Received: 25 May 2023 | Revised: 16 September 2023 | Accepted: 14 October 2023
DOI: 10.1111/wej.12907

RESEARCH ARTICLE

Water and Environment Journal Promoting Sustainable Solutions CIWEM WILEY

Assessment of novel hybrid treatment wetlands as nature-based solutions for pharmaceutical industry wastewater treatment

Othman Al-Mashaqbeh[1] | Layal Alsalhi[1] | Lana Salaymeh[1] | Tao Lyu[2]

[1]Emerging Pollutants Research Unit, Royal Scientific Society, Amman, Jordan

[2]School of Water, Energy and Environment, Cranfield University, Cranfield, UK

Correspondence
Tao Lyu, School of Water, Energy and Environment, Cranfield University, College Road, Cranfield, Bedfordshire MK43 0AL, UK.
Email: t.lyu@cranfield.ac.uk

Funding information
UK Royal Academy of Engineering, Grant/Award Number: TSP2021\100376

Abstract

This study investigated the use of nature-based solutions for treating real pharmaceutical industry wastewater in Jordan. A pilot-scale hybrid treatment wetland (TW) equipped with local zeolite was employed, comprising a tidal flow TW and a horizontal subsurface flow TW. This system was efficient in treating pharmaceutical wastewater with removal efficiencies of 61.4%, 52.6%, 60.1%, and 61.9% for chemical oxygen demand, total phosphorus, total nitrogen, and NH_4^+-N, respectively. The final effluent met Jordanian standards for the reuse of treated wastewater in irrigation (Class B). Five pharmaceuticals, namely, enrofloxacin, ciprofloxacin, ofloxacin, lincomycin, and trimethoprim, demonstrated nearly completed removal (93.6–99.9%). Moderated removal performances (59.2–68.2%) were observed for two compounds, flumequine and sulfaquinoxaline. However, three pharmaceuticals, namely, carbamazepine, diclofenac, and sulfadimidine, showed limited removal performances (1.1–20.5%). This study supported the feasibility of using nature-based solutions for treating pharmaceutical wastewater and highlighted that future studies are required to optimize this strategy for removing a broader range of pharmaceuticals.

KEYWORDS
constructed wetlands, green technology, micropollutants, treatment wetlands, wastewater treatment

Highlights

- Treatment wetland (TW) as a nature-based solution can treat pharmaceutical wastewater.
- Tidal flow TW with a better aerobic condition was favourable for pollutant removal.
- Jordanian zeolite was a promising wetland media to enhance the treatment performance.
- The final effluent complied with Jordanian standards for wastewater reuse in irrigation.
- Some pharmaceuticals could achieve completed removal by the hybrid TW system.

1 | INTRODUCTION

The pharmaceutical industry generates a significant amount of wastewater that threatens the aquatic environment, mainly because of its high content of pharmaceutical micropollutants that are difficult to treat (da Silveira Barcellos et al., 2022). Jordan is the second most water scarce country in the world (WHO/UNICEF, 2000). In addition, the pharmaceutical industry is one of the major pillars of the national economy and has a big share of the total Jordanian exports (Alabbadi et al., 2014). Therefore, treating pharmaceutical wastewater is essential to mitigate its negative impact on the environment and public health. Traditional wastewater treatment methods are inadequate in removing many pharmaceuticals (Zhang et al., 2017), and advanced technologies, such as advanced oxidation processes and membrane filtration, are expensive and unaffordable in such developing countries because of high energy costs and capital investments (Ganiyu et al., 2015). Consequently, it is crucial to develop effective, sustainable, and low-cost wastewater treatment methods for the pharmaceutical industry.

Treatment wetlands (TWs) are a type of nature-based solution that have shown great potential for treating a variety of wastewater types (Carvalho et al., 2022; Oral et al., 2020; Wu et al., 2018), including domestic sewage, stormwater, agricultural runoff, and industrial wastewater. TWs can eliminate pollutants, such as pharmaceutical compounds via a range of physical, chemical, and biological mechanisms (Zhang et al., 2018, 2019). Oxygen plays a vital role in TWs by supporting the growth and metabolism of microorganisms and plants, thereby improving the treatment efficiency of the system (Lyu et al., 2018). Artificial aeration through diffusers or mechanical devices is the most commonly used approach to introduce oxygen into the wetland to facilitate pollutant removal (Nivala et al., 2020). Additionally, TWs can be designed and operated with regular tidal cycles known as tidal flow TWs (TFTWs). In a TFTW, wastewater is periodically pumped into the wetland media and then drained, creating a "passive pump" to draw oxygen from the atmosphere into the system (Guo et al., 2017; Kizito et al., 2017). TFTWs only require half of the energy and area to treat the same volume of wastewater compared with aerated wetlands (Austin & Nivala, 2009). While TFTWs have been proven to remove organics, ammonia, and some organic micropollutants effectively, it is unclear whether and to what extent they can eliminate pharmaceutical compounds from real pharmaceutical industrial wastewater.

Certain pharmaceutical compounds, such as tetracyclines and metronidazole, are not easily degraded by aerobic microorganisms (Ahmed et al., 2017). TWs with anoxic/anaerobic conditions, such as horizontal subsurface flow TWs (HSSF TWs), may be more effective in removing such pharmaceuticals and their transformation products (Dhangar & Kumar, 2020). Therefore, it is hypothesized that a hybrid system with two sequences of TWs, containing aerobic and anaerobic conditions, could be an ideal option for treating pharmaceutical wastewater. The wetland substrate/media is important for providing the surface area to support microorganism growth and pollutant removal. River gravels/sands are the most commonly used substrates in TWs because of their low cost and widespread availability (Yazdania & Golestanib, 2019). However, advanced natural and artificial materials with high surface area and pore volume, such as zeolite, have been used as wetland substrates to increase pollutants' retention time in the system through adsorption processes (Bai et al., 2022). Moreover, it is reported that zeolite materials have significant adsorption capabilities towards high pharmaceutical compound removal (Al-Mashaqbeh et al., 2021). Besides the increased adsorption capability, zeolites can stimulate the growth and colonization of microorganisms leading to better biodegradation efficiency of pharmaceuticals.

Jordan is one of the world's largest producers of natural zeolite, presenting a unique opportunity to use local sources of zeolite in TWs for wastewater treatment. In this study, a pilot-scale hybrid TW system consisting of a TFTW and an HSSF TW was constructed in a local pharmaceutical factory to treat wastewater. Water quality, common pollutants (i.e., organics, nitrogen, and phosphorous), and 10 pharmaceutical compounds were monitored at different stages of the system. The focus of this study was to evaluate the feasibility of using TWs as nature-based solutions for real pharmaceutical wastewater treatment in Jordan.

