Journal of Environmental Chemical Engineering 11 (2023) 111167

Contents lists available at ScienceDirect

Journal of Environmental Chemical Engineering

journal homepage: www.elsevier.com/locate/jece

Enhancing pharmaceutical removal in a full-scale constructed wetland with effluent recirculation

José A. Herrera-Melián [a], Rayco Guedes-Alonso [a,*], Jean Carlos Tite-Lescano [b], Zoraida Sosa-Ferrera [a], José J. Santana-Rodríguez [a]

[a] Instituto Universitario de Estudios Ambientales y Recursos Naturales (i-UNAT), Universidad de Las Palmas de Gran Canaria, 35017 Las Palmas de Gran Canaria, Spain
[b] Escuela de Ingenierías Industriales y Civiles, Universidad de Las Palmas de Gran Canaria, 35017 Las Palmas de Gran Canaria, Spain

A R T I C L E I N F O

Editor: Stefanos Giannakis

Keywords:
Wastewater treatment
Pharmaceutical removal
Macrophyte facultative pond
Horizontal-flow constructed wetland
Effluent recirculation

A B S T R A C T

Emerging organic micropollutants pose a threat to aquatic environments even at trace levels. Among the many different groups of emerging pollutants, pharmaceutical residues are of special concern because of their toxicity and long-term effects on biota. Natural wastewater treatment systems are effective at eliminating pharmaceuticals, but removals are usually incomplete. In this regard, effluent recirculation can help to improve the removal of pharmaceuticals in natural wastewater treatment systems with the goal of producing a better-quality effluent for reuse. This is particularly interesting for water-scarce regions such as semi-arid islands of this study. The obtained results provide evidence that effluent recirculation can significantly improve the removal of pharmaceuticals in natural wastewater treatment systems. Of the 11 compounds studied, the highest concentrations and detection frequencies (in decreasing order) were those of caffeine, paraxanthine, nicotine, ibuprofen, naproxen and atenolol. The average removals increased from 87.5% (no recirculation) to 97% (100% recirculation ratio), and these results are associated with an improved ammonium and total N removal with 100% recirculation. To the knowledge of the authors, this is the first study showing the positive effect of effluent recirculation on the removal of pharmaceuticals in a full-scale natural wastewater treatment system.

1. Introduction

The consumption of pharmaceutical compounds (PhCs) has increased worldwide in recent decades, and their residues can now be found in almost all urban and domestic wastewaters [1-3]. In this regard, thousands of different PhCs have been found in aquatic ecosystems and some of them have been detected in all the continents [4]. A variety of deleterious effects of PhCs on aquatic systems appear even at low concentrations [5] including estrogenic disruption or development of antimicrobial resistance [6]. Consequently, research efforts have been focused on augmenting removal efficiency in wastewater treatment facilities.

Conventional wastewater treatments plants (WWTPs) can provide high PhCs removals, but natural wastewater treatment systems (NWTSs) can do it at lower economic cost [6]. NWTs such as ponds and constructed wetlands (CWs), are particularly suitable for small to medium size communities because of their minimum or zero energy consumption, low maintenance requirements, limited or nil use of chemical products, and positive visual and ecological impact [7,8]. Following the water flow, the classic structure of a pond system is composed of anaerobic pond, facultative pond and maturation pond. The main target pollutants to be removed in each pond are TSS (anaerobic), BOD (facultative) and pathogens (maturation) [9]. Ponds usually achieve good efficacy but quite often the effluent requires further polishing to meet the quality standards for reuse or discharge to natural streams [10]. CWs are basically a substrate of gravel and/or sand submerged in the water to be treated and the associated plants and microorganisms. According to water flow, CWs can be classified as surface or subsurface, vertical (VF) or horizontal flow (HF). In subsurface flow (SSF) CWs water flows through a bed of gravel and/or sand. CWs are usually the most effective, but the bed can be clogged if the influent is not pretreated [11]. Although CWs are efficient (70–90%) in the removal of organic matter (TSS, COD, BOD, turbidity), that of N is usually lower (40–50%), mainly because of the low concentration of dissolved oxygen (DO) in water. The combination of pond and CW has been proposed as a robust method for wastewater treatment including PhC removal [12-14,10].

* Corresponding author.
E-mail address: rayco.guedes@ulpgc.es (R. Guedes-Alonso).

https://doi.org/10.1016/j.jece.2023.111167
Received 26 May 2023; Received in revised form 24 September 2023; Accepted 30 September 2023
Available online 12 October 2023

The main elimination mechanisms of PhCs in NWTs are photodegradation, biodegradation and sorption [15-17]. It is generally accepted that biodegradation of PhCs is enhanced in aerobic media [18]. Different intensification strategies have been tested to enhance DO transfer to water in CWs, being tidal flow, artificial aeration and effluent recirculation (ER) the most studied. In ER, a part of effluent is pumped back to the system inlet. As a result, different effects such as increasing DO concentrations and the interaction between pollutants and microorganisms, and effluent dilution, are expected to improve pollutant removal [19,20]. The recirculation ratio (effluent recirculated flow to influent flow) usually falls in the range 50–250%, though Nivala et al. applied 300% in full-scale VF CWs in Jordan [21]. Some researchers have claimed negative effects of ER [22], but many others observed improved removal of organic matter (COD and TSS) and N in both subsurface vertical and horizontal flow CWs [20]. Additionally, vertical flow CW effluent denitrification has been another application of ER. In this case, the effluent is directed to an anaerobic unit such as septic or recirculating tank to combine anoxic conditions and BOD to provide remarkable denitrification [21]. Nevertheless, most studies devoted to determining the feasibility of applying ER have been performed in small systems (Wu et al., 2014) while only a few have been performed in full-scale plants [21,23]. To the best knowledge of the authors, this is the first study evidencing the positive effect of effluent recirculation on the removal of PhCs in a full-scale natural wastewater treatment.

Therefore, the objective of this research was to ascertain the effect of a 100% ER on PhC removal in a pilot NWTS treating wastewater from a university campus. Preliminary studies about low ER ratios (50% of influent flow) were not conclusive about the elimination of PhCs [12]. For this reason, monitoring with no ER (year 2018) and 100% ER (year 2021) were compared. The results obtained can help to achieve reliable and quantitative values on their concentrations, frequency of detection and removal efficiency in NWTs, considering that the differences in the removal efficiencies depend on the physic-chemical characteristics of the compounds.

2. Materials and methods

2.1. Materials and reagents

Pharmaceuticals' (Table 1) purities were above 97% and were purchased from Sigma-Aldrich (Madrid, Spain). To perform the quantification, atenolol–d7 (Toronto Research Chemical Inc, Toronto, Canada), ibuprofen–d3 (Sigma–Aldrich, Madrid, Spain) and sulfamethoxazole–d4 (Dr. Ehrenstorfer GmbH, Ausgburg, Germany) were used as internal standards. A mixture standard was prepared as working solution at a concentration of 10 mg·L^{-1} from individual stock solutions of 1000 mg L^{-1}. Water and methanol LC-MS grade were used in the chromatographic separation and were both from Panreac (Barcelona, Spain) as well as the acetic acid used as mobile phase modifier. Type I Ultrapure water used in solid phase extraction was obtained with a Millipore water purification system (Bedford, MA, USA).

