Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2023.29158

281 (2023) 91–102
January

The different units' performance and bed length effect of constructed wetland on the removal of organic substances, solids and nutrients from municipal wastewater: a case study, Iran

Reza Davoodi[a], Kiomars Sharafi[b], Hamed Soleimani[a], Amir Hossein Mahvi[a,c,*]

[a]*Department of Environmental Health Engineering, School of Public Health, Tehran University of Medical Sciences, Tehran, Iran, Tel.: +989123211827; email: ahmahvi@yahoo.com (A.H. Mahvi), Tel.: +989188592871; email: reza_yello_2000@yahoo.com (R. Davoodi), Tel.: +989198165160; email: hasulimany@yahoo.com (H. Soleimani)*

[b]*Research Center for Environmental Determinants of Health (RCEDH), Kermanshah University of Medical Sciences, Kermanshah, Iran, Tel.: +989183786151; email: kio.sharafi@gmail.com*

[c]*Center for Solid Waste Research (CSWR), Institute for Environmental Research (IER), Tehran University of Medical Sciences, Tehran, Iran*

Received 13 August 2021; Accepted 25 November 2022

ABSTRACT

This study investigated the overall performance and bed length effect of the horizontal subsurface flow constructed wetland (CW) process for full-scale municipal wastewater treatment. 168 samples were collected, including 84 samples in the hot and 84 in the cold season. Seven sampling points were selected as follows: (1) inlet raw wastewater, (2) effluent from an anaerobic pond, (3) from the first 5 m of the selected reed bed, (4) 5 m second, (5) 5 m third, (6) 5 m fourth, and (7) 5 m fifth from the reed bed. The evaluation parameters included biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP). The results showed that the removal efficiency for the BOD_5, COD, TSS, TN, and TP was equal to 90.6%, 90.1%, 94%, 50.2%, and 35.4%, respectively. In the final treated effluent, the concentration of all studied parameters was less than the maximum allowable amount for discharge to the receiving water. The results showed that although the treatment plant's pollution load for BOD_5 and COD parameters in winter was significantly higher than in summer, the treatment plant efficiency in winter was not significantly different from summer. The results also showed that a 15-m bed in the CW system is suitable for achieving the standard of the environmental protection organization of Iran for municipal wastewater treatment in the hot season; however, it seems not to be enough in the cold season. So, 25 m of reed bed length will be required in practice. Finally, it can be concluded that the Qasr-e-Shirin wastewater treatment plant has the proper capability to remove municipal wastewater pollutants in different temperature conditions and the quality of the final effluent indicates the accuracy of the design criteria for this system.

Keywords: Constructed wetland; Municipal wastewater; Reed bed; Wastewater pollutants; Qasr-e-Shirin

* Corresponding author.

1944-3994/1944-3986 © 2023 Desalination Publications. All rights reserved.

1. Introduction

Since the beginning of the twentieth century, mechanical wastewater treatment systems have been increasingly used and are developing daily [1–4]. Due to their high efficiency, small size, and low space requirement, these systems have always been considered the primary option for wastewater treatment in industrial areas, large urban, and even small rural areas [5,6]. Conventional activated sludge and extended aeration process are among the world's most common mechanical wastewater treatment systems [7,8]. These systems have disadvantages such as high manufacturing costs, high energy consumption, complex operation and maintenance, sludge treatment and disposal, and specialist personnel. Other disadvantages are the need for mechanized systems (mainly high-tech) such as aerators, pumps, process control systems, mechanical dewatering systems, and sludge dryers [7–10]. Compared to conventional systems, natural wastewater treatment techniques have low technology and are highly efficient [11–14].

Due to low investment and operation costs, low energy consumption, simple operation, and no need for specialized operators, natural wastewater treatment systems have interested researchers and operators looking for more suitable and cheaper systems [11,15,16]. The most common natural wastewater treatment methods include stabilization ponds, constructed wetlands, and land treatment systems. Among these systems, the wastewater stabilization pond has been implemented and operated almost worldwide [17,18]. In recent decades, the stabilization pond system has been prominent and is still in use in many countries, especially in developed ones, such as Germany, the USA, the Netherlands, China, Australia, Denmark, and India. This system consists of basins used for wastewater treatment by a natural process involving the use of plants or constructed wetlands. Since 1970, researchers have considered these systems' ability to treat various types of wastewater, especially municipal wastewater [19–22].

Constructed wetlands (CWs) systems have two general categories: surface and subsurface CWs. These systems expand more and more because of their simple and cheap operation, high treatment efficiency, and combination of biological, physical, and chemical processes that can occur in them [19,21,22]; and also some other advantages such as low investment costs, no need for specialized operators, utilizable for small communities, and applicable for final treatment step in large community systems [21–23].

Because of the limited use of CWs systems in Iran and many parts of the world, more detailed studies should be carried out. Therefore, determination of the removal pattern of organic matter, nitrogen, phosphorus, and suspended solids, achieving the highest treatment efficiency based on knowledge and awareness and specific study of local conditions with a reasonable cost, can contribute to the development of wastewater treatment technology using constructed wetlands in small and large communities. The more important innovation of this research is the study of the efficiency of the constructed wetlands process at full scale, which has more reliable results for practical purposes compared to studies on the pilot scale [24–27]. Therefore, this study investigated the overall efficiency of different stages and the effect of reed bed length on removing a parameter such as organic compounds, suspended solids, nitrogen, and phosphorus. For this purpose, the process of horizontal subsurface flow constructed wetlands of the wastewater treatment plant in Qasr-e-Shirin city (Iran) has been selected as a field of study.

2. Material and methods

2.1. Area studied

Qasr-e-Shirin County is located in Kermanshah province, Western Iran (Fig. 1). According to the official census results of 2016 in Kermanshah province, the city's population is 19,000. This city is 166 km from Kermanshah and is located near the border of Iran and Iraq. The elevation of this region is about 333 m above sea level, and it has a warm and somewhat temperate climate. The average of the year's coldest months fluctuating is 2.5°C–5°C, and for warmest months is 25°C–43°C. The amount of rainfall varies from 350 to 450 mm/y.

2.2. Specifications of the studied wastewater treatment plant

The study site is a wastewater treatment plant with constructed wetlands process. This treatment plant receives and treats the wastewater of Qasr-e-Shirin city with a flow rate of 2,200 m^3/d. The main parts of this treatment plant include an inlet flow channel, two screening units (mechanical and manual), two grit chamber units, two anaerobic ponds, 12 reed beds, a chlorination basin, and an outlet flow channel (Fig. 2). Anaerobic ponds and reed beds are the most important parts of the studied wastewater treatment plant. The specifications and design principles of these units are presented in Table 1.

2.3. Sampling and analysis

This study selected the coldest and warmest seasons for sampling "cold sampling season" included January, February, and March, and the "hot sampling season" included July, August, and September of 2019. Seven sampling points were selected in the studied wastewater treatment plant, and one sample was collected weekly from each point. Due to three months of sampling in the cold season and three months in the hot season, 24 samples were taken from each point (12 samples in the hot season and 12 samples in the cold season). So, 168 samples were taken in this study (84 samples in the warm season and 84 samples in the cold season). The seven sampling points were as follows:

- Inlet wastewater to the treatment plant (inlet wastewater to anaerobic ponds).
- Effluent from the anaerobic ponds (inlet to reed beds).
- Effluent from the first 5 m of the selected reed bed.
- Effluent from the second 5 m of the selected reed bed.
- Effluent from the third 5 m of the selected reed bed.
- Effluent from the fourth 5 m of the selected reed bed.
- Effluent from the fifth 5 m of the selected reed bed (effluent from the treatment plant).

