Assessment of the performance of intermittent planted filters in treating urban wastewater under arid climate

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ABSTRACT

Intermittent planted filters are extensive biological purification techniques aimed at oxidizing and decontaminating urban wastewater at a low cost and with minimum environmental impacts. The main purpose of this study was to evaluate the performances of intermittent planted filters in treating urban wastewater under arid conditions of southern Tunisia. The experimental study was carried out on a pilot scale plant comprising five constructed gravel-sand basins. Screened urban wastewater effluent was intermittently applied with a daily hydraulic load of 400 L/m². Several water quality parameters were monitored at the inlet and outlet of this treatment plant. The average removal rate were 94.8%, 92.3%, 99.3%, 89.9% and 93.3% for chemical and biological oxygen demand, total suspended solids, ammonium nitrogen and orthophosphate, respectively. Additionally, results demonstrated that this treatment system is capable of removing 3.67, 3.22 and 2.44 log units of total and faecal coliforms, and faecal streptococci, respectively. Results showed that Phragmites australis allowed the development of biofilm in the sand filter beds, improving their purification efficiency. Furthermore, no bio-sludge production, no mechanical aeration, low energy requirement (0.02 kW/m²) and green aesthetic ambience are the additional particular strengths of the proposed pilot plant.

Key words: arid climate, assessment, efficiency, planted filters, treatment, urban wastewater

HIGHLIGHTS

- Planted filters are efficient in treating urban wastewater under arid conditions.
- Results showed that Phragmites australis improved the purification efficiency of the planted filters.
- Planted filters accomplished significant removal rates of organic and nitrogen matter.
- This treatment system led a significant abatement of pathogens.
- The treated wastewater can be reused in irrigation.

1. INTRODUCTION

At this time, water resources shortage have become more and more serious and human activities continue to affect detrimentally the quality and quantity of existing fresh water resources. In the Middle East and North Africa (MENA) region, several countries are regularly facing significant water demand and supply imbalances, particularly during the summer period, due to simultaneous occurrence of low precipitation, high evaporation and increased demands for irrigation and tourism. So there is an urgent need for fresh water conservation and wastewater renovation.

Unmanaged wastewater is an important source of pollution and a hazard for human health and ecosystems services. The selection of the most appropriate wastewater management approach requires an economic appraisal of alternate options (Akpor & Muchie 2011). The reuse of treated wastewater involves significant environmental, social and health benefits (Munir et al. 2012).

Over the last few decades non-conventional approaches for wastewater treatment have gained importance as purification treatment systems. For waters already treated to primary and secondary levels, the land treatment technique is a promising tertiary treatment technology. Literature indicates different types of non-conventional treatment systems overland flow...
systems, rapid infiltration systems, sand filters, soil infiltration systems, intermittent buried sand filters and constructed soil filters (Kadam et al. 2009).

The use of intermittent sand filter systems (ISF) is increasing around the world for domestic wastewater treatment (Leverenz et al. 2009; Bali et al. 2010; Laaksonen et al. 2017), especially in small communities. ISF systems may offer a smaller footprint (Healy et al. 2007), due to the substantially higher organic loading rates that may be applied to their surfaces and are economically and ecologically sustainable systems due to their low investment, little maintenance needs and low energy requirements, which make them suitable wastewater treatment alternatives for small rural and decentralized communities (Wu et al. 2015).

In ISF systems the hydraulic load is applied intermittently and influent percolates vertically through a filter bed made up of sand and gravel layers (Borkar & Mahatme 2013). A substantial advantage of vertical flow systems is enhanced oxygen transfer to the soil layers (Melidies et al. 2010), thus improving the oxidation capacity to remove organic matter (Cooper 1999). Additionally, ISF systems remove contaminants in wastewater through physical, chemical, and biological treatment processes. Suspended solids and some of the organic matter are removed by physical processes and by biological degradation (Bali et al. 2010; Borkar & Mahatme 2013). The surface layer of the ISF is considered as an active biofilter layer, which contains bacterial mass and other microorganisms.

