DOI: 10.24850/j-tyca-15-02-03

Articles

Assessment of carbamazepine removal from hospital wastewater in a non-conventional biofilter and the application of electro-oxidation as pre-treatment

Evaluación de la eliminación de carbamazepina de aguas residuales de hospital en un biofiltro no convencional y aplicación de electro-oxidación como pretratamiento

Javier Alejandro Navarro-Franco[1], ORCID: https://orcid.org/0000-0002-6067-7246

Marco A. Garzón-Zúñiga[2], ORCID: https://orcid.org/0000-0003-0124-0447

Patrick Drogui[3], ORCID: https://orcid.org/0000-0002-3802-2729

Blanca Estela Barragán-Huerta[4], ORCID: https://orcid.org/0000-0002-4988-6303

Juan Manuel Vigueras-Cortés[5], ORCID: https://orcid.org/0000-0001-5599-4944

Eduardo Lozano-Guzmán[6], ORCID: https://orcid.org/0000-0001-6760-2063

Francisco Javier Moreno-Cruz[7], ORCID: https://orcid.org/0000-0002-9549-3498

[1]Instituto Politécnico Nacional (IPN), CIIDIR-Durango, Durango, Mexico, javinavarrofranco@gmail.com

[2]Instituto Politécnico Nacional (IPN), CIIDIR-Durango, Durango, Mexico, mgarzon@ipn.mx, marco.cuerna@gmail.com

[3]Institute Nationale de Recherche Scientifique Eau Terre et Environnement (INRS-ETE), Université du Quebec, Quebec, QC, Canada, patrick.drogui@inrs.ca

[4]Instituto Politécnico Nacional, Escuela Nacional de Ciencias Biológicas, Unidad Profesional Adolfo López Mateos, Mexico City, Mexico, bbarraganh@ipn.mx

[5]Instituto Politécnico Nacional (IPN), CIIDIR-Durango, Durango, Mexico, mviguer@ipn.mx

[6]Laboratorio de Farmacognosia, Faculty of Chemical Sciences, Universidad Juárez del Estado de Durango, Durango, Mexico, elozano@ujed.mx

[7]Laboratorio de Farmacognosia, Faculty of Chemical Sciences, Universidad Juárez del Estado de Durango, Durango, Mexico, jmoreno251116@gmail.com

Corresponding author: Marco A. Garzón-Zúñiga, mgarzon@ipn.mx, marco.cuerna@gmail.com

Tecnología y ciencias del agua, ISSN 2007-2422, 15(2), 98-163. DOI: 10.24850/j-tyca-15-02-03

Abstract

Hospital wastewater (HWW) is characterized by a high drug concentration, which can cause endocrine effects and bacterial resistance, among others. For this study, carbamazepine (CBZ) was selected as a contaminant model to evaluate the removal efficiency from HWW of recalcitrant pharmaceuticals in a non-conventional biofilter (BF), packed with a mixture of wood chips (Prosopis) and porous rock (pouzzolane). The effect of electro-oxidation (EO) as pre-treatment was assessed as well. A biofilm adapted to the HWW was developed in the BF. The addition of high concentrations of CBZ (1 000 and 10 000 µg/l) to the influent HWW did not affect the removal efficiency of the BF to remove organic matter (73 %) and ammonia nitrogen (99 %), proving that the biomass was not inhibited by the CBZ's concentration. The BF showed a significant removal of CBZ by adsorption during the start-up. The bed filter showed an adsorption capacity of 19.84 µg/g (Co = 10 000 µg/l). After the bed filter saturation operated in steady state, the BF removed by biotransformation 17.2 ± 7.4 % of CBZ which, in terms of concentration (1 551 ± 664 µg/l), is bigger than the concentration in most of the reports for hospital, pharmaceutical and municipal WW effluents, which are between 0.1 and 890 µg/l. By applying electro-oxidation as a pretreatment, the global removal efficiency of CBZ increased to 55 ± 5.96 %. In the hybrid system, the EO biotransformed the CBZ, and in the BF the nitrogen and the COD were removed and showed CBZ desorption.

Keywords: Biofiltration for EPs removal, natural supports for pharmaceutical removal, carbamazepine removal, pouzzolane and wood chips for pharmaceutical removal, electro-oxidation for EPs removal, hospital wastewater.

Tecnología y Ciencias del Agua

OPEN ACCESS

Check for updates

Resumen

Las aguas residuales hospitalarias (ARH) contienen fármacos que ocasionan efectos a la salud y el ambiente. Para este estudio se seleccionó la carbamazepina (CBZ) como contaminante modelo para evaluar la eficiencia de remoción de fármacos en un biofiltro no convencional (BF) empacado con astillas de madera (*Prosopis*) y roca porosa (tezontle). La electro-oxidación (EO) como pretratamiento también se evaluó. Se hizo crecer una biopelícula en el BF adaptada al ARH. Posteriormente, el ARH se enriqueció con altas concentraciones de CBZ (1 000 y 10 000 µg/l). La biomasa del BF no fue inhibida por estas concentraciones de CBZ, ya que la eficiencia de remoción de DQO (73 %) y NH_4^+-N (99 %) permanecieron constantes. El BF mostró una importante eliminación de CBZ por adsorción durante el arranque. La cama filtrante tuvo una capacidad de adsorción de 19.84 µg/g (Co = 10 000 µg/l). Después de la saturación del material filtrante, y operando en estado estable, el BF eliminó el 17.2 ± 7.4 % de CBZ por biotransformación, equivalente a 1 551 ± 664 µg/l de concentración. Esto es mayor que la concentración en la mayoría de los reportes para efluentes de ARH, AR municipales y AR farmacéuticas, que se encuentran entre 0.1 y 890 µg/l. Cuando se aplicó la EO como pretratamiento, la eficiencia de eliminación de CBZ aumentó a 55 ± 5.9 %. En este sistema híbrido, en la EO se biotransformó la CBZ y en el BF se removieron el nitrógeno y la DQO, y presentó desorción de CBZ.

Palabras clave: biofiltración no convencional de contaminantes emergentes, soportes naturales para remoción de fármacos, astillas de

madera y tezontle para remoción de fármacos, electro-oxidación contaminantes emergentes, aguas residuales de hospital.

Received: 12/08/2021

Accepted: 08/07/2022

Published Online: 29/08/2022

Introduction

Hospital wastewater (HWW) comes from hospitalization and operational areas, laboratories, administrative units, laundries, and kitchens (Carraro, Bonetta, & Bonetta, 2017). Therefore, its characteristics are different when compared to urban or municipal wastewater. HWW has a variety of toxic or persistent substances such as drugs, radio nucleotides, solvents, and disinfectants with medical components. Thus, greater concentrations of many drugs are expected, due to admitted patient's consumption. Some authors reported that microcontaminants (for example, antibiotics, analgesics, heavy metals) in HWWs can be found in concentrations of 1.5 and 150 times, which are higher than those found in municipal wastewater (MWW) (Klančar, Trontelj, Kristl, Justin, & Roškar, 2016; Verlicchi, Galletti, Petrovic, & Barceló, 2010). Also, HWW discharges into the environment represent a significant ecotoxicological risk. Therefore, in situ treatment of this water is desirable to reduce the contribution of pathogens, viruses, and bacteria to the collecting system (Verlicchi, Al-Aukidy, & Zambello, 2015). In addition, drugs as part of

emerging pollutants (EPs) or microcontaminants in water are a serious threat to human health and ecological balance due to their toxic, carcinogenic, and mutagenic risks (Garcia-Segura, Ocon, & Chong, 2018; Martín-de-Vidales *et al*., 2015).

Consequently, it is essential to remove these microcontaminants, even if there are 143 000 estimated compounds in aquatic systems (including drugs), making the evaluation for each one unfeasible (Sreejon *et al*., 2017). As a result, it is necessary to focus on objective pollutants or model pollutants that will help evaluate the removal of recalcitrant and non-recalcitrant drugs, like fecal coliforms, as an indicator of various pathogens in water.

Carbamazepine (CBZ) is a drug used for the treatment of epilepsy, trigeminal neuralgia, bipolar depression, and mania. During the intake of CBZ in humans, approximately 72 % of the applied dose is recovered in the urine, and only 2 % of that dose is found as unchanged CBZ. The 28 % that is absorbed by the gastrointestinal tract is recovered in the feces, 14 % being in the form of metabolites and the rest as the parent compound (Cunningham, Perino, D'Aco, Hartmann, & Bechter, 2010; Valdés *et al*., 2016).