2.2. Wastewater treatment description and sample collection

The NWTS is located in the Campus of Tafira of the University of Las Palmas de Gran Canaria and has been described in detail in previous studies (for further details, see supplementary data). The Campus is located 270 m above sea level and the average temperatures during the sampling period were between 16.5 and 22.6º C. Regarding rainfall, the sampling was performed in months with different rainfall amounts, which ranged from 30 mm to only 6 mm per month. These rainfall amounts are in accordance with the dominant semi-arid and subtropical climate of the archipelago. The NWTS consists of a septic tank from which wastewater is pumped into a macrophyte-covered facultative pond followed by a horizontal flow CW. The CW has three channels, the first two are surface flow channels and the last one is a sub-surface flow (Fig. 1). The pond and the channels have been completely covered by common reed, *Canna sp*. and *Cyperus sp*.

Grab samples were taken in amber-glass bottles every 15 days since February to May. Based on the results obtained in a preliminary study that evaluated two periods, one without ER and another one with an ER of 50% [12], it was decided to carry out a more in-depth investigation to evaluate the pharmaceuticals removal with 100% ER. Since the studied system is in the university Campus, the amount of wastewater produced is strongly reduced during Christmas and summer holidays, nevertheless, considering the physicochemical properties of the wastewater it can be considered as urban wastewater [12]. The effluent recirculation ratio indicated in the three periods was applied during the whole academic year, since September to July, but the analyses were restricted to February and May because in this period the required inflow, and then the recirculation ratio, was fully assured. Thus, the interval between September and February can be regarded as an acclimatation time for the system for the new conditions. Additionally, the influent sample dilution was considered no significative by the scarce of nil rainfall in the studied periods.

The total number of samplings per period was 6. The sample pretreatment consisted of adjusting the pH to a value under 3 and filtration to prevent bacterial degradation of the target analytes.

The NWTS was designed to treat the effluent produced by 150 population equivalent (p.e.), 7.5 m^3/d in a surface of about 300 m^2. The influent was pumped from the septic tank with a triturating, timer-controlled pump. The timer was programmed to work 12 times a day, every 2 h for 2 min. The inflow rate was 4.5 L s^{-1}, approximately. A small tank (Fig. 1) was built between the septic tank and the pond inlet to reduce the influent pressure at the pond inlet, to measure the influent and recirculated effluent flows and as a sampling point. ER was performed with a smaller, submergible, timer-controlled pump located at the outlet of the system. The nominal hydraulic retention time without recirculation (HRT= Reactor volume, m^3 / Influent, m^3 d^{-1}) was 49 d. The resulting HRT with 100% ER was 25 d considering that in the calculation of the HRT, the recirculated influent is added to the influent. During the period with ER= 100% the influent and the recirculated effluent were of 6–6.5 m^3 d^{-1} [19]. No influent dilution occurred at the

Table 1
Target pharmaceuticals and physical-chemical properties. Data extracted from Pubchem Database.

Pharmaceutical type	Compound	Acronym	CAS no.	Molecular weight (g/mole)	pKa	$LogK_{OW}$	Solubility in water (mg·L^{-1})	Vapour pressure (mmHg)
Stimulants	Nicotine	NICO	54–11–5	162.230	8.5	1.17	$1{\cdot}10^{6}$	0.038
	Caffeine	CAFF	58–08–2	194.191	14.0	-0.07	$2.2{\cdot}10^{4}$	$9{\cdot}10^{-7}$
	Paraxanthine	PRX	611–59–6	180.164	–	-0.22	27	–
Anti-inflammatories	Naproxen	NPX	22204–53–1	230.260	4.2	3.18	15.9	$1.89{\cdot}10^{-6}$
	Ibuprofen	IBU	15687–27–1	206.281	5.3	3.97	21	$4.74{\cdot}10^{-5}$
	Diclofenac	DCLF	15307–86–5	296.149	4.2	4.51	2.4	$6.14{\cdot}10^{-8}$
Lipid regulators	Gemfibrozil	GMF	25812–30–0	250.333	4.5	4.39	11	$3.1{\cdot}10^{-5}$
Anti-hypertensives	Atenolol	ATE	29122–68–7	266.336	9.6	0.16	$1.3{\cdot}10^{4}$	–
Anti-convulsants	Carbamazepine	CBZ	298–46–4	236.269	13.9	2.45	18	$1.84{\cdot}10^{-7}$
Antibiotics	Trimethoprim	TRIM	738–70–5	290.318	7.1	0.91	400	–
	Erythromycin	ERY	114–07–8	733.927	8.9	3.06	4.2	$2.12{\cdot}10^{-25}$

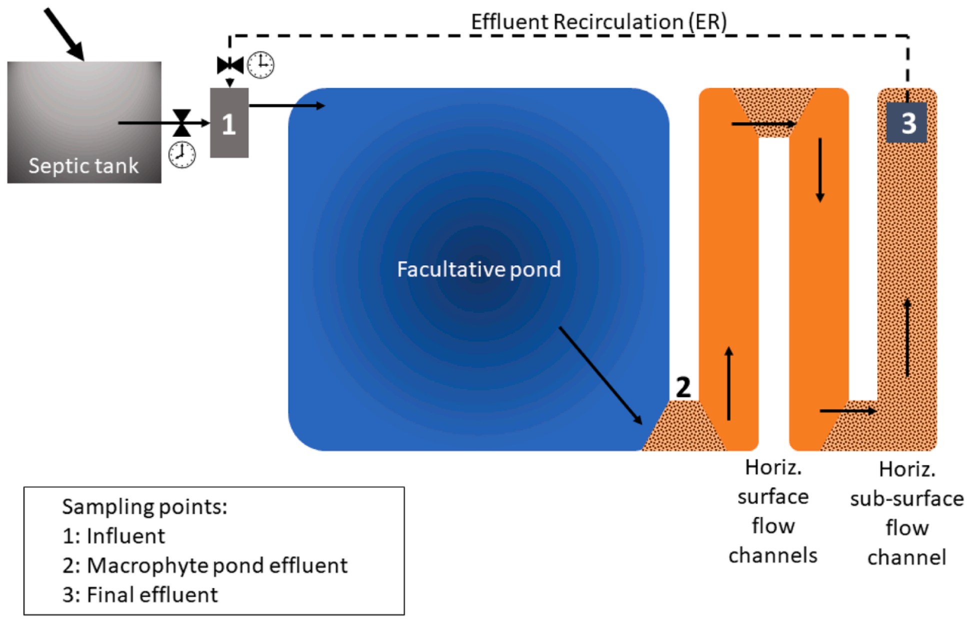

Fig. 1. Scheme of the NWTS (not to scale).

influent sampling point since the influent and the recirculated effluent pumps operation times were different and did not coincide. They were programmed to work at different time periods of the day because of their very different powers. Additionally, that way the influent concentrations could be compared among the experimental periods without recirculation and different recirculation ratios.