Intermittent sand filters are capable of consistently producing an effluent quality comparable to the quality expected from more complex and advanced wastewater treatment systems (Truax & Shindala 1994). Over the last decades, several studies on the key role of macrophytes (e.g. Phragmites australis, Saururus cernuus, Eleocharis) in removing pollutants in ISFs or similar systems have been carried out throughout the word: France (Liénard et al. 1990); Portugal (Kadam et al. 2009); Morocco (Sylla et al. 2018); Saudi Arabia (Al-Homaidan et al. 2020) and Spain (Carricondo et al. 2020). The most important effects of the macrophytes in relation to ISF systems are the physical effects of the plant tissues that give rise to filtration and provide a surface area for attached microorganisms. The removal of pollutants is favoured by plant uptake, fixation and stabilization. Oxygen release by the macrophytes improves the biological treatment process. Furthermore, macrophytes reduce the impacts of solar radiation, provide habitat for wildlife and are also aesthetically pleasing (Al-Homaidan et al. 2020).

The purification performances of experimental IFS under climatic conditions of southern Tunisia were demonstrated by Turki et al. (2011) and Bali et al. (2010; 2017). The main purpose of this study was to investigate, at pilot scale, the planted IFS efficiencies in treating urban wastewater effluent under arid conditions.

2. MATERIALS AND METHODS

2.1. Study area and sampling

The study was performed on the pilot scale plant at the Eco-site Park in Gabès city (southern Tunisia). Gabès Department climate is classified as arid with a mean annual rainfall about 190 mm. Autumn and winter are the seasons with higher pluviometry (70%). The mean daily air temperature is 16 °C. January to March is the coldest period, and the warmest period is between July and August.

An ecological treatment plant based on vertical flow planted filters was constructed in 2016 to treat raw wastewater in order to reuse the treated water for irrigation of shrubs and perennial ornamental herbs in the park. It has two treatment stages. The first stage consists of three buried gravel filter beds (GFB) and the second consists of two buried sand filter beds (SFB). These beds were in the shape of a rectangle (10 m × 8 m) of 1 m deep and lined with a geo-membrane.

The GFBs were filled with a 30 cm depth layer of fine gravel (2–8 mm) followed by a 20 cm depth medium gravel layer (5–20 mm). The basal layer was a drainage bed 30 cm in depth comprising very coarse gravel of 50–50 mm in diameter. The SFBs were filled with a 30 cm depth layer of local sand quarry (d50 = 0.26 mm; d60/d10 = 1.93) followed by a 20 cm depth fine gravel layer (2–8 mm). The basal layer was a drainage bed 30 cm in depth comprising medium gravel of 5–20 mm in diameter.

Furthermore, from bottom to top each filter bed consisted of a geo-membrane (5 mm), geotextile to protect this membrane from damage due to puncture caused by the upper-ling gravel layer, inlet structure, underdrain piping and filter media. A ventilation pipe connected to the drainage system is used to improve aerobic conditions inside the filter. A cross-sectional schematic and diagram of the system are presented in Figures 1 and 2. An 8 kWc solar photovoltaic plant provided electricity for three electric motor pumps, which operated in serial mode to deliver water for GFBs, SFBs and for the drip irrigation system.
2.2. Process description and operation

In this study the pilot plant was operated at single hydraulic loading rate of 400 L/m²/d. The treatment process starts up by feeding one of GFBs. A volume of 32 m³ of pre-settled wastewater is pumped over the top surface of the filter by means of a digital timer pump, discharging 3.95 L/s during 2 h 15 min. A distribution network was built from three 63 mm diameter PVC pipes with 24 orifices of 4 mm in each. After the mean retention time of 37 min, effluent percolates through the constructed media layers and collected into the collection tank. Each GFB was fed two times a week (five successive days no feeding). Collected water from these filters was recirculated by means of a pump, discharging an average load of 3.17 L/s during 2 h 43 min over one of two SFB through the same distribution. SFBs were fed three times a week (four successive days no feeding). Percolated water was collected into a storage tank then was pumped to a drip irrigation system. This experiment was run during an 11-month period. Details of the facility and the operating conditions are given in Table 1.

