



Performance Evaluation of Horizontal Flow Constructed Wetland for Removal of Pharmaceuticals from Synthetic Wastewater

Zeba Ali Mumtaj¹, Abdul Rahman Khan², Majed Alsubih³, Saimah Khan^{4*}

¹Department of Chemistry, Integral University, India

<https://orcid.org/0009-0009-8634-6945>

²Department of Chemistry, Integral University, India

³Department of Civil Engineering, King Khalid University, Abha, Saudi Arabia

<https://orcid.org/0000-0001-8226-1682>

⁴Department of Chemistry, Integral University, India

<https://orcid.org/0000-0002-6483-4325>

*Corresponding author's e-mail: saimah@iul.ac.in

Abstract: The removal efficiency of pharmaceutical compounds in wastewater treatment can be significantly influenced by seasonal variations and the presence of vegetation. This study evaluates the removal efficiencies of five pharmaceutical compounds – Cefadroxil (CFL), Ciprofloxacin (CIP), Cefpodoxime (CFD), Atenolol (ATN) and Avil-25 (AVL) – in non-planted (CW2) and planted (CW1) constructed wetlands across various parameters including Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), Alkalinity, Nitrate, and Phosphate during winter and summer seasons. Results indicate that CW1 consistently outperforms CW2 in all parameters and seasons. For example, CW1 achieved 54.28% BOD removal for CFL in winter compared to CW2's 39.67%, with summer values reaching 79.6% and 69.7%, respectively. The superior performance of CW1 was also observed for COD and other parameters, with phosphate removal reaching 94% in summer. The results of HPLC analysis indicated that CW1 showed better removal efficiencies of Cefadroxil (56.94%), Ciprofloxacin (90%), and Avil-25 (99.7%) than CW2. Even though Cefpodoxime showed low removal efficiency in both systems, CW1 still performed slightly better (13.99% vs. 0.7%). Atenolol removal was particularly notable in CW1 (93.79%), significantly outperforming CW2. Hazard quotient assessments revealed lower risks associated with pharmaceutical residues in CW1. For example, Ciprofloxacin's hazard quotient was reduced from 16% in CW2 to 10% in CW1, underscoring the effectiveness of vegetation in mitigating environmental risks. Atenolol showed a significant hazard quotient reduction from 2% in CW2 to less than 0.5% in CW1, while Avil-25's hazard quotient was negligible in CW1 compared to 4% in CW2. It was also concluded that vegetation positively influenced the treatment efficacy of constructed wetlands for pharmaceuticals with reduced eco-toxicity and the associated risks.

Keywords: horizontal flow constructed wetland, hazard quotient, removal efficiency, Ciprofloxacin, Cefadroxil, Cefpodoxime, Atenolol and Avil-25

Nomenclature

CW = constructed wetland,

CW1 = planted constructed wetland,

CW2 = unplanted constructed wetland,

PhACs = pharmaceutical active compounds,

Cefadroxil = CFL,

Ciprofloxacin = CIP,

Cefpodoxime = CFD,

Atenolol = ATN,

Avil-25 = AVL,

High-Performance Liquid Chromatography = HPLC.

1. Introduction

Constructed wetlands have been used for managing wastewater since the early nineties (Abad et al. 2023). However, their use was characterised by shortcomings due to their large size, which did not follow the urban land use planning. Nevertheless, with the recent policies and strategies developed in striving to mitigate the impacts of climate change and global warming, it is perhaps necessary to maximise green density in cities. Due to its simple applicability, functionality, and management, it has become one of the most widely used treatments (Hu et al. 2021, Parde et al. 2021). These include over 700 emerging pollutants, for instance, the active pharmaceutical compounds popularly referred to as PhACs (Alsubih et al. 2021, Geissen et al. 2015). These aspects of a better life and availability of facilities also led to increased population and medical facilities (hospitals, clinics, pathology labs, etc.) (Khan R.A. et al. 2022, Hu et al. 2021). Environmental wastewater,



such as domestic and municipal wastewater, obtains pharmaceutical compounds from patients' human and animal excreta (Khan N.A. et al. 2022). Several researches have been conducted to assess the treatment efficiency of constructed wetlands in removing pharmaceuticals from wastewater (Ávila et al. 2021b, Cheng et al. 2021, Mumtaj et al. 2024b). However, a literature review revealed a research gap in these studies; none of the research works utilised hospital wastewater. Using a simulated wastewater approach, the performance of constructed wetlands for pharmaceutical removal has been studied by Chen et al. 2021, Li et al. 2020, Alsubih et al. 2022a, Alsubih et al. 2022b, Mumtaj et al. 2024a. The pharmaceutical compounds removal efficiency analysis has been carried out by using septic tank effluent, according to Ávila et al. (2021). The work of Stroski et al. (2020) intends to report the study's results on the presence of pharmaceutical compounds in the receiving waters of the Arctic. Moreover, pharmaceutical compounds are sourced not only from pharmaceutical industries but also from health-related structures such as hospitals and other health-care centres, which have not been included in most of the investigations. This brings out the research gap in a way that constructed wetland treatment systems are being assessed for their ability to remove pharmaceutical compounds in hospital effluents. Moreover, the local climatic factors and weather influence constructed wetlands as open landscape wastewater treatment systems. Again, this needs not much elaboration considering that there is little literature on hospital wastewater, more so regarding this perspective. Also, because of their open landscape nature, constructed wetlands are likely to be influenced by climatic changes, particularly rainfall. Constructed wetlands have been discussed by Zhang et al. (2020) for arranged treatment efficiency during dry seasons with low flow rates of influent. In a study by Zhao et al. (2020), nitrogen removal efficiencies of F CWs were evaluated in dry and cold climatic conditions. Wang et al. (2021) examined the dynamics of constructed wetlands during the monsoon period. In a study conducted by Bojcevska & Tonderski (2007), the amount of moisture, the time of the year, the nature of the plant and plant density were considered. Wu et al. (2023) showed the influence of constructed wetlands on nitrogen removal during the cold season analysis. Another element Ma et al. (2017) took in the study is the effect of low temperature on the ability to remove cadmium from wastewater by the constructed wetland. From the available literature, it can be deduced that the effect of climate on the performance of constructed wetlands in the removal of pharmaceutical compounds has not been defined in previous works.

Therefore, wastewater treatment is becoming an area of interest within the health facility due to pharmaceutical waste. Khan N.A. et al. (2019) and Khan R.A. et al. (2023) studied the efficiency of extended aeration in treating hospital wastewater. Alsubih et al. (2021) used an aerobic fluidised bed bioreactor to examine its treatment capacities. Horizontal flow constructed wetlands have also been tested by Khan N.A. et al. (2020) for treating hospital wastewater. However, such investigations have been made regarding the general pollutant, removal of the nutrients such as nitrate (NO_3^-) and phosphate (PO_4^{3-}) as well as the organic matter, including the chemical oxygen demand (COD) and the biochemical oxygen demand (BOD). Table 1 shows the various studies for the removal of pharmaceuticals using CW.