2 | MATERIALS AND METHODS

2.1 | Chemicals and reagents

All reagents utilized for liquid chromatography–tandem mass spectrometry (LC–MS/MS) detection were analytical grade. Acetonitrile, acetone, and methanol were acquired from Carlo Erba (99.9% purity). Formic acid (≥98% purity) and ammonium formate (99% purity) were obtained from Scharlau and Merck, respectively.

2.2 | Experimental set-up and operation

A pilot-scale hybrid TW system was built at a local pharmaceutical factory in Amman, Jordan (Figure 1), and this factory produces more than 100 generic and branded pharmaceuticals, including anti-infective, dermatological preparations, diabetes treatments, eye–ear preparations, analgesics, and vitamins. In this study, 10 pharmaceutical compounds with the highest concentrations were reported out of 17 detected compounds representing three types of medicine (anticonvulsant, antibiotic, and analgesic). The wetland system consists of a TFTW and a saturated HSSF TW. Both systems were built in 1 m^3 intermediate bulk container (IBC), with dimensions of 1 m in height, length, and width. The TFTW and HSSF TW were each composed of a drainage layer (20 cm in height) at the bottom and a main treatment layer (70 cm in height) at the top. The drainage layer was filled with clean gravel (3–5 cm in diameter), while the main treatment layer was filled with washed local zeolite (0.6–1 cm in diameter) obtained from Agriculture Green Zeolite CO. in Amman, Jordan. The total height of the media layer was approximately 90 cm in both TWs, and the water level in the HSSF TW remained consistent at a height of 80 cm. One of the most common wetland plants in Jordan, that is, *Typha angustifolia* (Typha), was collected and planted in both systems. The pilot was

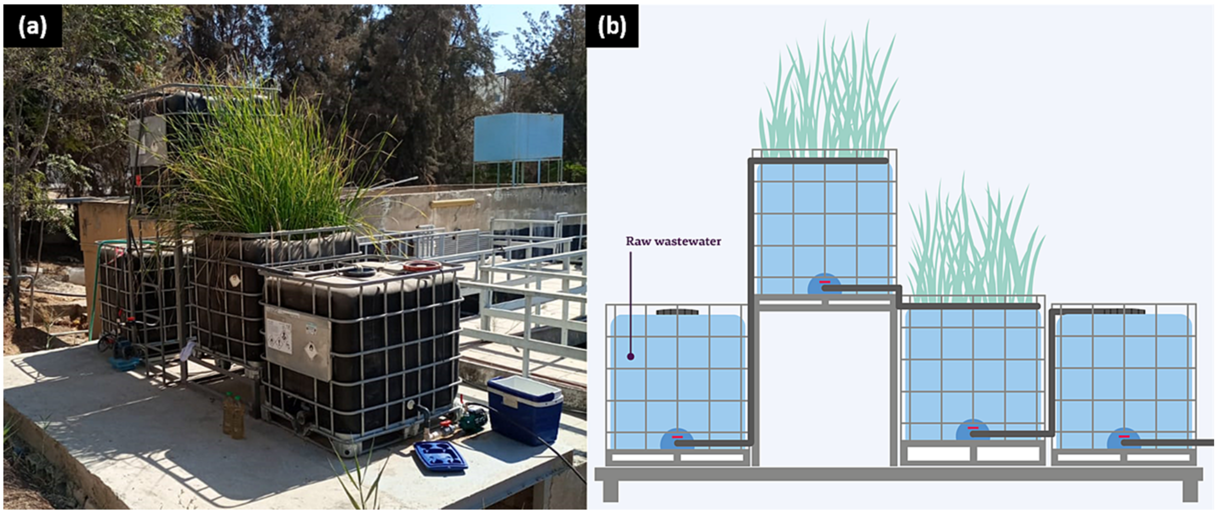

FIGURE 1 The (a) photo and (b) schematic diagram of the pilot-scale treatment wetland system at a local pharmaceutical factory in Amman, Jordan.

installed after the secondary activated sludge system operated at the factory. Therefore, the plants were irrigated directly by this water without any stabilization period.

The system was commissioned in July 2022 receiving the activated sludge treatment effluent and operated for 5 months. The first 2 months of operation was the stabilization period enabling the development of biofilms and plant growth. The sampling campaigns were conducted for 3 months until December 2022. During both stabilization and sampling periods, pharmaceutical industrial wastewater was induced to the surface of the TFTW in batch mode with a hydraulic loading rate of 1.26 m/day. The tidal operation was controlled by a pump and an automatic drain valve that was controlled by a timer under a flooded/drained time ratio of 3:3 h (four cycles per day). The HSSF TW was continuously saturated with a hydraulic retention time of 0.25 days (hydraulic loading rate of 1.26 m/day).

2.3 | Water quality and pollutant analysis

Water samples were collected in 1 L clean sampling bottles from the influent and effluent of each TW approximately every 2 weeks. The collected samples were tested for pH, electrical conductivity (EC), and turbidity using multiprobes (Multi 9630 IDS WTW, Hach, Germany). The concentrations of chemical oxygen demand (COD), total phosphorus (TP), total nitrogen (TN), NH_4^+-N, and NO_3^--N were analysed using a Lovibond spectrophotometer (XD 7000 (VIS), Lovibond, Germany) and commercially available test kits. COD and TP were quantified using Lovibond LR test kits (0–150 mg/L) and VARIO Total Phosphorus LR reagent set (1.5–20 mg/L), respectively. The Lovibond VARIO Total Nitrogen LR Reagent Set (5–150 mg/L) was used for TN measurement. Lovibond Ammonia HR (1–50 mg/L) and Nitrite LR (1–30 mg/L) reagent sets were used to determine NH_4^+-N, and NO_3^--N concentrations, respectively. All operations followed the manufacturer's instructions.