2.3. Measurement of water quality parameters

The treatment system began to operate at the beginning of December 2017 and, the system was allowed to stabilize for three months. After the stabilization period, influent (E0) and effluents from the first stage (E1) and the second one (E2) were sampled over three months (unplanted period). Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD₅), Total Suspended Solids (TSS) Ammonium Nitrogen (NH₄-N), Nitrate-Nitrogen (NO₃-N), Orthophosphate (PO₄-P) were analysed, according to standard methods, at the Hydro-Sciences Laboratory of the Higher Institute of Water Sciences and
Techniques, University of Gabès. Influent and effluent samples were collected using plastic bottles for chemical parameters, and in sterile glass bottles for microbial studies at varying intervals, with the highest frequency at the beginning of the experiment (two times per week) and decreasing as the beds stabilized (once every two weeks). In July 2018, all filter beds were planted with native *Phragmites australis* (reed) harvested from nearby ditches. During the following five months (planted period), influent (E0) and effluents (E1, E2) were sampled for the same parameters and frequency as in unplanted period.

COD was analysed according to the dichromate open reflux method (APHA *et al.* 2005). NH$_4$-N concentrations were analysed by the indophenol method (APHA *et al.* 2005). The BOD$_5$ was measured by a DBO meter HACH TRAK II Respirometric Biological Oxygen Demand Apparatus. The TSS was measured by an oven drying process with a membrane filter (pore diameter of 0.45 μm) and a laboratory drying oven. A HACH DR/4000 UV spectrophotometer (Hach Co., Loveland, CO, USA) was used to analyse samples for NO$_3$-N (Cadmium Reduction Method 8039) and PO$_4$-P (Molybdovanadate with Acid Persulfate Digestion Method 10127). Percent removal efficiencies of the measured parameters were calculated from:

$$RE = 100 \times \left( \frac{E_0 - E_i}{E_0} \right)$$

where: RE : percent removal efficiency (%), $E_0$: influent concentration (mg/L), and $E_i$ ($i = 1, 2$) effluent concentration (mg/L).

The detection of total and faecal coliforms (TC, FC) and faecal streptococci (FS) was determined by the classical methods of culture in medium liquid using the most probable number (MPN) technique (Rodier 2009). Results were expressed by logarithm colony forming units (CFU) per 100 mL of sample (log CFU 100 mL).

### 3. RESULTS AND DISCUSSION

#### 3.1. Evolution of *Phragmites australis* growth

The young plants of *Phragmites australis* were planted at the beginning of July 2018 with a density of nine plants/m$^2$. The *Phragmites australis* growth was estimated monthly by recording shoots height in a 0.6 × 0.6 m harvest area from all beds. SFBs showed better growth of *Phragmites australis*, the average height of living shoots reached 214 ± 26 cm and the
colonization of the whole surface before the end of the experiment was observed and no signs of intolerance to influent quality were observed. Whereas for GFBs, *Phragmites australis* growth was quite different from that in SFBs (Figure 3). This means that the top layer of gravel in GFBs is not conducive to reed growth.

3.2. Physicochemical purification performances

Screened urban wastewater was treated at the pilot scale plant for 11 months with a low hydraulic loading of 400 L/m²/d. During 8-month monitoring period, large variations in the influent parameters were observed; consequently, large variations in the effluent values were observed too.

The results of the water analyses performed on the influent (E0) and the effluents (E1 and E2), as well as the removal efficiency of COD, BDO₅, TSS, NH₄-N, NO₃-N and PO₄-P for the unplanted period and planting period are presented in Table 2. Figure 4 describes the monthly pattern for physicochemical contaminant concentrations over the time.

**Figure 3**  |  Mean and standard deviation of *Phragmites australis* shoots height in GFB and SFB.

**Table 2**  |  Averages and standard deviations (minimum-maximum) of physico-chemical (mg/l) parameters in influent (E0) and effluents (E1, E2)