Table 1. The pharmaceutical compounds removal using various CW in wastewater containing drug

Pharmaceutical compounds	Drug Class	Type of CW used for removal	References
Amoxicillin	Penicillin Antibiotics	Horizontal flow CW	Hijosa-Valsero et al. (2011)
Ciprofloxacin	Fluroquinol Antibiotics	Vertical flow CW and hybrid flow CW	Sun & Zheng (2022), Yuan et al. (2020), Dan et al. (2021)
Levofloxacin	Fluroquinol Antibiotics	Horizontal flow CW, hybrid flow CW and Vertical flow CW	Sun & Zheng (2022), Alsalihiy et al. 2024
Omeprazole	Proton pump Antibiotics	Horizontal flow CW	Chaves Barquero (2022)
Ofloxacin	Beta-lactam Antibiotics	Vertical flow CW	Ávila et al. (2021)
Azithromycin	Macrolide Antibiotics	Vertical flow CW	Ávila et al. (2021)
Diclofenac	NSAIDs	Horizontal flow CW and Vertical flow CW	Carranza-Diaz et al. (2014), Sohacki et al. (2018), Cheng et al. (2022)
Naproxen	NSAIDs	Horizontal flow CW and Vertical flow CW	Lancheros et al. (2019), de Oliveira, Milina, et al. 2019, Kucerak, L. N. 2014
Ibuprofen	NSAIDs	Horizontal flow CW and Vertical flow CW	Lancheros, Juan Camilo, et al. 2019, de Oliveira et al. (2019), Kucerak (2014)
Carbamazepine	NSAIDs	Horizontal flow CW	Carranza-Diaz et al. (2014)
Ketoprofen	NSAIDs	Vertical flow CW	Cavalheri et al. (2023)

This study aims to assess the efficiency of two constructed wetlands for the degradation process of pharmaceutical compounds. In addition to removal efficacy, the possible hazards to the environment originating from the effluent of the constructed wetland were assessed. Therefore, the main highlight of this study is the assessment of rare and exotic pharmaceutical ingredients and types of plants in constructed wetland systems. Moreover, each compound was analysed selectively, based on conventional characteristics. Also, this study investigates the remediation of pharmaceutical compounds such as CFL, CFD, and AVL through the use of constructed wetlands – a relatively innovative approach. Examining these particular pharmaceuticals within such systems is not commonly found in existing research, highlighting the novel aspect of this investigation.

2. Material and Methods

2.1 Chemicals and Chemical Structure

The chemicals used in this study to prepare synthetic wastewater were purchased from Sigma-Aldrich. The chemical structure of the pharmaceutical compounds analysed in this study is presented in Figure 1.

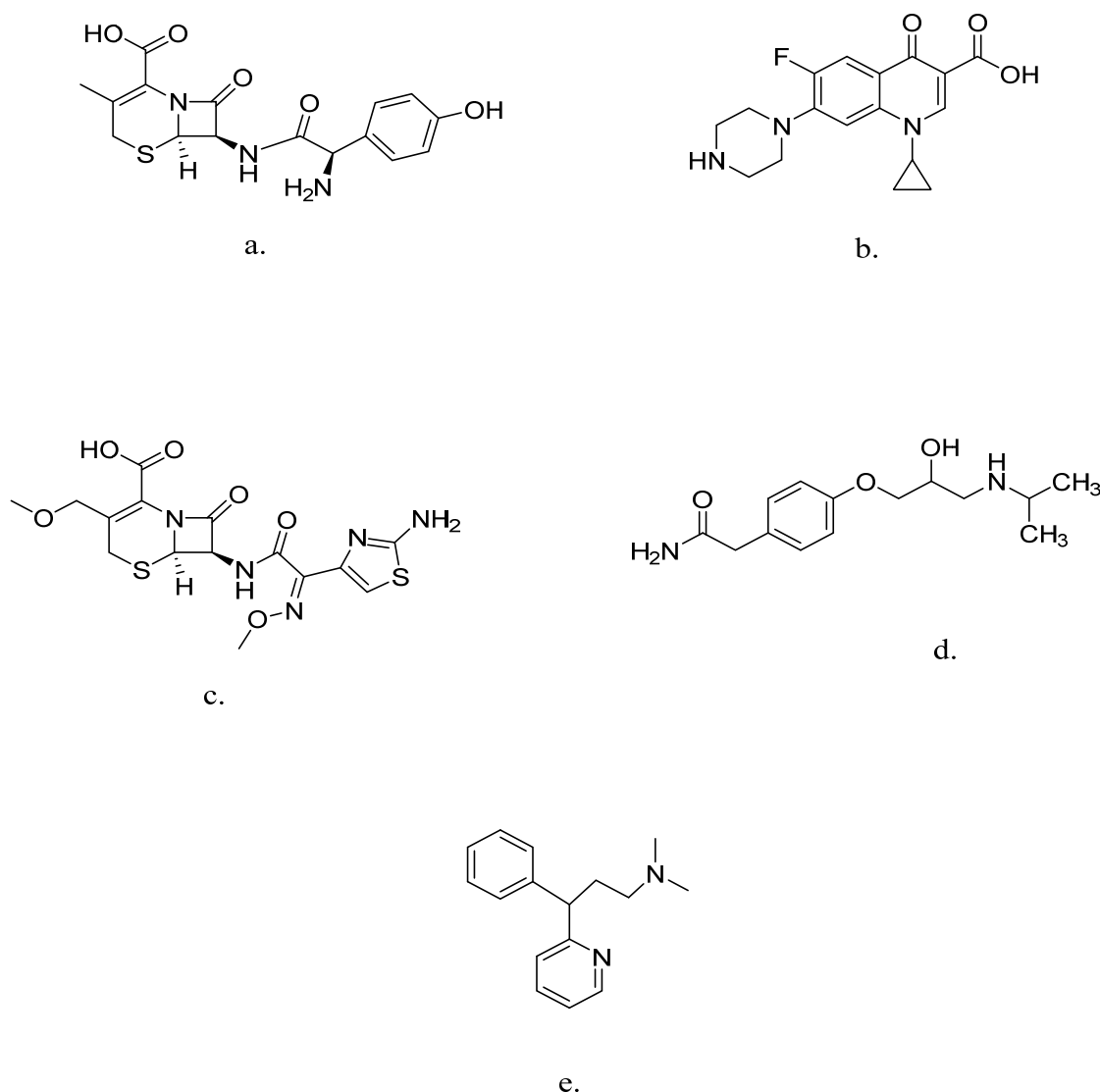


Fig. 1. The chemical structure of Cefadroxil (a), Ciprofloxacin (b), Cefpodoxime (c), Atenolol (d) and Avil-25 (e)

2.2. Preparation of Synthetic wastewater

Home wastewater was most closely mimicked by synthetic wastewater, which was least accurate in capturing the features of home wastewater. Nonetheless, due to its shortcoming in mimicking household wastewater in a perfect way, synthetic wastewater does come with some benefits, including more favourable control of several factors within the experiment, creating perfect redox conditions (van Loosdrecht et al. 2016), removing health risks, batch differences, and storage (Prieto et al. 2019). For example, synthetic

wastewater should be supplemented with carbon-containing material, nitrogen, phosphate, and other additives (Lima et al. 2018). In the current study, the synthetic wastewater composition used consists of 40 mg/L of glucose as a source of carbon, 50 mg/L of acetic acid, a source of organic acids, 10 mg/L of K_2HPO_4 that is a source of phosphorus and 60 mg/L of urea that is a source of nitrogen (Haritash et al. 2015, Tang et al. 2019). 0.5 mg/L $MnCl_2 \cdot 4H_2O$, 0.5 mg/L $FeCl_2 \cdot 6H_2O$, 7.5 mg/L $CaCl_2 \cdot 2H_2O$, and 100 mg/L $MgCl_2 \cdot 6H_2O$ were the trace elements observed (Biplob et al. 2011). Tap water was used to dissolve each of these. To prevent changes in pH level, 0.5 mol/L $NaHCO_3$ is used (Nasseri et al. 2014). In the synthetic wastewater, the level of antibiotic concentration is at 50 ppm. The drugs employed in synthetic wastewater are Ciprofloxacin, Cefadroxil, Cefpodoxime, Atenolol and Avil-25.

2.4. Study location

Constructed Wetlands were set up in Integral University, Kursi Road, Lucknow, India, Latitude 26.95862° or $26^\circ 57' 31''$ north. It is located at the Dashauli in the Northeastern part of the city, about 17 km from the city centre.

2.5. Constructed wetland design

The experiment consisted of two horizontal flow constructed wetlands of 1 m width and 2 m length; one planted with *Arundo donax* and the other unplanted. They range from 1.5 inches in length to 0.5 inches in width. The wetlands were constructed using a concrete layer of 5 inches and a soil layer of 7 inches. Figure 2 shows the schematic representation of the HFCW set-up.