2.3. Pharmaceutical analysis procedure

The pharmaceuticals were extracted and pre-concentrated by means of a solid phase extraction (SPE) methodology [12]. In brief, a volume of 250 mL of filtered wastewater at pH 7 was extracted using OASIS HLB cartridges (500 mg, 6 mL, Waters, Barcelona, Spain). After loading the samples, water-soluble interferences were eliminated using 5 mL of Milli-Q water and then the target compounds were eluted with 5 mL of methanol. Next, the extracts were evaporated using N_2 and reconstituted with 1 mL of Milli-Q water with 100 μg L^{-1} of internal standards. Extracts were filtered using Chromafil Xtra PET of 0.20 μm syringe filters (Machery–Nagel, Düren, Germany) to avoid chromatographic column clogging. The extracts were analysed by ultra-high performance liquid chromatography-tandem mass spectrometry (UHPLC–MS/MS). using an Acquity BEH chromatographic column (50 mm × 2.1 mm, 1.7 μm) from Waters (Barcelona, Spain) and the mobile phase consisted of LC–MS grade water and methanol, both with 0.5% of acetic acid. The separation of the target compounds was done in gradient mode at a flow rate of 0.3 mL min^{-1}. Detection was carried out using electrospray ionization (ESI) in both positive and negative mode, applying capillary voltage of 3.5 kV and − 3.0 kV in positive and negative mode, respectively. The quantification of target pharmaceuticals was done using external calibrations curves with IS at a fixed concentration. Calibration curves showed appropriate regression coefficients (r^2) higher than 0.990. The analytical methodology used reports recovery rates in the range of 92–116.1% in influent samples and between 79.4% and 125.1% in effluent samples [24] and very appropriate quantification limits between 0.88 and 628 ng·L^{-1}, being for most of the compounds below 180 ng·L^{-1}.

2.4. Statistical analysis

To perform the statistical analysis, it is important to highlight how effluent recirculation and pharmaceuticals removal were calculated. The effluent recirculation ratio ER was calculated as follows:

$$\text{ER, } 100\% = 100 \text{ x (influent /recirculated effluent), both in } m^3\ d^{-1} \quad (1)$$

The particular removals for each pollutant were calculated according to the following expression:

$$\text{Removal, } \% = 100 \text{ x } (C_{influent} - C_{effluent})/C_{influent} \quad (2)$$

where: $C_{influent}$ is the average concentration of the pollutant in the influent sample analyzed by triplicate, $C_{effluent}$ is the average concentration of the pollutant in the triplicate of the effluent sample.

The general removal efficiencies of each recirculation period were calculated as the average of the removals of each sampling for each compound. Average pharmaceutical removals of the different experimental periods were compared by means of the ANOVA test. Normality and homoscedasticity were determined with the Shapiro-Wilk and Bartlett tests. If these conditions were not met, the non-parametric Kruskal-Wallis test was used. In all cases a 95% confidence level was adopted, i.e. the means of the compared groups of data were considered to be different when p-values < 0.05.

3. Results and discussion

3.1. Evaluation of pharmaceuticals occurrence

The 11 PhCs analysed were selected according to their uses and presence in wastewaters in Gran Canaria (Spain) [24,25]. These were nicotine, caffeine and paraxanthine (stimulants present in pharmaceuticals and products like coffee, energy drinks and tobacco), naproxen, ibuprofen and diclofenac (non-steroidal anti-inflammatory drugs (NSAIDs), trimethoprim and erythromycin (antibiotics) and atenolol (β-blocker), gemfibrozil (lipid regulator) and carbamazepine (antiepileptic).

Table 2 summarizes (in decreasing order of concentrations) the average concentrations ± std. dev. and number of positive values in the 2 sampling periods (year 2018 with ER= 0% and 2021 with ER= 100%) and the 3 sampling points (influent, pond effluent and CW effluent). As can be observed, the highest average concentrations were those of caffeine (108–124 μg L^{-1}) and its metabolite paraxanthine (14–96 μg L^{-1}). Caffeine is a common wastewater contaminant and the concentrations of this study fall in the range of those of influents of WWTPs (0.22

Table 2
Average concentrations (μgL^{-1}) ± std. dev. and (% of positive readings) in the sample points in the three studied periods (0% and 100% ER). The total number of samplings per sampling period was 6. Data of 0% ER extracted from [12].

	Recirculation rate	Influent	Pond effluent	CW effluent
CAFF	0%	124 ± 101 (100%)	6.7 ± 4,1 (100%)	2.8 ± 1,5 (100%)
	100%	108 ± 56 (100%)	2.0 ± 1.1 (100%)	0.2 ± 0.1 (100%)
PRX	0%	14 ± 8 (100%)	0.6 ± 0.8 (100%)	0.5 ± 0.5 (100%)
	100%	96 ± 66 (100%)	1.9 ± 0.9 (100%)	0.85 ± 0.66 (100%)
NICO	0%	3.2 ± 2.0 (100%)	0.7 ± 0.4 (100%)	0.2 ± 0.1 (100%)
	100%	15 ± 9 (100%)	0.7 ± 0.3 (100%)	0.2 ± 0.1 (83%)
IBU	0%	14 ± 9 (100%)	6.8 ± 2.5 (100%)	3.3 ± 1.6 (100%)
	100%	20 ± 19 (100%)	7.7 ± 5.0 (83%)	2.9 ± 2.0 (83%)
NPX	0%	3.4 ± 2.3 (100%)	1.2 ± 0.2 (10%)	0.9 ± 0.4 (100%)
	100%	220 ± 357 (83%)	9.4 ± 3.4 (83%)	0.2 ± 0.3 (83%)
ATE	0%	0.008 ± 0.015 (50%)	0.001 ± 0.001 (67%)	0.000 ± 0.001 (33%)
	100%	0.94 ± 0.50 (83%)	0.14 ± 0.06 (100%)	0.06 ± 0.05 (100%)
CBZ	0%	0.002 (17%)	-	-
	100%	-	0.35 (17%)	0.07 ± 0.10 (33%)
DCLF	0%	-	0.015 ± 0.01 (83%)	0.019 ± 0.008 (100%)
	100%	-	-	-
GMF	0%	-	0.04 ± 0.07 (33%)	0.19 ± 0.05 (100%)
	100%	-	0.18 ± 0.13 (50%)	0.24 ± 0.17 (83%)
TRIM	0%	-	0.01 (17%)	-
	100%	-	-	-
ERY	0%	-	-	-
	100%	-	-	-

and 209 μg L^{-1}) of different countries [26]. The concentrations of paraxanthine, are similar to those of Italy and Spain [27]. Although nicotine is the most abundant alkaloid in tobacco, some other plants, such as potatoes or tomatoes also contain nicotine [28]. The main nicotine sources to the environment are human excretions and leaching from tobacco product waste, which represents the most littered item in cities and coasts [29]. The concentrations of nicotine of the present study (2.3–15 μg L^{-1}) are related to its consumption since it is the most consumed substance of licit abuse after alcohol, in Spain and worldwide [30]. Martínez-Bueno et al. found a greater mean concentration (22.4 μg L^{-1}) than this study in the influent a conventional WWTPs in south-east of Spain [28].

