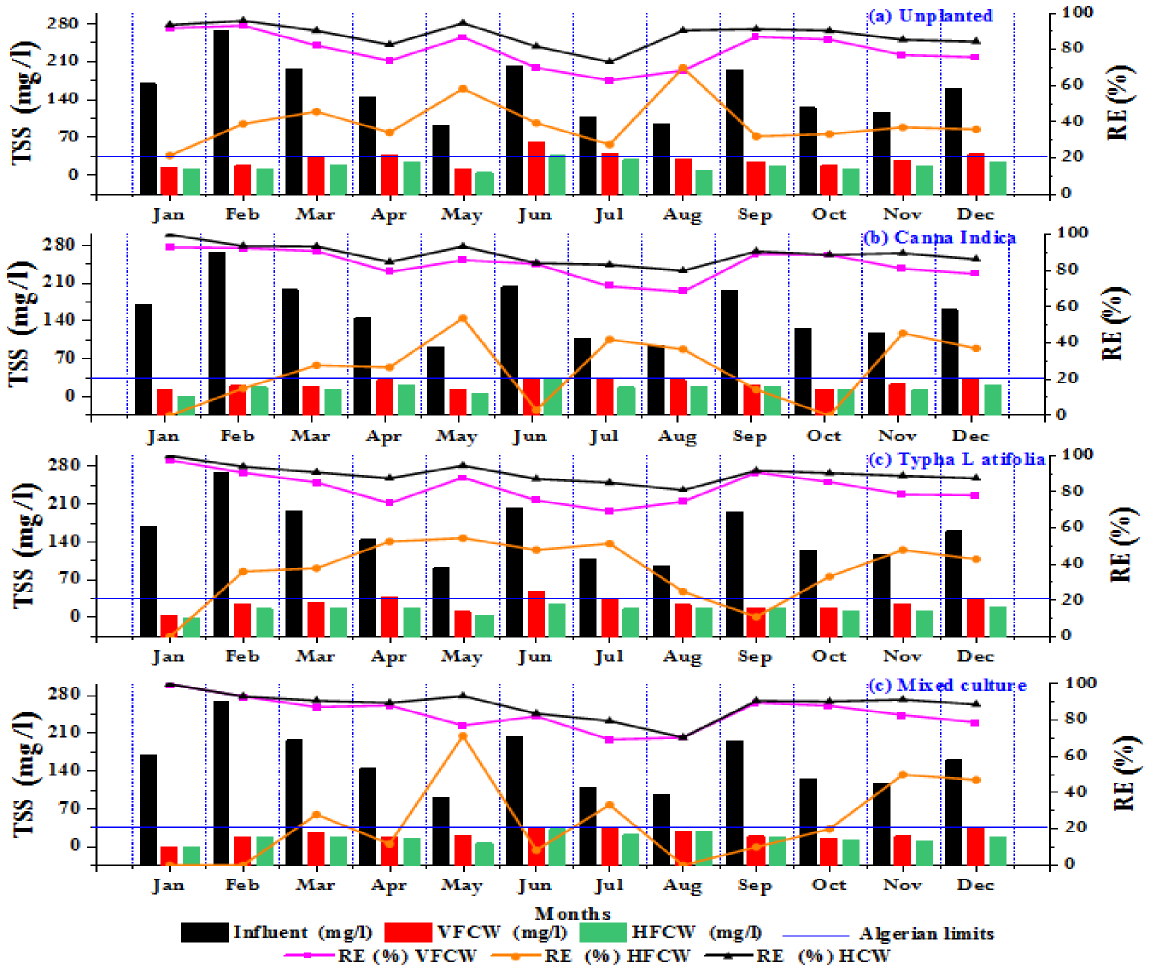


Fig. 2. Comparison TSS concentrations in the inlet and in the different HCWs, VFCW (1st stage) outlet and, HFCW (2nd stage) outlet. (**a**) Unplanted, (**b**) *Canna Indica*, (**c**) *Typha Latifolia*, and (**d**) Mixed culture.