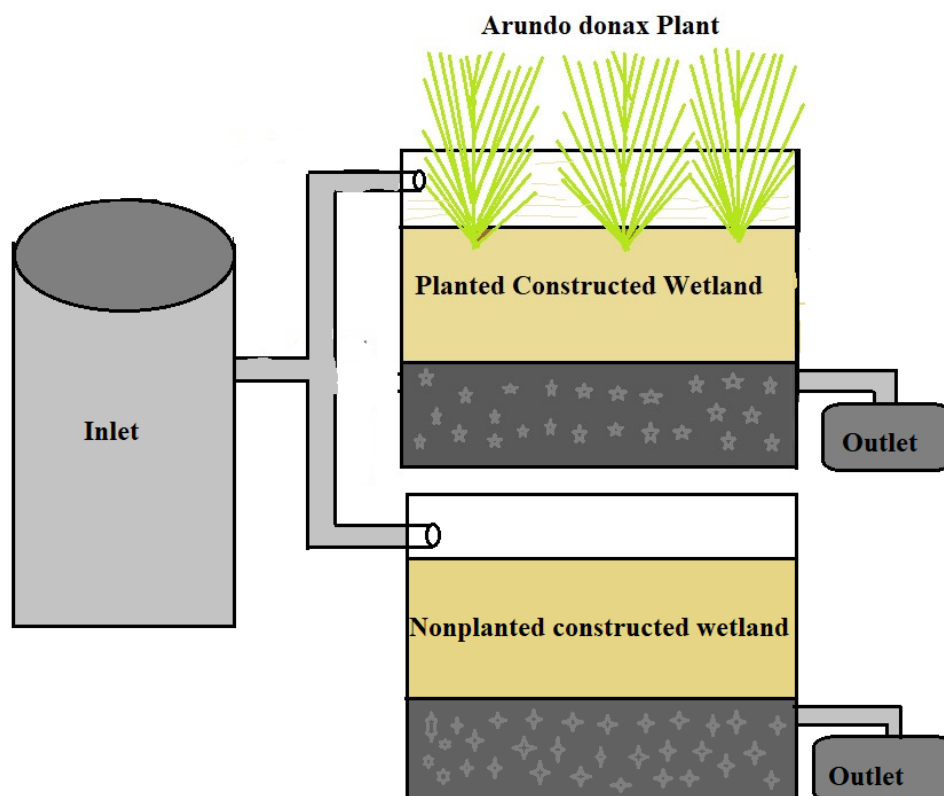


Fig. 2. Horizontal Flow Constructed Wetland Schematic Representation

2.6. Wastewater sampling

The sampling was conducted on the outlets at 24-hour intervals. Clean and pre-rinsed polypropylene bottles of 500 ml each were used for sampling. The bottles used to collect the samples were 500 ml capacity polypropylene bottles which had been previously cleaned and rinsed. All the samples were then acidified with 2% HNO_3 and kept in a refrigerator at a temperature of $4^\circ C$ until they were examined. To maintain the reliability of the outcomes, the experiment was performed three times, and an average of three was used in the present study, according to the research conducted by Rana & Maiti (2018).

2.7. Laboratory analysis (influent and effluent)

The chemical parameters studied here include pH, BOD, COD, TSS, alkalinity, nitrate, and sand phosphate. The pH values of the influent and effluent wastewater samples were measured using a pH meter. The measurement of the BOD parameter was observed by subjecting the sample water to a biological oxygen demand test using the BOD bottles at an incubation temperature of 22°C for 5 days. The COD test was also carried out in the laboratory by measuring the chemical oxygen demand of the water sample. A known amount of $K_2Cr_2O_7$ is then added to the unrushed amount of the sample, and both are boiled with conc. H_2SO_4 . The titration continued with the addition of $K_2Cr_2O_7$, after which the reaction was titrated with ferrous ammonium sulphate indicator, Ferroin. This is calculated to show the amount of oxygen needed to arrest the matter's oxidation and the dichromate taken. Nitrate concentration was identified with the help of the UV-visible spectrophotometric technique, and the sulphate anion concentration was determined using a spectrophotometer or turbidity meter.

The HPLC samples were prepared by first extracting and concentrating the water samples. Working standard solutions of high to low and low to high concentrations were made for various types of pharmaceutical compounds. The pharmaceutical compounds studied included ciprofloxacin, cefadroxil, cefpodoxime, atenolol and avil-25. The first set of water samples was measured in duplicate, while the subsequent measurements were done in a single run as no significant difference was observed between the duplicate measurements. Wastewater samples and standards were prepared as a standard procedure (Sabri et al. 2020). All examined samples were tested by HPLC for ciprofloxacin, cefadroxil, cefpodoxime, atenolol, and avil-25, and the results are presented in Table 2. These details regarding the method have already been explained in our prior research by Sabri et al. (2020). Pharmaceutical compounds were analysed using isocratic HPLC analysis in Shimadzu model SPD-M20A 230 V C18 (Luna 5 μ m C18 (2) 100 LC Column 250 \times 4.6 mm) and 1 mL/min flow rate. The mobile phase comprised eluent A buffer solution (KH_2PO_4 and K_2HPO_4) and eluent B (methanol) in the ratio of 53:47 V/V, pH 3.5 was adjusted with phosphoric acid 1 ml min^{-1} . The method's linearity, stability, accuracy, precision, and detection selectivity were all confirmed.

2.8. Removal efficiency of constructed wetlands

This research investigated the efficiency of constructed wetlands with *Arundo donax* plants and without plants in removing pharmaceutical compounds from synthetic wastewater. However, the concentration of influent and effluent was measured to determine the efficiency of the current treatment method for eradicating the pharmaceuticals in synthetic wastewater (Guedes-Alonso et al. 2020). Both the influent and effluent concentrations of pharmaceutical substances were then used to determine percentage removal efficiency. The following procedure was followed to evaluate the constructed wetlands' removal efficiency to determine the removal efficiency (%) as indicated in Equation 1.

2.8.1. Removal efficiency

$$(RE \%) = (C_{in} - C_{out} / C_{in}) \times 100 \quad (1)$$

where:

C_{in} – Pharmaceutical compounds concentration in influent (inlet) and,

C_{out} – Pharmaceutical compounds concentration in effluent (outlet).

3. Ecology Risk Assessment

Using different terminology, the hazard quotient and risk assessment are, in fact, equivalent (Lancheros et al. 2019, Vymazal et al. 2017). Hazard identification entails employing the measures of concentration (MEC) and predicted no effect concentration (PNEC). According to the research, the risk is well represented by hazard quotients (HQs) (Chen et al. 2016). Given that most pharmaceutical substances can change the metabolic processes within living organisms, assessing the risks offered by these products during their disposal within the environment is necessary. They defined the abbreviated name HQ as the ratio of the MEC of each pharmaceutical compound in the sample to its potential non-target ecological concentration. The respective HQ was assessed for every medicinal compound to observe its potential effect on the water bodies. PNEC values in this study were derived using data from HQ for three trophic levels, including fish, algae, and *Daphne*. Table 2 shows the PNEC value of the compounds whereby the HQ in this study is estimated. HQ was also calculated using Equation 2, which was used by Chen et al. (2016), Lancheros et al. (2019) and Avila et al. (2021) to estimate it. These studies have adopted four categories for the risk of eco-toxicity eval-

uation of compounds: HQ insignificant: less than 0.1 Low risk: 0.1-1.0 Moderate Risk: 1-10 High Risk: above 10 (Council 2012).

$$HQ = MEC/PNEC \quad (2)$$

Table 2. PNEC values used in this study for the target pharmaceutical compound for evaluating potential risk

Pharmaceutical compound	Code	PNEC value (μgL^{-1})	Reference
Cefadroxil	CFL	2	Alliance (2020)
Ciprofloxacin	CIP	0.06	Alliance (2020)
Cefpodoxime	CFD	0.25	Alliance (2020)
Atenolol	ATN	148	Küster et al. (2010)

4. Results and Discussions

Seasonal variations and vegetation presence can significantly influence pharmaceutical compounds' removal efficiency in wastewater treatment processes. This study evaluates the removal efficiencies of five pharmaceutical compounds – Cefadroxil (CFL), Ciprofloxacin (CIP), Cefpodoxime (CFD), Atenolol (ATN), and Avil-25 (AVL) – across various parameters including Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), Alkalinity, Nitrate, and Phosphate. The results are compared between non-planted (CW2) and planted (CW1) constructed wetlands during winter and summer.