| Parameter | Unplanted period | Planted with *Phragmites australis* |
|-----------|------------------|-----------------------------------|
|           | E0 | E1 | E2 | RE (%) | E1 | E2 | RE (%) | E1 | E2 | RE (%) |
| pH (range) | 7.2–8.3 | 6.3–8.0 | 6.8–7.5 | – | – | 7.6–8.0 | 7.3–8.1 | 7.6–8.0 | – | – |
| COD | 537.0 ± 48.7 (456.0–582.6) | 373.3 ± 26.2 (293.8–402.9) | 72.4 ± 6.6 (32.0–77.8) | 30.5 | 86.5 | 457.2 ± 87.1 (364.3–571.3) | 285.0 ± 42.8 (237.3–331.3) | 23.8 ± 9.4 (13.0–34.2) | 37.7 | 94.8 |
| BOD₅ | 362.2 ± 38.8 (320.8–397.7) | 190.0 ± 20.7 (167.6–208.4) | 71.7 ± 10.2 (64.3–83.4) | 47.5 | 80.2 | 274.6 ± 51.7 (274.6–331.4) | 135.7 ± 37.0 (86.2–180.5) | 21.0 ± 10.4 (12.6–38.1) | 50.6 | 92.3 |
| TSS | 452.9 ± 37.2 (417.3–491.5) | 172.2 ± 29.7 (150.9–206.1) | 9.3 ± 0.8 (9.3–10.8) | 62.0 | 97.8 | 488.6 ± 82.9 (388.0–597.5) | 183.4 ± 23.6 (160.0–216.0) | 5.2 ± 2.2 (1.5–6.6) | 62.5 | 99.3 |
| NO₃-N | 3.2 ± 1.9 (1.3–5.0) | 8.5 ± 1.2 (7.2–9.6) | 10.6 ± 1.7 (8.7–11.9) | – | – | 3.6 ± 1.3 (2.0–5.1) | 13.8 ± 3.3 (11.0–18.0) | 17.7 ± 3.4 (14.4–22.4) | – | – |
| NH₄-N | 35.0 ± 10.5 (28.1–47.1) | 11.2 ± 1.9 (9.1–12.8) | 5.0 ± 1.0 (4.1–6.1) | 68.0 | 85.8 | 37.1 ± 8.2 (28.8–49.3) | 11.0 ± 2.4 (8.3–14.5) | 3.7 ± 0.8 (2.6–5.0) | 70.3 | 89.9 |
| PO₄-P | 15.3 ± 1.2 (12.9–23.8) | 13.2 ± 1.1 (12.1–14.3) | 4.1 ± 0.2 (3.9–4.4) | 13.5 | 73.4 | 16.7 ± 4.6 (12.9–23.8) | 11.3 ± 1.9 (9.5–13.5) | 1.1 ± 0.7 (0.6–2.4) | 32.6 | 93.3 |
3.2.1. Chemical oxygen demand (COD)

Figure 4(a) shows the monthly mean COD concentrations in the effluents (E1 and E2) and in the influent (E0) during the study period. Before reed plantation, the average COD concentration in the influent was very high with a monthly mean value of $537.0 \pm 48.7 \text{ mg O}_2/\text{L}$. The monthly mean removal efficiencies for GFBs were 30.5% and 37.7% for unplanted and planted periods, respectively. This suggest that used gravel media filter contributed to removing less than 40% of the COD load. For SFBs, COD removal performances were much better with a monthly mean removal efficiency of 86.5%. As expected, the average COD removal performances were increased after the plantation of Phragmites australis. Data indicated a monthly mean COD removal rate of 94.8% for SFBs. The monthly mean COD concentration in the pilot outlet was $23.8 \pm 9.4 \text{ mg O}_2/\text{L}$ (Table 1) and less than the concentration recommended by the Tunisian standards of 90 mgO$_2$/L for landscape irrigation (INNORPI 1989). The obtained COD removal rates in this work are higher than the average values of 75 and 85% found by Al-Jadhai (2003) and Sylla et al. (2018) respectively but similar to the results of 90.5–99.0% COD removal efficiency reported by Healy et al. (2007) and Bali et al. (2010) for similar sand filters.

3.2.2. Biological oxygen demand (BOD)

The monthly mean inflow/outflow BOD concentrations for the treatment system over time are shown in Figure 4(b). As shown in Table 2, the BOD5 concentrations in the influent ranged from 274.6 to 397.7 mg O$_2$/L and the monthly mean concentrations were $362.2 \pm 38.8 \text{ mg O}_2/\text{L}$ and $274.6 \pm 51.7 \text{ mg O}_2/\text{L}$ for unplanted and planted periods, respectively. During the unplanted period, the average BOD5 in GFB effluent was $190.0 \pm 20.7 \text{ mg O}_2/\text{L}$ and then it fell to $71.7 \pm 10.2 \text{ mg O}_2/\text{L}$ in SFB effluent. This reduction represents an average removal efficiency of 47.5% and 80.2% in GFBs and SFBs, respectively. Compared to COD, results indicate a better contribution of the geotextile sand filter (GSF) to remove BOD which contributed to a maximum removal rate of 50% of BOD load. The results showed that planted filters were considerably more efficient in BOD$_5$ removal from the wastewater than in the unplanted filters. Maximum removal efficiency (92.3%) was obtained in SFBs. As expected, BOD removal was improved in the presence of macrophytes. The monthly mean BOD observed at the pilot outlet (E2) was $21.0 \pm 10.4 \text{ mg O}_2/\text{L}$ and met the current Tunisian Standard for treated wastewater reuse for irrigation of 30 mg O$_2$/L (INNORPI 1989). Furthermore, the removal efficiencies observed for the pilot study fell within the range of results found in the literature for similar systems. Sabbah et al. (2004) reported that a BOD removal rate of 95% in an intermittent sand filtration system was observed. This result showed that this treatment technique is very efficient in eliminating organic matter from wastewater effluent. Mottier et al. (2000), Bali et al. (2010) and Laaksonen et al. (2017) showed that >90% BOD$_5$ was removed in coarse/fine sand filtration and in intermittent sand filter systems, respectively.