CBZ is frequently found in wastewater in a wide range of concentrations, from a few ng/l to mg/l (Table 1). During the treatment of wastewater in biological conventional systems like activated sludge, removal efficiencies are mostly below 10 % (Palo, Domínguez, González, Sánchez-Martin, & Cuerda-Correa, 2014). However, according to Wang and Wang (2018), after biomass acclimation, some bioremoval could be achieved. Efficiencies for CBZ of 22.8 % (equivalent to 810 µg/l in terms

of concentration) were removed after the biomass was acclimated to different concentrations (0.2, 1, 5, 10, 15 mg/l), which proved that CBZ removal is difficult even under acclimatization conditions in activated sludge. To this regard, it is expected that CBZ registered no significant changes or degradation during its conduction between the generation point and the input of the treatment systems. On the other hand, there are other drugs that are easily transformable and can significantly change their composition before reaching a treatment system. Meanwhile, more stable drugs arrive to the system in a larger proportion in the form of the parent molecule and better information can be obtained from what happens to this molecule within the treatment system. Due to its molecular stability and its hydrophobicity characteristics, some authors have proposed CBZ as a good marker of anthropogenic activity in natural aquatic environments (Clara, Strenn, & Kreuzinger, 2004; Dvory *et al*., 2018; Hai, Li, Price, & Nghiem, 2011). Therefore, one contribution to this study is to propose and to use CBZ as a pharmaceutical model to evaluate the removal/transformation efficiency and mechanisms by which these occur in EPs (pharmaceuticals) present in HWW.

Tecnología y ciencias del agua, ISSN 2007-2422, 15(2), 98-163. DOI: 10.24850/j-tyca-15-02-03

Table 1. Carbamazepine concentrations reported for municipal and hospital wastewater.

Source	Concentration (µg/l)	Type of source	References
Spain	≥ 0.400	MWW	Jelic *et al*. (2011)
Canada (Ontario)	0.369	MWW	Miao and Metcalfe (2003)
USA (Las Vegas)	0.232	MWW	Vanderford and Snyder (2006)
Brazil	0.441-0.587	HWW	De-Almeida, Oliveira, Mallmann and Martins (2015)
Japan	0.080-0.120<	HWW	Azuma *et al*. (2016)
Canada (Ontario)	0.018-0.331	HWW	McBean, Salsali, Bhatti and Huang-Jeanne (2018)
Slovenia	0.194-0.270	MWW	Klančar *et al*. (2016)
China (Taiwan)	0.339-0.428	HWW	Li and Lin (2015)
Sweden	0.580-2.6	MWW	Dalahmeh, Ahrens, Gros, Wiberg and Pell (2018)
Switzerland	0.482	MWW	Sreejon *et al*. (2017)
Israel	840 ± 190	PHWW	Lester, Mamane, Zucker and Avisar (2013)
India	442 080 ± 2 580	PHWW	Dwivedi, Morone, Chakrabarti and Pandey (2018)
Mexico (Mexico City)	5.68 ± 0.52	HWW	Calderón, Meraz and Tomasini (2019)
Spain	4.12 ± 0.31	HWW	Mir-Tutusaus *et al*. (2021)

MWW: Municipal wastewater.

HWW: Hospital wastewater.

PHWW: Pharmaceutical wastewater.

Tecnología y ciencias del agua, ISSN 2007-2422, 15(2), 98-163. DOI: 10.24850/j-tyca-15-02-03

Tecnología y Ciencias del Agua
OPEN ACCESS
Check for updates

Biofiltration over organic filter bed (BF)

BF is a non-conventional biological trickling filter process that uses biomass adhered to an organic support material, commonly forest or agricultural waste (Garzón-Zúñiga & Buelna, 2011), which makes it a locally available and low-cost material, when compared with packaging materials such as plastics used in trickling filters. This technology is being evaluated for a couple of decades with different organic packaging materials to treat different types of wastewaters, from industrial to municipal, usually with very high pollutant removal efficiencies. However, this technology has not been enough evaluated for EPs removal. There is only one work using a BF packed with wood chips of *Ficus benjamina* to evaluate Metformin and Ciprofloxacin removal in MWW (García-Sánchez, Gutiérrez-Macías, & Estrada-Arriaga, 2019), showing promising results for the removal of pharmaceuticals. However, it is important to assess this technology for the removal of EPs with other kind of wood chips and more recalcitrant EPs. Mesquite (*Prosopis* sp.) is a tree with a very extended distribution from the south of US to Argentina (Carrillo-Parra, Hapla, Mai, & Garza-Ocañas, 2011), present in arid and semi-arid regions, which makes it a species available in many countries. *Prosopis* wood chips were evaluated by Sosa-Hernández, Vigueras-Cortés and Garzón-Zúñiga (2016) for the treatment of municipal wastewater. They found high removal efficiencies of 92, 78 and 95 % for Biochemical Oxygen Demand (BOD_5), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), respectively and 4 logarithmic units for fecal coliforms. Therefore, it would be important to evaluate its capacity to remove EPs. Another natural

Tecnología y ciencias del agua, ISSN 2007-2422, 15(2), 98-163. DOI: 10.24850/j-tyca-15-02-03

material of high distribution is volcanic rock known as pouzzolane or tezontle, which is an interesting material to be used as a filtering biofilm support due to its great porosity (82 %). Tezontle is available in the central region of Mexico, and it is widely used for building construction and ornamental purposes. This material has been used as a support material in wetlands and has also shown high removal efficiencies of organic matter and nutrients (Tejeda, Torres-Bojorges, & Zurita, 2017b). Therefore, both mesquite and tezontle could be a good option as filter material for the evaluation of a non-conventional biofilter for CBZ removal.

Electro-oxidation processes (EO)

Complex matrices like HWW have recalcitrant compounds that might be difficult to remove with biological processes only. Some studies suggested to use electrochemical advanced oxidation processes (AOP) to remove recalcitrant compounds, reduce organic matter or even increase biodegradability of industrial effluents when used as pre-treatment, thus delivering an effluent easier to treat in a biological process (Thirugnanasambandham & Ganesamoorthy, 2019; Trellu *et al*., 2016). Among AOP, electro-oxidation (EO) is one of the most studied processes due to its easy implementation and good performance. Some authors have studied EO for CBZ removal as the main treatment process. They found efficiencies between 88 and 99 % of CBZ removal for a large range of initial concentrations between 22 and 10 000 µg CBZ/l (Al-Qaim, Mussa, Yuzir, Abdullah, & Othman, 2018; García-Espinoza, Mijaylova-

Nacheva, & Avilés-Flores, 2018; García-Gómez *et al*., 2014). Nevertheless, these high removals were carried out in synthetic solutions and these results need to be validated with real wastewater. On the other hand, some authors mention that EO costs can be high due to the consumption of electrical energy, which is why the use of EO in combination with a biological process (hybrid system) has been recommended to make the application of the technology more accessible (Chettiar & Watkinson, 1983).

Electro-oxidation plus biological process

Electro-oxidation has been used as a pretreatment to increase the biodegradability of recalcitrant compounds from the effluents of different industries and subsequently remove them successfully by means of a biological process. There are a few reports of studies of drug degradation in a combined EO system as a pretreatment, followed by a biological process (Fontmorin *et al*., 2014; Ouarda *et al*., 2018; Rodríguez-Nava, Ramírez-Saad, Loera, & González, 2016a). These studies show different results. On one hand, those that obtain a low removal during the EO process and later with the biological process achieve a complete removal of the drugs. On the other hand, other authors report a good removal in the EO process and a desorption phenomenon when the pretreated effluent goes through the biological process.

For example, Rodríguez-Nava, Ramírez-Saad, Loera and González (2016) studied the simultaneous removal of bezafibrate, gemfibrozil, indomethacin and sulfamethoxazole (with a concentration of 200 µg/l)

Tecnología y ciencias del agua, ISSN 2007-2422, 15(2), 98-163. DOI: 10.24850/j-tyca-15-02-03

from synthetic wastewater in an EO system (operated with: BDD electrode, current density of 1.56 mA/cm^2 and 20 min of electrolysis) followed by an activated sludge (AS) system (operated with: TRH 1.29 - 1.38 d) and they report that EO removed more than 50 % of all drugs in a stable way, and when this effluent was treated in the AS system, 100 % of the drugs and 83 % in COD were removed. But when they treated the synthetic wastewater only by AS process, a variable removal was observed, with efficiencies that remained below 40 %.