mg/l), (40.26±18.26 mg/l), and (46.24±18.82 mg/l), respectively (Table 4). There were significant differences ($P< 0.05$) between the water used in the alimentation and the various CWs planted in the vertical and horizontal systems. In contrast, no significant differences ($p>0.05$) between the unplanted control and the rest of the VFCWs and HFCWs cultivated by Canna, Typha, and mixed culture. The organic matter decreases with the longer HRT (Rani & Pohekar. 2019; and Wang et al. 2018), where microbial degradation played a meaningful role in COD degradation (Xu & Cui. 2019). There are significant statistical differences ($p > 0.05$) between the VFCWs and HFCWs in each series of the HCWs, which confirms that the removal of organic matter occurs mainly in the first phase of the HCWs system, the result is similar to that obtained by He et al. (2018). The high efficiency of COD removal by VFCWs is due to the custom design in aerobic processes and filtration and sedimentation mechanisms, which are the main removal mechanisms in VFCWs (Stefanakis et al., 2014; Gholipour & Stefanakis, 2021), and the upper part of the substrate is the site of organic compound accumulation (Xu & Cui. 2019). Also, the organic matter decays more rapidly at higher temperatures (Sierra et al., 2015; Conant et al., 2011). The final overall removal efficiency in order of performance was (Typha latifolia, 90.77±7.39 %) > (Mixed culture, 83.21±10.02 %) > (Canna indica, 81.86±8.59 %) > (Unplanted, 77.53±10.66 %) (See Figure **3**). This result is comparable to COD removal (91.4 %) recorded by El Fassi et al. (**2019**) in Morocco and (86.00 %) recorded by Gholipour & Stefanakis. (2021).

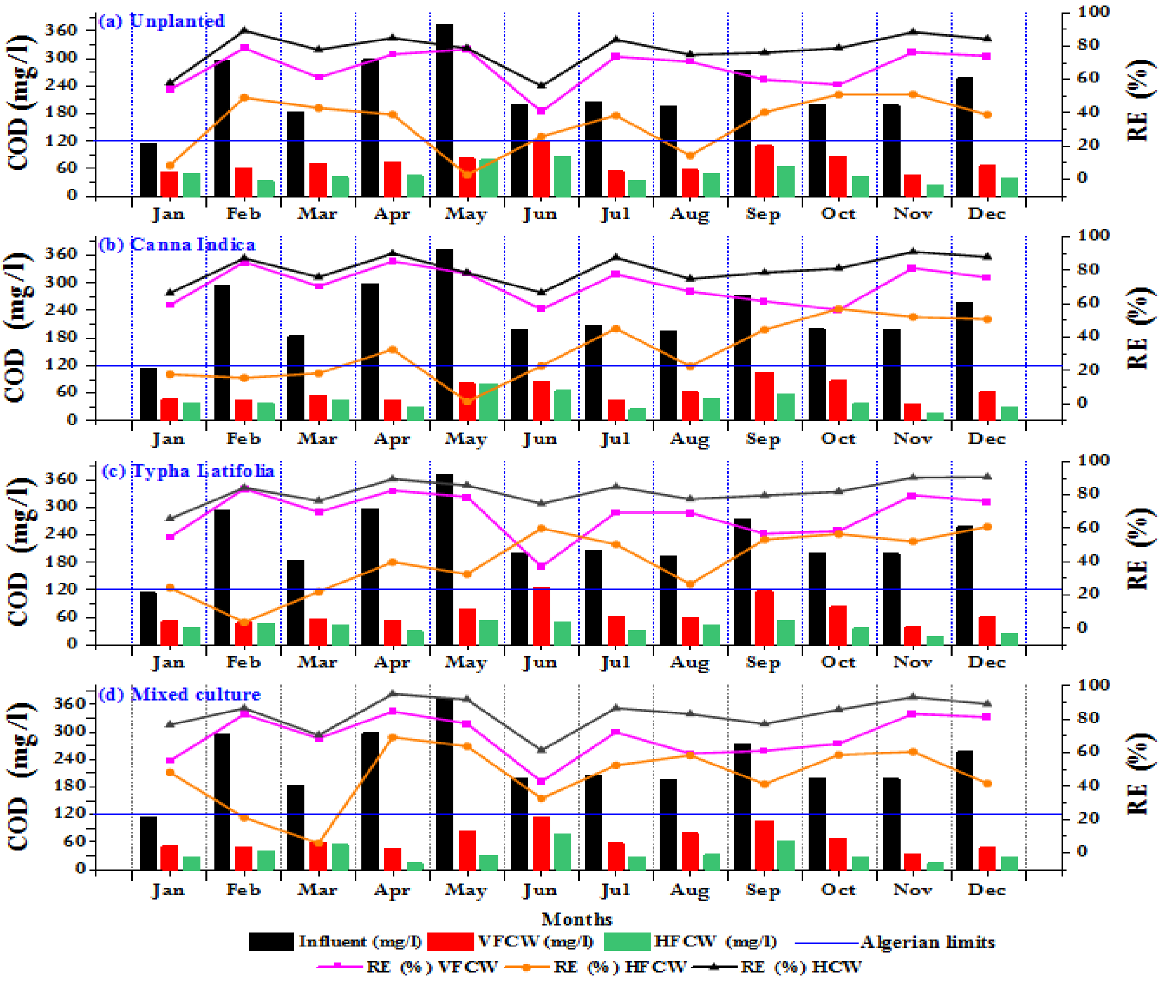


Fig. 3. Comparison of COD concentrations in the inlet and in the different HCWs, VFCW (1st stage) outlet and, HFCW (2nd stage) outlet. (a) Unplanted, (b) Canna Indica, (c) Typha Latifolia, and (d) Mixed culture.