Regarding analgesic and anti-inflammatory drugs, ibuprofen vary widely in untreated wastewaters within the interval < 0.004–603 μg L^{-1} [26]. Thus, it can be said that the average valued of the present study (4.4–20 μg L^{-1}) fall in the lower side of the range. Naproxen also belongs to the group of analgesic and anti-inflammatory drugs, but its maximum concentrations in wastewater (52.9 μg L^{-1}) are lower than those of ibuprofen [31]. In the present study, the average concentrations in the influent for 2018 and 2019 (3.4 and 4 μg L^{-1}, respectively) are in the range, but those when ER= 100% are much higher (220 μg L^{-1}). The β-blocker atenolol was frequently found in the three sampling points of this study, but at very low concentrations (0.007–0.94 μg L^{-1}) in comparison to those reported in wastewater (0.1–33.1 μg L^{-1}) [31].

The other compounds were found sporadically and at very low concentrations. Hence, they were excluded from the study of the effect of ER. For example, in spite that the anti-convulsive drug carbamazepine is one of the most frequently detected and persistent PhCs in WWTPs effluents [32], in the present study it was found only 4 times at concentrations that vary between 0.002 μg L^{-1} and 0.35 μg L^{-1}. Diclofenac, another NSAID, was found at average concentrations ranging from 0.01 μg L^{-1} to 0.08 μg L^{-1}. Such low concentrations can be caused by its restriction in Spain because of its associated cardiovascular problems [33]. It was detected at measurable concentrations in the influent only when ER= 0%, but the detection frequency was high in the intermediate and effluent sampling points with ER= 0% and 50% [12]. It was not detected when high ER was implemented. The results of the lipid regulator gemfibrozil were like those of diclofenac regarding their low detection frequency in the influent, but high in the intermediate and effluent. Unlike diclofenac, gemfibrozil was detected in the period with ER= 100%. The antibiotic trimethoprim was observed twice in the influent when ER= 50% with an average concentration of 0.007 μg L^{-1}, and 3 times in the intermediate point (pond effluent), but never in the effluent [12]. Another antibiotic, erythromycin was never detected in any of the three periods studied.

The average concentrations of some compounds with 100% ER, such as nicotine, paraxanthine, naproxen and atenolol, are particularly high in comparison to the previous years. This could be related to changes in the use of these drugs and variation in the attendance of the university population to the campus motivated by the pandemic. Except for these values, the concentrations found in this study are in the upper range of those obtained by Afonso-Olivares et al. for the influent of a conventional WWTP in Gran Canaria [24].

3.2. Effect of effluent recirculation on PhCs removal

The analysis of PhC removal outliers by means of the box-and-whiskers plot identified 4 values, as shown in Table 3.

Negative removals, i.e. higher concentrations in the effluent than in the influent, can be associated with the fact that grab sampling does not consider residence time distribution [34], conjugation/deconjugation reactions [35] and matrix interference, particularly in influent samples because of their higher pollutant load [36]. After the removal of the identified outliers the average values were calculated. Fig. 2 illustrates the average removals obtained for each PhCs and ER applied.

As can be observed, nicotine removals found in the present study were remarkable with values of 91% (no ER) and 98% (100% ER), falling in the upper range of those of the literature. Though ER seemed to improve efficiency, it was not significant (Anova, $p = 0.256$). Information on nicotine removal in NWTs is very scarce. In fact, Ekpeghere et al. found that nicotine removal efficiencies for different types of conventional WWTPs were 2.9–99% [37]. Martínez-Bueno et al. observed nicotine removal of 75% in a WWTP in south-east Spain while those of Nguyen et al. were above 80% in large scale conventional WWTPs in Ho Chi Minh city, Vietnam [28,38]. Such high removal rates in activated sludge, the low K_{OW} (1.17) and high solubility in water (~16 g/L) suggest that the main removal mechanism of nicotine in NWTs is biodegradation. However, photodegradation [29,39], can also play a role in open systems such as ponds and surface flow CWs though is not probably the case of the present study because of the high plant cover of our system.

The results of the β-blocker atenolol do not reflect a clear effect of ER, since 0% and 100% ERs provided good but similar results, i.e. 93% and 90%, respectively. However, these data should be taken with care because of the low number of positive results, 2 with 0% ER and 5 with 100% ER. Atenolol removal has been observed to be 27–97% in HSSF

Table 3
Average PhC removal identified as outliers for each ER ratio.

ER ratio	Removals identified as outliers
0%	-57%
100%	4.7%, 55.5%, 73%

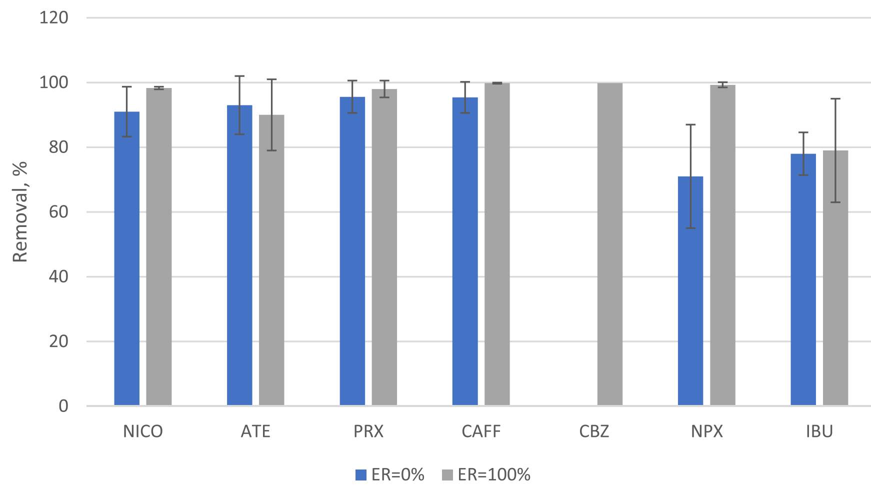

Fig. 2. Average PhC removals with 100% ER, and those with 0% ER[12] for comparison.

and hybrid CWs [6]. Sorption to organic matter is an important removal mechanism. Park et al. [17] studied the sorption of atenolol, carbamazepine and ibuprofen to soil organic matter in a CW by means of electrostatic interactions. The authors concluded that atenolol showed the highest sorption efficiency (~60%), followed by carbamazepine (~40%) and ibuprofen (~30%).