For CFL, planted wetlands consistently outperform non-planted ones across all parameters and seasons. In winter, CW1 shows significantly higher removal efficiency for BOD (54.28%) compared to CW2 (39.67%), and this trend continues in summer (79.6% vs. 69.7%). Similar patterns are observed for COD and other parameters. Notably, phosphate removal in CW1 is superior in both seasons, with 75% in winter and 94% in summer, indicating enhanced nutrient removal capabilities in planted wetlands. Figure 3 shows the % RE of CFL in CW1 and CW2 during summer and winter.

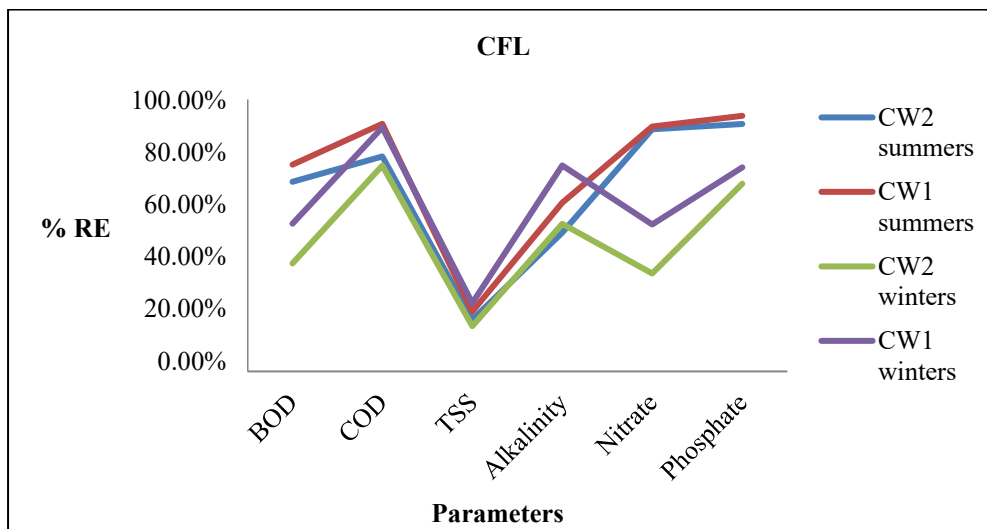


Fig. 3. Indicates the % RE of CFL in CW1 and CW2 during summer and winter

CIP also demonstrates higher removal efficiencies in CW1. For instance, in winter, CW1 achieves 72.7% COD removal compared to CW2's 36.3%, and this advantage persists in summer. A significant improvement is seen in alkalinity removal during winter (80.64% in CW1 vs. 22.58% in CW2) and summer (83% in CW1 vs. 19% in CW2), highlighting the effectiveness of planted wetlands in stabilising water chemistry. Figure 4 shows the % RE of CIP in CW1 and CW2 during summer and winter.

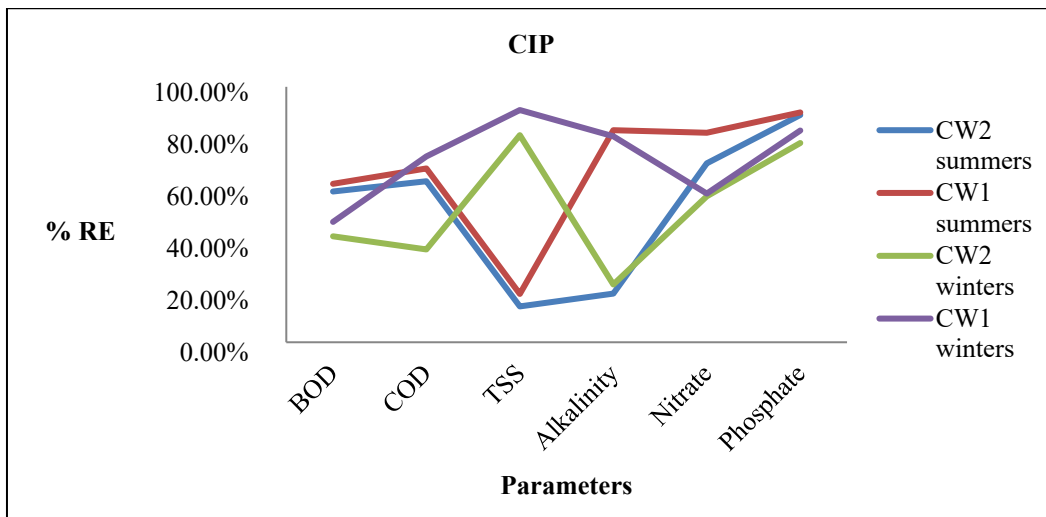


Fig. 4. The % RE of CIP in CW1 and CW2 during summer and winter

CFD follows a similar trend, with planted wetlands showing superior performance. In winter, CW1 achieves 80% BOD removal compared to CW2's 56%; in summer, the figures are 88.9% and 85%, respectively. The highest COD removal efficiency is observed in summer, with CW1 reaching 99.3%, demonstrating the peak performance of planted systems under warm conditions. Nitrate and phosphate removal efficiencies are also markedly higher in CW1, particularly in summer. Figure 5 shows the % RE of CFD in CW1 and CW2 during summer and winter.

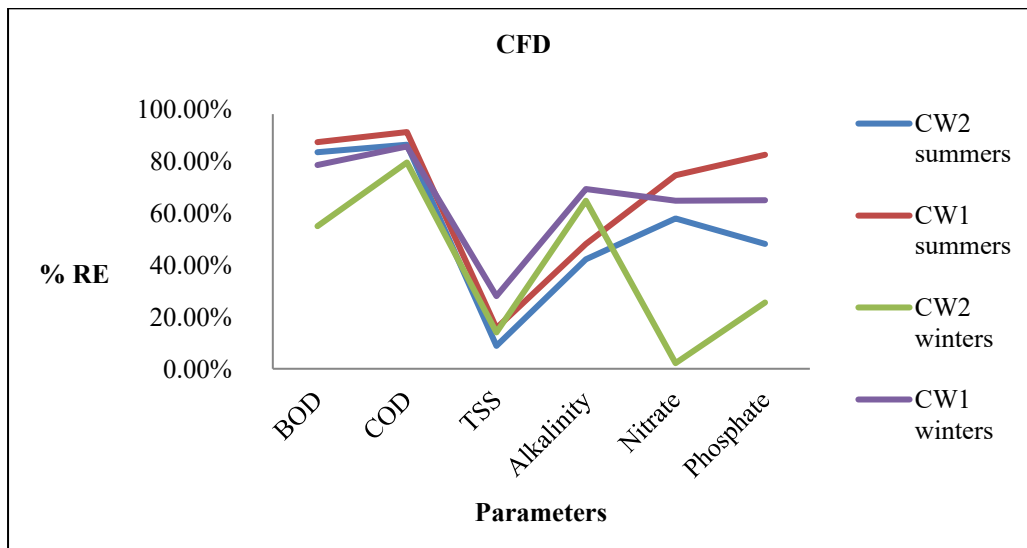


Fig. 5. The % RE of CFD in CW1 and CW2 during summer and winter

ATN exhibits an unusual pattern, where CW1 shows extremely high removal efficiencies in summer for BOD and COD (557% and 776.92%, respectively). This anomaly suggests possible errors in data recording or exceptional treatment conditions that warrant further investigation. However, for other parameters like nitrate and phosphate, CW1 consistently outperforms CW2 across both seasons. Figure 6 shows the % RE of ATN in CW1 and CW2 during summer and winter.