Over the study period, the treated effluents generated WW with a concentration of COD< 120 mg/l, as a maximum value allowed for discharges to surface water bodies by Algerian legislation (JORA. 2006).

Removal of BOD

The BOD_5 concentrations and removal efficiencies in HCWs during the monitoring period shows in (Figure 4). Before treatment, the average concentration of BOD_5 was (124.50±38.85 mg/l), the BOD_5 concentrations decreased to (18.58±11.53 mg/l), (14.50±9.96 mg/l), (13.75±7.39 mg/l), and (12.33±6.58 mg/l), in VFCW (0), (1), (2), and (3), respectively, similarly, the concentrations of BOD_5 in HFCW (0), (1), (2), and (3) decreased to (8.33±5.63 mg/l), (6.58±4.07 mg/l), (6.91±4.35 mg/l), and (6.16±3.63 mg/l), respectively.

We observed a significant statistical difference between the inlet and the outlet sampling points that may be due to the effect of plants that mimic natural treatment processes involving vegetation, soils, and their associated microbial assemblages to improve water quality (Vymazel, 2011). Removal efficiency by *Typha latifolia*, *Canna indica*, mixed culture, and the unplanted bed was largely convergent, as we did not record a significant difference (P>0.05) between planted and unplanted systems. These results indicate that the elimination of organic compounds expressed by BOD_5 is produced without plant intervention and carried out by physical processes