Fig. 1. Map of Kermanshah province and Qasr-e-Shirin city and location of the studied wastewater treatment plant.

Three main objectives were investigated In this study, including "determination of overall system performance", "determination of anaerobic ponds and reed beds performance", and "determination of reed bed length effect on the removal of organic matter, suspended solids, and nutrients". In the following, each unit's inlet wastewater and outgoing effluent were used to determine its efficiency. For this aim, one of the beds (reed bed number 11 with a length of 25 m) was divided into five parts (5 m each). Four perforated polyethylene pipes with a depth equal to the bed depth were installed on the beds to sample at intervals of 5 m. So, six points were studied for bed sampling: The inlet flow to the bed was as point number 1, four perforated pipes were considered points 2 to 5, and the bed output flow was considered point number 6. Also, due to the uniformity of all hydraulic conditions and the concentration of incoming wastewater to all reed beds, the studied bed's output was considered the treatment plant's output (Fig. 3).

For each sample, the most important quality parameters of raw wastewater and treated effluent, including biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP), were measured according to standard methods of water and wastewater examinations [28].

2.4. Statistical analysis

All data have been investigated using the statistical package IBM SPSS Version 16.00 (SPSS Inc., Chicago, IL, USA). Two-group independent *t*-test at a significant level ($\alpha = 0.05$) was used to compare the efficiency of the treatment plant and the concentration of each parameter between the hot and cold seasons. Also, one way ANOVA test was used at a significant level ($\alpha = 0.05$) to compare the amount of each of the effluent parameters at different distances of the reed bed.

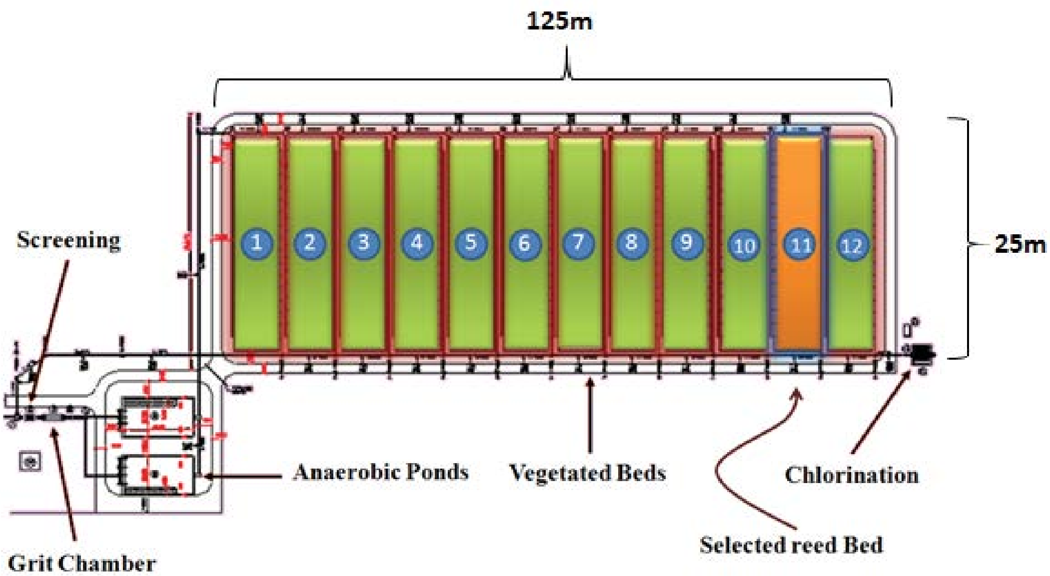

Fig. 2. Schematic of unit arrangement in Qasr-e-Shirin wastewater treatment plant.

Table 1
Specifications and design principles of reed beds and anaerobic ponds of Qasr-e-Shirin wastewater treatment plant

Parameter	Characteristic	Parameter	Characteristic
		Specifications of anaerobic ponds	
Volume of each pond	4,400 m^3	Hydraulic retention time	4 d
Area of each pond	880 m^2	Interval of sludge discharging	3 y
Useful depth	5 m	Floor-type	Compacted clay: height 20 cm
Input flow	180 m^3/d	Volumetric organic	40 kg/d
		Specifications of reed beds	
System type	Subsurface horizontal flow	Average depth of the sand bed	0.85 m
Type of plant	*Phragmites australis* and *Typha latifolia*	Bed porosity	35%
Input flow	180 m^3/d	Hydraulic retention time	5.2 d
BOD_5 loading	450 kg/d	Number of input tubes	16
Total surface area	3,125 m^2	Number of output tubes	16
Length of the sand bed	125 m	Floor-type	Compacted clay
Width of the sand bed	25 m	Distance between two consecutive straw	5 m

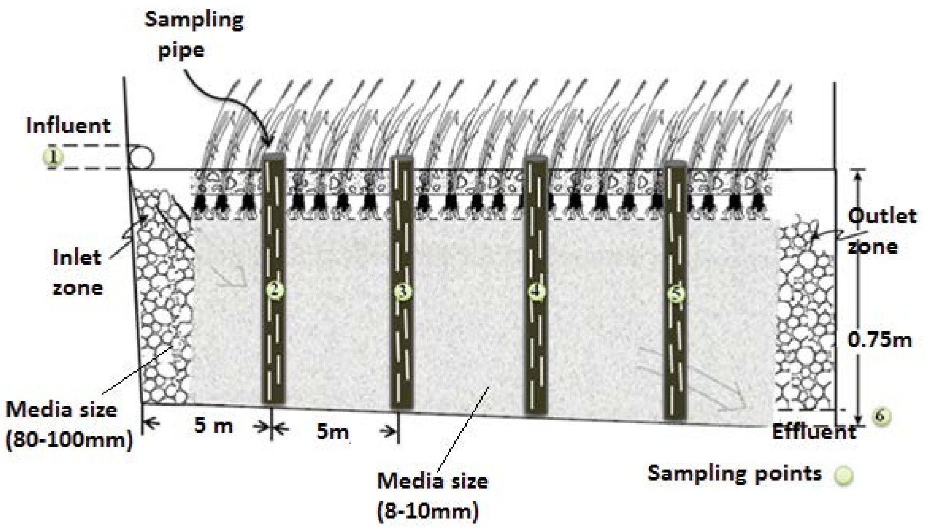

Fig. 3. Cross-sectional cutting of reed bed (Cell-No. 11) and how to install perforated pipes and inlet and outlet position.

3. Results and discussion

The results showed that the average of BOD_5 in the inlet raw wastewater to anaerobic ponds, the effluent from the anaerobic ponds (inlet to reed beds), and the effluent from reed beds (effluent of treatment plant) were equal to 237.9 ± 19.4, 125.5 ± 26.3 and 22.7 ± 4.3 mg/L, respectively (Table 2). Accordingly, the overall efficiency of this plant in BOD_5 removal was equal to 90.6% (anaerobic ponds: 56% and reed beds: 34.6%) (Fig. 4).

Based on the results, the total efficiency of COD removal by the treatment plant is 90.1%, and the share of anaerobic ponds and reed beds equal 42.8% and 47.3%, respectively (Fig. 5). Similarly, the total efficiency of the treatment plant, anaerobic ponds, and reed beds were 94%, 59.3%, and 34.7% in TSS removal (Fig. 6), 50.2%, 9%, and 41.2% in TN removal (Fig. 7), and 35.4%, 9.6% and 25.8% in TP removal (Fig. 8).