Very high removals of caffeine and its intermediate, paraxanthine, were obtained in the present study. In the case of caffeine, the mean values were 95% (0% ER) and 99.8% (100% ER), with the latter being significantly improved (p-value: 0.028, Anova). The removals obtained in this study are higher than those observed by other authors, such as Ávila et al. [40] who obtained an average removal of 80% in both HF and VF. Considering that caffeine is a hydrophilic compound, its main removal mechanisms are biodegradation and plant uptake [41]. The case of paraxanthine is like that of caffeine and nicotine, in the sense that high removal values were obtained, 95.5% and 98% with ER of 0% and 100%, respectively. It can be said that the removal of paraxanthine was improved with recirculation, but not significantly (p-value: 0.127, Anova).

In the case of carbamazepine which has been largely identified as a recalcitrant compound in wastewaters and CWs [42], only an adequate average removal value was obtained corresponding to ER= 100% in the CW. Although the mean removal obtained was quite high (99.8%), it does not allow to determine the effect of recirculation for this drug because it was detected in intermediate and effluent points in 1 and 2 samples, respectively.

ER had a clear effect on naproxen removal since it was significantly increased from 71% (0% ER) up to 99% (100% ER) (p-value: 0.014, Anova). Naproxen is a commonly detected NSAID in wastewater and its removal efficiencies in HSSF CW are 43–99% [43]. The simultaneous elimination of ammonium and different pharmaceuticals such as naproxen and ibuprofen has been described by means of the cometabolic biotransformations induced by autotrophic aerobic bacteria. The facts that naproxen is readily biotransformed under both, anaerobic and aerobic environments and that nitrification enhances its biotransformation [44] can explain the positive effect of ER. Ibuprofen removal without recirculation was 78% and 79% with 100% ER, without a significant difference (p-value: 0.209, Anova). Dvořáková Březinova et al. studied the removal of ibuprofen and its major metabolites, hydroxyibuprofen and carboxyibuprofen, in full-scale subsurface horizontal flow CWs in the Czech Republic [45]. Their removals amounted to 44.7%, 29.3% and 47.5%, respectively. The authors justified their results considering such medium efficiency of anoxic and anaerobic conditions. Lancheros et al. found higher ibuprofen removals (92%) in a lab-scale HSSF CW and claimed that biodegradation, sorption and plant uptake were, in that order, the main removal mechanism of ibuprofen and naproxen [43].

3.3. Global performance and environmental risk assessment

Finally, regarding the global performance of the system for all the PhCs (Fig. 3), it was observed that after the elimination of the outliers (Table 2), the average removal obtained when no recirculation applied was 87.5%. This good result can be explained by warm temperatures throughout the studied periods (minimum recorded water temperature was 13ºC) that favor microbial activity, the long theoretical HRT and dense plant cover of the system. In fact, Vystavna et al. observed improved removal efficiency for androstenedione, carbamazepine, caffeine, diclofenac, estrone, ibuprofen, paracetamol, propranolol and triclosan associated to longer water residence time and an increase in macrophyte cover in a full-scale CW in Ukraine [46]. In addition to this, in this study the average removal value (86.5%) with 50% ER was like that without ER [12]. However, the application of a 100% recirculation provided a significant improvement of the average removal up to 97% (Anova, p-value = 0.0074) (Fig. 3).

These results fall in the upper range of those observed by other authors. For example, Matamoros and Salvadó found an average value of 71% in a study of 27 emergent pollutants in a system composed of a pond and a surface horizontal flow CW treating the effluent of a conventional WWTP [47]. The authors claimed that the efficient combination of biodegradation, sorption and photodegradation provided such good results. However, in the present study, the effect of the latter might be negligible because of the dense plant cover of all the system. In

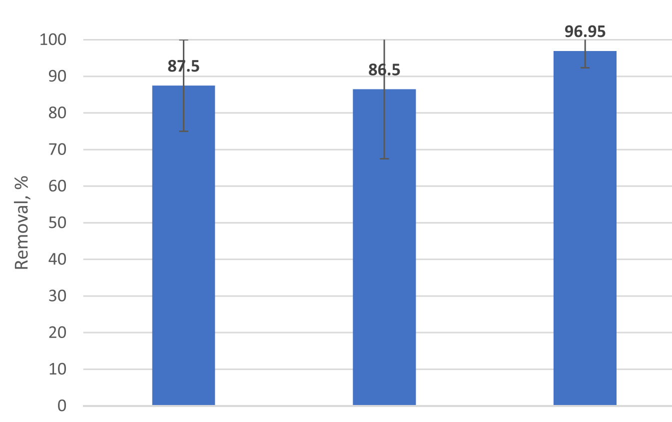

Fig. 3. Average removals of all the PhCs for ER = 50% and 100% [12] and the present study with ER= 100%.

another study, Matamoros et al. compared different intensive treatment systems (extended aeration and rotating biological contactor) with CW and ponds for the removal of 25 emerging contaminants. The average removal efficiencies were 42% for the CW, 62% for the extended aeration, 63% for the rotating biological contactor and 82% for the ponds [48].

There are different ways to improve pollutant removal in CWs by increasing aeration such as tidal flow, effluent recirculation and artificial aeration [20].

The environmental risk associated to the PhCs studied, was evaluated with their concentrations in the effluent for 0% and 100% ER. To calculate the risk coefficients, the recommendations of the Technical Guidance Document (TGD) on Risk Assessment of the European Commission in support of Commission Directive 93/67/EEC on risk assessment for new notified substances were followed. The risk coefficients (RQs) were calculated by dividing these mean concentrations by the predicted no-effect concentration (PNEC). The PNECs for daphnids and algae were obtained from the literature and the RQs were categorized as low ecological risk: RQ < 0.1; medium ecological risk: RQ between 0.1 and 1; high ecological risk: RQ > 1. As can be seen in Fig. 4, for both daphnids and algae the environmental risk decreases for all the detected compounds (except paraxanthine that experiments a slight increase for algae) with ER. Only nicotine presents a high ecological risk for daphnids in both periods (0% and 100% ER). Ibuprofen showed a medium ecological risk for daphnids and algae, being a little higher for the latter. Regarding the environmental risk for algae produced by nicotine, it is 10 times lower than for daphnids. The rest of detected and quantified compounds (caffeine, paraxanthine, naproxen and gemfibrozil) showed low environmental risk quotients that remain stable or are lower with 100% ER.