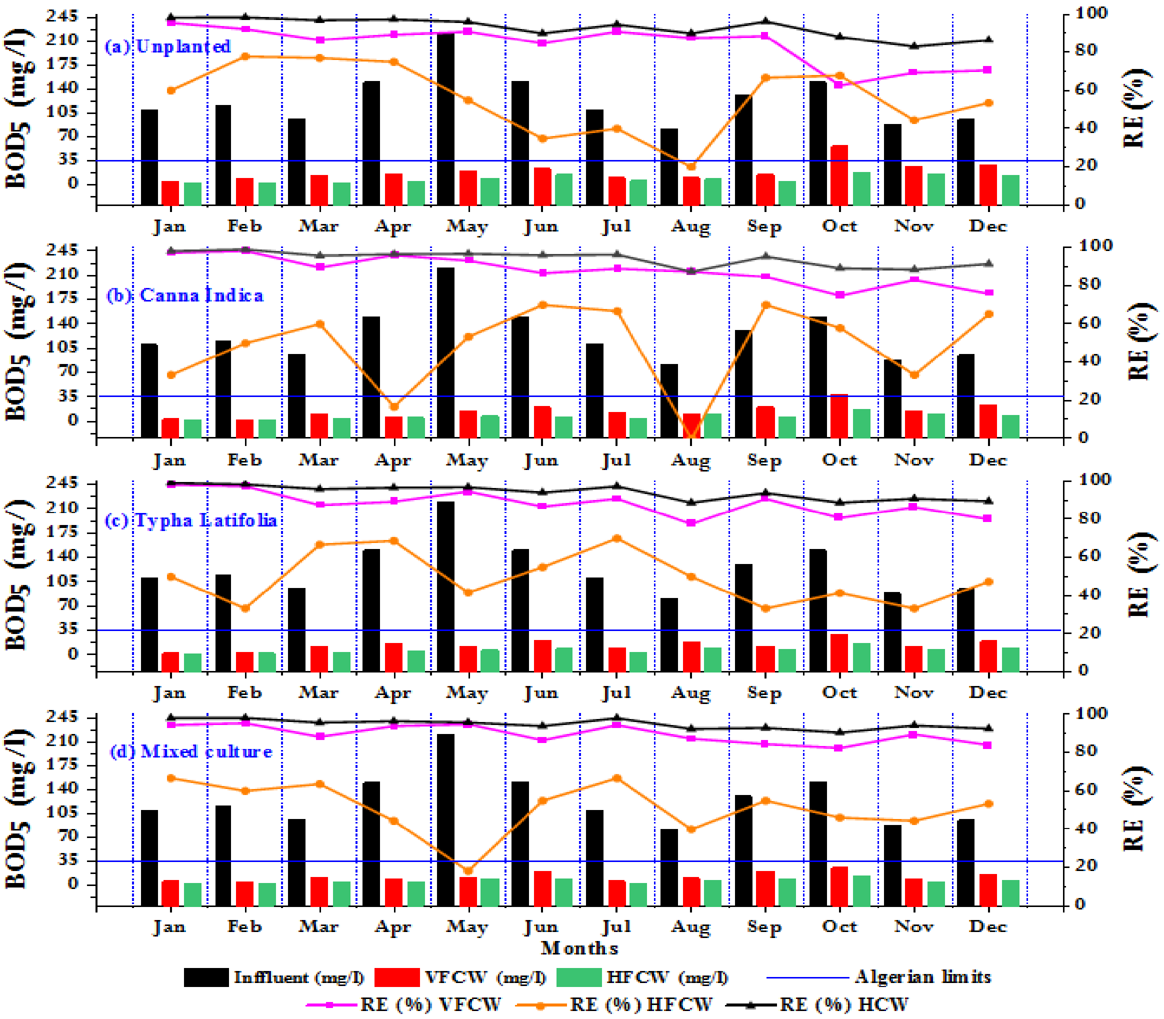


Fig. 4. Comparison of BOD_5 concentrations in the inlet and in the different HCWs, VF (1st stage) outlet and **HF** (2nd stage) outlet. Unplanted (**a**), *Canna Indica* (**b**), *Typha Latifolia* (**c**), and Mixed culture (**d**).

and microbial decomposition (De Lille et al., 2020).

The mean BOD_5 removal efficiency of VFCW (0), (1), (2), (3) was (84.03±10.50 %), (87.96±7.69 %), (88.31±6.63 %), and (89.80±4.76 %), respectively, while the removal efficiency in HFCW (1), (2), (3), and (4) was (56.00±18.30%), (48.03±22.56 %), (49.23±13.58 %), and (51.12±13.73 %), respectively. All systems showed significant differences in BOD_5 removal capacity ($P < 0.05$) between the VFCWs and HFCWs in each series of the HCWs, probably due to the lack of oxygen in HFCWs (Rehman et al., 2017). The order of performance was (Mixed cultures, 95.01%) > (*Canna indica*, 94.28%) > (*Typha latifolia*, 94.13%) > (Unplanted, 92.87%). Similar to various HCWs treating the MWW (El Fassi et al., 2019) in Morocco (91.4 %); (Gizińska-Górna et al., 2020) by Four-Stage HCWs (96.6 %) and (Herrera-Melián et al., 2020) by two HCWs (96.00%). Over the study period, the treated effluents generated WW with a concentration of $BOD_5 < 35$ mg/l, as a maximum value allowed for discharges to surface water bodies by Algerian legislation (JORA, 2006).

Nutrients Removal in the HCWs

Ammonium NH_4^+

The process of nitrogen removal in the CW system is carried out by uptake plants and some living organisms, ammonia volatilization, cation exchange for ammonium, nitrification, and denitrification (Anum et al., 2021). Table 2 and 4 summarizes the mean value of NH_4^+ concentrations at the input and the output of the VFCW and HFCW systems, respectively. NH_4^+ concentrations in the influent ranged from (18.6 to 46.4 mg/l), with a mean value of (29.70±8.00 mg/l), NH_4^+ in the untreated sample WW was slightly elevated (Table **2**). While she was at the output in VFCW systems (0), (1), (2), and (3), (14.97±10.83 mg/l), (0.932±1.42 mg/l), (0.615±0.783 mg/l) and (0.383±0.472 mg/l), respectively. The NH_4^+ was reduced significantly in VFCW systems ($P<0.05$), the high nitrification is due to the aerobic conditions provided by VFCWs (A design that allows the availability of oxygen) (Vymazal, 2007; Stefanakis et al., 2014; Vymazal & Kröpfelová, 2015; Fernandez et al., 2020). The removal efficiency of NH_4^+ by VFCW (0), (1), (2), and (3) was (49.43±35.35 %), (96.57±5.22 %), (97.93±2.33 %) and (98.69±1.44 %), respectively (Figure 5). The higher concentration of DO in the VFCWs systems (>3.5 mg/l) improved the removal of NH4+ by nitrification (Almeida et al., 2020). On the other hand, the decline of NH_4^+ was lower in the HFCW systems as it amounted to (0.057±0.117 mg/l), (0.0226±0.065 mg/l), (0.005±0.013 mg/l) and (0.0226±0.065 mg/l), due to the low percentage of total ammonia contained by VFCWs, and the anaerobic conditions (denitrification) that