The removal of different parameters in the present research is significant and almost equal to many common mechanical systems. In previous studies, the removal of BOD_5 and TSS was 90% to 95%. Also, the removal of total phosphorus and total nitrogen was reported in the range of 10%–20% and 15%–25%, respectively [29–39]. A conventional activated sludge process (with a total nitrogen content of 35 mg/L and a BOD_5 of 200 mg/L) can remove nitrogen and phosphorus at 20%–25% [40].

Therefore, the results of the Qasr-e-Shirin wastewater treatment plant show that, in general, the rate of pollutants removal in this system, compared to many expensive mechanical systems, with high energy consumption and complex operation, was in good and acceptable

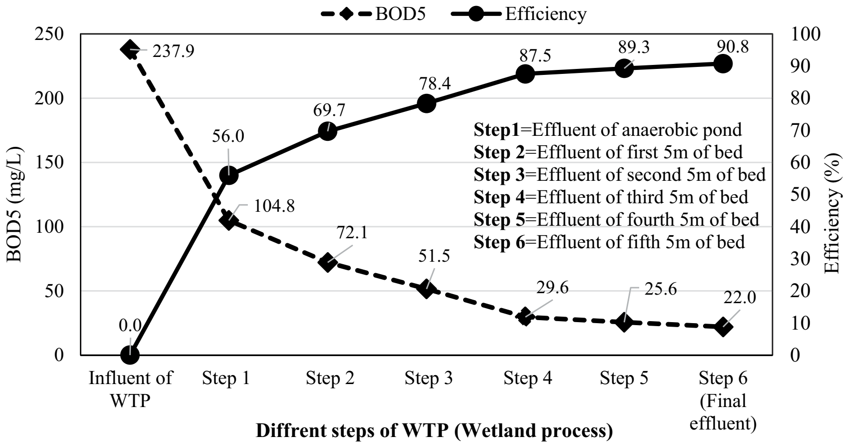

Fig. 4. Overall amount and removal fluctuation of BOD_5 by different steps of WTP (wetland process).

Table 2
Mean, the minimum and maximum amount of various parameters in influent of WTP, the effluent of anaerobic pond and effluent of WTP (wetland process) in sampling warm and cold seasons

Parameters	Sample number	Influent of WTP (Influent of the anaerobic pond)			Influent of bed (Effluent of the anaerobic pond)			Effluent of WTP (Effluent of bed)		
		Min.	Max.	Mean ± SD	Min.	Max.	Mean ± SD	Min.	Max.	Mean ± SD
Warm season										
BOD_5 (mg/L)	12	205.0	241.0	13.5 ± 224.9	77.6	130.3	19.7 ± 104.8	12.5	31.5	5.7 ± 22.0
COD (mg/L)	12	356.0	392.0	11.7 ± 375.0	156.0	248.0	35.1 ± 211.8	30.2	40.5	3.5 ± 36.0
TSS (mg/L)	12	182.0	224.0	17.5 ± 202.5	57.5	96.0	14.0 ± 80.3	7.4	16.3	2.6 ± 11.2
TN (mg/L)	12	33.0	41.3	2.4 ± 38.1	32.3	37.0	1.4 ± 35.5	13.8	18.1	1.5 ± 16.4
TP (mg/L)	12	4.6	8.2	1.2 ± 6.8	5.5	6.8	0.4 ± 6.0	3.6	4.6	0.3 ± 4.1
Cold season										
BOD_5 (mg/L)	12	221.0	276.0	18.9 ± 248.3	124.5	158.9	11.2 ± 146.2	20.1	27.7	2.2 ± 23.5
COD (mg/L)	12	382.0	438.0	22.0 ± 409.7	221.6	254.2	10.7 ± 237.0	31.6	49.3	4.8 ± 41.8
TSS (mg/L)	12	176.0	231.0	20.3 ± 201.4	66.5	97.4	10.4 ± 84.2	8.9	17.5	3.0 ± 13.2
TN (mg/L)	12	26.0	40.2	4.6 ± 34.3	24.0	39.4	5.1 ± 30.4	16.9	22.1	1.8 ± 19.6
TP (mg/L)	12	5.4	7.4	0.7 ± 6.6	4.8	7.1	0.8 ± 6.0	4.2	4.9	0.3 ± 4.6
Total										
BOD_5 (mg/L)	12	205.0	276.0	19.4 ± 237.9	77.6	158.9	26.3 ± 125.5	12.5	31.5	4.3 ± 22.7
COD (mg/L)	12	356.0	438.0	24.7 ± 392.3	156.0	254.2	28.4 ± 224.4	30.2	49.3	5.1 ± 38.9
TSS (mg/L)	12	176.0	231.0	18.5 ± 201.9	57.5	97.4	12.2 ± 82.2	7.4	17.5	3.0 ± 12.2
TN (mg/L)	12	26.0	41.3	4.1 ± 36.2	24.0	39.4	4.5 ± 32.9	13.8	22.1	2.3 ± 18.0
TP (mg/L)	12	4.6	8.2	1.0 ± 6.7	4.8	7.1	0.7 ± 6.0	3.6	4.9	0.4 ± 4.3

condition. It is even more efficient at TSS, nitrogen, and phosphorus removal than conventional mechanical systems. One of the concerns in the water and wastewater industry is achieving low-cost, efficient, simple systems and meeting the receiving water standard. In many cases, meeting these standards results in high construction and operation costs, especially in nutrient removal. Therefore the initial analysis of wastewater and determination of input pollutants can play an essential role in the appropriate treatment system selection before designing mechanical systems. Using simple systems and low-cost constructed wetlands, the number of pollutants in raw wastewater can meet environmental standards, especially in small towns and rural areas such as Qasr-e-Shirin. The results show that the natural treatment system is cost-effective according to the conditions of the studied city.

In general, the efficiency of pollutant removal in the Qasr-e-Shirin wastewater treatment plant is a function of the performance of each unit because the system consists

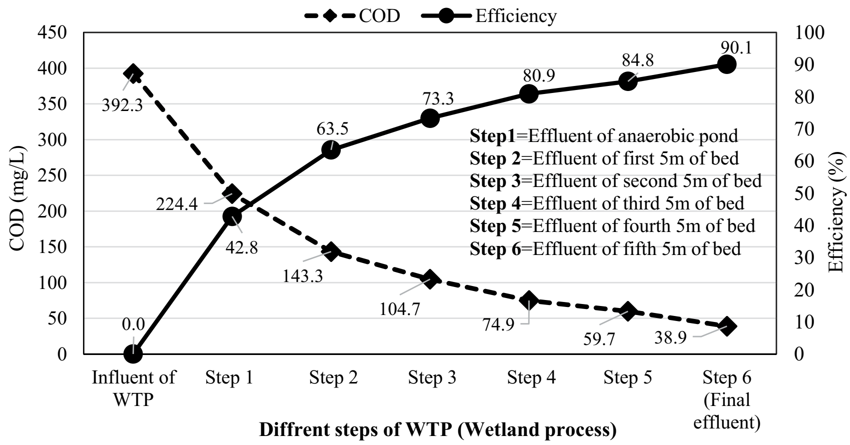

Fig. 5. Overall amount and removal fluctuation of COD by different steps of WTP (wetland process).