3.2.3. Total suspended solid (TSS)

As shown in Figure 4(c) the influent showed high TSS concentrations which ranged from 388.0 to 597.5 mg/L (Table 2). The TSS are substantially reduced after percolation through GFB and FSB systems. Without planting, TSS concentration decreased from $452.9 \pm 37.2 \text{ mg/L}$ to $8.7 \pm 0.9 \text{ mg/L}$ after three months of treatment. Results indicated a relative important reduction of the TSS concentrations in GSF (>60%) (Figure 4(c)). The pilot performance was improved by reeds and a higher TSS removal (>99%) was observed. The mean TSS concentrations in the SFB effluent were $3.2 \pm 2.2 \text{ mg/L}$ and less than the maximum concentration recommended by the national standards of 30 mg/L for landscape irrigation (INNORPI 1989). The removal TSS efficiencies remained important and no clogging was observed. As a result, the final pilot effluent quality is suitable for the drip irrigation method. Similar results were obtained by Mottier et al. (2000), Achak et al. (2009) and Bali et al. (2010).

3.2.4. Nitrate (NO$_3$-N)

Figure 4(d) illustrates the influent and effluent NO$_3$-N concentrations during the study period. In the applied wastewater, nitrate ranged from 1.3 mg/L to 5.1 mg/L (Table 2). Even though nitrate is typically absent in raw wastewater (Almeida et al. 2017), results showed an increase in NO$_3$-N concentration over time (Table 2). The increase in nitrate concentration in the effluent can be explained by the nitrification of ammonia favoured by autotrophic bacteria. At the GSF outlet, the monthly mean NO$_3$-N concentrations increased gradually. They reached a peak value of 11.0 mg/L at the end of experimentation. In addition, monthly NO$_3$-N concentration for SFBs increased gradually reaching a peak value of 22.4 mg/L and started to decline to reach 15.3 mg/L at the end of the experimental period.
Figure 4 | Monthly variation in (a) COD, (b) BDO₅, (c) TSS, (d) NO₃-N, (e) NH₄-N and (f) PO₄-P concentrations of influent (E0) and effluents (E1 & E2).
The obtained results are quite different from those found by Mottier et al. (2000) and Bali et al. (2010) for unplanted filtration systems. Similar results were reported by Torrens et al. (2009) for planted river sand filters. Vymazal (2009) reported that up to 70% of nitrate was reduced by Phragmites australis in planted units. This suggest that the relatively low nitrate concentration observed at the pilot outlet may be attributed to Phragmites australis uptake. Many studies have shown that plant uptake is a significant route for nitrogen removal in planted sand filter systems (Lee et al. 2009).

3.2.5. Ammonium (NH$_4$-N)

Ammonium concentrations in the influent and in the effluents as well as their removal efficiencies before and after filter plantation are shown in Figure 4(e) and in Table 2. Results showed a high ammonia concentration in the raw wastewater ranging from 28.1 to 49.3 mg/L. An important reduction of NH$_4$-N content was observed at the beginning of the experiments (68.0% for GFBs and 85.8% for SFBs). Planted filters performed slightly better for NH$_4$-N removal. In fact, the elimination rates were 70.3% and 89.9% for GFBs and SFBs, respectively. This suggests that ammonia assimilation by Phragmites australis contributes to the reduction of ammonia concentrations in the effluents and improves the removal efficiency of this pollutant. These findings are in agreement with those founded by Vymazal (2009) and Lee et al. (2009). The reduction of ammonium content in the effluents is accompanied by an increase in nitrate concentrations which was provided by the nitrification process.