On the other hand, Ouarda *et al*. (2018) when evaluating the removal of carbamazepine in a synthetic HWW in an EO process followed by a Membrane Bioreactor (MBR) process, observed that 60 % of the CBZ was removed during the EO, but in the MBR effluent the removal was negative due to a desorption phenomenon of the CBZ, having an overall removal of 42 %.

It is worth mentioning that several factors must take place to obtain these very different results. On one hand, the drugs bezafibrate, gemfibrozil, indomethacin and sulfamethoxazole are less recalcitrant than CBZ, since it has been reported that the first drugs are removed by about 40 % in an LA system (Rodríguez-Nava *et al*., 2016) while for CBZ removal efficiencies < 10 % have been reported in a AS system (Zhang, Geißen, & Gal, 2008). On the other hand, the type of biomass (suspended or biofilm) of the biological process in which the electroxidation effluent is treated seems to also influence since it has been reported that biofilm systems can be up to 500 times more resistant in terms of survival mechanisms and mitigation of sudden variations in pH, temperature, salinity, type of substrate and concentration of biocides (Dzionek, Wojcieszyńska, & Guzik, 2016; Freedman *et al*., 2017). In addition, a

biofilm presents a more complex community of microorganisms due to the aerobic, anaerobic and anoxic microenvironments that can be present. To this regard, there are few reports mentioning that when anoxic conditions are present and a denitrifying community is present, CBZ removal efficiencies can achieve higher values than those obtained in conventioal AS systems (Hai *et al*., 2011; Tejeda , Barrera, & Zurita, 2017a).

Therefore, the present investigation seeks to study, first, whether in fact a biofilm system, which is known to promote nitrification and denitrification phenomena, removes higher concentrations of CBZ than a conventional AS process, and second, it evaluates a combined biofiltration system with EO as pretreatment to corroborate whether in this type of combination the efficiency of CBZ removal improves or not, since contradictory results have been reported, as it has been mentioned. Finally, another novel and important aspect is conducting the study using real HWW enriched with CBZ and not synthetic water.

The objectives of this study were a) to evaluate a non-conventional biofilter (BF) containing a biofilm growing over *Prosopis* and Tezontle as a mixed filter bed for the removal of CBZ, organic matter and ammoniacal nitrogen from a real hospital wastewater (HWW), and b) to evaluate a hybrid treatment system combining BF and EO, using EO as a pre-treatment.

Tecnología y ciencias del agua, ISSN 2007-2422, 15(2), 98-163. DOI: 10.24850/j-tyca-15-02-03

Tecnología y Ciencias del Agua
OPEN ACCESS
Check for updates

Materials and methods

Hospital wastewater (HWW) sampling and characterization

The wastewater used in this study was obtained from a wastewater treatment plant (WWTP) from a hospital in Durango City, Mexico, with a capacity of 238 beds. Punctual samples were taken after the grid system and before the biological process (Moving Bed Biofilm Reactor, MBBR). The hospital wastewater (HWW) was collected each week and stored in polypropylene bottles of 20 l and kept at 4 °C until use.

COD, TSS and VSS were measured according to Methods 5220 C, 2540 D and 2540 E, of the Standard Methods, respectively (APHA, 1991). ammonia nitrogen, total nitrogen (TN), total phosphorus (TP) and orthophosphate (PO_{4-}) were measured according to methods 8038, 10072 10127, 8048 of HACH, respectively, using a HACH DR/3900 spectrophotometer. Samples for the determination of COD, TN, TP, and PO_{4-} were not filtered, but rather allowed to settle prior to analysis. Electrical conductivity was tested with a conductivity meter TRACER Code 1766 and pH was measured with a pH meter Thermo scientific Orion 3-Star with glass electrode.

To test the biofiltration process under different experimental conditions and to simulate high levels of CBZ contamination found in hospital and industrial (pharmaceutical) WW of between 0.5 and 442 000 µg/l (Table 1) HWW was enriched with CBZ (Sigma-Aldrich purity ≥ 98 %). During the experiments desired CBZ concentrations of 1 000 and 10

Tecnología y ciencias del agua, ISSN 2007-2422, 15(2), 98-163. DOI: 10.24850/j-tyca-15-02-03

000 µg/l, respectively, were adjusted before treatment (see subsection "Experimental procedure stages": stages 2 and 3). A mixing and stirring time of 12 hours was required to completely dissolve CBZ in HWW prior to treatment. It was selected to work with high concentrations of CBZ found in PHWW, assuming that if the processes to be evaluated (EO and biofiltration) can efficiently treat these high concentrations, they can also treat lower concentrations reported in HWW and MWW.

Biofilter experimental unit

The biofilter was made with Polyvinylchloride (PVC) with a dimension of 150 cm height and a diameter of 10.5 cm. The biofilter was packed with two layers of filter material arranged vertically as follows (from the top to the bottom): 36 cm of mesquite wood chips (*Prosopis*), 76 cm of pouzzolane (commonly known as tezontle) and 12 cm of a layer of gravel that works as a base for the filter material. The working volume of the liquid inside the column is estimated to 9.6 l. The BF unit was fed with HWW by regulating the flow rate using a peristaltic pump.

Mesquite wood chips (*Prosopis*) were obtained from pruning bushes of mesquite trees wastes from Durango, Mexico. Mesquite wood was shredded in an industrial chipping machine which produces wood chips with dimensions of 2.33 ± 0.79 cm (width) x 1.16 ± 0.35 cm (length) x 0.44 ± 0.32 cm (thick). Sieve was necessary to remove pieces of bark and dust. The resulting material had a porosity of 79 ± 0.5 %, a bulk and real density of 246 ± 2.05 and 1 118 ± 40.54 kg/m^3, respectively.

Pouzzolane volcanic rock was obtained from a carrier in Durango state, Mexico, which had the following measurements: 2.87 ± 0.54 long, 2.02 ± 0.41 width and 1.5 ± 0.36 cm height, 65 ± 0.013 % porosity, 693 ± 16 kg/m^3 bulk density and 2 002 ± 72 kg/m^3 real density. The arrangement of the filtration bed (70 % pouzzolane and 30 % wood chips) and the granulometry of filtration materials were selected because they were previously successfully used by Zamora-Acevedo (2016), and Garzón-Zúñiga, Vigueras-Cortés and Zamora-Acevedo (2021) in a biofilter for the treatment of municipal wastewater, achieving removal efficiencies over 90 % of BOD_5, TSS, NH_4^+-N and over 80 % of COD. Pouzzolane was washed with tap water before being added to the reactor.

Electro-oxidation experimental set-up

EO was carried out in an electrolytic cell manufactured in acrylic with dimensions of 10 cm (width) x 10 cm (length) x 11 cm (depth) with a working volume of 1 l and an electrode gap of 1 cm. This device utilized a titanium cathode and a lead dioxide (Ti/PbO_2) anode (acquired from Baoji Qixin Titanium Co., Ltd). The electrodes were 9 cm wide and 8 cm high. Ti/PbO_2 was selected since it is classified as a non-active anode (Comninellis & Chen, 2010), anodes of this type produce higher concentrations of oxidizing agents, thus resulting in higher levels of decontamination (Barbosa-Ferreira *et al*., 2020). To ensure complete mixing of the solution, a magnetic bar was used at 900 revolutions per minute. The power supply used was a direct current (DC) supply with a capacity of 30 V and 10 A.

No electrolyte solution was added because it was expected that the electrical conductivity of the wastewater (as observed in the HWW characterization) was sufficient for the process to be carried out. The working pH was 7.4±0.4.

Electrolysis time and the relations electrode area/volume, and current/cm^2 of electrode were determined in two preliminary experimental tests as follows:

1. CBZ was degraded over 120 minutes at different current intensities (0, 1.0, 1.5 A) using one pair of electrodes (one cathode and one anode). This study employed the anode PbO2 and the matrix HWW enriched with CBZ at a concentration of 14 000 µg/l and a conductivity of 1 251 S/cm, with magnetic stirring at 900 rpm.
2. CBZ was degraded over 120 minutes applying three different relations electrode area/volume: 7.2, 14.4 and, 21.6 m^2/m^3 equivalent to one, two, and three pairs of electrodes and each pair of electrodes was fed with 1 A of current.