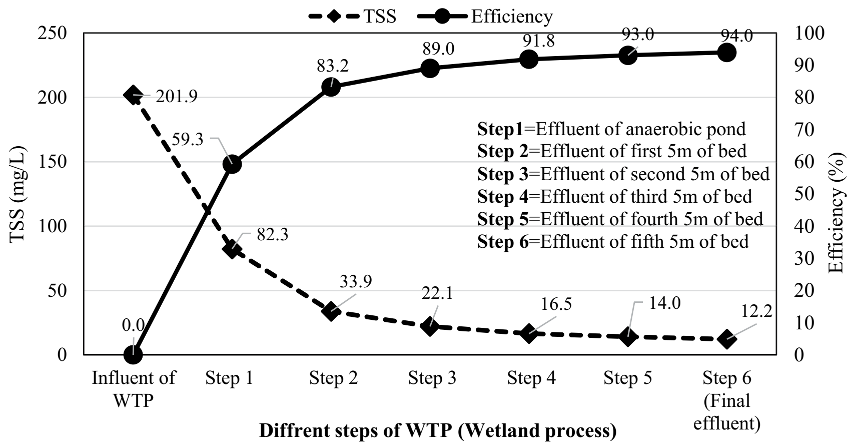

Fig. 6. Overall amount and removal fluctuation of TSS by different steps of WTP (wetland process).

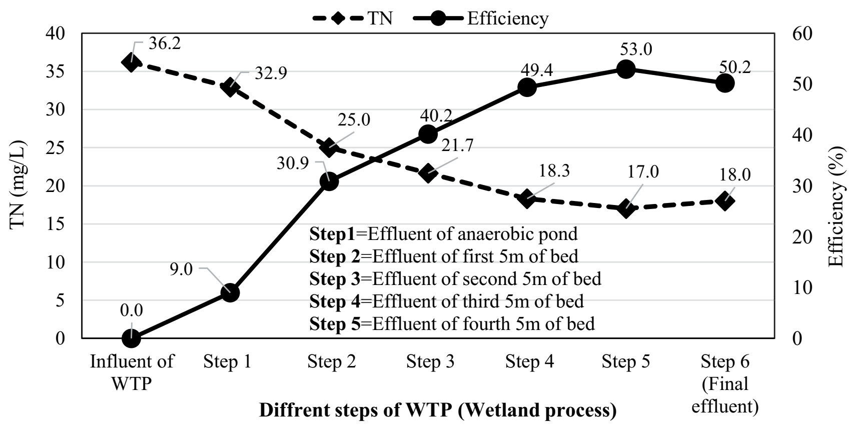

Fig. 7. Overall amount and removal fluctuation of TN by different steps of WTP (wetland process).

of two consecutive units of anaerobic ponds and reed beds. Proper performance and high removal in the anaerobic unit as the first process unit can increase the treatment plant's efficiency and reduce the input load to the reed beds. Different studies show that the combination of anaerobic ponds and subsurface reed beds has high efficiency in contaminants removal. In a study by Sani et al. [41], anaerobic pond units were applied before subsurface reed beds, and the system was tested in continuous and discontinuous flow conditions. Our results showed that in continuous flow mode, the removal rates of BOD_5, TSS, TN, and TP were 77.2%, 92%, 91%, and 89%, respectively. Also, the results of discontinuous

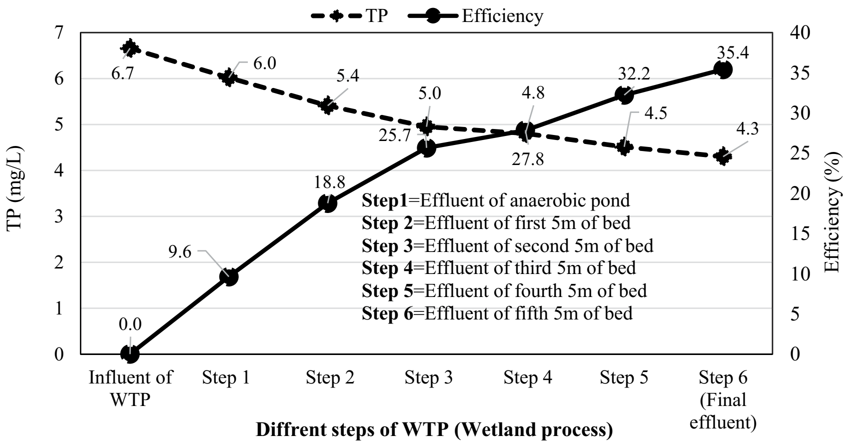

Fig. 8. Overall amount and removal fluctuation of TP by different steps of WTP (wetland process).

removal efficiency for the above parameters were 92%, 97%, 97.5% and 97%, respectively. The BOD_5 and TSS removal results were similar to those obtained in the above study, but the TN and TP removal was at a lower rate in their study.

In the study of Merlin et al. [42], it was reported that the overall average TSS removal from rural wastewater by horizontal subsurface flow constructed wetlands in the pilot scale was more than 95.5%, and the removal of BOD_5 and COD was more than 90%. In Barco and Borin [43], the efficiency of full-scale hybrid-constructed wetlands in COD, TN, and TP removal from municipal wastewater was 46.7%, 74.3%, and 37.4%, respectively. While the results of the present study from the removal efficiency of COD and TN was very different from this study, it was similar in terms of TP removal rate. The results of the Masi et al. [44] study showed that the efficiency of the four-stage constructed wetlands (CW) system in parameters removal of organic compounds, TN, TP, and TSS were 86%, 60%, 43%, and 89%, respectively. In addition, based on Elfanssi et al. [45], the main removal percentages of total suspended solids (TSS), biochemical oxygen demand measured in a 5-day test (BOD_5), chemical oxygen demand (COD), total nitrogen, and total phosphorus were respectively 95%, 93%, 91%, 67%, and 62% which is significantly different from our results. The difference can be due to the quality of raw wastewater entering the treatment plant, design parameters, site climatic conditions, single-stage or multi-stage treatment process, pilot scale, or full scale of the relevant system [17–27,42–45].

According to Iranian Environmental Standards about the discharge of treated wastewater into surface water, the maximum allowable levels of BOD_5, COD, TSS, and TP are 30, 60, 40, and 6 mg/L, respectively [46]. While based on the results, the mean of the above parameters in the final effluent of the Qasr-e-Shirin treatment plant in the hot season was 22.0 ± 5.7, 36.0 ± 3.5, 11.2 ± 2.6 and 4.1 ± 0.3 mg/L, respectively, and in the cold season was 23.5 ± 2.2, 41.8 ± 4.8, 13.2 ± 3.0, and 4.6 ± 0.3 mg/L (Table 2). By comparing the results with the standard, it is clear that the quality of the treated wastewater is much lower than the declared maximum allowable value. Therefore, it can be said that the constructed wetlands system has an initial construction cost and lower operation and maintenance costs than the most common mechanical systems (including conventional and extended aeration-activated sludge processes). Also, the efficiency and quality of treated effluent are relatively equal to conventional mechanical wastewater treatment systems and can be considered even better.

Based on the results, the share of anaerobic ponds in BOD_5 and TSS removal was more than in reed beds, while in TN and TP removal, the share of reed beds was more. The efficiency of COD removal was similar in both anaerobic ponds and reed beds (Figs. 3–7).