3.2.6. Orthophosphate (PO$_4$-P)

The mean PO$_4$-P concentrations in applied wastewater and in the effluents and their removal efficiencies during the experimental period are depicted in Table 1. Figure 4(f) presents the influent and effluents PO$_4$-P concentrations as function of time. Results clearly indicated that the media structure played an important role in phosphorus removal. At GFBs, PO$_4$-P removal efficiency did not exceed 14%. This means that these beds operate as rapid gravity filters (hydraulic retention time 37 min) and are not adequate to eliminate material by the process of sorption or by direct precipitation. These results are in agreement with those obtained by Bunce et al. (2018). Results indicated a high removal efficiency of phosphate on SFBs (>90%) (Table 2) which is composed of a fine filter medium at the upper layer and characterized by a longer hydraulic retention time (1 h 33 min). At the end of experimentation, the mean phosphorus concentration was 1.1 ± 0.7 mg/L. Bali et al. (2010) and Bunce et al. (2018) reported that the intermittent sand filter had a high capacity for phosphorus removal (>92%). The high phosphorus removal efficiency observed in this work can be explained by the Phragmites australis uptake. This finding is in agreement with results obtained by Carricondo et al. (2020) who highlighted the significant capacity of Phragmites australis for removing phosphorus from wastewater.

3.3. Disinfection performance

Bacterial indicators were investigated only for the planted period (July to November). Figure 5 shows the variation in the bacterial performances of the pilot plant. Results revealed a significant improvement in the sanitary quality of the treated wastewater. The raw wastewater was highly loaded with indicating faecal pollution bacteria. During the monitoring period, total and faecal coliforms, and faecal streptococci contents were about 6.47 ± 0.75, 5.04 ± 0.30, and 4.50 ± 0.03 FCU/100 ml, respectively. Table 3 shows the removal efficiencies in microbiological performances of the studied treatment system. Total and faecal coliforms and faecal streptococci were reduced after rapid filtration through the GFBs. The mean removal rates were 0.97, 0.94 and 1.2 log units, respectively. The combined system (GFB–SFBs) was very efficient in reducing bacterial indicators of faecal contamination during the planted period. The average faecal coliforms content observed at the pilot outlet was 2.06 ± 0.39 FCU/100 mL and is less than the World Health Organization (WHO 1989) guidelines limit for faecal coliform bacteria in unrestricted irrigation (< or = 3 log units). The reduction rates of total and faecal coliforms, and faecal streptococci were 3.67, 3.22 and 2.44 log units, respectively.

Similar results were reported by Ausland et al. (2002) who observed a removal rate of 2.9–6.3 log units of faecal coliforms and 2.5–2.9 log units of faecal streptococci in infiltration systems loaded with a municipal wastewater. Gold et al. (1992) observed a removal rate of faecal coliforms of about 1.69 and 5.03 log units in buried and sand filters, respectively.

According to Latracha et al. (2016) the removal rate of bacteria from wastewater in porous media was attributed to a combination of several physical and biological processes. Stevik et al. (2004) reported that straining and adsorption are the main mechanisms in infiltration media explaining the removal of faecal coliforms. The probability of bacterial straining would be higher due to smaller pore sizes. In the present work, the high bacteria removal rate could be mainly attributed to the fine pore size of the used sand ($d_{50} = 0.26$ mm; $d_{60}/d_{10} = 1.93$).
4. CONCLUSION

The purification performances of the treatment system composed of gravel filter beds and sand filter beds was investigated. Those filters were planted with *Phragmites australis* (reed). The GFBs were designed mainly to remove TSS by physical processes. The SFBs acted as bioreactor to achieve better nutriments and bacteria reduction. Results showed that the GFB has been proved efficient to remove TSS (>60%) and NH$_4$-N (68%) from urban wastewater. High physicochemical performances were achieved by the GFB–SFB system. The abatement rates were about 94%, 92%, 99, 89 and 95%, respectively for COD, BOD$_5$, TSS, NH$_4$-N and PO$_4$-P. Additionally, the pilot scale plant allowed the reduction of 3.67, 3.22 and 2.44 log units, respectively for total and faecal coliforms, and faecal streptococci. The presence of *Phragmites australis* led to the development of biofilm in SFBs, which improved organic and inorganic pollutant removal thanks to the biodegradation process. The combination of the GFB–SFB treatment system has been found to be useful to efficiently reduce contaminants from urban wastewater at minimal cost. Regarding the Tunisian water resources context as well as other MENA countries, the proposed treatment system can be recommended as an appropriate solution for polishing wastewater in small municipality or rural areas and for irrigation reuse.
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DATA AVAILABILITY STATEMENT