Experimental procedure stages

Stage 1. Biomass development in the biofilter

The initial experiments were conducted to develop biomass in the biofilter, which was fed with raw HWW (without addition of CBZ) by keeping a hydraulic loading rate (HLR) of 0.2030 m^3/m^2 d. No inoculum was used. Microorganisms present in HWW were retained in the filtering bed and

Tecnología y ciencias del agua, ISSN 2007-2422, 15(2), 98-163. DOI: 10.24850/j-tyca-15-02-03

progressively formed a biofilm. The experiment was run at room temperature. The influent was fed with a flow rate of 1.1 mL/min.

These conditions were maintained constant until the biofilter showed a steady sate of the removals of macro-pollutants (COD and NH_4^+-N).

Stage 2. Biofilter operation in the presence of high CBZ concentration

Once the biofilm was developed and the BF achieved removal stability of macro-pollutants, it was fed with HWW enriched with a relatively high CBZ concentration of 10 000 µg/l. This concentration was chosen because it is known that organic filter material (wood chips) has an important adsorption capacity of macro (Garzón-Zúñiga, Lessard, Aubry, & Buelna, 2005) and micro-pollutants (Garzón-Zúñiga, Sandoval-Villasana, & Moeller-Chávez, 2011) and the saturation of the filter bed can last long periods of time. Thus, this high concentration was selected to saturate the media in a short time and see the effect of adsorption and later the effect of biological degradation. An HLR of 0.2030 m^3/m^2 d was applied during a period of 67 days. The removal efficiency of COD and ammoniacal nitrogen were measured to determine if the relatively high concentration of CBZ in HWW caused a negative effect on the biofilm performance. Once the biofilm achieved removal stability of these macro-pollutants, punctual samples were withdrawn at the inlet and outlet of the biofilter unit for the measurements of CBZ concentrations.

Tecnología y ciencias del agua, ISSN 2007-2422, 15(2), 98-163. DOI: 10.24850/j-tyca-15-02-03

Important adsorption of CBZ over the filtering material was expected once CBZ started to be added to HWW feeding the biofilter. Therefore, the CBZ adsorption capacity of the filter bed was estimated by applying Equation (1):

$$q = \sum_{i=0}^{n} \frac{(S_0 - S_e) * \Delta t * Q}{M} \quad (1)$$

q = Adsorption capacity, µg/g.

S_0 = Influent concentration, CBZ µg/l.

M = Filtering material mass, g.

S_e = Effluent concentration, CBZ µg/l.

Q = Flow, l/d.

Δt = Time interval (d), between the beginning of addition of CBZ and the saturation of the bed filter defined as removal efficiency equal to zero and before a period of equilibrium characterized by desorption–adsorption.

Stage 3. Hybrid system

During this stage HWW was spiked with a CBZ concentration of 1 000 µg/l which is lower than the concentration applied in stage 2 (10 000 µg/l), used to saturate the filter bed. This CBZ concentration was chosen because it is among the highest reported for pharmaceutical wastewater (PHWW) in countries like Israel, even if it is higher than the concentration reported in HWW in countries like Brazil, China, and Sweden (Table 1).

This spiked HWW was then treated by EO followed by a BF process. EO was applied under the operational conditions presented in section "Electro-oxidation experimental set-up" to transform the parent molecule of CBZ. The EO reaction time was set to 60 min because earlier experimentation showed that at 60 min a maximum % of CBZ was transformed (See results section "Hybrid system"). EO was performed using two pairs of electrodes (two anodes of Ti/PbO_2 and two cathodes of titanium) in mesh configuration with dimensions of 9 cm (width) x 8 cm (length) and a working volume of 1 l. The current intensity applied to each pair of electrodes was 1.0 A. At the end of the EO process, the removal efficiencies for CBZ, COD, NH_4^+-N were measured, and the EO effluent was drawn in a homogenization tank from where the BF was fed, because EO worked in batch mode and BF in continuous mode.

The BF was operated with a flow of approximately 3 l/d equivalent to an HLR of 0.4060 m^3/m^2 d. This means that the EO unit had to perform between three and four treatment cycles per day to have enough effluent to feed the BF.

Carbamazepine (CBZ) determination

CBZ concentration in the aqueous solutions was measured with an Agilent series 1260P (ABC Instrumentation, Mexico City, México), high performance liquid chromatograph (HPLC) with a quaternary pump coupled to a diode array detector (DAD). The separation was carried out on an Agilent ZORBAX SB C-18 column (4.6 X 100, 3.5 µm). The mobile phase that was used was composed by HPLC water (A) and acetonitrile

(B), Fermont lot 718361, in isocratic flow of 0.8 ml/min (A 40 % and B 60 % v/v). The injection volume was 20 µL. CBZ was monitored at a wavelength of 286 nm. Retention time of CBZ was 1.753 min and detection limit (DL) and quantification limit (QL) are 25 µg/l and 50 µg/l of CBZ, respectively. The range of the calibration curve was established between 25 and 1 200 µg/l of CBZ, applying a lineal model with R^2 = 0.9966. Precision and accuracy were evaluated obtaining a standard relative deviation of ± 15 % (0.4-13.8 %) and a coefficient of variation of ≤ 15 % (0.21-6.94 %).

Measurements of other parameters

COD, TSS and VSS were measured according to Methods 5220 C, 2540 D and 2540 E of the Standard Methods, respectively (APHA, 1991). Ammoniacal nitrogen, Total nitrogen, total phosphorus, and orthophosphate were measured according to methods 8038, 10072 10127, 8048 of HACH, respectively, using a HACH DR/3900 spectrophotometer. The electrical conductivity was tested with a conductivity meter TRACER Code 1766 and the pH was tested with a pH meter Thermo scientific Orion 3-Star with glass electrode.

Tecnología y ciencias del agua, ISSN 2007-2422, 15(2), 98-163. DOI: 10.24850/j-tyca-15-02-03

Results and discussion

Hospital wastewater (HWW) characterization

The HWW characterization (Table 2) showed that it has a high concentration of total nitrogen (95 mg TN/l) mainly in the form of ammoniacal nitrogen content (90 ± 0.4 mg NH_4^+-N/l), which corresponds to a high strength wastewater, if compared to the domestic one. On the other hand, the HWW presented a low content of chemical oxygen demand (COD) of 379±144 mg COD/l, which is similar to a low-medium strength domestic wastewater according to Tchobanoglous, Burton, Franklin, Stensel and Metcalf & Eddy (2003). In addition, it presented a high concentration of total suspended solids (870 mg TSS/l) from which the most part are volatile suspended solids (730 mg VSS/l). A particular characteristic observed is the presence of a high electrical conductivity between 1 494 and 2 559 µS/cm, which is approximately equivalent to 821.7 to 1 407 mg/l (ppm) of salinity (https://www.landscape.sa.gov.au/mr/publications/measuring-salinity, June 22, 2021). This high salinity allows to perform EO without the addition of any supporting electrolyte (Kumari & Tripathi, 2019).

Tecnología y ciencias del agua, ISSN 2007-2422, 15(2), 98-163. DOI: 10.24850/j-tyca-15-02-03

Table 2. Main chemical characteristics of hospital wastewater.

Parameter	Unit	Dry season	Rainy season
Chemical oxygen demand (COD)	mg/l	379 ± 144	181 ± 71
Total nitrogen (TN)	mg/l	95 ± 2.3	57 ± 7.2
Ammoniacal nitrogen (NH_4^+-N)	mg/l	90 ± 0.4	49.9 ± 5.5
Nitrate (NO_3^-)	mg/l	4.1 ± 0.9	3.7 ± 0.4
Total suspended solids (TSS)	mg/l	870 ± 61.8	---
Volatile suspended solids (VSS)	mg/l	730 ± 57.4	---
pH		7.4 ± 0.4	7.5 ± 0.2
Electrical conductivity	µS/cm	2 559 ± 216	1 494 ± 62
Total phosphate (TP)	mg/l	33 ± 0.8	---
Ortophosphate (PO_4^{3-})	mg/l	26 ± 0.1	---
Total chlorine	mg/l	0.08 ± 0.01	---
Free chlorine	mg/l	0.065±0.005	---
Carbamazepine*	µg/l	<25	---

The presence of CBZ was detected in the HWW but in low concentration, in the order of micro-grams per liter, under the detection limit of the equipment used (25 µg/l) (Table 2). This agrees with the order of concentration reported for other HWW in Sweden, China, and Brazil (Table 1). It is known that HWW contains toxic or persistent substances such as drugs, radio nucleotides, solvents, heavy metals, disinfectants,

EPs and other micro-contaminants, all of them difficult to degrade in biological processes. So, in this work the effect of using a short EO to transform these molecules in other more biodegradable molecules to favor a greater removal is being studied.