The reason for the high efficiency of reed beds in the TN removal compared to anaerobic ponds is the nature of the anaerobic process. Because the recipient is the raw wastewater, there is no oxygen for the nitrification and denitrification processes. So, only the conversion of urea to ammonia nitrogen occurs, and TN is removed in small amounts. In practice, sedimentation can be considered the main factor in the same small amount of removal in anaerobic ponds. However, the TN removal rate in reed beds is much lower than in anaerobic ponds due to multiple mechanisms such as sedimentation, adsorption, adsorption, accumulation, nitrification, and denitrification. Overall these findings are in accordance with Sani et al. [41]. In the TSS removal, the sedimentation mechanism causes the anaerobic ponds to play a more prominent role than the reed beds because sedimentation is the predominant removal mechanism in the anaerobic ponds [47].

The study results showed that the concentration of BOD_5, COD, and TN parameters in the raw wastewater entering the treatment plant in both hot and cold seasons are significantly different (P-value > 0.05). The concentration of the above parameters in the cold season (248.3 ± 18.9, 409.7 ± 22.0 and 34.3 ± 4.6 mg/L, respectively) was significantly higher than in the warm season (224.9 ± 13.5, 375.0 ± 11.7 and 38.1 ± 2.4 mg/L, respectively). The mean TSS and TP of raw wastewater were not significantly different between the hot and cold seasons (P-value > 0.05) (Table 3). Higher concentrations of BOD_5, COD, and TN parameters in the raw wastewater in the cold season can increase the input load. The tourist nature of the city can be one of the reasons for the increased load. In winter, several million pilgrims pass through this area to Iraq for pilgrimage and religious ceremonies.

The results also showed that the removal efficiency of all parameters in the warm season was higher than in the cold season, but this difference was significant only for TN ($P < 0.05$). The slightly higher value of the removal efficiency of mentioned parameters in the warm season compared to the cold season can be due to the higher temperature of the warm season, which improves the biological activity of the wastewater treatment process [48,49].

The above results show that although the treatment plant efficiency was lower in winter than in summer, the removal load in terms of kg/d in winter for BOD_5, COD, and TN parameters was higher than in summer. The results indicate that the treatment plant still has sufficient capacity to treat more contaminants entering the system. The results found that the removal load of anaerobic ponds in the cold season for BOD, COD, and TN is less than in the warm season. This situation is the opposite in reed beds for the same parameters, and the removal load in the cold season is more than in the hot season. As discussed, this is because more input load enters the system during the cold season, and the efficiency of anaerobic ponds decreases, which increases the input load to the reed beds.

The results also showed that the concentration of all parameters (except BOD_5) in the treated effluent between the third and fourth 5 m of the bed was not significantly different ($P > 0.05$). While in other cases, there was a significant difference ($P > 0.05$). In addition, the concentration of all parameters (except COD) in the treated effluent between the fourth and fifth parts of the bed was not significantly different ($P > 0.05$), while in other cases, there was a significant difference ($P > 0.05$), (Tables 4–6). According to the statistical analysis, in the parameters that were not significantly different, the average concentration of that parameter is approximately the same between the third and fourth 5-m distances or between the fourth and fifth 5-m distances. Therefore, the parameter's concentration difference between the mentioned distances is insignificant.

Based on the statistical analysis, a distance of 15 m from the bed is sufficient for desired pollutants removal in the hot season because the average parameters of BOD_5, COD, TSS, and TP in the effluent from the third 5 m of the bed were 29.6 ± 4.2, 58.9 ± 2.8, 15.4 ± 1.4 and 4.5 ± 0.3 mg/L, respectively, which are less than the amount allowed by the Iran standard to discharge effluent into the receiving water (30, 60, 40 and 6 mg/L, respectively). The quality of the effluent from the third 5 m of the bed (length 15 m) in the cold season shows that although the average TSS and TP meet the standard, the BOD_5 (54.3 ± 4.2 mg/L) and COD (91.0 ± 0.5 mg/L) are higher than the acceptable standard (Table 4). Therefore, a longer bed length is required to meet these parameters' standards in the cold season. According to the results obtained in the cold season (Table 4), although the fourth 5 m of the bed (20 m in length) caused the BOD_5 (29.9 ± 2.1 mg/L) to fall below the standard (30 mg/L), the mean COD (73.7 ± 2.3 mg/L) is still higher than the standard limit (60 mg/L). So, more bed length is needed to further reduce the amount of COD, especially in the cold season. Based on Table 4, it is clear that the average amount of COD in the effluent from the fifth part of the bed compared to the fourth part has decreased significantly (73.7 ± 2.3 to 41.8 ± 4.8 mg/L) ($P < 0.05$). The above results show that based on the quality of raw wastewater and the design parameter of anaerobic ponds, a bed of 25 m is needed to produce an effluent meeting the recommended guidelines. It is necessary to explain that if the efficiency of anaerobic ponds can be improved by changing the design criteria or operating conditions, with a length of 15 or 20 m from the reed beds, the treated effluent can be obtained according to the standard of the environmental protection organization of Iran.

Table 3
Statistical analysis for comparison of the warm and cold seasons in terms of parameters concentration of influent wastewater to WWTP and overall efficiency of WWTP for removal of parameters

Parameters	Warm season		Cold season		P-value
	Number of samples	Mean ± SD	Number of samples	Mean ± SD	
The parameters concentration of influent wastewater to WWTP (mg/L)					
BOD_5 (mg/L)	12	13.5 ± 224.9	12	18.9 ± 248.3	0.002
COD (mg/L)	12	11.7 ± 375.0	12	22.0 ± 409.7	<0.001
TSS (mg/L)	12	17.5 ± 202.5	12	20.3 ± 201.4	0.886
TN (mg/L)	12	2.4 ± 38.1	12	4.6 ± 34.3	0.024
TP (mg/L)	12	1.2 ± 6.8	12	0.7 ± 6.6	0.578
Overall efficiency of WWTP for parameters removal (%)					
BOD_5 (mg/L)	12	2.4 ± 90.5	12	2.4 ± 90.4	0.768
COD (mg/L)	12	0.95 ± 90.4	12	1.5 ± 89.7	0.211
TSS (mg/L)	12	1.2 ± 94.5	12	1.9 ± 93.3	0.091
TN (mg/L)	12	4.0 ± 56.8	12	12.6 ± 41.3	0.001
TP (mg/L)	12	14.3 ± 37.9	12	9.7 ± 29.6	0.110

Table 4
Mean, the minimum and maximum amount of various parameters in influent of bed, effluent from first and second 5 m of bed related to wetland process in sampling warm and cold seasons