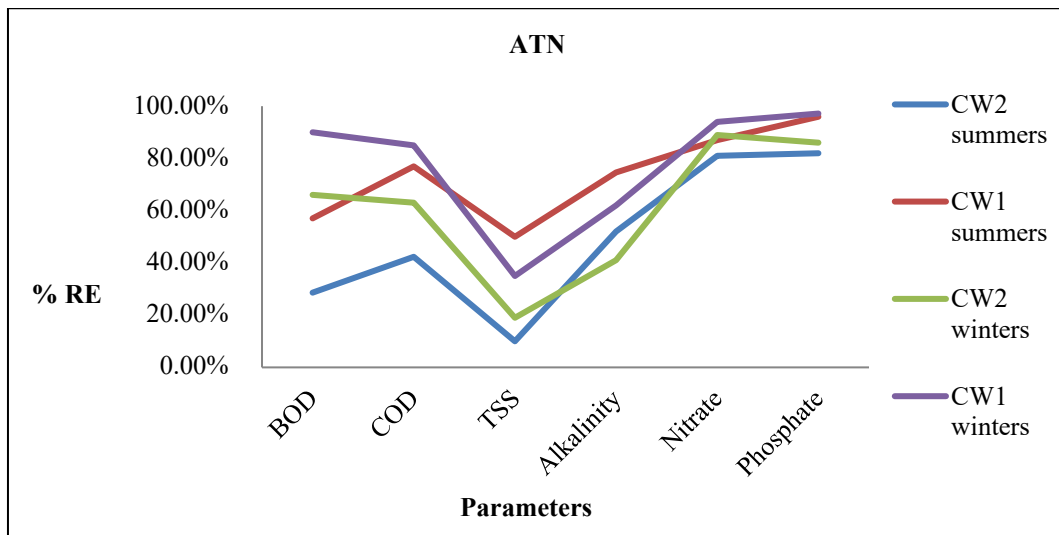


Fig. 6. The % RE of ATN in CW1 and CW2 during summer and winter

AVL maintains the trend where planted wetlands outperform non-planted ones. In winter, BOD removal in CW1 is 47.44% compared to CW2's 10.94%, and in summer, CW1 achieves 66.8% compared to CW2's 59%. CW1 also shows superior removal efficiencies for nitrate and phosphate, reaching up to 96.05% for phosphate in winter. The Figure 5 shows the % RE in CW1 and CW2 during summer and winter. Figure 7 shows the % RE of AVL in CW1 and CW2 during summer and winter.

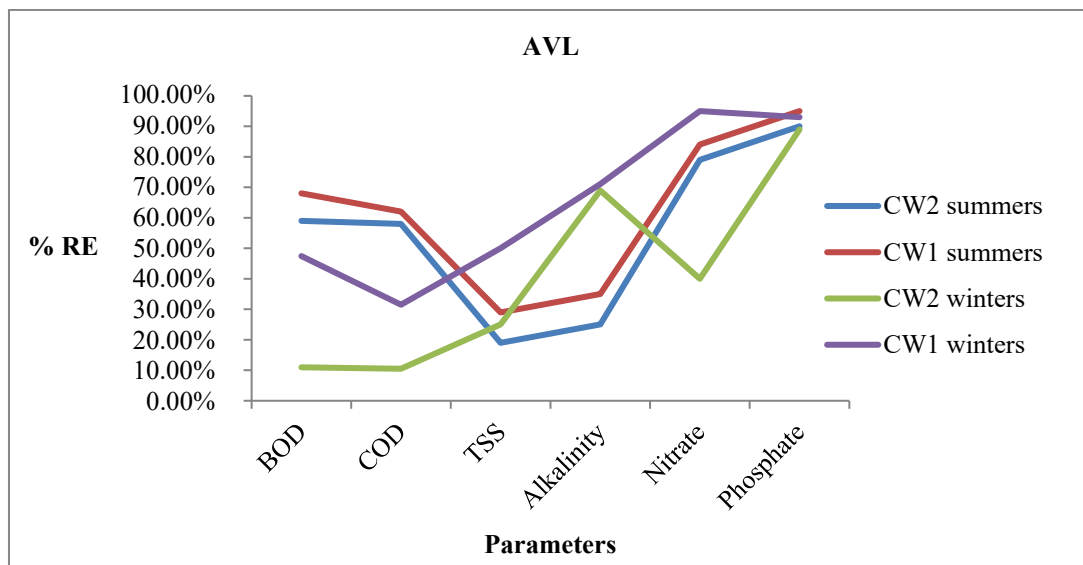


Fig. 7. The % RE of AVL in CW1 and CW2 during summer and winter

The presence of vegetation in constructed wetlands (CW1) consistently improves the removal efficiencies of various pharmaceutical compounds and associated water quality parameters. This improvement is more pronounced during summer, likely due to enhanced microbial activity and plant growth facilitated by higher temperatures. Planted systems (CW1) perform better across almost all parameters and compounds than non-planted systems (CW2). The seasonal variations also significantly impact the treatment efficiency, with generally higher removal rates observed during summer for most parameters. This highlights the importance of considering seasonal dynamics when designing and managing constructed wetlands for wastewater treatment.

4.1. Pharmaceutical compounds measurement using HPLC

The provided data in Figure 8 highlights the removal efficiency percentages (% RE) of various pharmaceutical compounds measured by HPLC in planted (CW1) and non-planted (CW2) constructed wetlands, comparing the influent concentrations with the effluent concentrations. For CFL, the influent concentration is 5.11 $\mu\text{g/L}$. The effluent concentration in the planted wetland (CW1) is 2.20 $\mu\text{g/L}$, reflecting a % RE of 56.94%.

In the non-planted wetland (CW2), the effluent concentration is 3.80 $\mu\text{g/L}$, resulting in a % RE of 25.63%. This indicates that CW1 is more effective in removing Cefadroxil from the water. CIP shows an influent concentration of 0.02 $\mu\text{g/L}$. CW1 achieves an effluent concentration of 0.002 $\mu\text{g/L}$, corresponding to a % RE of 90%. In contrast, CW2 has an effluent concentration of 0.007 $\mu\text{g/L}$, with a % RE of 65%. The planted wetland again demonstrates superior removal efficiency. CFD has an influent concentration of 1.43 $\mu\text{g/L}$. The removal efficiency is relatively low in both systems, with CW1 having an effluent concentration of 1.23 $\mu\text{g/L}$ (% RE of 13.99%) and CW2 with an effluent concentration of 1.42 $\mu\text{g/L}$ (% RE of 0.7%). This suggests neither system is particularly effective in removing Cefpodoxime, although CW1 performs slightly better. For ATN, the influent concentration is 0.029 $\mu\text{g/L}$. The planted wetland achieves an impressive effluent concentration of 0.0018 $\mu\text{g/L}$, translating to a % RE of 93.79%. In comparison, the non-planted wetland has an effluent concentration of 0.008 $\mu\text{g/L}$, resulting in a % RE of 72.41%. This again highlights the superior performance of CW1 in removing ATN. AVL has an influent concentration of 1.0 $\mu\text{g/L}$. The effluent concentration in CW1 is 0.003 $\mu\text{g/L}$, indicating a % RE of 99.7%. In CW2, the effluent concentration is 0.08 $\mu\text{g/L}$, with a % RE of 92%. While both systems show high removal efficiencies, CW1 outperforms CW2.