Start-up and stabilization of biofilter operation

During this stage, the biofilter was fed with HWW without addition of CBZ, with a flow of 1.5 l/d (equivalent to an HLR of 0.2030 m^3/m^2 d) to develop a biofilm on the filtering material. As it can be seen in Figure 1a, there is a constant increase in the removal efficiency of organic matter measured as COD from day 1 to 73 of the operation period. At the same time, the biofilter also increases its removal efficiency in ammoniacal nitrogen in a similar period, from day 1 to 80 (Figure 1b). This was assumed as the occurrence of a heterotrophic and nitrifying biomass activity increase because the effluent concentration of COD and ammonia nitrogen showed a typical curve of progressive reduction between days 20 and 70. This removal is assumed not to be du by adsorption because the typical adsorption curves shows that initially the effluent concentration is low, associated at a high removal efficiency, and by the time, the effluent concentration tends to increase because the saturation of the filtering materials.

Tecnología y ciencias del agua, ISSN 2007-2422, 15(2), 98-163. DOI: 10.24850/j-tyca-15-02-03

Tecnología y Ciencias del Agua
OPEN ACCESS
Check for updates

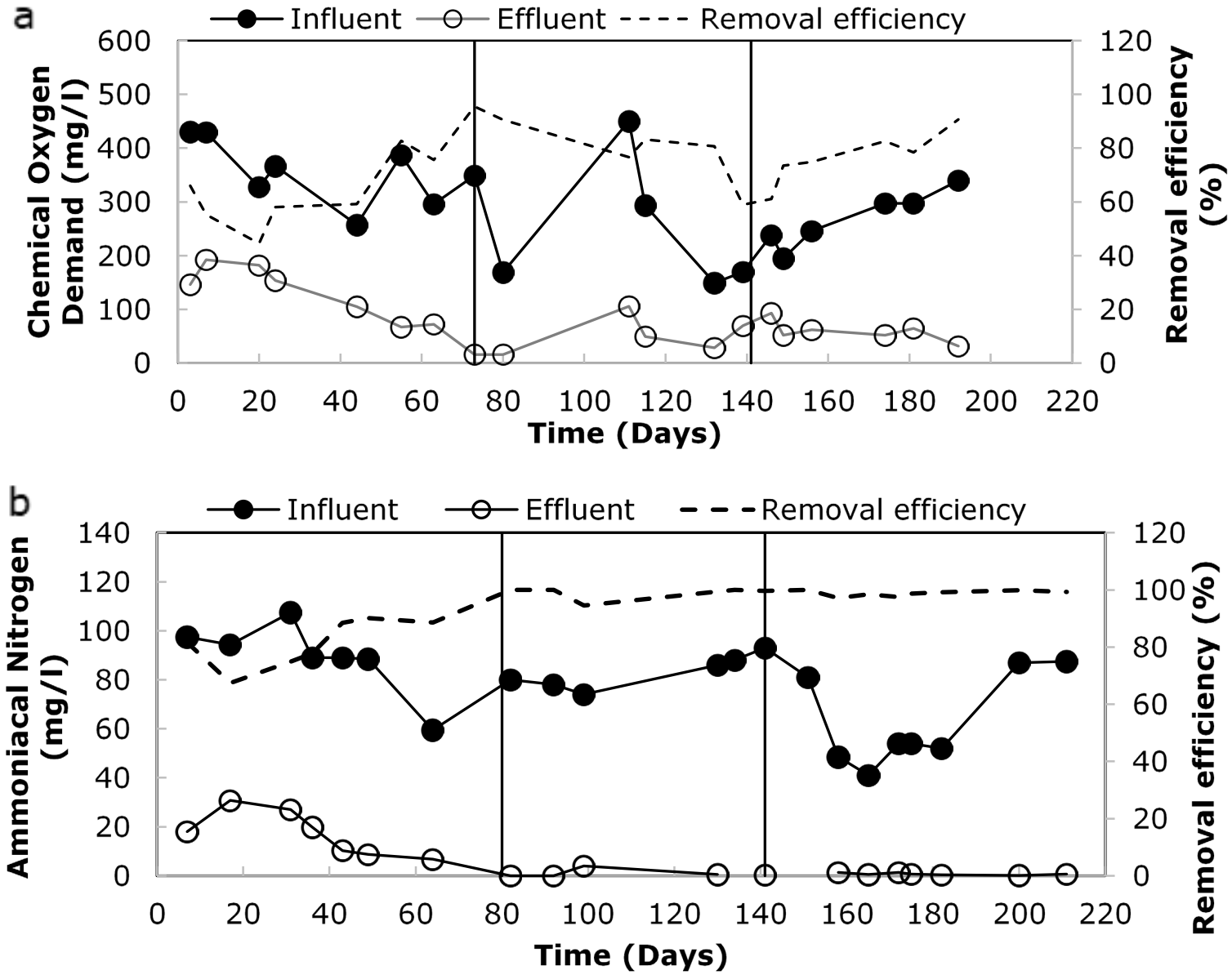

Figure 1. a) Chemical Oxygen Demand and b) ammoniacal nitrogen removal in biofilter. Operating conditions: hospital wastewater, hydraulic loading rate 0.2030 m^3/m^2 d; Initial concentration of carbamazepine of 10 000 µg/l since day 141.

Subsequently, a stabilization period can be observed from day 73 to 141. During this period, COD (81 ± 13 %) and NH_4^+-N (99 ± 2 %) removal efficiencies reached a plateau. Thus, it was assumed that the biological activity in the biofilter reached the stationary phase from day 73 to 141.

CBZ removal in a biofiltration process

Effect of CBZ addition over macro-pollutants (COD and NH_4^+-N) removal in the biofilter

Once the biofilm was formed and the BF operated in a stable way, the biofilter was evaluated regarding the addition of CBZ. From day 141 on, HWW started to spike with a CBZ concentration of 10 000 µg/l. In Figure 2 (day 141 to 211) it can be observed that despite of adding 10 000 µg/l, the initial concentration presented some variation, being the average concentration equal to 9 368 ± 1 579 µg CBZ/l. It is possible that this variation is related to an adsorption effect of CBZ on the HWW solids (Malvar, Santos, Martín, Aparicio, & Alonso, 2020). This is because the concentration of total suspended solids measured in the wastewater was very variable and presented concentrations three times higher than those for municipal wastewater. On the other hand, the polypropylene bottles used to contain the feed water can adsorb some CBZ too (Torres, Dioses-Salinas, Pizarro-Ortega, & De-la-Torre, 2021).