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

REFERENCES

Achak, M., Mandi, L. & Ouazzani, N. 2009 Removal of organic pollutants and nutrient from olive mill wastewater by a sand filter. Journal of Environmental Management 90, 2771–2779.

Akpor, O. B. & Muchie, M. 2011 Environmental and public health implications of wastewater quality. African Journal of Biotechnology 10 (13), 2379–2387.

Al-Homaidan, A. A., Al-Otaibi, T. G., El-Sheikh, M. A., Al-Ghanayem, A. A. & Ameen, F. 2020 Accumulation of heavy metals in a macrophyte Phragmites australis: implications to phytoremediation in the Arabian Peninsula wadis. Environmental Monitoring and Assessment 192, 202.

Al-Jadhai, I. S. 2005 Pilot-plant study of the tertiary filtration of wastewater using local sand. Journal of King Saud University – Engineering Sciences (JKSUES) 16 (1), 83–95.

Almeida, A., Carvalho, F., Imaginário, M. J., Castanheira, I., Prazeres, A. R. & Ribeiro, C. 2017 Nitrate removal in vertical flow constructed wetland planted with Vetiveria zizanioides: effect of hydraulic load. Ecological Engineering 99, 535–542.

APHA, AWWA & WEF 2005 Standard Methods for the Examination of Water and Wastewater, 21st edn. American Public Health Association/American Water Works Association/Water Environment Federation, Washington, DC, USA.

Ausland, G., Stevik, T. K., Hanssen, J. F., Kohler, J. C. & Jenssen, P. D. 2002 Intermittent filtration of wastewater-removal of fecal coliforms and fecal streptococci. Water Research 36, 3507–3516.

Bali, M., Gueddari, M. & Boukchina, R. 2010 Treatment of secondary wastewater effluents by infiltration percolation. Desalination 258, 1–4.

Bali, M., Jridi, H., Farhat, S. & Boukchina, R. 2017 Treatment of secondary effluents by infiltration-percolation process using sand fortified with activated charcoal. International Journal of Environmental Science and Technology 14, 1209–1216.

Borkar, R. P. & Mahatme, P. S. 2013 Wastewater treatment using vertical flow constructed wetland, internat. Journal of Engineering Research and Applications (IJERA) 3, 1523–1532.

Bunce, J. T., Ndam, E., Ofiteru, I. D., Moore, A. & Graham, D. W. 2018 A review of phosphorus removal technologies and their applicability to small-scale domestic wastewater treatment systems. Frontiers in Environmental Science 6 (8), 1–15.

Carricando, J. M., Oliver-Villanueva, J. V., Turégano, J. V., González, J. A. & Mengual, J. 2020 Use of Phragmites australis for controlling phosphorus contamination in anthropogenic wetland ecosystems. Environmental Technology 42 (19), 3055–3064.

Cooper, P. 1999 A review of the design and performance of vertical-flow and hybrid reed bed treatment systems. Water Science and Technology 40 (3), 1–9.

Gold, A. J., Lamb, B. E., Loomis, G. W., Boyd, J. R., Cabelli, V. J. & McKiel, C. G. 1992 Wastewater renovation in buried and recirculating sand filters. Journal of Environmental Quality 21, 720–723.

Healy, M. G., Rodgers, M. & Muiqueen, J. 2007 Treatment of dairy wastewater using constructed wetlands and intermittent sand filters. Bioresource Technology 98, 2268–2281.

INNORPI 1989 Environment Protection – Use of reclaimed water for agricultural purposes – Physical, chemical and biological specifications, Tunisian standards, NT 106.03.

Kadam, A. M., Nemade, P. D., Oza, G. H. & Shankar, H. S. 2009 Treatment of municipal wastewater using laterite-based constructed soil filter. Ecological Engineering 35, 1051–1061.