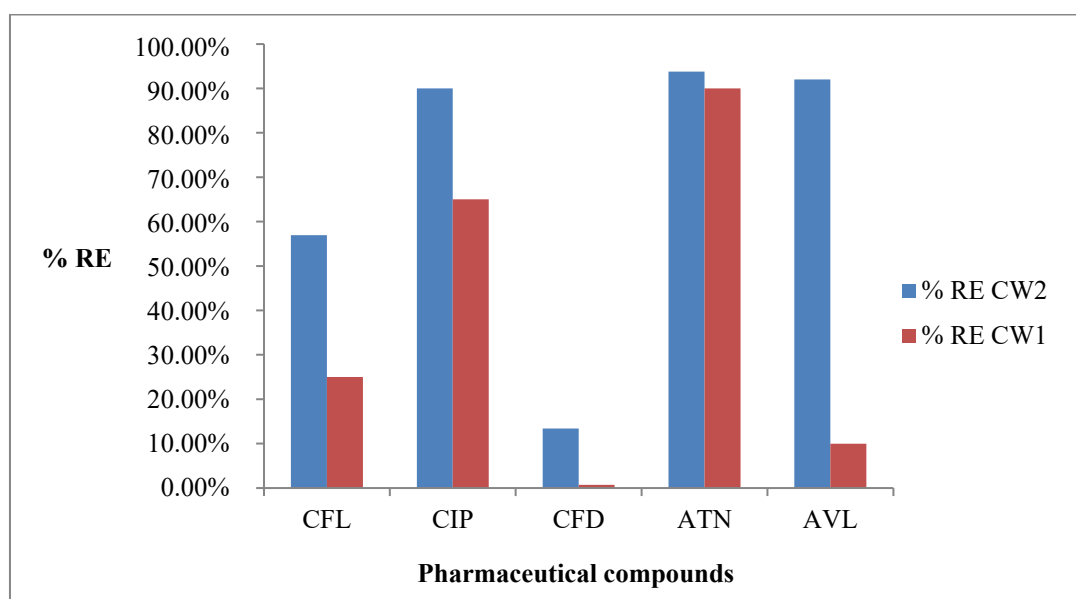


Fig. 8. Indicates the % RE of CFL, CIP, CFD, ATN and AVL in CW1 and CW2 using HPLC

The data consistently shows that planted constructed wetlands (CW1) have higher removal efficiencies for most pharmaceutical compounds than non-planted wetlands (CW2). This is particularly evident for CIP, ATN, and AVL, where CW1 demonstrates significantly higher removal efficiencies.

4.2. Risk Assessment

The hazard quotient (HQ) is the calculated value of the risk that the examined chemical compounds may implicate to the environment or health of people, with higher figures characterising higher risk (Chen et al. 2016). Based on this metric, the substances that may warrant regulatory intervention/s or remediation are quickly recognised and targeted for management. Regarding constructed wetlands (CWs), the HQ can be employed to determine how these systems reduce the environmental threats posed by these compounds (Lancheros et al. 2019, Vymazal et al. 2017, Avila et al. 2021).

For CFL, the hazard quotient is significantly lower in the planted wetland (approximately 8%) compared to the non-planted wetland (approximately 10%). This demonstrates that the presence of plants helps reduce the risk associated with CFL. CIP exhibits a notable difference in hazard quotients between the two constructed wetlands. In CW2, the hazard quotient is the highest among all compounds at about 16%, whereas in CW1, it is significantly reduced to around 10%. This substantial decrease underscores the effectiveness of plants in mitigating the environmental risk of CIP. CFD has the lowest hazard quotients among the compounds tested, with both scenarios showing minimal values. The difference between CW1 and CW2 is marginal, indicating that CFD poses a relatively low risk in both conditions, and plants do not significantly impact its hazard quotient. ATN shows a substantial reduction in hazard quotient from approximately 2% in the CW2 to less than 0.5% in the CW1. This significant reduction indicates that plants play a crucial role in lowering the environmental risk of ATN. AVL presents a marked difference, with the hazard quotient in the

CW2 wetland being about 4%, which is negligible in the CW1. This drastic reduction highlights the plants' ability to mitigate the risk posed by AVL effectively. Figure 9 shows the hazard quotient of CFL, CIP, CFD, ATN and AVL in CW1 and CW2.

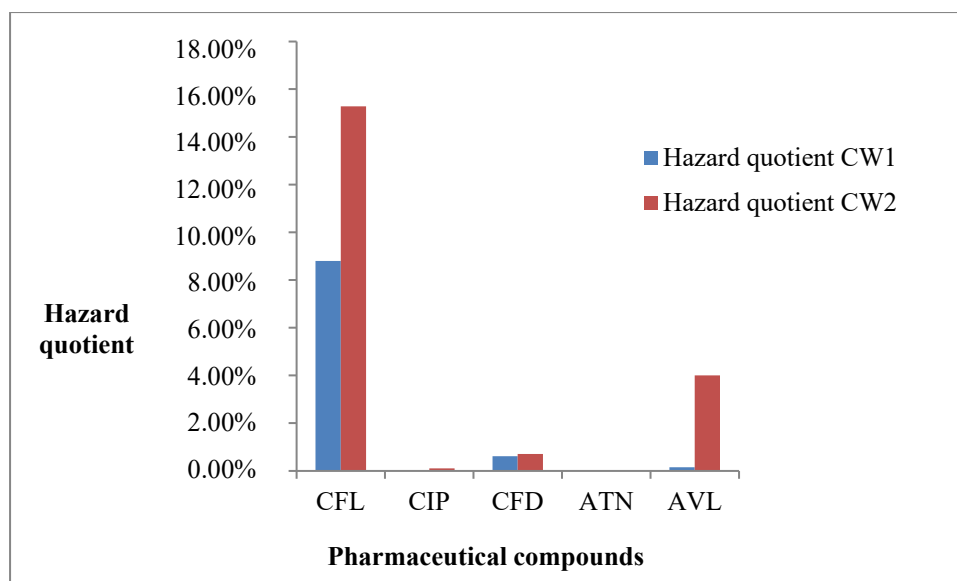


Fig. 9. Indicates the hazard quotient of CFL, CIP, CFD, ATN and AVL in CW1 and CW2

Overall, the presence of plants in constructed wetlands significantly enhances the removal of pharmaceutical contaminants, reducing their eco-toxicity and associated environmental risks. This underscores the importance of incorporating vegetation in the design and implementation of wetland systems for effective water treatment.

5. Conclusion and Recommendations

Thus, the study reveals that vegetation and seasonal changes strongly influence the efficiency of pharmaceutical compounds removal in constructed wetlands. This research established that wetland planted with vegetation (CW1) was more efficient than unplanted wetland (CW2) in removing some compounds, including CFL, CIP, CFD, ATN, and AVL, in terms of BOD, COD, TSS, Alkalinity, Nitrate, and phosphate. It was even more notable during summer, perhaps because of the high activity of microbes and plant growth.

The HPLC measurements demonstrate that planted wetlands (CW1) consistently achieve higher pharmaceutical compound removal efficiencies than non-planted wetlands (CW2). For CFL, CW1 shows a removal efficiency of 56.94% with an effluent concentration of 2.20 $\mu\text{g/L}$, whereas CW2 has a lower removal efficiency of 25.63% with an effluent concentration of 3.80 $\mu\text{g/L}$. CIP removal is markedly higher in CW1 at 90%, with an effluent concentration of 0.002 $\mu\text{g/L}$, compared to CW2's 65% removal efficiency and 0.007 $\mu\text{g/L}$ effluent concentration. CFD exhibits low removal efficiencies in both systems, with CW1 at 13.99% and CW2 at 0.7%, indicating limited effectiveness, though CW1 performs slightly better. ATN removal is significantly higher in CW1, achieving a 93.79% removal efficiency with an effluent concentration of 0.0018 $\mu\text{g/L}$, compared to CW2's 72.41% and 0.008 $\mu\text{g/L}$ effluent concentration. AVL shows the highest removal efficiencies, with CW1 achieving 99.7% removal and an effluent concentration of 0.003 $\mu\text{g/L}$, while CW2 achieves 92% removal and an effluent concentration of 0.08 $\mu\text{g/L}$.