Parameters	Sample number	Influent of bed			Effluent from the first 5 m of bed			Effluent from the second 5 m of bed		
		Min.	Max.	Mean ± SD	Min.	Max.	Mean ± SD	Min.	Max.	Mean ± SD
Warm season										
BOD_5 (mg/L)	12	77.6	130.3	19.7 ± 104.8	65.0	86.5	6.8 ± 72.1	45.8	56.3	3.1 ± 51.5
COD (mg/L)	12	156.0	248.0	35.1 ± 211.8	100.9	127.8	7.9 ± 119.3	74.5	87.5	4.3 ± 81.7
TSS (mg/L)	12	57.5	96.0	14.0 ± 80.3	27.0	39.0	4.1 ± 32.5	19.5	22.4	0.8 ± 21.1
TN (mg/L)	12	32.3	37.0	1.4 ± 35.5	22.8	27.6	1.4 ± 25.2	20.4	23.8	1.3 ± 22.1
TP (mg/L)	12	5.5	6.8	0.4 ± 6.0	4.7	5.9	0.3 ± 5.3	4.3	5.3	0.3 ± 4.7
Cold season										
BOD_5 (mg/L)	12	124.5	158.9	11.2 ± 146.2	89.9	110.5	5.4 ± 98.9	15.0	84.5	18.9 ± 72.9
COD (mg/L)	12	221.6	254.2	10.7 ± 237.0	163.2	171.3	2.6 ± 167.4	123.7	132.9	3.0 ± 127.7
TSS (mg/L)	12	66.5	97.4	10.4 ± 84.2	25.8	40.7	4.3 ± 35.2	20.5	29.9	2.8 ± 23.2
TN (mg/L)	12	24.0	39.4	5.1 ± 30.4	22.9	26.7	1.0 ± 24.8	19.9	22.6	0.8 ± 21.2
TP (mg/L)	12	4.8	7.1	0.9 ± 6.0	5.1	5.9	0.3 ± 5.6	5.1	5.3	0.1 ± 5.2
Total										
BOD_5 (mg/L)	12	77.6	158.9	26.3 ± 125.5	65.0	110.5	14.9 ± 85.5	15.0	84.5	17.2 ± 62.2
COD (mg/L)	12	156.0	254.2	28.4 ± 224.4	143.3	25.2	171.3 ± 100.9	74.5	132.9	23.7 ± 104.7
TSS (mg/L)	12	57.5	97.4	12.3 ± 82.3	25.8	40.7	4.3 ± 33.9	19.5	29.9	2.3 ± 22.1
TN (mg/L)	12	24.0	39.4	4.5 ± 32.9	22.8	27.6	1.2 ± 25.0	19.9	23.8	1.1 ± 21.7
TP (mg/L)	12	4.8	7.1	0.7 ± 6.0	4.7	5.9	0.3 ± 5.4	4.3	5.3	0.3 ± 5.0

Table 5
Mean, the minimum and maximum amount of various parameters in effluent from third, fourth, and fifth 5 m of bed related to wetland process in sampling warm and cold seasons

Parameters	Sample number	Effluent from the third 5 m of bed			Effluent from the fourth 5 m of bed			Effluent from the fifth 5 m of bed		
		Min.	Max.	Mean ± SD	Min.	Max.	Mean ± SD	Min.	Max.	Mean ± SD
Warm season										
BOD_5 (mg/L)	12	22.6	38.3	4.2 ± 29.6	22.1	32.8	0.3 ± 25.6	12.5	31.5	5.7 ± 22.0
COD (mg/L)	12	54.8	63.6	2.8 ± 58.9	41.5	49.5	2.4 ± 45.8	30.2	40.5	3.5 ± 36.0
TSS (mg/L)	12	13.0	17.4	1.4 ± 15.4	11.9	14.1	0.7 ± 13.0	7.4	16.3	2.6 ± 11.2
TN (mg/L)	12	17.5	19.5	0.7 ± 18.7	17.2	17.9	0.2 ± 17.4	13.8	18.1	1.5 ± 16.4
TP (mg/L)	12	4.0	4.9	0.3 ± 4.5	3.9	4.9	0.3 ± 4.3	3.6	4.6	0.3 ± 4.1
Cold season										
BOD_5 (mg/L)	12	48.5	61.0	4.2 ± 54.3	26.8	34.0	2.1 ± 29.9	20.1	27.7	2.2 ± 23.5
COD (mg/L)	12	84.6	99.5	0.5 ± 91.0	70.1	77.4	2.3 ± 73.7	31.6	49.3	4.8 ± 41.8
TSS (mg/L)	12	15.2	19.3	1.1 ± 17.6	13.2	16.3	0.9 ± 15.1	8.9	17.5	3.0 ± 13.2
TN (mg/L)	12	16.9	18.9	0.6 ± 17.9	14.9	19.1	1.2 ± 16.6	16.9	22.1	1.8 ± 19.6
TP (mg/L)	12	5.0	5.3	0.1 ± 5.1	4.3	4.9	0.2 ± 4.8	4.2	4.9	0.3 ± 4.6
Total										
BOD_5 (mg/L)	12	22.6	61.0	13.2 ± 41.9	22.1	34.0	3.4 ± 27.7	12.5	31.5	4.3 ± 22.7
COD (mg/L)	12	54.8	99.5	16.9 ± 74.9	41.5	77.4	14.4 ± 59.7	30.2	49.3	38.9 ± 5.1
TSS (mg/L)	12	13.0	19.3	1.6 ± 16.5	11.9	16.3	1.3 ± 14.0	7.4	17.5	3.0 ± 12.2
TN (mg/L)	12	16.5	19.5	0.8 ± 18.3	14.9	19.1	0.9 ± 0.17	13.8	22.1	2.3 ± 18.0
TP (mg/L)	12	4.8	5.3	0.4 ± 4.8	3.9	4.9	0.3 ± 4.5	3.6	4.9	0.4 ± 4.3

Table 6
Statistical analysis for comparison of different sampling steps in terms of parameters concentration of effluent

Sampling step		BOD_5	COD	TSS	TN	TP
Influent of bed	Effluent from the first 5 m of bed	<0.001	<0.001	<0.001	<0.001	<0.001
	Effluent from the second 5 m of bed	<0.001	<0.001	<0.001	<0.001	<0.001
	Effluent from the third 5 m of bed	<0.001	<0.001	<0.001	<0.001	<0.001
	Effluent from the fourth 5 m of bed	<0.001	<0.001	<0.001	<0.001	<0.001
	Effluent from the fifth 5 m of bed	<0.001	<0.001	<0.001	<0.001	<0.001
Effluent from the first 5 m of bed	Influent of bed	<0.001	<0.001	<0.001	<0.001	<0.001
	Effluent from the second 5 m of bed	<0.001	<0.001	<0.001	<0.001	0.003
	Effluent from the third 5 m of bed	<0.001	<0.001	<0.001	<0.001	<0.001
	Effluent from the fourth 5 m of bed	<0.001	<0.001	<0.001	<0.001	<0.001
	Effluent from the fifth 5 m of bed	<0.001	<0.001	<0.001	<0.001	<0.001
Effluent from the second 5 m of bed	Influent of bed	<0.001	<0.001	<0.001	<0.001	<0.001
	Effluent from the first 5 m of bed	<0.001	<0.001	<0.001	<0.001	0.003
	Effluent from the third 5 m of bed	<0.001	<0.001	0.008	<0.001	0.836
	Effluent from the fourth 5 m of bed	<0.001	<0.001	<0.001	<0.001	0.006
	Effluent from the fifth 5 m of bed	<0.001	<0.001	<0.001	<0.001	<0.001
Effluent from the third 5 m of bed	Influent of bed	<0.001	<0.001	<0.001	<0.001	<0.001
	Effluent from the first 5 m of bed	<0.001	<0.001	<0.001	<0.001	<0.001
	Effluent from the second 5 m of bed	<0.001	<0.001	0.008	<0.001	0.836
	Effluent from the fourth 5 m of bed	0.020	0.113	0.665	0.335	0.163
	Effluent from the fifth 5 m of bed	<0.001	<0.001	0.091	0.997	0.001
Effluent from the fourth 5 m of bed	Influent of bed	<0.001	<0.001	<0.001	<0.001	<0.001
	Effluent from the first 5 m of bed	<0.001	<0.001	<0.001	<0.001	<0.001
	Effluent from the second 5 m of bed	<0.001	<0.001	<0.001	<0.001	0.006
	Effluent from the third 5 m of bed	0.020	0.113	0.665	0.335	0.163
	Effluent from the fifth 5 m of bed	0.870	0.008	0.858	0.633	0.502
Effluent from the fifth 5 m of bed	Influent of bed	<0.001	<0.001	<0.001	<0.001	<0.001
	Effluent from the first 5 m of bed	<0.001	<0.001	<0.001	<0.001	<0.001
	Effluent from the second 5 m of bed	<0.001	<0.001	<0.001	<0.001	<0.001
	Effluent from the third 5 m of bed	<0.001	<0.001	0.091	0.997	0.001
	Effluent from the fourth 5 m of bed	0.870	0.008	0.858	0.663	0.502