2.4 | Pharmaceutical analysis

Ten pharmaceutical compounds frequently detected in the wastewater effluent, that is, carbamazepine (anticonvulsant), enrofloxacin, ciprofloxacin, ofloxacin, lincomycin, trimethoprim, flumequine, sulfaquinoxaline, sulfadimidine (antibiotics), and diclofenac (analgesic), were monitored in this study. Pharmaceutical compounds in the water samples were detected using the method developed by Al-Mashaqbeh et al. (2019). Initially, the polymeric hydrophilic–lipophilic balance Oasis 6 cc cartridge (Milford, MA, USA) was conditioned by passing 6 mL acetone and 6 mL methanol sequentially, followed by 6 mL distilled deionized water. Then, 50 mL of the water sample flowed through the solid phase extraction cartridge and was kept at a flow rate of approximately 10 mL/min or less. The cartridge was rinsed with 5 mL of deionized water, and room air was allowed to flow through the cartridge by continued suction for at least 5 min to dry the cartridge. All extracted samples were eluted by adding 10 mL of methanol. The pharmaceuticals were analysed using liquid chromatography–mass spectrometry (AB SCIEX Triple Quad 5500, USA) with a limit of detection (LOD) of 0.02 μg/L for the targeted compounds in this study. If the detected concentration was below the LOD, the LOD value was used for calculating the removal performance. The LC–MS/MS is equipped with Luna Omega polar C18 embedded column (100 mm * 3.0 mm, particle size of 3 μm). Gradient elution mode was considered in the following order: Eluent A is 5 mM ammonium formate and 0.1% formic acid, and eluent B is acetonitrile and 0.1% formic acid. Among the reagents, formic acid was utilized to provide essential protons for LC–MS/MS analysis and improve the peak shapes of the resulting separations. The initial mobile phase conditions started with 98:2 A/B for 1 min; then, a linear gradient pattern was used to reach a ratio of 70:30 A/B at 2 min, and then, the ratios were changed to reach 60:40 A/B at 3 min. The ratios were changed to 50:50 A/B at 6 min; then, the ratios were changed to reach 0:100 A/B at 8.5 min. Before returning to the initial conditions, the last ratio was maintained for 10 min. The flow rate was set at 0.6 mL/min and the injection volume of 5 μL. Multiple reaction monitoring was conducted with AB-Sciex 5500 equipped with an electrospray ionization interface, using the positive– negative ion mode. Instrument control, data acquisition, and quantitation were run using analyst software. The temperatures of the drying gas, column oven, and autosampler were set at 500°C, 30°C, and 5.0°C, respectively. The detection time lasted for 13 min.

2.5 | Calculation and statistical analysis

The difference in pollutant concentrations between the influent and effluent of each system was obtained through Kruskal–Wallis one-way analysis of variance using PAST 4.03 software at a 95% confidence level. Different forms of nitrogen were calculated based on the deduction of the concentrations of TN and NH_4^+-N and NO_3^--N.

3 | RESULTS AND DISCUSSION

3.1 | Dynamics of pH, EC, and turbidity

Pharmaceutical industrial wastewater can exhibit varying pH levels depending on the specific substances involved in the manufacturing process (Gadipelly et al., 2014). The wastewater generated by the Jordanian pharmaceutical factory in this study was found to be neutral, with a pH of 7.5 ± 0.2 (Figure 2a). Although the removal of NH_4^+-N from the wastewater can lower the pH level in the effluent (Lyu et al., 2018), the presence of wetland plants and microorganisms as well as the buffer capacity of zeolite can contribute to ion uptake or release, thereby regulating pH (Ram & Vineet, 2015). As a result, after treatment by both TFTW (7.2 ± 0.4) and HSSF TW (7.3 ± 0.2), the pH of the water was maintained at a neutral level.

During the experiment, the EC values of the effluent from TFTW and HSSF TW were slightly higher than those of the influent (2.1–2.2 mS/cm) (Figure 2b). TWs can effectively remove various types of pollutants, such as organics, N, and P, and lead to a decrease in EC values for domestic sewage treatment (Wang et al., 2021). The slight increase in the EC might be because of the warm climate weather at Jordan which causes more evapotranspiration. In this study, some pharmaceutical compounds may have been difficult to remove completely and/or their transformation products may have remained in the water as dissolved ions, leading to similar EC values in the effluent. However, TFTW achieved a removal efficiency of 72.7% for turbidity, which increased to a total removal efficiency of 82.4% after the second stage of treatment (Figure 2c). These findings are consistent with previous studies demonstrating that TFTW can provide a turbidity removal range of 70–99% during wastewater treatment (Hamisi et al., 2022). Furthermore, TFTW can offer better performance in terms of turbidity reduction compared with conventional HSSH TW under the same conditions (Saeed & Sun, 2017).

3.2 | Removal of organics and nutrients

The average removal efficiency of COD in TFTW was found to be 50.5% at an influent concentration of 309 mg/L (Figure 3a). Further treatment by HSSF TW resulted in an overall removal efficiency of 61.4%. Similar trends were observed for the reduction of NH_4^+-N (Figure 3d), where TFTW removed 57.7% of influent NH_4^+-N and the final treatment efficiency was 61.9%. When comparing the loading removal capacity of the two systems, TFTWs exhibited significantly higher removal rates for COD (196.6 g/m^2/day) and NH_4^+-N (7.27 g/m^2/day) compared with the HSSF TWs, which had removal rates of 42.4 and 0.53 g/m^2/day for COD and NH_4^+-N, respectively. This can be attributed to the sufficient oxygenation of the TW beds during the drained cycles under tidal operation. Previous studies have shown

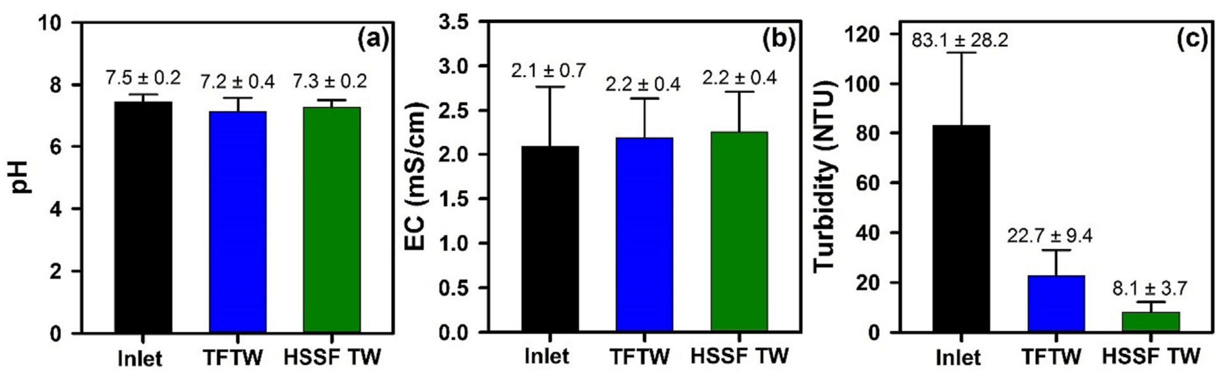

FIGURE 2 The levels of (a) pH, (b) electrical conductivity (EC), and (c) turbidity in the inlet and outlet of the first stage tidal flow treatment wetland (TFTW) and second stage horizontal subsurface flow treatment wetland (HSSF TW). The numbers above the bars represent the mean values (± standard deviation).