The risk assessment also provided lower hazard quotients of pharmaceutical contaminants in the planted wetlands to prove that vegetation reduces environmental and human health risks. Specifically, CW1 demonstrated a high level of performance in reducing the risks associated with compounds such as CIP and ATN. In conclusion, including plants in the constructed wetlands improves its overall performance and makes it a viable solution for wastewater treatment. The findings of this study suggest that it is critical to incorporate vegetation into wetland designs to achieve the maximum accessibility of pharmaceutical contaminants and their consequent reduction.

This study also explores the remediation of pharmaceutical compounds like CFL, CFD, and AVL using constructed wetlands, a relatively novel approach. These specific pharmaceuticals are not commonly examined in such systems, emphasising the innovative nature of the research. By focusing on these less-studied compounds, the study offers new insights into the potential of constructed wetlands for pharmaceutical re-

mediation. This novel focus broadens the scope of constructed wetland applications and contributes valuable information on their effectiveness in treating a wider range of pharmaceutical contaminants. Additionally, research focusing on optimising wetland design, operation, and maintenance practices could help improve removal efficiencies and overall effectiveness in treating wastewater containing pharmaceutical compounds.

Declaration

All the authors of the manuscript have no conflict of interest to declare.

Acknowledgement

The authors extend their appreciation to the Deanship of Research and Graduate Studies at King Khalid University for funding this research work through the project number RGP2/40/45. This manuscript has Integral University Manuscript Communication Number IU/R&D/2024-MCN0002539.

Ethical approval

Not applicable.

Consent to participate

The authors declare that they consent to participate the work.

Consent for publication

The authors declare that they consent to publish this paper.

Author Contributions

Zeba Ali Mumtaj: Conceptualisation, Methodology, Resources; Writing-original draft preparation.

Saimah Khan: Conceptualization, Methodology, Resources; Writing-original draft preparation; Visualisation; Formal analysis; Funding acquisition.

Abdul Rahman Khan: Writing-Review and Editing.

Majed Alsubih: Project Administration: Writing-Review and Editing.

Funding

The authors extend their appreciation to the Deanship of Research and Graduate Studies at King Khalid University for funding this research work through the project number RGP2/40/45.

Conflict of interest

The authors declare no competing interests.

References

- Alsubih, M., Khan, R.A., Khan, N.A., Khan, A.R., Sharma, G. (2021). Performance evaluation of aerobic fluidised bed bioreactor coupled with tube-settler for hospital wastewater treatment. *Journal of Environmental Chemical Engineering*, 9(5), 105896.
- Alsubih, M., El Morabet, R., Khan, R.A., Khan, N.A., Khan, A.R., Khan, S., ... Yousefi, M. (2022). Performance evaluation of constructed wetland for removal of pharmaceutical compounds from hospital wastewater: Seasonal perspective. *Arabian Journal of Chemistry*, 15(12), 104344. <https://doi.org/10.1016/j.arabjc.2022.104344>
- Alsubih, M., El Morabet, R., Khan, R. A., Khan, N. A., Khan, A. R., Khan, S., ... Singh, L. (2022). Field performance investigation for constructed wetland clubbed with tubesettler for hospital wastewater treatment. *Journal of Water Process Engineering*, 49, 103147.
- Alliance, A.I. (2020). AMR Alliance Science-Based PNEC Targets for Risk Assessments.
- Ávila, C., García-Galán, M.J., Borrego, C.M., Rodríguez-Mozaz, S., García, J., Barceló, D. (2021). New insights on the combined removal of antibiotics and ARGs in urban wastewater through the use of two configurations of vertical subsurface flow constructed wetlands. *Science of the Total Environment*, 755, 142554.
- Avila, J., Long, B., Holladay, D., Gottlieb, M. (2021). Thrombotic complications of COVID-19. *The American journal of emergency medicine*, 39, 213-218.
- Biplob, P., Fatihah, S., Shahrom, Z., Ahmed, E. (2011). Nitrogen-removal efficiency in an upflow partially packed biological aerated filter (BAF) without backwashing process. *Journal of Water Reuse and Desalination*, 1(1), 27-35. <https://doi.org/10.2166/wrd.2011.008>
- Bojcevska, H., Tonderski, K. (2007). Impact of loads, season, and plant species on the performance of a tropical constructed wetland polishing effluent from sugar factory stabilisation ponds. *Ecological engineering*, 29(1), 66-76.
- Council, F. B. (2012). *Identifying Health Concerns Relating to Oil and Gas Development in Northeastern BC: Human Health Risk Assessment-Phase 1 Report*. British Columbia Ministry of Health.