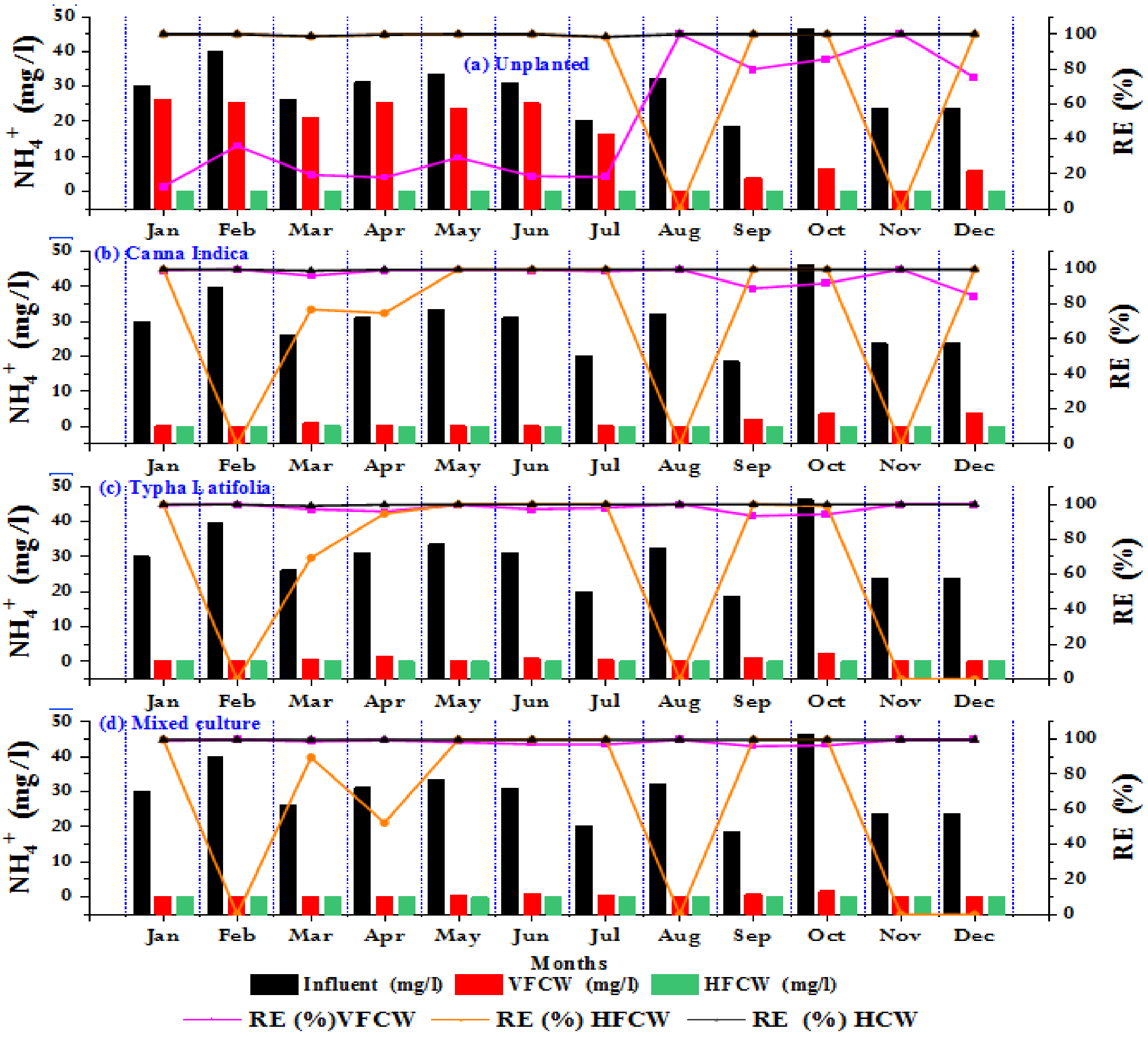
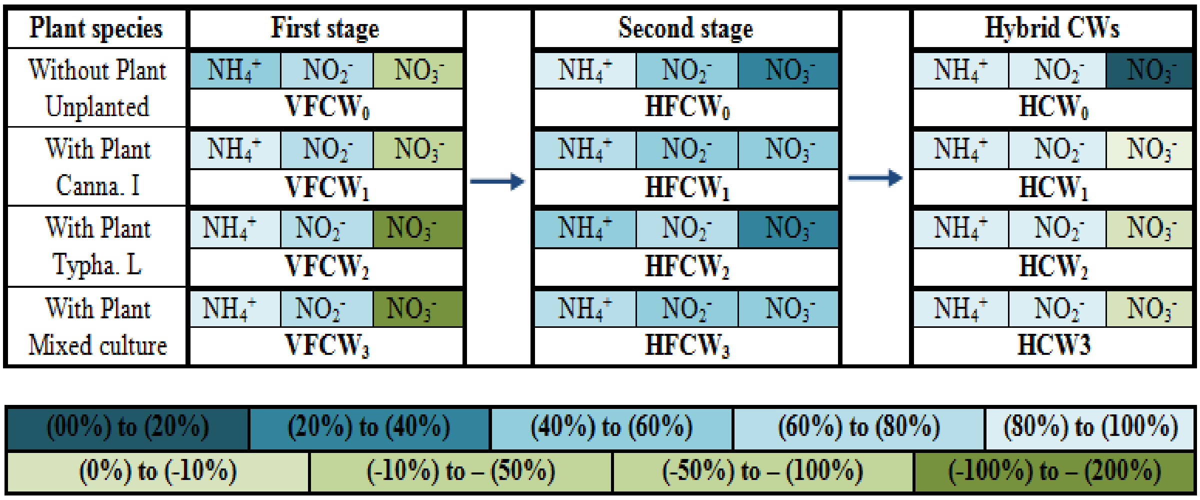