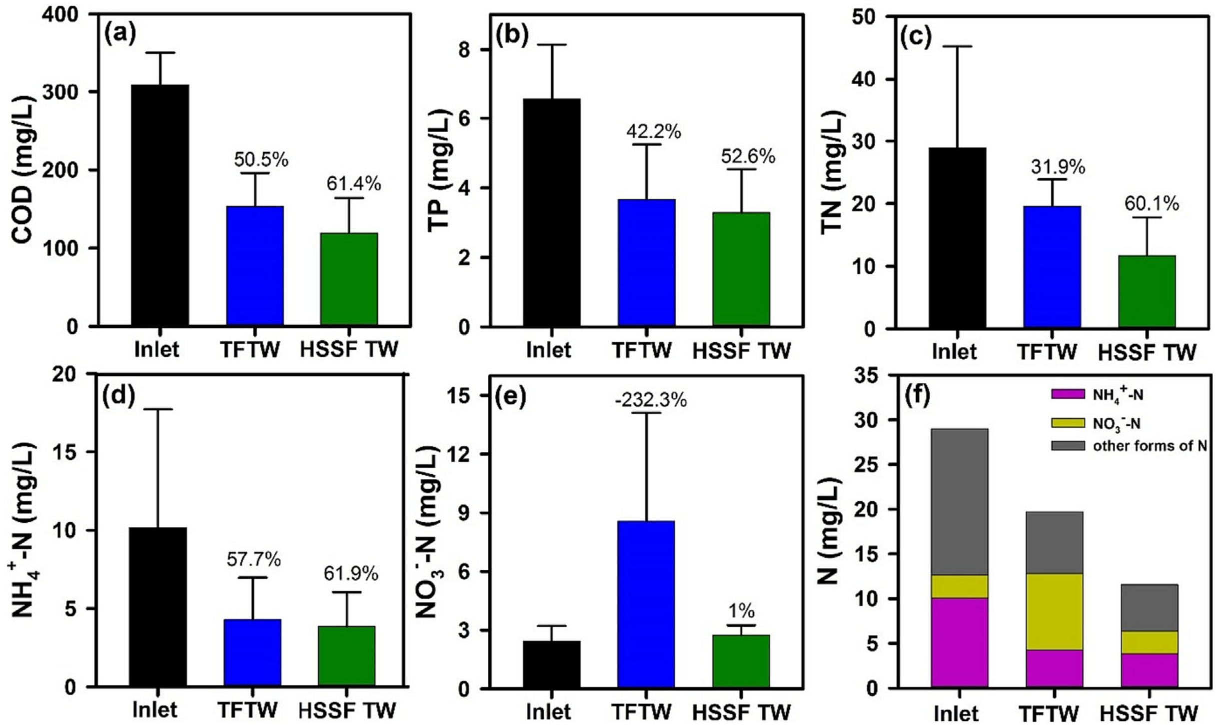

FIGURE 3 The concentrations of (a) chemical oxygen demand (COD), (b) total phosphorus (TP), (c) total nitrogen (TN), (d) NH_4^+-N, and (e) NO_3^--N in the inlet and outlet of the first stage tidal flow treatment wetland (TFTW) and second stage horizontal subsurface flow treatment wetland (HSSF TW). The numbers above the bars represent the average removal efficiency of corresponding pollutants against the inlet. (f) The dynamics of different forms of nitrogen along the two treatment stages.

that sufficient oxygen entrapped within the TFTW supports microbial degradation of organics and ammonia adsorbed onto the medium during the flooded period, by organotrophic and nitrifying bacteria during the drained periods (Guo et al., 2017; Hamisi et al., 2022; Lv et al., 2013).

Phosphorus removal in TWs can occur via various processes, such as substrate adsorption, chemical precipitation, bacterial immobilization, plant and algal uptake, and sediment accretion (Dotro et al., 2017). However, the removal capacity tends to be much lower and more variable, and TWs can be either sources or sinks of phosphorus (Bhomia et al., 2015). Previous studies have demonstrated that the overall P-removal capacity of a TW is strongly dependent on the sorption characteristics of the substrate, with the removal usually in the range of 45–60% in traditional TWs (Vymazal, 2010). Several studies have suggested that the use of zeolite in TWs can increase the removal of P because of its high surface area and ion-exchange capacity and provide a habitat for microorganisms for biological P removal (Andrés et al., 2018; Vera et al., 2014). In this study, the overall removal efficiency of TP was found to be 52.6% against an influent TP level of 6.5 mg/L (Figure 3b). Surprisingly, HSSF TW showed much less ability for TP removal compared with TFTW, which may be because of the characteristics of the pharmaceutical wastewater. The active sites of zeolite were primarily occupied by pharmaceutical compounds, which were competitive with P.

Unlike the removal of NH_4^+-N, the concentration of NO_3^--N significantly increased from 2.6 to 8.6 mg/L from the influent to TFTW effluent (Figure 3e). Moreover, the sum of NH_4^+-N and NO_3^--N did not exhibit a significant difference from the influent to the TFTW effluent (Figure 3f). The results demonstrate that the increased concentration of NO_3^--N in the TFTW effluent primarily resulted from the transformation of NH_4^+-N via the nitrification process in the well-oxygenized TFTW bed. Meanwhile, the removal of TN in TFTW (Figure 3c,f) was mainly attributable to other forms of nitrogen, such as nitrogen-containing organic compounds like proteins, amino acids, and urea in pharmaceutical wastewater (Wang et al., 2022). The subsequent stage of HSSF TW with the anoxic condition was found to be more conducive for the denitrification process, leading to significant removal of NO_3^--N (Figure 3e) and contributing to the reduction of TN (Figure 3c). However, it was not as effective in removing NH_4^+-N (Figure 3d).