4. Conclusion

Based on the results of this study, it can be concluded that the Qasr-e-Shirin wastewater treatment plant with horizontal subsurface flow constructed wetlands process can have good efficiency in organic compounds, nitrogen and phosphorus, and TSS removal from municipal wastewater. So that the overall efficiency of the process in BOD_5, COD, TSS, TN, and TP parameters removal, were 90.6%, 90.1%, 94%, 50.2%, and 35.4%, respectively. In addition, the amount of high parameters in the final treated effluent was less than the maximum allowable amount of these parameters for discharge to receiving water. It can be said that although the pollution load of the treatment plant for BOD_5 and COD parameters in winter was significantly higher than in summer, the treatment plant efficiency in winter was not significantly different from the summer. Thus, it can be concluded that the treatment plant still has sufficient capacity to treat more pollutants. Based on the results, although a distance of 15 m from the reed beds is sufficient to achieve quality following the standard, this reed bed length is not enough in the cold season, and 25 m of reed beds will be required.

References

[1] E. Bazrafshan, F. Kord Mostafapour, M. Farzadkia, K.A. Ownagh, A.H. Mahvi, Slaughterhouse wastewater treatment by combined chemical coagulation and electrocoagulation process, PLoS One, 7 (2012) e40108, doi: 10.1371/journal.pone.0040108.

[2] E. Ahmadi, S. Yousefzadeh, A. Mokammel, M. Miri, M. Ansari, H. Arfaeinia, M.Y. Badi, H.R. Ghaffari, S. Rezaei, A.H. Mahvi, Kinetic study and performance evaluation of an integrated two-phase fixed-film baffled bioreactor for bioenergy recovery from wastewater and bio-wasted sludge, Renewable Sustainable Energy Rev., 121 (2020) 109674, doi: 10.1016/j.rser.2019.109674.

[3] M. Rezvani Ghalhari, H. Schönberger, B. Askari Lasaki, K. Asghari, E. Ghordouei Milan, N. Rezaei Rahimi, S. Yousefi, B. Vakili, A.H. Mahvi, Performance evaluation and siting index of the stabilization ponds based on environmental parameters: a case study in Iran, J. Environ. Health Sci. Eng., 19 (2021) 1681–1700.