Though the results obtained in this study have been encouraging, the complete removal of the emergent pollutants studied, and the associated risk was not achieved. In general, effluent recirculation can be easily implemented since it requires only a time-meter controller, a recirculation pipe, and a small pump which evince the low economic cost of this strategy. The small pump would provide a low recirculation flow, low energy consumption and low or nil sediment resuspension at the outlet. Also, it is important to highlight that ER should not be greater than 100% to minimize the energy consumption. If possible, recirculation should promote effluent re-oxygenation by turbulence. Thus, the future investigation will be focused on testing the following options: i) combining the effluent recirculation with its aeration by turbulence or bubbling, ii) applying an internal recirculation between two points of the CW, since the great reduction of BOD obtained in the pond, would allow to aerate this part of the system more easily, iii) filling the subsurface flow channels with sorbent material, such as biochar or agroforestry residues, with the goal of adding adsorption to biodegradation, and increasing the active surface for the establishment of biofilm, as well, iv) constructing a vertical flow CW filled with organic substrate, prior to the system to reduce its organic load (mainly TSS and BOD) and allow more oxidizing conditions in the pond-CW system.

4. Conclusions

The effect of effluent recirculation as an easy to implement strategy to enhance the removal efficiency of pharmaceutical compounds was studied in a full-scale CW treating wastewater from a university campus. The highest concentrations were found for stimulants such as caffeine and nicotine and other pharmaceuticals with unrestricted use such as ibuprofen and naproxen. Under normal operation (no effluent recirculation) the pond-CW combination was very efficient at the removal of pharmaceuticals since it achieved 86% average removal, especially for stimulants and non-steroidal anti-inflammatories. However, the 100% recirculation provided a significant removal improvement of 97%, probably related to improved ammonium removal. Nevertheless, the complete elimination of the studied pollutants and the associated risk was not achieved. Thus, different strategies such as combining ER with forced or natural aeration, testing the effect of internal recirculation, or filling the surface flow channels with sorbing materials will be subject of future research.

CRediT authorship contribution statement

José Alberto Herrera-Melián: Conceptualization, Validation, Investigation, Data curation, Formal analysis, Funding acquisition, Resources, Supervision, Writing – original draft, Writing – review & editing. **Rayco Guedes-Alonso:** Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Jean Carlos Tite-Lezcano:** Methodology, Investigation, Data curation. **Zoraida Sosa-Ferrera:** Conceptualization, Funding acquisition, Project administration, Supervision, Resources, Writing – review & editing. **José Juan Santana-Rodríguez:** Conceptualization, Supervision, Resources, Writing – review & editing.

Declaration of Competing Interest

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.

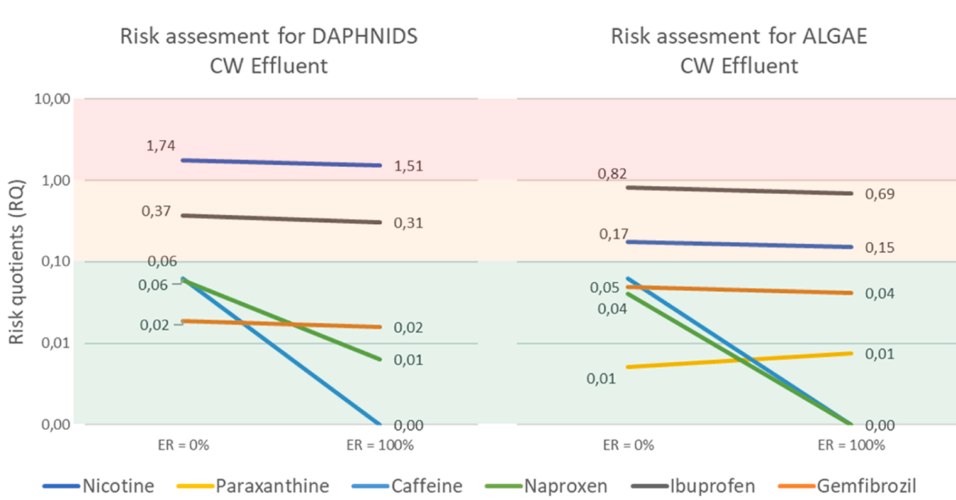

Fig. 4. Risk quotients for daphnids and algae in the effluent for ER= 0% and ER= 100%.

Data Availability

Data will be made available on request.

Acknowledgements

This work was supported by funds provided by Fundación CajaCanarias and Fundación Bancaria “La Caixa” through Project 2017RECO05; the Spanish Ministry of Science, Innovation and Universities Research Project GOB-ESP2019-08; and the Cabildo Insular de Gran Canaria through Project CABILDO20-02. The authors also acknowledge Héctor Guerra Yanez for the assistance in the laboratory.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jece.2023.111167.