Taking into account the Jordanian standards for treated wastewater reuse in irrigation (European Environment Agency, 2014), the water quality of the final effluent complied with the Class B standard for COD, TN, and NO_3^--N with concentrations below 500, 70, and 45 mg/L, respectively, and the pH within 6–9. Nevertheless, our results suggest that hybrid TW systems with the combination of different types of TWs, such as the well-oxygenated TFTW and saturated HSSF TW, show promising potential for industrial wastewater treatment to address water security and scarcity issues in Jordan.

3.3 | Removal of pharmaceuticals

Ten compounds were selected in this study because of their high production in the factory and frequent detection in wastewater effluent. These compounds were detected in high concentrations ranging from 121 to 1350 μg/L in the industrial wastewater, as shown in Figure 4, compared with the lower values typically reported in domestic and hospital wastewater (Escher et al., 2011; Reis et al., 2019). The influent concentrations of pharmaceuticals obtained here were consistent with those of similar studies on the treatment of pharmaceutical industry wastewater in Jordan (Al-Mashaqbeh et al., 2019). The removal of pharmaceuticals in TWs varied significantly depending on

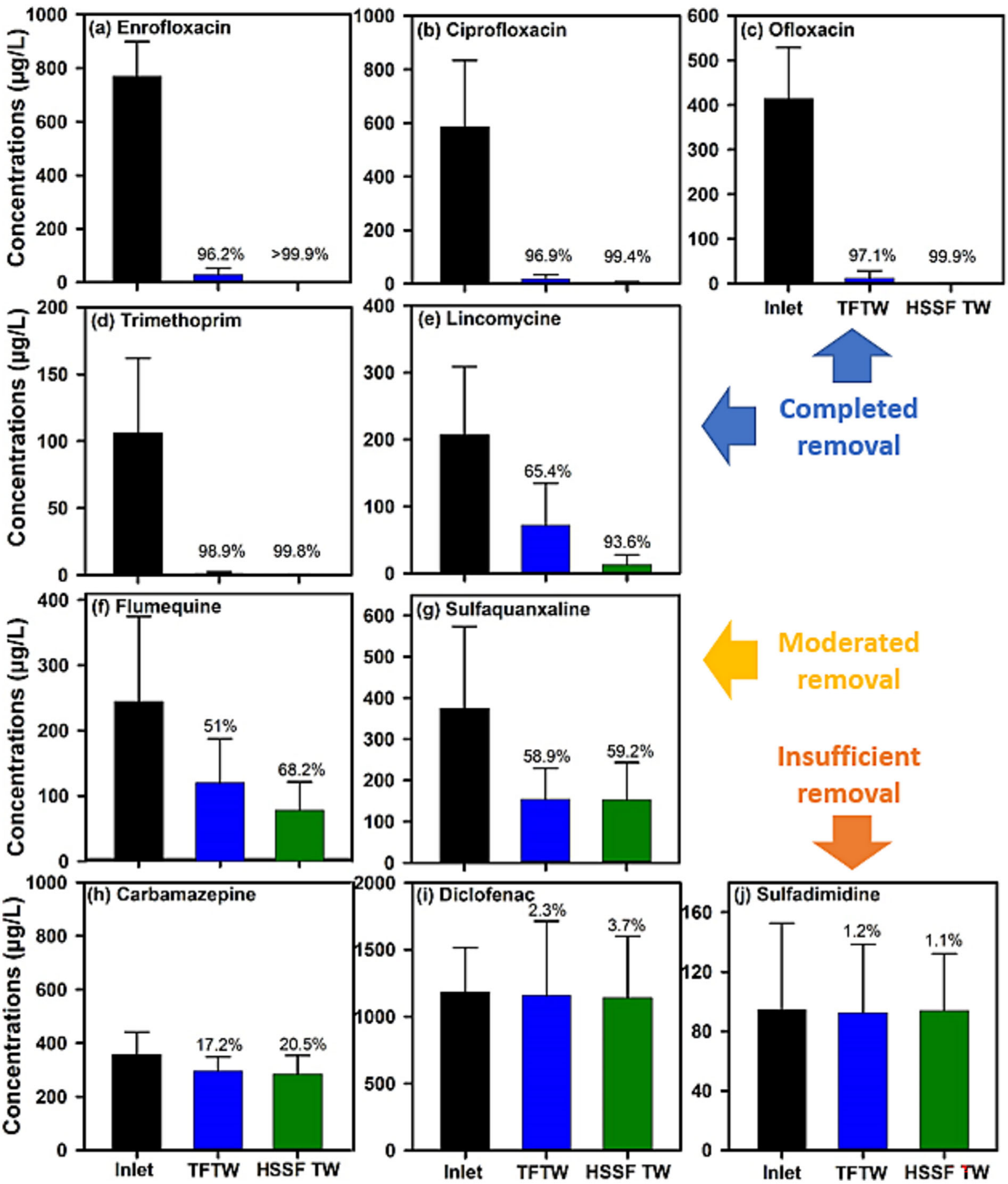

FIGURE 4 The concentrations of (a–j) 10 pharmaceutical compounds detected in the inlet and outlet of the first stage tidal flow treatment wetland (TFTW) and second stage horizontal subsurface flow treatment wetland (HSSF TW). The numbers above the bars represent the average removal efficiency of corresponding pollutants against the inlet.

their chemical structure and characteristics. In this study, the removal of those 10 compounds can be categorized into three groups (Figure 4), that is, completed removal (five compounds), moderated removal (two compounds), and insufficient removal (three compounds).

3.3.1 | Completed removed compounds (enrofloxacin, ciprofloxacin, ofloxacin, lincomycin, and trimethoprim)

In this study, a comprehensive removal (>96%) of enrofloxacin, ciprofloxacin, ofloxacin, and trimethoprim was observed by the first stage TFTW (Figure 4a–d), regardless of their initial concentrations (ranging from 100 to 770 μg/L). The second stage HSSF TW further improved the removal efficiency to almost 100%. The results from this study agreed with the findings of Carvalho et al. (2013) and Santos et al. (2019), who have reported a removal efficiency of 90–98% for enrofloxacin in lab- and pilot-scale TWs. Ciprofloxacin (97%) (Liu et al., 2019), ofloxacin (38–98%) (Dan et al., 2020), and trimethoprim (65–99%) (Dan et al., 2013) have also been found to be significantly removed in previous TW studies for pharmaceutical removal.