Fig. 5. Comparison of NH_4^+ concentrations in the inlet and in the different HCWs, VFCW (1st stage) outlet and, HFCW (2nd stage) outlet. (a) Unplanted, (b) Canna Indica, (c) Typha Latifolia, and (d) Mixed culture.



Plant species	First stage				Second stage				Hybrid CWs		
Without Plant	NH_4^+	NO_2^-	NO_3^-		NH_4^+	NO_2^-	NO_3^-		NH_4^+	NO_2^-	NO_3^-
Unplanted	$VFCW_0$				$HFCW_0$				HCW_0		
With Plant	NH_4^+	NO_2^-	NO_3^-		NH_4^+	NO_2^-	NO_3^-		NH_4^+	NO_2^-	NO_3^-
Canna. I	$VFCW_1$			→	$HFCW_1$			→	HCW_1		
With Plant	NH_4^+	NO_2^-	NO_3^-		NH_4^+	NO_2^-	NO_3^-		NH_4^+	NO_2^-	NO_3^-
Typha. L	$VFCW_2$				$HFCW_2$				HCW_2		
With Plant	NH_4^+	NO_2^-	NO_3^-		NH_4^+	NO_2^-	NO_3^-		NH_4^+	NO_2^-	NO_3^-
Mixed culture	$VFCW_3$				$HFCW_3$				HCW3		

(00%) to (20%)	(20%) to (40%)	(40%) to (60%)	(60%) to (80%)	(80%) to (100%)
(0%) to (-10%)	(-10%) to – (50%)	(-50%) to – (100%)	(-100%) to – (200%)	

Fig. 6. Average removal efficiency for NH_4^+, NO_2^-, and NO_3^-, of the 1st stage and 2nd stage of different hybrid constructed wetlands HCW_0, HCW_1, HCW_2 and HCW_3.

HFCWs provide (Vymazal, 2018). The removal efficiency by HFCW (0), (1), (2), and (3) were, (83.03±38.78 %), (70.98±43.75 %), (63.57±47.71 %) and (61.84±47.58 %), respectively (Figure 5).

There were significant differences ($P< 0.05$) between the unplanted control and the rest of the VFCWs and HFCWs cultivated by *Canna indica*, *Typha latifolia*, and mixed culture. High aeration provided by the aerenchyma cells of *Canna indica* and *Typha latifolia* roots may be the main reason for the high rate of NH_4^+ elimination (Karungamye, 2022).

In this study, the average removal exceeded 99 % in the HCW systems with *Canna indica*, *Typha latifolia*, and mixed culture. NH_4^+ removal is adequate and is higher than that reported by other authors (Nguyen, **2018**; Fernandez-Fernandez et al., **2020**; Rousso et al., **2019**), and was almost completely removed in mixed cultures (99.98 %), where the uptake of inorganic nitrogen forms (ammonia, nitrates) by macrophages leads to their transformation into organic compounds, for the construction of cells and tissues (Lee, 2009). Note that the moderate temperature confined between (12.2 °C and 29.4 °C) helps the removal rate of NH_4^+ to rise significantly (Redmond et al., 2014; Vymazal & Kröpfelová, 2015).