[4] A.H. Mahvi, A. Naghizadeh, A.R. Mesdaghinia, M. Alimohammadi, Application of Membrane Technology in High Quality Effluent Production, The First National Seminar on the Role of Recycled Water and Wastewater in Water Resources Management, CIVILICA, Tehran, Iran, 2008.
[5] A. Kettab, H. Bouanani, Urban Wastewater Treatment Plants. Pharmaceutical Wastewater Treatment Technologies, 2021.
[6] A. Asgari, R. Nabizadeh, A.H. Mahvi, S. Nasseri, M.H. Dehghani, S. Nazmara, K. Yaghmaeian, Biodegradation of total petroleum hydrocarbons from acidic sludge produced by re-refinery industries of waste oil using in-vessel composting, J. Environ. Health Sci. Eng., 15 (2017) 3, doi: 10.1186/s40201-017-0267-1.
[7] D. Brockmann, Y. Gérand, C. Park, K. Milferstedt, A. Hélias, J. Hamelin, Wastewater treatment using oxygenic photogranule-based process has lower environmental impact than conventional activated sludge process, Bioresour. Technol., 319 (2021) 124204, doi: 10.1016/j.biortech.2020.124204.
[8] M.F.U.B. Md Hafiz, S.R.B. Mohamed Kutty, S.N.B.S.I. Hakmi, Impact of Treating Ammonia-Nitrogen Contamination from Chemical Fertilizer Plant Using Extended Aeration Activated Sludge System, Proceedings of the International Conference on Civil, Offshore and Environmental Engineering, Springer, New York, NY 10036, USA, 2021, pp. 163–173.
[9] A. Al-Mamun, Biological efficiency and control of a membrane bioreactor and conventional activated sludge process for treating municipal wastewater, J. Agric. Mar. Sci., 26 (2021) 27–36.
[10] M. Nowrouzi, H. Abyar, A. Rostami, Cost coupled removal efficiency analyses of activated sludge technologies to achieve the cost-effective wastewater treatment system in the meat processing units, J. Environ. Manage., 283 (2021) 111991, doi: 10.1016/j.jenvman.2021.111991.
[11] D.J. Sarkar, S.D. Sarkar, B.K. Das, B.K. Sahoo, A. Das, S.K. Nag, R.K. Manna, B.K. Behera, S. Samanta, Occurrence, fate and removal of microplastics as heavy metal vector in natural wastewater treatment wetland system, Water Res., 192 (2021) 116853, doi: 10.1016/j.watres.2021.116853.
[12] A. Almasi, A. Dargahi, A. Amrane, M. Fazlzadeh, M. Mahmoudi, A. Hashemian, Effect of the retention time and the phenol concentration on the stabilization pond efficiency in the treatment of oil refinery wastewater, Fresenius Environ. Bull., 23 (2014) 2541–2548.
[13] A. Dargahi, M. Mohammadi, F. Amirian, A. Karami, A. Almasi, Phenol removal from oil refinery wastewater using anaerobic stabilization pond modeling and process optimization using response surface methodology (RSM), Desal. Water Treat., 87 (2017) 199–208.
[14] A. Almasi, A. Dargahi, A. Amrane, M. Fazlzadeh, M. Soltanian, A. Hashemian, Effect of molasses addition as biodegradable material on phenol removal under anaerobic conditions, Environ. Eng. Manage. J., 17 (2018), doi: 10.30638/eemj.2018.146.
[15] K. Sharafi, M. Pirsaheb, T. Khosravi, A. Dargahi, M. Moradi, M.T. Savadpour, Fluctuation of organic substances, solids, protozoan cysts, and parasite egg at different units of a wastewater integrated stabilization pond (full scale treatment plant): a case study, Iran, Desal. Water Treat., 57 (2016) 4913–4919.
[16] M.S. Alves, F.J.A. da Silva, A.L.C. Araújo, E.L. Pereira, Performance evaluation and coefficients of reliability for waste stabilization ponds in northeast Brazil, Rev. Ambient. Água, 16 (2021) 2571, doi: 10.4136/ambi-agua.2571.
[17] N. Mburu, S.M. Tebitendwa, J.J.A. van Bruggen, D.P.L. Rousseau, P.N.L. Lens, Performance comparison and economics analysis of waste stabilization ponds and horizontal subsurface flow constructed wetlands treating domestic wastewater: a case study of the Juja sewage treatment works, J. Environ. Manage., 128 (2013) 220–225.
[18] G.-J. Liu, D. Zheng, L.-W. Deng, Q. Wen, Y. Liu, Comparison of constructed wetland and stabilization pond for the treatment of digested effluent of swine wastewater, Environ. Technol., 35 (2014) 2660–2669.
[19] S. Kataki, S. Chatterjee, M.G. Vairale, S. Sharma, S.K. Dwivedi, D.K. Gupta, Constructed wetland, an eco-technology for wastewater treatment: a review on various aspects of microbial fuel cell integration, low temperature strategies and life cycle impact of the technology, Renewable Sustainable Energy Rev., 148 (2021) 111261, doi: 10.1016/j.rser.2021.111261.
[20] T. González, J. Puigagut, G. Vidal, Organic matter removal and nitrogen transformation by a constructed wetland-microbial fuel cell system with simultaneous bioelectricity generation, Sci. Total Environ., 753 (2021) 142075, doi: 10.1016/j.scitotenv.2020.142075.
[21] W. Zhufang, Z. Zhimiao, C. Mengyu, C. Mengqi, Z. Yinjiang, S. Zonglin, Influence of plant community on the purification of domestic sewage by constructed wetland, Chin. J. Environ. Eng., 15 (2021) 126–135.
[22] Y. Zhang, Z. Ji, Y. Pei, Nutrient removal and microbial community structure in an artificial-natural coupled wetland system, Process Saf. Environ. Prot., 147 (2021) 1160–1170.
[23] R.S. Sutar, B. Lekshmi, D.R. Ranade, Y.J. Parikh, S.R. Asolekar, Towards Enhancement of Water Sovereignty by Implementing the 'Constructed Wetland for Reuse' Technology in Gated Community, K.R. Reddy, A.K. Agnihotri, Y. Yukselen-Aksoy, B.K. Dubey, A. Bansal, Eds., Sustainable Environment and Infrastructure, Lecture Notes in Civil Engineering, Vol. 90, Springer, Cham, 2021. Available at: https://doi.org/10.1007/978-3-030-51354-2_15
[24] E. Alayu, S. Leta, Post treatment of anaerobically treated brewery effluent using pilot scale horizontal subsurface flow constructed wetland system, Bioresour. Bioprocess, 8 (2021) 1–19, doi: 10.1186/s40643-020-00356-0.
[25] T.Y. Chen, C.M. Kao, T.Y. Yeh, H.Y. Chien, A.C. Chao, Application of a constructed wetland for industrial wastewater treatment: a pilot-scale study, Chemosphere, 64 (2006) 497–502.
[26] C.H. Sim, M.K. Yusoff, B. Shutes, S.C. Ho, M. Mansor, Nutrient removal in a pilot and full scale constructed wetland, Putrajaya city, Malaysia, J. Environ. Manage., 88 (2008) 307–317.
[27] S.Ç. Ayaz, Ö. Aktaş, L. Akça, N. Fındık, Effluent quality and reuse potential of domestic wastewater treated in a pilot-scale hybrid constructed wetland system, J. Environ. Manage., 156 (2015) 115–120.
[28] W.E. Federation, A. Association, Standard Methods for the Examination of Water and Wastewater, American Public Health Association (APHA), Washington, DC, USA, 2005.
[29] H.E. Muga, J.R. Mihelcic, Sustainability of wastewater treatment technologies, J. Environ. Manage., 88 (2008) 437–447.
[30] N. Kretschmer, L. Ribbe, H. Gaese, Wastewater reuse for agriculture, Technol. Resour. Manag. Dev. Sci. Contrib. Sus. Dev., 2 (2002) 37–64.
[31] USEPA, Process Design Manual: Land Treatment of Municipal Wastewater Effluents, U.S. Environmental Protection Agency Cincinnati, OH, USA, 2006.
[32] R. Gilbert, C.P. Gerba, R. Rice, H. Bouwer, C. Wallis, J. Melnick, Virus and bacteria removal from wastewater by land treatment, Appl. Environ. Microbiol., 32 (1976) 333–338.
[33] L.E. Leach, C.G. Enfield, C.C. Harlin, Summary of Long-Term Rapid Infiltration System Studies, Environmental Protection Agency, Office of Research and Development, Robert S. Kerr Environmental Research Laboratory, 1980.
[34] G. Pettygrove, T. Asano, Irrigation With Reclaimed Municipal Wastewater. A Guidance Manual, California State Water Res, Control Board. Davis, California, 1984.
[35] S.A. Hannah, B.M. Austern, A.E. Eralp, R.H. Wise, Comparative removal of toxic pollutants by six wastewater treatment processes, J. Water Pollut. Control Fed., 58 (1986) 27–34.
[36] R. Otis, J. Kreissl, R. Frederick, R. Goo, P. Casey, B. Tonning, Onsite Wastewater Treatment Systems Manual (EPA/625/R-00/008), U.S. Environmental Protection Agency, Washington, DC, USA, 2002.
[37] E. Vaiopoulou, P. Melidis, A. Aivasidis, An activated sludge treatment plant for integrated removal of carbon, nitrogen and phosphorus, Desalination, 211 (2007) 192–199.
[38] R. Crites, S. Reed, R.Bastin, Land Treatment Systems for Municipal and Industrial Wastes, McGraw Hill Professional, New York, NY 10019, USA, 2000.

[39] J. Vymazal, Constructed wetlands for wastewater treatment: five decades of experience, Environ. Sci. Technol., 45 (2011) 61–69.
[40] M. Christensson, Enhanced Biological Phosphorus Removal: Carbon Sources, Nitrate as Electron Acceptor and Characterisation of the Sludge Community. Nitrogen Removal, Ph.D. Thesis, Lund University, Sweden, 1997.
[41] A. Rahmani Sani, N. Mehrdadi, A.A. Azimi, A. Torabian, Performance of the subsurface flow wetland in batch flow for municipal wastewater treatment, J. Water Wastewater, Ab va Fazilab, 20 (2009) 32–40 (in Persian).
[42] G. Merlin, J.-L. Pajean, T. Lissolo, Performances of constructed wetlands for municipal wastewater treatment in rural mountainous area, Hydrobiologia, 469 (2002) 87–98.
[43] A. Barco, M. Borin, Treatment performance and macrophytes growth in a restored hybrid constructed wetland for municipal wastewater treatment, Ecol. Eng., 107 (2017) 160–171.
[44] F. Masi, S. Caffaz, A. Ghrabi, Multi-stage constructed wetland systems for municipal wastewater treatment, Water Sci. Technol., 67 (2013) 1590–1598.
[45] S. Elfanssi, N. Ouazzani, L. Latrach, A. Hejjaj, L. Mandi, Phytoremediation of domestic wastewater using a hybrid constructed wetland in mountainous rural area, Int. J. Phytorem., 20 (2018) 75–87.
[46] Wastewater Effluent Standard, Article 5 of the Regulation on Prevention of Water Pollution, Department of Environment Islamic Republic of Iran, Tehran, Iran, 2005.
[47] B. Beran, F. Kargi, A dynamic mathematical model for wastewater stabilization ponds, Ecol. Modell., 181 (2005) 39–57.
[48] G. Tchobanoglous, F.L. Burton, Wastewater Engineering: Treatment, Disposal Reuse, Metcalf & Eddy Inc., McGraw-Hill, New York, 1991.
[49] F.D. Moreira, E.H.O. Dias, Constructed wetlands applied in rural sanitation: a review, Environ. Res., 190 (2020) 110016, doi: 10.1016/j.envres.2020.110016.