It is difficult to quantify the contributions of HSSF TW in the removal of these compounds in this study, because the first stage treatment by TFTW was already effective in eliminating the majority of the compounds. Dan et al. (2013) found that vertical flow TWs operated under aerobic conditions had higher removal efficiency for trimethoprim compared with HSSF TW that operated under anaerobic conditions. The aerobic conditions appear to be more favourable for the removal of these compounds in TWs. The involvement of aerobic bacteria in the degradation of some pharmaceuticals may require oxygen to carry out metabolic processes that break down the structure. Additionally, oxygen can help promote the growth of plants and other macrophytes, which can further enhance the removal of antibiotics through processes, such as adsorption and uptake.

For lincomycin (Figure 4e), TFTW removed 65.4% of the compound from the influent (207 μg/L), and the final removal efficiency of 93.6% was achieved with the second stage treatment. The results were supported by the findings from Ilyas and van Hullebusch (2019), who reviewed and summarized that the vertical flow wetland under aerobic conditions achieved a removal efficiency of 70–74% of lincomycin while the HSSF TWs under anaerobic/anoxic conditions had lower removal efficiency (40–46%). In general, this study highlights the potential of TWs equipped with Jordanian zeolite as nature-based solutions to effectively remove these compounds and emphasizes that aerobic conditions can enhance treatment performance. It is important to mention here that there are many removal pathways of antibiotics in TWs systems that were reported in the literature, such as microbial degradation, photodegradation, sorption, plant uptake, and phytodegradation (Carvalho et al., 2013).

3.3.2 | Moderated removed compounds (flumequine and sulfaquinoxaline)

The overall removal efficiencies of flumequine (Figure 4f) and sulfaquinoxaline (Figure 4g) in the hybrid TW systems were 68.2% and 59.2%, respectively. To our knowledge, no previous study has investigated the removal of these compounds in TWs. However, our study suggests that a TW with a better aerobic condition would be favourable for the removal of these compounds. In a lab-scale hydroponic experiment conducted by Forni et al. (2001), the aquatic plants *Azolla filicuolides Lam*., *Lythrum salicaria L*., and *Lemna minor L*. were evaluated for their capacity to remove flumequine from wastewater. Flumequine induced hormesis in *Lythrum* (with a higher effect at 50 mg/L), while *Lemna* growth and photosynthetic pigments were weakly affected. The tested concentration was much higher than the level in this study, which supports the idea that TWs could maintain a healthy condition and function for the treatment of pharmaceutical wastewater in real implementations.

The results demonstrated that the system could provide promising capabilities to effectively remove various pharmaceuticals, which enhanced the safety of using the treated wastewater for irrigation reuse. It should be noted that the degradation of pharmaceuticals in TWs relies primarily on microbial-mediated biodegradation processes (Ilyas & van Hullebusch, 2020). Thus, there is a high potential for antimicrobial resistance (AMR) to be generated and present in the discharged effluent (Bai et al., 2022). AMR monitoring was not included in the current study. However, future efforts to determine and mitigate AMR will be important to safeguard the environment and human health associated with water reuse procedures. Additionally, it is important to assess the transformation by-products of pharmaceuticals to ensure that the treated wastewater is safe for reuse and to help address the water scarcity issues faced in Jordan.

3.3.3 | Insufficient removed compounds (carbamazepine, diclofenac, and sulfadimidine)

Limited removal of carbamazepine, diclofenac, and sulfadimidine (1.1–20.5%) was observed in the hybrid TW (Figure 4h–j). These results are consistent with previous studies that reported low removal efficiency of carbamazepine in TWs (1–12%) and even negative removal (−8.5% to −2.5%) (Ilyas & van Hullebusch, 2020). The low removal of carbamazepine could be because of the main removal mechanism in TWs. A major fraction of carbamazepine is removed by the adsorption process; however, these adsorbed compounds can be released back because of changes in operational/environmental conditions that affect binding, such as fluctuations in pH and temperature. Additionally, the non-biodegradable and refractory nature of carbamazepine may also contribute to its low removal efficiency. In this study, a similar trend of carbamazepine removal occurred with a maximum removal (20.5%) achieved, which may be attributed to the selection of zeolite, which could provide high adsorption capabilities.

The low removal efficiency of diclofenac may be attributed to the presence of chlorine in its structure, which makes it highly recalcitrant to biodegradation (Kimura et al., 2005). There is a lack of available references to compare the removal of sulfadimidine in TWs. As the removal of diclofenac and sulfadimidine in both TFTW and HSSF TW was not significant in this study, further optimization or incorporation with other treatment technologies is needed to address the risks of these recalcitrant compounds and protect the receiving waters.

4 | CONCLUSION

The results of the current study demonstrate that nature-based solutions in the form of a hybrid TFTW and HSSF TW system show promise as an approach for pharmaceutical wastewater management. The configurations achieved removal efficiencies of 61.4%, 52.6%, 60.1%, and 61.9% for COD, TP, TN, and NH_4^+-N, respectively, with final effluent water quality meeting Jordanian Class B standards for treated wastewater for irrigation. Encouragingly, nearly complete removal (93.6–99.9%) was observed for 5 of the 10 pharmaceuticals present in the industrial wastewater. Moderated removal performances (59.2–68.2%) were achieved for two other compounds. With three recalcitrant pharmaceuticals remaining at low removal levels (1.1–20.5%), this highlights opportunities to further optimize the approach or integrate it with complementary technologies to achieve comprehensive removal of a wider range of pharmaceuticals.

ACKNOWLEDGEMENTS

This work was supported by the Transforming Systems through Partnership (TSP) project sponsored by the UK Royal Academy of Engineering (TSP2021\100376). The project title is “Development of a nature-based solution for pharmaceutical wastewater treatment in Jordan.”

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Tao Lyu https://orcid.org/0000-0001-5162-8103

REFERENCES

Ahmed, M.B., Zhou, J.L., Ngo, H.H., Guo, W., Thomaidis, N.S. & Xu, J. (2017) Progress in the biological and chemical treatment technologies for emerging contaminant removal from wastewater: a critical review. *Journal of Hazardous Material*, 323(Pt A), 274–298. Available from: https://doi.org/10.1016/j.jhazmat.2016.04.045

Alabbadi, I., Abbott, R. & Jaber, D. (2014) Jordanian stakeholder attitudes toward generic substitution. *Generic Medicines*, 11(1-2), 24–34. Available from: https://doi.org/10.1177/1741134314560289

Al-Mashaqbeh, O., Alsafadi, D., Dalahmeh, S., Bartelt-Hunt, S. & Snow, D. (2019) Removal of selected pharmaceuticals and personal care products in wastewater treatment plant in Jordan. *Water*, 11, 2004.