Nitrite NO_2^- and Nitrate NO_3^-

NH_4^+ in the presence of oxygen is converted to nitrogen nitrite (NO_2^-), and then into nitrogen nitrate (NO_3^-) by bacteria (Nitrification) (Tanveer & Guangzhi, 2012). The variation of the Nitrite and Nitrate of the influent and the effluents of the lab scale HCWs in each phase (VFCWs and HFCWs) of the MWW treatment are given in Table 2 and Table 4. In this study, the NO_2^- and NO_3^- concentrations were deficient at the input (0.068±0.033 mg/l) and (0.44±0.231 mg/l), respectively. With high ammonium reduction rates due to the nitrification by nitrified bacteria attached to the substrate and root (Tanveer, 2020), the nitrate concentration in the effluent of all planted and unplanted systems increased (See Figure **6**). as expected, nitrates increased ($p < 0.05$) in the four VFCWs systems (0), (1), (2), and (3) where amounted to, (0.749±0.432 mg/l), (0.762±0.344 mg/l), (0.850±0.451 mg/l) and (0.998±0.829 mg/l) respectively. Due to the nitrification capacity in the VFCWs and the lack of organic carbon due to the removal of BOD_5 (Vymazal & Kröpfelová, **2015),** these indicated that adequate nitrification occurred at this stage due to the presence of dissolved oxygen (Tang et al., 2009). Comparison with VFCWs, the

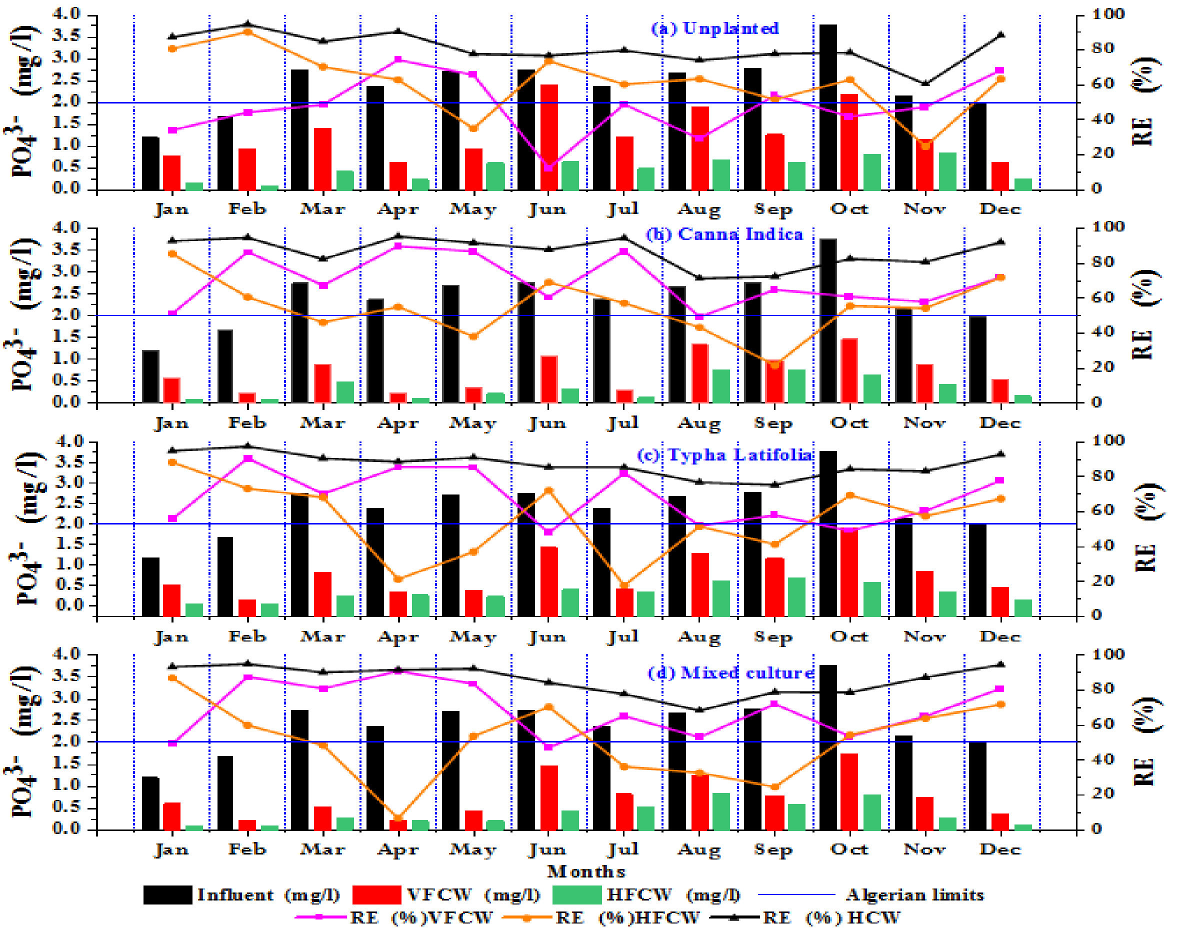


Fig. 7. Comparison of PO_4^{3-} concentrations in the inlet and in the different hybrid, VFCW (1st stage) outlet and, HFCW (2nd stage) outlet. Unplanted, (b) Canna Indica, (c) Typha Latifolia, and (d) Mixed culture (b)

nitrate values were reduced ($p < 0.05$) by HFCWs systems (0), (1), (2), and (3) to (0.361±0.201), (0.383±0.253 mg/l), (0.606±0.361 mg/l) and (0.588±0.507 mg/l) respectively. While 68.16 %,69.34 %,67.97 %, and 69.22 % of nitrite were removed in 1st stage VFCWs (0), (1), (2), and (3) respectively. In 2nd stage, HFCW (0), (1), (2), and (3), nitrite removal was 50.45 %, 44.77 %, 60.80 %, and 52.28 % respectively.