Tecnología y ciencias del agua, ISSN 2007-2422, 15(2), 98-163. DOI: 10.24850/j-tyca-15-02-03

Tecnología y Ciencias del Agua
OPEN ACCESS
Check for updates

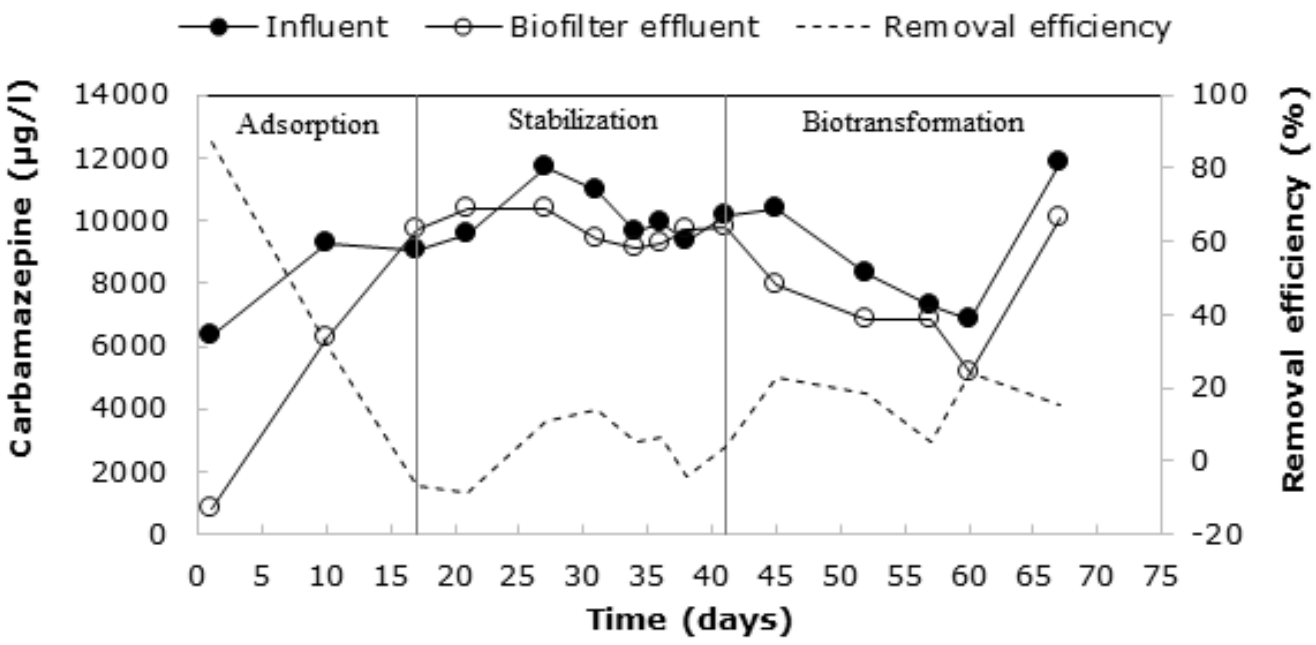

Figure 2. Carbamazepine efficiency removal in biofilter after spike hospital wastewater.

The initial high concentration of CBZ (9 368 ± 1 579 µg CBZ/l) did not affect the performance of the biomass for organic matter and ammoniacal nitrogen removal efficiencies. In this period, the removal efficiency for COD and NH_4^+-N was 78.9 ± 11 % and 98.8 ± 1.5 %, respectively. To verify that the addition of CBZ did not affect the biomass activity, a single factor ANOVA test was performed with a reliability of $p < 0.05$. Table 3 shows the statistical analysis. F-value was under the critical value of F for both COD and NH_4^+-N removal efficiencies, demonstrating that there is no statistically significant difference between removal efficiencies before and after spiking HWW with CBZ. This suggests that a CBZ concentration of 10 000 µg/l did not inhibit the

Tecnología y ciencias del agua, ISSN 2007-2422, 15(2), 98-163. DOI: 10.24850/j-tyca-15-02-03

activity of the microorganisms for the removal of macro-pollutants (COD and NH_4^+-N). However, it has been reported that CBZ has negative effects on natural ecosystems. For instance, Lawrence, Swerhone, Wassenaar and Neu (2005) developed a lotic riverine biofilm on a reactor and by adding 10 µg/l of CBZ significant effects were observed: bacterial biomass reduction, meanwhile algal biomass increased and exopolymer production decreased. In other study, Tian *et al.* (2019) found maximum reduction of 69 % in fecundity and 60 % in fertility while exposing *Daphia magna* to 50 µg/l of CBZ.

Table 3. Analysis of variance (ANOVA) for the elimination of organic matter and ammoniacal nitrogen in a biofilter, with natural filtering material, before and after fortifying hospital wastewater with 10 000 µg/l of carbamazepine.

Parameter	Removal efficiency before CBZ fortifying (%)	Removal efficiency after CBZ fortifying (%)	F-value	Critical value for F-value	Probability
Chemical Oxygen Demand	80.9±12.7 (*n* = 6)	78.9±11.1 (*n* = 6)	0.309	4.600	0.587
Ammoniacal Nitrogen	98.9±2.1 (*n* = 6)	98.8±1.5 (*n* = 8)	1.559	4.747	0.236

The fact that biomass in the biofilter was not affected under such high CBZ concentration for a period of 70 days could be releated to the following facts:

1. Biofilter promotes the formation of several layers of biofilm where anaerobic, anoxic and aerobic bacteria coexist surrounded by self-produced polymer matrix consisting of polysaccharide, protein, DNA and humic acids commonly known as extracellular polymeric substance (EPSs) (Mazumder, Falkinham, Dietrich, & Puri, 2010). In this sense, EPSs protect bacteria against noxious environemtal conditions (Shama & Iffat, 2016; Tuson & Weibel, 2013).
2. Another possibility is that having been fed the biofilter with HWW, microorganisms in this effluent growing as a biofilm in the biofilter could already be acclimatized to different pharmaceuticals, including CBZ. To this respect, Zhang *et al*. (2020) reported changes in microorganism populations when feeding a biofilm system with CBZ.
3. On the other hand, CBZ is less toxic if compared to other paharmaceuticais like ciprofloxacin and metformin. For example, García-Sánchez *et al*. (2019) found a negative effect on nitrifier community, in a similar non-conventional biofilter packed with *Ficus* chips, treating municipal wastewater at much lower concentrations of ciprofloxacin (5 µg/l) and metformin (100 µg/l).

Removal of CBZ from HWW in the Biofilter

Once the Biofilter presented stable removal of COD and NH_4^+-N, it was operated with HWW spiked with 10 000 µg CBZ/l (resulting in an influent average concentration of 9 368 ± 1 579 µg CBZ/l), for additional 67 days and was fed with an HLR of 0.2030 m^3/m^2 d. It is worth noting that, a high removal efficiency of CBZ of 87.4 % was recorded during the first days of addition of CBZ in the raw HWW due principally to a phenomenon of adsorption. However, the efficiency decreased rapidly during the subsequent 17 days of operation (Figure 2). This important mechanism of adsorption has been reported before in a biofilter packed with an organic filtration bed, as being the principal mechanism of removing micropollutans. For example, colorant molecules (Garzón-Zúñiga *et al*., 2011) or macro-pollutants like nitrogen (Garzón-Zúñiga *et al*., 2005) until the filter bed is saturated.

Adsorption is a function of different factors such as initial concentration, pH, temperature, the octanol-water partition coefficient (K_{ow}) and the constant acid dissociation (pK_a) of carbamazepine molecule (Aubertheau *et al*., 2017; Silva, Jaria, Otero, Esteves, & Calisto, 2019). To this regard, CBZ has hydrophilic characteristics and a neutral charge, which would make it a difficult molecule to remove from water through adsorption. However, hydrophobicity interactions do not always direct the adsorption process. For example, Wunder, Bosscher, Cok and Hozalski, (2011) did not find a direct correlation between the adsorption capacity of different pharmaceuticals molecules and their K_{ow} properties, as it was observed for CBZ in the present study. Other studies have reported significant adsorption capacities of CBZ in adsorbent materials like

carbon. For example, Silva *et al*. (2019) reported between 12 600 and 212 000 µg/g for activated carbon. Such capacities would be sufficient to remove CBZ from wastewater for a long time given the actual concentrations of this molecule reported in municipal wastewater, up to 2.6 µg/l (Dalahmeh *et al*., 2018). In the case of pouzzolane-Tezontle, pore size adsorption effect (deposition of the molecules of CBZ in the pores) may be another mechanism occurring since the size of the CBZ molecule is between 0.72 and 1.35 nm and pore size of pouzzolane-Tezontle is between 2 and 50 nm (Punyapalakul & Sitthisorn, 2010; Tejeda *et al*., 2017a).

The adsorption capacity of the filter material (mix of pouzzolane-tezontle and mesquite wood chips) for CBZ was calculated in 19.84 µg/g (Figure 2) for an average initial concentration of 9 368 ± 1 579 µg CBZ/l. In a previous study, Tejeda *et al*. (2017a) determined the adsorption capacity of pouzzolane-Tezontle for CBZ in 3.2 µg/g. This difference in adsorption capacity should belong to the combination of both filter materials, pouzzolane-Tezontle and mesquite wood chips. This important difference between both filtering material could be explained by the mesquite wood chips characteristics like microporosity and ionic electric charge (Garzón-Zúñiga & Buelna, 2011). However, it is recommended to determine the adsorption capacity of pouzzolane-Tezontle and mesquite alone to understand the contribution of each material to the adsorption capacity of the biofilter used in this study.