References

[1] W. Fang, T. Liu, Z. Gu, Q. Li, C. Luo, Consumption trend and prescription pattern of opioid analgesics in China from 2006 to 2015, Eur. J. Hosp. Pharm. 26 (2019) 140–145, https://doi.org/10.1136/ejhpharm-2017-001460.
[2] K. Hider-Mlynarz, P. Cavalié, P. Maison, Trends in analgesic consumption in France over the last 10 years and comparison of patterns across Europe, Br. J. Clin. Pharm. 84 (2018) 1324–1334, https://doi.org/10.1111/bcp.13564.
[3] E.Y. Klein, M. Milkowska-Shibata, K.K. Tseng, M. Sharland, S. Gandra, C. Pulcini, R. Laxminarayan, Assessment of WHO antibiotic consumption and access targets in 76 countries, 2000–15: an analysis of pharmaceutical sales data, Lancet Infect. Dis. (2020), https://doi.org/10.1016/S1473-3099(20)30332-7.
[4] (aus) T. der Beek, F.A. Weber, A. Bergmann, S. Hickmann, I. Ebert, A. Hein, A. Küster, Pharmaceuticals in the environment-Global occurrences and perspectives, Environ. Toxicol. Chem. 35 (2016) 823–835, https://doi.org/10.1002/etc.3339.
[5] C.R. dos Santos, G.S. Arcanjo, L.V. de Souza Santos, K. Koch, M.C.S. Amaral, Aquatic concentration and risk assessment of pharmaceutically active compounds in the environment, Environ. Pollut. 290 (2021), 118049, https://doi.org/10.1016/J.ENVPOL.2021.118049.
[6] Y. Li, G. Zhu, W.J. Ng, S.K. Tan, A review on removing pharmaceutical contaminants from wastewater by constructed wetlands: design, performance and mechanism, Sci. Total Environ. 468–469 (2014) 908–932, https://doi.org/10.1016/J.SCITOTENV.2013.09.018.
[7] C. Liquete, A. Udias, G. Conte, B. Grizzetti, F. Masi, Integrated valuation of a nature-based solution for water pollution control. Highlighting hidden benefits, Ecosyst. Serv. 22 (2016) 392–401, https://doi.org/10.1016/J.ECOSER.2016.09.011.
[8] X. Su, P. Chiang, S. Pan, G. Chen, Y. Tao, G. Wu, F. Wang, W. Cao, Systematic approach to evaluating environmental and ecological technologies for wastewater treatment, Chemosphere 218 (2019) 778–792, https://doi.org/10.1016/J.CHEMOSPHERE.2018.11.108.
[9] K. Adhikari, C.B. Fedler, Water sustainability using pond-in-pond wastewater treatment system: case studies, J. Water Process Eng. 36 (2020), 101281, https://doi.org/10.1016/J.JWPE.2020.101281.
[10] T. Omidinia-Anarkoli, M. Shayannejad, Improving the quality of stabilization pond effluents using hybrid constructed wetlands, Sci. Total Environ. 801 (2021), 149615, https://doi.org/10.1016/J.SCITOTENV.2021.149615.
[11] H. Wang, L. Sheng, J. Xu, Clogging mechanisms of constructed wetlands: a critical review, J. Clean. Prod. 295 (2021), 126455, https://doi.org/10.1016/J.JCLEPRO.2021.126455.
[12] R. Guedes-Alonso, J.A. Herrera-Melián, F. Sánchez-Suárez, V. Díaz-Mendoza, Z. Sosa-Ferrera, J.J. Santana-Rodríguez, Removal of pharmaceuticals in a macrophyte pond-constructed wetland system and the effect of a low effluent recirculation, Water Vol. 14 (2022), https://doi.org/10.3390/W14152340.
[13] Herrera-Melián, J.A., González-Díaz, Ó., Araña-Mesa, J., Martel, G., Doña-Rodríguez, J.M., Pérez-Peña, J., 2012. Constructed Wetland for Improving the Performance of a Facultative Pond Treating High Strength Urban Wastewater, in: Baranyai, A., Benkô, D. (Eds.), Wetlands: Ecology, Management and Conservation. Nova Science Publishers, Nerw York, pp. 203–218.
[14] M. Hijosa-Valsero, V. Matamoros, J. Martín-Villacorta, E. Bécares, J.M. Bayona, Assessment of full-scale natural systems for the removal of PPCPs from wastewater in small communities, Water Res. 44 (2010) 1429–1439, https://doi.org/10.1016/j.watres.2009.10.032.
[15] M. Escolà Casas, V. Matamoros, Novel Constructed Wetland Configurations for the Removal of Pharmaceuticals in Wastewater, in: Removal and degradation of pharmaceutically active compounds in wastewater treatment, Springer, Berlin, Heidelberg, 2020, pp. 163–190, https://doi.org/10.1007/698_2020_681.
[16] E. Lee, H.K. Shon, J. Cho, Role of wetland organic matters as photosensitizer for degradation of micropollutants and metabolites, J. Hazard Mater. 276 (2014) 1–9, https://doi.org/10.1016/j.jhazmat.2014.05.001.
[17] J. Park, K.H. Cho, E. Lee, S. Lee, J. Cho, Sorption of pharmaceuticals to soil organic matter in a constructed wetland by electrostatic interaction, Sci. Total Environ. 635 (2018) 1345–1350, https://doi.org/10.1016/j.scitotenv.2018.04.212.
[18] H. Ilyas, E.D. van Hullebusch, Performance comparison of different types of constructed wetlands for the removal of pharmaceuticals and their transformation products: a review, Environ. Sci. Pollut. Res. (2020), https://doi.org/10.1007/s11356-020-08165-w.
[19] J.A. Herrera-Melián, R. Guedes-Alonso, J.C. Tite-Lezcano, D.E. Santiago, E. Ranieri, I. Alonso-Bilbao, The effect of effluent recirculation in a full-scale constructed wetland system, Sustainability 15 (2023) 4310, https:// doi.org/10.3390/su15054310References.
[20] H. Ilyas, I. Masih, The performance of the intensified constructed wetlands for organic matter and nitrogen removal: a review, J. Environ. Manag. (2017), https://doi.org/10.1016/j.jenvman.2017.04.098.
[21] J. Nivala, G. Abdallat, T. Aubron, I. Al-Zreiqat, B. Abbassi, G.M. Wu, M. van Afferden, R.A. Müller, Vertical flow constructed wetlands for decentralized wastewater treatment in Jordan: optimization of total nitrogen removal, Sci. Total Environ. 671 (2019) 495–504, https://doi.org/10.1016/J.SCITOTENV.2019.03.376.
[22] A.I. Stefanakis, V.A. Tsihrintzis, Effect of outlet water level raising and effluent recirculation on removal efficiency of pilot-scale, horizontal subsurface flow constructed wetlands, Desalination 248 (2009) 961–976, https://doi.org/10.1016/J.DESAL.2008.08.008.
[23] B.M. Al-Wahaibi, T. Jafary, A. Al-Mamun, M.S. Baawain, M. Aghbashlo, M. Tabatabaei, A.I. Stefanakis, Operational modifications of a full-scale experimental vertical flow constructed wetland with effluent recirculation to optimize total nitrogen removal, J. Clean. Prod. 296 (2021), 126558, https://doi.org/10.1016/J.JCLEPRO.2021.126558.
[24] C. Afonso-Olivares, Z. Sosa-Ferrera, J.J. Santana-Rodríguez, Occurrence and environmental impact of pharmaceutical residues from conventional and natural wastewater treatment plants in Gran Canaria (Spain, Sci. Total Environ. 599–600 (2017) 934–943, https://doi.org/10.1016/j.scitotenv.2017.05.058.
[25] R. Guedes-Alonso, S. Montesdeoca-Esponda, J. Pacheco-Juárez, Z. Sosa-Ferrera, J. J. Santana-Rodríguez, A survey of the presence of pharmaceutical residues in wastewaters. Evaluation of their removal using conventional and natural treatment procedures, Molecules 25 (2020) 1639, https://doi.org/10.3390/molecules25071639.
[26] Y. Luo, W. Guo, H.H. Ngo, L.D. Nghiem, F.I. Hai, J. Zhang, S. Liang, X.C. Wang, A review on the occurrence of micropollutants in the aquatic environment and their fate and removal during wastewater treatment, Sci. Total Environ. 473–474 (2014) 619–641, https://doi.org/10.1016/j.scitotenv.2013.12.065.
[27] I. Senta, E. Gracia-Lor, A. Borsotti, E. Zuccato, S. Castiglioni, Wastewater analysis to monitor use of caffeine and nicotine and evaluation of their metabolites as biomarkers for population size assessment, Water Res 74 (2015) 23–33, https://doi.org/10.1016/j.watres.2015.02.002.
[28] M.J. Martínez Bueno, S. Uclés, M.D. Hernando, E. Dávoli, A.R. Fernández-Alba, Evaluation of selected ubiquitous contaminants in the aquatic environment and their transformation products. A pilot study of their removal from a sewage treatment plant, Water Res. 45 (2011) 2331–2341, https://doi.org/10.1016/J.WATRES.2011.01.011.
[29] S. Alberti, M. Sotiropoulou, E. Fernández, N. Solomou, M. Ferretti, E. Psillakis, UV-254 degradation of nicotine in natural waters and leachates produced from cigarette butts and heat-not-burn tobacco products, Environ. Res. 194 (2021), 110695, https://doi.org/10.1016/J.ENVRES.2020.110695.
[30] R. Montes, R. Rodil, A. Rico, R. Cela, I. González-Mariño, F. Hernández, L. Bijlsma, A. Celma, Y. Picó, V. Andreu, M.L. de Alda, E. López-García, C. Postigo, E. Pocurull, R.M. Marcé, M. Rosende, M. Olivares, Y. Valcárcel, J.B. Quintana, First nation-wide estimation of tobacco consumption in Spain using wastewater-based epidemiology, Sci. Total Environ. 741 (2020), 140384, https://doi.org/10.1016/J.SCITOTENV.2020.140384.
[31] Y. Luo, W. Guo, H.H. Ngo, L.D. Nghiem, F.I. Hai, J. Zhang, S. Liang, X.C. Wang, A review on the occurrence of micropollutants in the aquatic environment and their fate and removal during wastewater treatment, Sci. Total Environ. 473–474 (2014) 619–641, https://doi.org/10.1016/j.scitotenv.2013.12.065.
[32] M. Čelić, M. Gros, M. Farré, D. Barceló, M. Petrović, Pharmaceuticals as chemical markers of wastewater contamination in the vulnerable area of the Ebro Delta (Spain, Sci. Total Environ. 652 (2019) 952–963, https://doi.org/10.1016/J.SCITOTENV.2018.10.290.
[33] P. McGettigan, D. Henry, Cardiovascular risk with non-steroidal anti-inflammatory drugs: systematic review of population-based controlled observational studies, PLoS Med. 8 (2011), e1001098, https://doi.org/10.1371/journal.pmed.1001098.
[34] N.H. Tran, M. Reinhard, K.Y.H. Gin, Occurrence and fate of emerging contaminants in municipal wastewater treatment plants from different geographical regions-a review, Water Res. (2018), https://doi.org/10.1016/j.watres.2017.12.029.
[35] E. Archer, B. Petrie, B. Kasprzyk-Hordern, G.M. Wolfaardt, The fate of pharmaceuticals and personal care products (PPCPs), endocrine disrupting contaminants (EDCs), metabolites and illicit drugs in a WWTW and environmental waters, Chemosphere 174 (2017) 437–446, https://doi.org/10.1016/J.CHEMOSPHERE.2017.01.101.
[36] M. Čizmić, S. Babić, M. Kaštelan-Macan, Multi-class determination of pharmaceuticals in wastewaters by solid-phase extraction and liquid chromatography tandem mass spectrometry with matrix effect study, Environ. Sci. Pollut. Res. 24 (2017) 20521–20539, https://doi.org/10.1007/S11356-017-9660-7/FIGURES/8.
[37] K.I. Ekpeghere, W.J. Sim, H.J. Lee, J.E. Oh, Occurrence and distribution of carbamazepine, nicotine, estrogenic compounds, and their transformation products