The residual nitrite concentrations after treatment in the vertical system and the increase in nitrates indicates that the nitrification process has not been completed in HFCWs, while a decrease in nitrate concentrations is observed at the exit of HCWs (Rousso et al., 2019 ; De Lille et al., 2020).

Phosphorus Removal

The PO_4^{3-} concentrations at the input and the output of the VFCWs and HFCWs systems are illustrated in Figure 7. The influential PO_4^{3-} concentration was between 1.19 mg/L and 3.77 mg/L, with an average value of 2.43±0.65 mg/L. effluent concentrations decrease significantly compared to influent concentrations in VFCWs and HFCWs. The concentrations of PO_4^{3-} in the effluent observed during the sampling period were (1.281±0.595 mg/l), (0.742±0.431 mg/l), (0.809±0.536 mg/l), and (0.762±0.490 mg/l) in the vertical flow (0), (1), (2), and (3) respectively, and (0.482±0.259 mg/l), (0.347±0.261 mg/l),(0.333±0.209 mg/l), and (0.363±0.268 mg/l) in the horizontal flow (0), (1), (2), and (3) respectively. with an overall elimination rate reaching 80.95

%, 86.68 %,87.22 %,and 86.17 % for HCWs cells (0), (1), (2), and (3) respectively. Considering the results, in planted and unplanted HCWs wetlands it was found that the pathological removals of PO_4^{3-} are not much affected by the presence or absence of plants (Ayaz et al., 2012). The lab scale HCW planted by *Typha latifolia* had a mean PO_4^{3-} removal efficiency of 87.22%. Adsorption, precipitation, and plant uptake are the major PO_4^{3-} removal mechanisms in CW systems (Rasheed et al., 2014). The best results in different HCWs were obtained at the beginning of the experiments [Month of February, HCW_0 (94.67 %), HCW_2 (97.54 %), and HCW_3 (95.14 %)], and [Month of April, HCW_1 (95.48 %)]. The lowest efficiencies in different HCWs were obtained in the last stages of experiments [Month of August, HCW_1 (71.42 %), HCW_3 (68.53 %), Month of September, HCW2 (75.45 %) and, Month of November, HCW2 (60.46 %)], same observations that were reported by (Rousso et al., 2019). Previous research results showed that the mean PO_4^{3-} removal efficiency of HCWs wetlands with a VFCWs flow followed by a HFCWs flow ranged between 70 % and 96 % (Jehawi et al., 2020; Rousso et al., 2019). Although the removal rate of PO_4^{3-} in VFCWs and HFCWs was relatively low, the results of this work showed that HCW experimental units are an outstanding technological solution for PO_4^{3-} disposal in WW treatment. The adsorption of phosphorus decreases throughout the experimental period due to the ability of the bed media to retain it over time. The final PO_4^{3-} concentrations met the Algeria discharge maximum limits for domestic WW treated in constructed wetlands, enforcing $PO_4^{3-} < 2$ mg/l recommended by (JORA. 2006).

According to the results obtained this investigation remains related to the operating conditions of the retention time, flow, and climatic conditions, which can be exploited at the real level by the design of the HCW system.

CONCLUSION

This study evaluated the improvement of organic matter and nutrient treatment performance of a hybrid system (HCWs) monoculture and mixed culture in southern Algeria during one year of operation on a lab scale under arid conditions. Results suggest that this hybrid CW can achieve pollutant control for TSS, COD, BOD_5, NH_4^+, NO_2^-, and PO_4^{3}- with removal efficiencies exceeding (89.93 % with Typha latifolia), (90.77 % with Typha latifolia), (95.01 % with Mixed cultures), (99.98 % with Mixed cultures), (89.99 % with Mixed cultures), and (87.22% with Typha latifolia) respectively. The presence of nitrite in the effluent of HCW systems may indicate that nitrification was not complete. Moreover, T and pH values recorded in this study were below the limited value of the Algerian standards. The high salinity and conductivity were due to the high evapotranspiration process during the monitoring period. The results showed that this system has sufficient capacity to remove various organic matter and nutrients to the desired levels under the arid climate and achieve the guarantee of respecting the limits of WW in Algeria.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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