Al-Mashaqbeh, O.A., Snow, D.D., Alsafadi, D.A., Alsalhi, L.Z. & Bartelt-Hunt, S.L. (2021) Removal of carbamazepine onto modified zeolitic tuff in different water matrices: batch and continuous flow experiments. *Water*, 13, 1084.

Andrés, E., Araya, F., Vera, I., Pozo, G. & Vidal, G. (2018) Phosphate removal using zeolite in treatment wetlands under different oxidation-reduction potentials. *Ecolological Engineering*, 117, 18–27. Available from: https://doi.org/10.1016/j.ecoleng.2018.03.008

Austin, D. & Nivala, J. (2009) Energy requirements for nitrification and biological nitrogen removal in engineered wetlands. *Ecolological Engineering*, 35(2), 184–192. Available from: https://doi.org/10.1016/j.ecoleng.2008.03.002

Bai, S., Wang, X., Zhang, Y., Liu, F., Shi, L., Ding, Y. et al. (2022) Constructed wetlands as nature-based solutions for the removal of antibiotics: performance, microbial response, and emergence of antimicrobial resistance (AMR). *Sustainability*, 14(22), 14989. Available from: https://doi.org/10.3390/su142214989

Bhomia, R.K., Inglett, P.W. & Reddy, K.R. (2015) Soil and phosphorus accretion rates in sub-tropical wetlands: Everglades stormwater treatment areas as a case example. *Science of the Total Environment*, 533, 297–306. Available from: https://doi.org/10.1016/j.scitotenv.2015.06.115

Carvalho, P.N., Araújo, J.L., Mucha, A.P., Basto, M.C.P. & Almeida, C.M.R. (2013) Potential of constructed wetlands microcosms for the removal of veterinary pharmaceuticals from livestock wastewater. *Bioresource Technology*, 134, 412–416. Available from: https://doi.org/10.1016/j.biortech.2013.02.027

Carvalho, P.N., Finger, D.C., Masi, F., Cipolletta, G., Oral, H.V., Tóth, A. et al. (2022) Nature-based solutions addressing the water-energy-food nexus: review of theoretical concepts and urban case studies. *Cleaner Production*, 338, 130652. Available from: https://doi.org/10.1016/j.jclepro.2022.130652

da Silveira Barcellos, D., Procopiuck, M. & Bollmann, H.A. (2022) Management of pharmaceutical micropollutants discharged in urban waters: 30 years of systematic review looking at opportunities for developing countries. *Science of the Total Environment*, 809, 151128. Available from: https://doi.org/10.1016/j.scitotenv.2021.151128

Dan, A., Yang, Y., Dai, Y.N., Chen, C.X., Wang, S.Y. & Tao, R. (2013) Removal and factors influencing removal of sulfonamides and trimethoprim from domestic sewage in constructed wetlands. *Bioresource Technology*, 146, 363–370. Available from: https://doi.org/10.1016/j.biortech.2013.07.050

Dan, A., Zhang, X., Dai, Y., Chen, C. & Yang, Y. (2020) Occurrence and removal of quinolone, tetracycline, and macrolide antibiotics from urban wastewater in constructed wetlands. *Cleaner Production*, 252, 119677. Available from: https://doi.org/10.1016/j.jclepro.2019.119677

Dhangar, K. & Kumar, M. (2020) Tricks and tracks in removal of emerging contaminants from the wastewater through hybrid treatment systems: a review. *Science of the Total Environment*, 738, 140320. Available from: https://doi.org/10.1016/j.scitotenv.2020.140320

Dotro, G., Langergraber, G., Molle, P., Nivala, J., Puigagut, J., Stein, O. et al. (2017) *Treatment wetlands*. Biological Wastewater Treatment Series. London, IWA Publishing.

Escher, B.I., Baumgartner, R., Koller, M., Treyer, K., Lienert, J. & McArdell, C.S. (2011) Environmental toxicology and risk assessment of pharmaceuticals from hospital wastewater. *Water Research*, 45(1), 75–92. Available from: https://doi.org/10.1016/j.watres.2010.08.019

European Environment Agency. (2014) *Horizon 2020 Mediterranean report, Annex 2: Jordan*. Luxembourg: Publications Office of the European Union.

Forni, C., Cascone, A. & Migliore, L. (2001) Drugs uptake and degradation by aquatic plants as a bioremediation technique. *Minerva Biotecnologica*, 13, 151–152.

Gadipelly, C., Pérez-González, A., Yadav, G.D., Ortiz, I., Ibáñez, R., Rathod, V.K. et al. (2014) Pharmaceutical industry wastewater: review of the technologies for water treatment and reuse. *Industrial & Engineering Chemistry Research*, 53(29), 11571–11592. Available from: https://doi.org/10.1021/ie501210j

Ganiyu, S.O., Van Hullebusch, E.D., Cretin, M., Esposito, G. & Oturan, M.A. (2015) Coupling of membrane filtration and advanced oxidation processes for removal of pharmaceutical residues: a critical review. *Separation and Purification Technology*, 156, 891–914. Available from: https://doi.org/10.1016/j.seppur.2015.09.059

Guo, L., Lv, T., He, K., Wu, S., Dong, X. & Dong, R. (2017) Removal of organic matter, nitrogen and faecal indicators from diluted anaerobically digested slurry using tidal flow constructed wetlands. *Environmental Science and Pollution Research*, 24(6), 5486–5496. Available from: https://doi.org/10.1007/s11356-016-8297-2

Hamisi, R., Renman, A., Renman, G., Wörman, A. & Thunvik, R. (2022) Performance of a tidal flow constructed wetland used for post-treatment of on-site wastewater in cold climate. *Water Process Engineering*, 47, 102679. Available from: https://doi.org/10.1016/j.jwpe.2022.102679

Ilyas, H. & van Hullebusch, E.D. (2019) Role of design and operational factors in the removal of pharmaceuticals by constructed wetlands. *Water*, 11, 2356.