After the saturation of the filter material, an equilibrium period characterized by a phenomenon of desorption and adsorption that lasted approximately 24 days (Figure 2, day 17 to 41) was observed. During this period, those initial concentration variations were seen, which produced

a slight increase of removal efficiency when influent concentration increases and vice versa (Figure 2).

Finally, from day 41 onwards, a constant removal efficiency was reached. The average concentration of CBZ in the influent and effluent from day 45 to 67 was 8 935 ± 2 136 µg/l and 7 384 ± 1 804 µg/l, respectively. This shows a stable average removal efficiency of CBZ of 17.2 ± 7.4 % or 1 551 ± 664 µg/l that can be related to biotransformation, which is relatively higher than most of the removal efficiencies reported for activated sludge processes, which is under 10 %, and removing lower concentrations in the order of ng/l (Zhang *et al*., 2008). It is worth noting that even if only 17 % of CBZ removal was achieved, the removal of CBZ in terms of concentration (1 551 ± 664 µg/l) is higher than the concentration in most of the reports for HWW, MWW and PHWW effluents, which are between 0.1 and 890 µg/l (Table 1).

The best performance on the CBZ removal efficiency observed in this study in HWW could be related to the high degree of nitrification achieved in this biofilter which agrees with the results of some previous investigations studying emerging organic pollutants and nitrification. For example, Servos *et al*. (2005), by evaluating eighteen WWTP for 17h-estradiol removal, claimed that there might be an association between the degree of nitrification in the treatment system and the removal of estrogens. This association has been tested before by Vader *et al*. (2000). They compared sludges with low and high nitrification degrees, demonstrating that those sludges with low degree were not capable of degrading 17h-estradiol. But the role of nitrifiers to biotransform organic micro-pollutants is also important for recalcitrant

pharmaceuticals like CBZ. Tran, Urase and Kusakabe (2009) observed a significant improvement in the removal efficiency of CBZ with a nitrifying activated sludge, if compared to the removal efficiency found in a conventional activated sludge. High degree of nitrification improved biological diversity and growth conditions resulting in increased biological transformations (Lema & Martínez, 2017; Servos *et al*., 2005). Likewise, Zhang, Zhu, Szewzyk, Lübbecke and Uwe-Geissen (2017) reported a significant difference in the removal efficiency of CBZ when using a microbial consortium (more diversity of microorganisms) developed with real wastewater than when use a microbial community (less divers) in synthetic wastewater.

Hybrid system: Electro-oxidation followed by biofiltration

Preliminary experimental tests were conducted to determine the best operational conditions for the EO process. As mentioned in methodology, CBZ was degraded over 120 minutes at different current intensities (0, 1.0, 1.5 A). The results are presented in Figure 3.

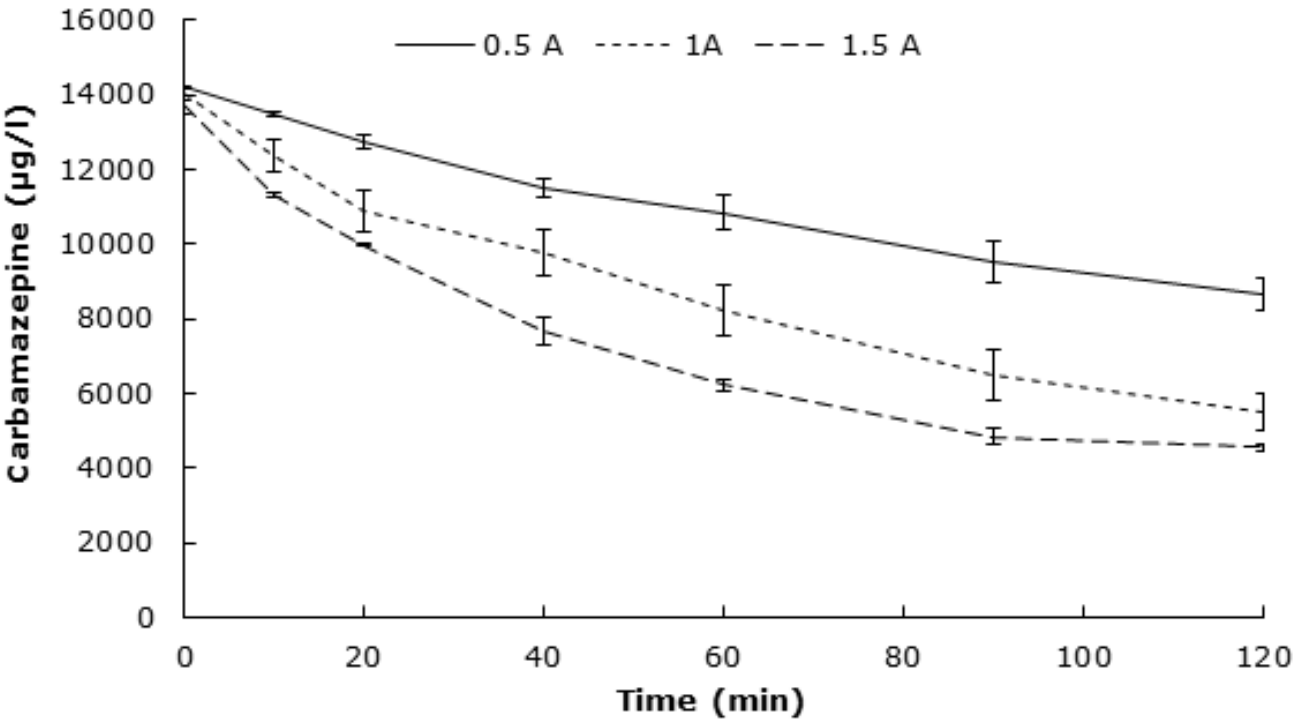

Figure 3. CBZ degradation with different current intensities. Applying a, A/V ratio of 7.2 m^2/m^3.

ANOVA analysis and a mean comparison test were conducted using the Tukey method ($P < 0.05$ = Statistically different). Within 10 minutes, there were already significant differences between 0.5 and 1.5 A (P = 0.0188) and these differences remained significant throughout the entire experiment. The difference in CBZ removal efficiency between the 0.5 A and 1.0 A treatments was significant from 60 minutes forward (60 min, P = 0.0041; 90 min, P = 0.0145; 120 min, P = 0.0098). The difference between 1.0 A and 1.5 A was not statistically significant since the P value was always greater than 0.05. As a result of this preliminary study, it was determined that in subsequent experiments, the current intensity should

be 1.0 A equivalent to 13.88 mA/cm^2 and the electrolysis time should be 60 minutes, which are common values considered in recent literature.

To select the value of electrode area per working volume of the reactor, a kinetic test was performed at different electrolysis times, that is, 10, 20, 40, 60, 90, and 120 minutes, using one, two, and three pairs of electrodes equivalent to three different A/V ratios: 7.2, 14.4 and 21.6 m^2/m^3, respectively. The results are shown in Figure 4.