- Cavalleri, P.S., Machado, B.S., da Silva, T.F., Rodrigues, J.P.B.G., Gozzi, F., Magalhães Filho, F.J.C., ... Junior, A.M. (2023). Optimisation of a combined system of vertical flow constructed wetland and solar photo-Fenton for keto-profen removal in sewage and landfill leachate. *Chemical Engineering Journal*, 475, 146282.
- Carranza-Díaz, O., Schultze-Nobre, L., Moeder, M., Nivala, J., Kuschik, P., Koeser, H. (2014). Removal of selected organic micropollutants in planted and unplanted pilot-scale horizontal flow constructed wetlands under conditions of high organic load. *Ecological Engineering*, 71, 234-245.
- Chen, H., Zhu, J., Li, Z., Chen, A., Zhang, Q. (2016). The occurrence and risk assessment of five organophosphorus pesticides in river water from Shangyu, China. *Environmental monitoring and assessment*, 188, 1-9.
- Cheng, C., Zhang, J., Xu, J., Yang, Y., Bai, X., He, Q. (2022). Enhanced removal of nutrients and diclofenac by birnesite sand vertical flow constructed wetlands. *Journal of Water Process Engineering*, 46, 102656.
- de Oliveira, M., Atalla, A.A., Frihling, B.E.F., Cavalleri, P.S., Migliolo, L., Magalhães Filho, F.J. (2019). Ibuprofen and caffeine removal in vertical flow and free-floating macrophyte constructed wetlands with *Heliconia rostrata* and *Eichornia crassipes*. *Chemical Engineering Journal*, 373, 458-467.
- Dan, A., Chen, C.X., Zou, M.Y., Deng, Y.Y., Zhang, X.M., Du, J.J., Yang, Y. (2021). Removal efficiency, kinetic, and behavior of antibiotics from sewage treatment plant effluent in a hybrid constructed wetland and a layered biological filter. *Journal of Environmental Management*, 288, 112435.
- Guedes-Alonso, R., Montesdeoca-Esponda, S., Herrera-Melián, J.A., Rodríguez-Rodríguez, R., Ojeda-González, Z., Landívar-Andrade, V., ... Santana-Rodríguez, J.J. (2020). Pharmaceutical and personal care product residues in a macrophyte pond-constructed wetland treating wastewater from a university campus: Presence, removal and ecological risk assessment. *Science of the Total Environment*, 703, 135596. <https://doi.org/10.1016/j.scitotenv.2019.135596>
- Geissen, V., Mol, H., Klumpp, E., Umlauf, G., Nadal, M., van der Ploeg, M., ... Ritsema, C.J. (2015). Emerging pollutants in the environment: a challenge for water resource management. *International soil and water conservation research*, 3(1), 57-65.
- Haritash, A.K., Sharma, A., Bahel, K. (2015). The potential of Canna lily for wastewater treatment under Indian conditions. *International journal of phytoremediation*, 17(10), 999-1004.
- Hu, X., Xie, H., Zhuang, L., Zhang, J., Hu, Z., Liang, S., Feng, K. (2021). A review on the role of plant in pharmaceuticals and personal care products (PPCPs) removal in constructed wetlands. *Science of the Total Environment*, 780, 146637.
- Kucerak, L.N. (2014). *The removal of pharmaceuticals ibuprofen and naproxen from natural wastewater by subsurface vertical flow constructed wetlands*. State University of New York College of Environmental Science and Forestry.
- Küster, A., Alder, A.C., Escher, B.I., Duis, K., Fenner, K., Garric, J., ... Knacker, T. (2010). Environmental risk assessment of human pharmaceuticals in the European Union: A case study with the β -blocker atenolol. *Integrated Environmental Assessment and Management*, 6(S1), 514-523.
- Khan, R.A., Morabet, R.E., Khan, N.A., Ahmed, S., Alsubih, M., Mubarak, N.M., ... Zomorodiyani, N. (2022). Removal of organic matter and nutrients from hospital wastewater by electro bioreactor coupled with tubesettler. *Scientific Reports*, 12(1), 9279.
- Khan, N.A., Bokhari, A., Mubashir, M., Klemeš, J.J., El Morabet, R., Khan, R.A., ... Show, P.L. (2022). Treatment of Hospital wastewater with submerged aerobic fixed film reactor coupled with tube-settler. *Chemosphere*, 286, 131838.
- Khan, R.A., Khan, N.A., El Morabet, R., Alsubih, M., Khan, A.R., Khan, S., ... Khoo, K.S. (2023). Comparison of constructed wetland performance coupled with aeration and tubesettler for pharmaceutical compound removal from hospital wastewater. *Environmental Research*, 216, 114437.
- Khan, N.A., El Morabet, R., Khan, R.A., Ahmed, S., Dhingra, A. (2019). Extended Aeration Tubesettler Performance Evaluation for Hospital Wastewater Treatment. no. February.
- Lancheros, J.C., Madera-Parra, C.A., Caselles-Osorio, A., Torres-López, W.A., Vargas-Ramírez, X.M. (2019). Ibuprofen and Naproxen removal from domestic wastewater using a horizontal subsurface flow constructed wetland coupled to ozonation. *Ecological Engineering*, 135, 89-97.
- Li, H., Cai, Y., Gu, Z., Yang, Y.L., Zhang, S., Yang, X.L., Song, H.L. (2020). Accumulation of sulfonamide resistance genes and bacterial community function prediction in microbial fuel cell-constructed wetland treating pharmaceutical wastewater. *Chemosphere*, 248, 126014.
- Lima, E.C. (2018). Removal of emerging contaminants from the environment by adsorption. *Ecotoxicology and environmental safety*, 150, 1-17. <https://doi.org/10.1016/j.ecoenv.2017.12.026>
- Ma, N., Wang, W., Gao, J., Chen, J. (2017). Removal of cadmium in subsurface vertical flow constructed wetlands planted with *Iris sibirica* in the low-temperature season. *Ecological engineering*, 109, 48-56.
- Mumtaz, Z.A., Khan, A.R., Alsubih, M., Aleya, L., Khan, R.A., Khan, S. (2024a). Removal of pharmaceutical contaminants from hospital wastewater using constructed wetlands: a review. *Environmental Science and Pollution Research*, 31(9), 12856-12870.
- Mumtaz, Z.A., Khan, A.R., Ansari, J.A., Asiri, A., Khan, S. (2024b). A Brief Overview of Antibiotic Contamination Sources in Wastewater and Elimination Approaches.
- Nasseri, S., Baghapour, M.A., Derakhshan, Z., Faramarzian, M. (2014). Degradation of atrazine by microbial consortium in an anaerobic submerged biological filter. *Journal of water and health*, 12(3), 492-503. <https://doi.org/10.2166/wh.2014.162>

- Prieto, A.L., Criddle, C.S., Yeh, D.H. (2019). Complex organic particulate artificial sewage (COPAS) as surrogate wastewater in anaerobic assays. *Environmental Science: Water Research & Technology*, 5(10), 1661-1671. <https://doi.org/10.1039/C9EW00365G>
- Parde, D., Patwa, A., Shukla, A., Vijay, R., Killedar, D.J., Kumar, R. (2021). A review of constructed wetland on type, treatment and technology of wastewater. *Environmental Technology & Innovation*, 21, 101261.
- Rana, V., Maiti, S.K. (2018). Municipal wastewater treatment potential and metal accumulation strategies of *Colocasia esculenta* (L.) Schott and *Typha latifolia* L. in a constructed wetland. *Environmental monitoring and assessment*, 190(328), 1-15.
- Sochacki, A., Nowrotek, M., Felis, E., Kalka, J., Ziemińska-Buczyńska, A., Bajkacz, S., ... Miksch, K. (2018). The effect of loading frequency and plants on the degradation of sulfamethoxazole and diclofenac in vertical-flow constructed wetlands. *Ecological Engineering*, 122, 187-196.
- Sabri, N.A., Van Holst, S., Schmitt, H., van der Zaan, B.M., Gerritsen, H.W., Rijnaarts, H.H., Langenhoff, A.A.M. (2020). Fate of antibiotics and antibiotic resistance genes during conventional and additional treatment technologies in wastewater treatment plants. *Science of the Total Environment*, 741, 140199.
- Sun, W., Zheng, Z. (2022). Research on removal of fluoroquinolones in rural domestic wastewater by vertical flow constructed wetlands under different hydraulic loads. *Chemosphere*, 303, 135100.
- Stroski, K.M., Luong, K.H., Challis, J.K., Chaves-Barquero, L.G., Hanson, M.L., Wong, C.S. (2020). Wastewater sources of per-and polyfluorinated alkyl substances (PFAS) and pharmaceuticals in four Canadian Arctic communities. *Science of the total environment*, 708, 134494.
- Tang, J., Wang, X.C., Hu, Y., Pu, Y., Huang, J., Ngo, H.H., ... Li, Y. (2019). Nutrients removal performance and sludge properties using anaerobic fermentation slurry from food waste as an external carbon source for wastewater treatment. *Bioresource technology*, 271, 125-135.
- Vymazal, J., Březinová, T.D., Koželuh, M., Kule, L. (2017). Occurrence and removal of pharmaceuticals in four full-scale constructed wetlands in the Czech Republic – the first year of monitoring. *Ecological Engineering*, 98, 354-364.
- Wang, X., Xu, Y., Pan, Y., Li, Y., Xu, J., Chen, J., ... Lei, W. (2021). Low-noise X-ray PIN photodiodes made of perovskite single crystals by solution-processed dopant incorporated epitaxial growth. *Nano Energy*, 89, 106311.
- van Loosdrecht, M.C., Nielsen, P.H., Lopez-Vazquez, C.M., Brdjanovic, D. (Eds.). (2016). *Experimental methods in wastewater treatment*. IWA publishing. ISBN 9781780404745
- Wu, H., Wang, R., Yan, P., Wu, S., Chen, Z., Zhao, Y., Zhang, J. (2023). Constructed wetlands for pollution control. *Nature reviews earth & environment*, 4(4), 218-234.
- Yuan, Y., Yang, B., Wang, H., Lai, X., Li, F., Salam, M. M. A., ... Zhao, Y. (2020). The simultaneous antibiotics and nitrogen removal in vertical flow constructed wetlands: Effects of substrates and responses of microbial functions. *Bioresource technology*, 310, 123419.
- Zhang, M., Chen, C., Zhou, S., Yang, J., Qiu, H., Zhao, D., An, S. (2020). Operation strategy for constructed wetlands in dry seasons with insufficient influent wastewater. *Bioresource Technology*, 317, 124049.
- Zhao, D., Chen, C., Lu, Q., Zhang, M., Zhang, H., An, S. (2020). Combined use of cold-season and warm-season macrophytes in floating constructed wetlands to increase nitrogen removal in the early cold season. *Journal of cleaner production*, 254, 120054.