Ilyas, H. & van Hullebusch, E.D. (2020) Performance comparison of different types of constructed wetlands for the removal of pharmaceuticals and their transformation products: a review. *Environmental Science and Pollution Research*, 27(13), 14342–14364. Available from: https://doi.org/10.1007/s11356-020-08165-w

Kimura, K., Hara, H. & Watanabe, Y. (2005) Removal of pharmaceutical compounds by submerged membrane bioreactors (MBRs). *Desalination*, 178(1-3), 135–140. Available from: https://doi.org/10.1016/j.desal.2004.11.033

Kizito, S., Lv, T., Wu, S., Ajmal, Z., Luo, H. & Dong, R. (2017) Treatment of anaerobic digested effluent in biochar-packed vertical flow constructed wetland columns: role of media and tidal operation. *Science of the Total Environment*, 592, 197–205. Available from: https://doi.org/10.1016/j.scitotenv.2017.03.125

Liu, L., Li, J., Fan, H., Huang, X., Wei, L. & Liu, C. (2019) Fate of antibiotics from swine wastewater in constructed wetlands with different flow configurations. *International Biodeterioration and Biodegradation*, 140, 119–125. Available from: https://doi.org/10.1016/j.ibiod.2019.04.002

Lv, T., Wu, S., Hong, H., Chen, L. & Dong, R. (2013) Dynamics of nitrobenzene degradation and interactions with nitrogen transformations in laboratory-scale constructed wetlands. *Bioresource Technology*, 133, 529–536. Available from: https://doi.org/10.1016/j.biortech.2013.02.003

Lyu, T., He, K., Dong, R. & Wu, S. (2018) The intensified constructed wetlands are promising for treatment of ammonia stripped effluent: nitrogen transformations and removal pathways. *Environmental Pollution*, 236, 273–282. Available from: https://doi.org/10.1016/j.envpol.2018.01.056

Nivala, J., Murphy, C. & Freeman, A. (2020) Recent advances in the application, design, and operations & maintenance of aerated treatment wetlands. *Water*, 12, 1188.

Oral, H.V., Carvalho, P., Gajewska, M., Ursino, N., Masi, F., van Hullebusch, E.D. et al. (2020) A review of nature-based solutions for urban water management in European circular cities: a critical assessment based on case studies and literature. *Blue-Green Systems*, 2(1), 112–136. Available from: https://doi.org/10.2166/bgs.2020.932

Ram, C. & Vineet, K. (2015) Mechanism of wetland plant rhizosphere bacteria for bioremediation of pollutants in an aquatic ecosystem. *Advances in Biodegradation and Bioremediation of Industrial Waste*, 12, 343–394. Available from: https://doi.org/10.1201/b18218-16

Reis, E.O., Foureaux, A.F.S., Rodrigues, J.S., Moreira, V.R., Lebron, Y.A.R., Santos, L.V.S. et al. (2019) Occurrence, removal and seasonal variation of pharmaceuticals in Brasilian drinking water treatment plants. *Environmental Pollution*, 250, 773–781. Available from: https://doi.org/10.1016/j.envpol.2019.04.102

Saeed, T. & Sun, G. (2017) A comprehensive review on nutrients and organics removal from different wastewaters employing subsurface flow constructed wetlands. Critical reviews. *Environmental Science and Technology*, 47(4), 203–288. Available from: https://doi.org/10.1080/10643389.2017.1318615

Santos, F., Almeida, C.M.R., Ribeiro, I. & Mucha, A.P. (2019) Potential of constructed wetland for the removal of antibiotics and antibiotic resistant bacteria from livestock wastewater. *Ecological Engineering*, 129, 45–53.

Vera, I., Araya, F., Andrés, E., Sáez, K. & Vidal, G. (2014) Enhanced phosphorus removal from sewage in mesocosm-scale constructed wetland using zeolite as medium and artificial aeration. *Environmental Technology*, 35(13), 1639–1649. Available from: https://doi.org/10.1080/09593330.2013.877984

Vymazal, J. (2010) Constructed wetlands for wastewater treatment. *Water*, 2, 530–549.

Wang, Y., Song, H., Li, L., Ma, J. & Yu, F. (2022) *Generation characteristics and spreading risk of VOCs released from a biological fermentation pharmaceutical factory*. Environmental Science: Processes & Impacts. 25(3), 507–518. Available from: https://doi.org/10.1039/D2EM00378C

Wang, H., Sun, J., Xu, J. & Sheng, L. (2021) Study on clogging mechanisms of constructed wetlands from the perspective of wastewater electrical conductivity change under different substrate conditions. *Environmental Management*, 292, 112813. Available from: https://doi.org/10.1016/j.jenvman.2021.112813

WHO/UNICEF. (2000) *Global water supply and sanitation assessment, 2000 report*. United Nations Child: Fund Geneva, World Heal. Organ. New York.

Wu, S., Lyu, T., Zhao, Y., Vymazal, J., Arias, C.A. & Brix, H. (2018) Rethinking intensification of constructed wetlands as a green eco-technology for wastewater treatment. *Environmental Science & Technology*, 52(4), 1693–1694. Available from: https://doi.org/10.1021/acs.est.8b00010

Yazdania, V. & Golestanib, H.A. (2019) Advanced treatment of dairy industrial wastewater using vertical flow constructed wetlands. *Desalination Water Treatment*, 162, 149–155. Available from: https://doi.org/10.5004/dwt.2019.24335

Zhang, Y., Lv, T., Carvalho, P.N., Zhang, L., Arias, C.A., Chen, Z. et al. (2017) Ibuprofen and iohexol removal in saturated constructed wetland mesocosms. *Ecological Engineering*, 98, 394–402. Available from: https://doi.org/10.1016/j.ecoleng.2016.05.077

Zhang, L., Lyu, T., Ramírez Vargas, C.A., Arias, C.A., Carvalho, P.N. & Brix, H. (2018) New insights into the effects of support matrix on the removal of organic micro-pollutants and the microbial community in constructed wetlands. *Environmental Pollution*, 240, 699–708. Available from: https://doi.org/10.1016/j.envpol.2018.05.028

Zhang, Y., Lyu, T., Zhang, L., Button, M., Arias, C.A., Weber, K.P. et al. (2019) Microbial community metabolic profiles in saturated constructed wetlands treating iohexol and ibuprofen. *Science of the Total Environment*, 651(Pt 2), 1926–1934. Available from: https://doi.org/10.1016/j.scitotenv.2018.10.103

How to cite this article: Al-Mashaqbeh, O., Alsalhi, L., Salaymeh, L. & Lyu, T. (2023) Assessment of novel hybrid treatment wetlands as nature-based solutions for pharmaceutical industry wastewater treatment. *Water and Environment Journal*, 1–9. Available from: https://doi.org/10.1111/wej.12907