Laaksonen, P., Sinkkonen, A., Zaitsev, G., Mäkinen, E., Grönnroos, T. & Romantschuk, M. 2017 Treatment of municipal wastewater in full-scale on-site sand filter reduces BOD efficiently but does not reach requirements for nitrogen and phosphorus removal. Environmental Science and Pollution Research International 24 (12), 11446–11458.

Latracha, L., Ouazzania, N., Masunagac, T., Hejjaja, A., Bouhoumb, K., Mahid, M. & Mandi, L. 2016 Domestic wastewater disinfection by combined treatment using multi-soil-layering system and sand filters (MSL–SF): a laboratory pilot study. Ecological Engineering 91, 294–301.

Lee, C. G., Fletcher, T. & Sun, G. 2009 Nitrogen removal in constructed wetland systems. Engineering in Life Sciences 9, 11–22.

Leverenz, H. L., Tchobanoglous, G. & Darby, J. L. 2009 Clogging in intermittently dosed sand filters used for wastewater treatment. Water Research 43, 695–705.

Liènard, A., Boutin, C. & Esser, D. 1990 Domestic wastewater treatment with emergent hydrophyte beds in France. In: Proceedings of the International Conference on the Use of Constructed Wetlands in Water Pollution Control, held on the 24–28 September 1990, Cambridge, UK, pp. 183–192. doi.org/10.1016/B978-0-08-040784-5.50022-X.

Melidies, P., Gikas, G. D., Akrotos, C. S. & Tsirhrintzin, V. A. 2010 Dewatering of primary settled urban sludge in a vertical flow wetland. Desalination 250, 395–398.
Mottier, V., Brissaud, F., Nieto, P. & Alamy, Z. 2000 Wastewater treatment by infiltration percolation: a case study. *Water Science and Technology* 41 (1), 77–84.

Munir, A., Hanjra, M. A., Blackwell, J., Carr, G., Zhang, F. & Jackson, T. M. 2012 Wastewater irrigation and environmental health: implications for water governance and public policy. *International Journal of Hygiene and Environmental Health* 215 (3), 255–269.

Rodier, J. 2009 *L'analyse de L'eau: Eaux Naturelles, Eaux Résiduaires, eau de mer*, 7ème édition. Dunod, Bordas, Paris, p. 1365.

Sabbah, I., Ghattas, B., Hayek, A., Omari, J., Haj, Y., Admon, S. & Green, M. 2004 Intermittent sand filtration for wastewater treatment in rural areas of the Middle East: a pilot study. *Water Science and Technology* 48 (11–12), 147–152.

Stevik, T. K., Aa, K., Ausland, G. & Hanssen, J. F. 2004 Retention and removal of pathogenic bacteria in wastewater percolating through porous media: a review. *Water Research* 38, 1555–1567.

Sylla, A., Rihani, M., Amine, J., Assobhei, O. & Etahiri, S. 2018 Exploitation of *Phragmites australis* (Reeds) in filter basins for the treatment of wastewater. *International Journal of Environmental Science and Technology* 11, 56–67.

Torrens, A., Molle, P., Boutin, C. & Salgot, M. 2009 Impact of design and operation variables on the performance of vertical-flow constructed wetlands and intermittent sand filters treating pond effluent. *Water Research* 43 (7), 1851–1858.

Truax, D. D. & Shindala, A. 1994 A filtration technique for algal removal from lagoon effluents. *Water Environment Research* 66 (7), 894–898.

Turki, S., Makni, H., Boukchina, R. & Ben Dhia, H. 2011 Study of the purification performance of sand filter drained in a complementary treatment of urban wastewater under soil and climatic conditions of southern Tunisia. *Journal of Water Resource and Protection* 3, 487–494.

Vymazal, J. 2009 The use constructed wetlands with horizontal sub-surface flow for various types of wastewater. *Ecological Engineering* 35, 1–17.

WHO 1989 *Health Guidelines for the use of Wastewater in Agriculture and Aquaculture. Report of a WHO Scientific Group*. World Health Organization, Geneva. (WHO Technical Report Series, No. 778).

Wu, S., Wallace, S., Brix, H., Kuschk, P., Kipkemoi, W., Masi, F. & Dong, R. 2015 Treatment of industrial effluents in constructed wetlands: challenges, operational strategies and overall performance. *Environmental Pollution* 201 (2015), 107–120.

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