in wastewater from various treatment plants and the aquatic environment, Sci. Total Environ. 640–641 (2018) 1015–1023, https://doi.org/10.1016/j.scitotenv.2018.05.218.

[38] H.T. Nguyen, P.K. Thai, S.L. Kaserzon, J.W. O`Brien, G. Eaglesham, J.F. Mueller, Assessment of drugs and personal care products biomarkers in the influent and effluent of two wastewater treatment plants in Ho Chi Minh City, Vietnam, Sci. Total Environ. 631–632 (2018) 469–475, https://doi.org/10.1016/J.SCITOTENV.2018.02.309.

[39] M. Passananti, F. Temussi, M.R. Iesce, L. Previtera, G. Mailhot, D. Vione, M. Brigante, Photoenhanced transformation of nicotine in aquatic environments: involvement of naturally occurring radical sources, Water Res. 55 (2014) 106–114, https://doi.org/10.1016/J.WATRES.2014.02.016.

[40] C. Ávila, C. Pelissari, P.H. Sezerino, M. Sgroi, P. Roccaro, J. García, Enhancement of total nitrogen removal through effluent recirculation and fate of PPCPs in a hybrid constructed wetland system treating urban wastewater, Sci. Total Environ. 584–585 (2017) 414–425, https://doi.org/10.1016/j.scitotenv.2017.01.024.

[41] D. Zhang, R.M. Gersberg, W.J. Ng, S.K. Tan, Removal of pharmaceuticals and personal care products in aquatic plant-based systems: a review, Environ. Pollut. 184 (2014) 620–639, https://doi.org/10.1016/J.ENVPOL.2013.09.009.

[42] N. Delgado, L. Bermeo, D.A. Hoyos, G.A. Peñuela, A. Capparelli, D. Marino, A. Navarro, J.C. Casas-Zapata, Occurrence and removal of pharmaceutical and personal care products using subsurface horizontal flow constructed wetlands, Water Res. 187 (2020), 116448, https://doi.org/10.1016/J.WATRES.2020.116448.

[43] J.C. Lancheros, C.A. Madera-Parra, A. Caselles-Osorio, W.A. Torres-López, X. M. Vargas-Ramírez, Ibuprofen and Naproxen removal from domestic wastewater using a horizontal subsurface flow constructed wetland coupled to ozonation, Ecol. Eng. 135 (2019) 89–97, https://doi.org/10.1016/J.ECOLENG.2019.05.007.

[44] T. Alvarino, S. Suarez, J. Lema, F. Omil, Understanding the sorption and biotransformation of organic micropollutants in innovative biological wastewater treatment technologies, Sci. Total Environ. 615 (2018) 297–306, https://doi.org/10.1016/J.SCITOTENV.2017.09.278.

[45] T. Dvořáková Březinova, J. Vymazal, M. Koželuh, L. Kule, Occurrence and removal of ibuprofen and its metabolites in full-scale constructed wetlands treating municipal wastewater, Ecol. Eng. 120 (2018) 1–5, https://doi.org/10.1016/J.ECOLENG.2018.05.020.

[46] Y. Vystavna, Z. Frkova, L. Marchand, Y. Vergeles, F. Stolberg, Removal efficiency of pharmaceuticals in a full scale constructed wetland in East Ukraine, Ecol. Eng. 108 (2017) 50–58, https://doi.org/10.1016/J.ECOLENG.2017.08.009.

[47] V. Matamoros, V. Salvadó, Evaluation of the seasonal performance of a water reclamation pond-constructed wetland system for removing emerging contaminants, Chemosphere 86 (2012) 111–117, https://doi.org/10.1016/j.chemosphere.2011.09.020.

[48] V. Matamoros, Y. Rodríguez, J. Albaigés, A comparative assessment of intensive and extensive wastewater treatment technologies for removing emerging contaminants in small communities, Water Res. 88 (2016) 777–785, https://doi.org/10.1016/j.watres.2015.10.058.