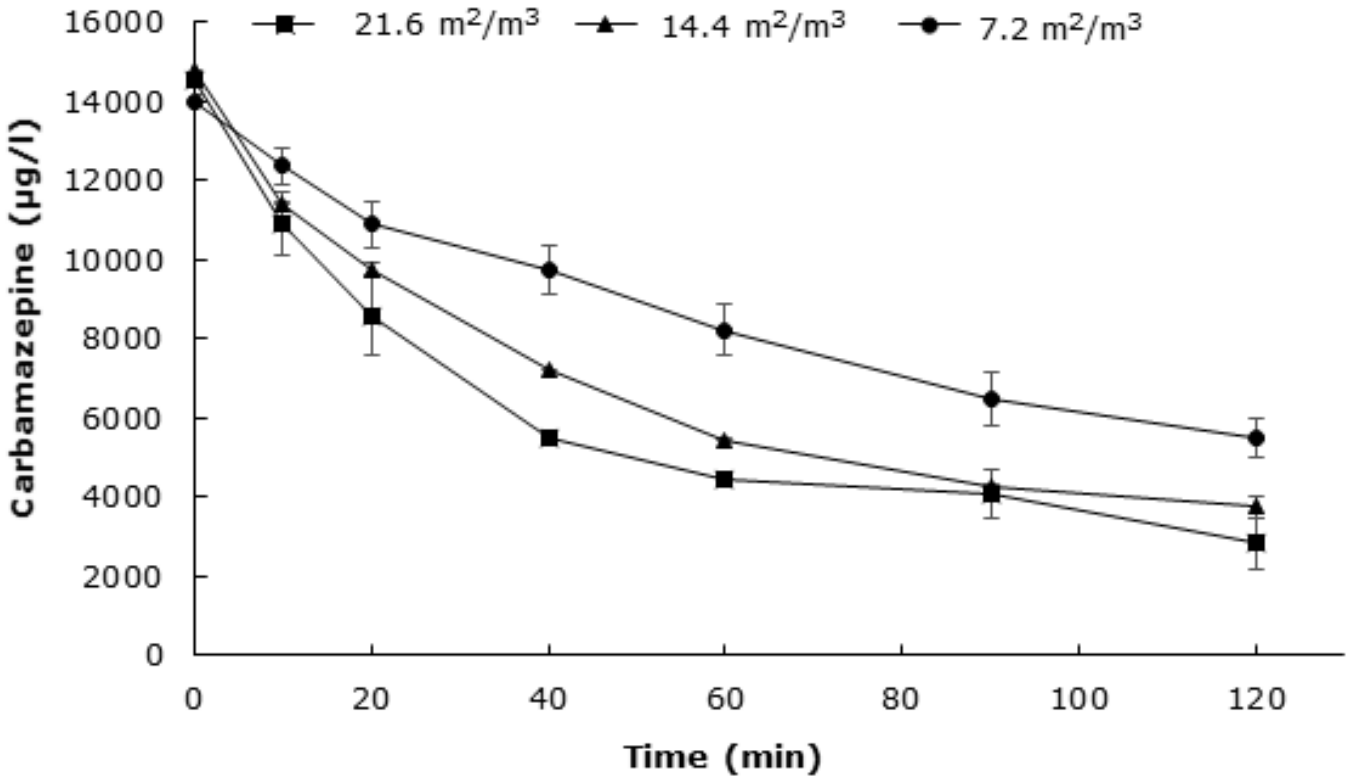

Figure 4. CBZ degradation with three different A/V ratios.

The results were analyzed using a variance analysis and a mean comparison test using the Tukey method (P = 0.05). From 40 min forward, the A/V ratios of the three groups began to differ significantly (ANOVA P = 0.0086). During the experiment, 14.4 and 21.6 m^2/m^3 treatments did not differ statistically except at min 40 (P = 0.0.088). Thus, an A/V of 14.4 m^2/m^3 was chosen to carry out the EO process in this study.

Electro-oxidation as pretreatment

The initial concentration of CBZ, in the spiked HWW, was between 1 250 and 1 800 µg/l with an average value of 1 491 ± 256 µg/l (Figure 5). This HWW was first treated by EO using an anodic electrode of Ti/PbO_2, 1.0 A (13.88 mA/cm^2) and a 60 min reaction time.

Tecnología y ciencias del agua, ISSN 2007-2422, 15(2), 98-163. DOI: 10.24850/j-tyca-15-02-03

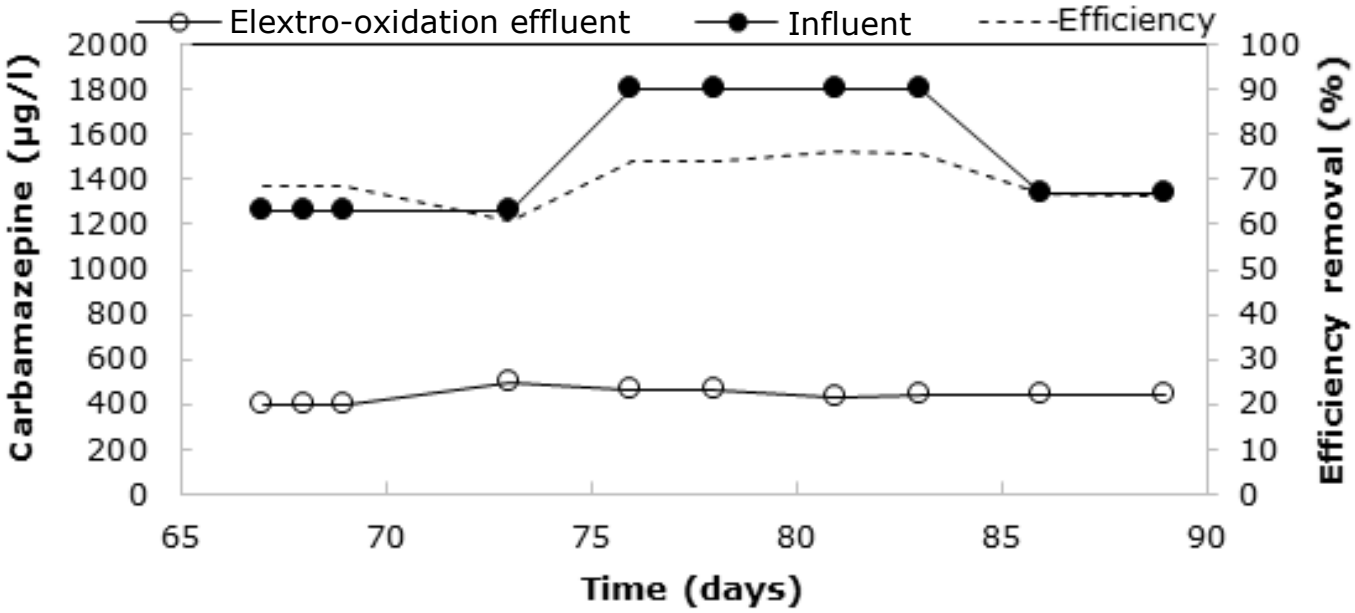

Figure 5. Electro-oxidation of raw hospital wastewater spiked with carbamazepine.

Under these conditions, EO had an average removal efficiency of CBZ of 70.0 % with a standard deviation of 4.6 % (Figure 5), which agrees with the previously reported CBZ degradation in EO processes using synthetic WW. For example, Komtchou, Dirany, Drogui and Bermond (2015) reached 73.2 ± 0.31 % with a BDD anode and the following experimental conditions: 120 min of treatment, 0.2 A (1.8 mA/cm^2), Fe^{2+} concentration of 0.25 mM, initial pH 3.0, initial CBZ concentration of 12 000 µg/l. Ouarda *et al*. (2018), when applied EO as pre-treatment for the removal of CBZ and venlafaxine, obtained 50 and 66 %, respectively.

Similarly, in an EO process, Gurung, Ncibi, Shestakova, & Sillanpää (2018) reached a CBZ removal of 75.5 % from a spiked wastewater (20

000 µg/l) with a Ti/Ta_2O_5-SnO_2 anode, after 8 h of electrolysis, 9 mA/cm^2 of current density, pH 6, temperature of 30 °C, and using 0.1 M Na_2SO_2 as supporting electrolyte. As it can be seen on these references, 75 % efficiency was not exceeded. This could be due to limitations in the process that have been previously reported such as parasitic reactions in which the •OH evolve to O_2 and stop oxidizing the recalcitrant molecules (Hmani, Samet, & Abdelhédi, 2012) or the passivation of electrodes (Zhu *et al*., 2010) or the kind and amount of supporting electrolyte in synthetic HWW. Regarding the CBZ oxidation process during EO, there are two well-documented mechanisms for the degradation of organic pollutants in an EO system: Direct oxidation and indirect oxidation. Direct oxidation takes place on the surface of the anode by direct electron transfer from physiosorbed hydroxyl radicals (•OH) formed by the anodic oxidation of water at the electrode surface (Comninellis & Chen, 2010). The indirect oxidation occurs in the liquid matrix where ionic species such as chlorides, sulfates and carbonates can be oxidized to generate intermediate oxidants in the solution that oxidize organic molecules (Drogui, Blais, & Mercier, 2007). Direct oxidation is favored with "non-active" electrode types like the ones used in this study. However, and due to the natural presence of chlorides in HWW, indirect oxidation also takes place. To this regard, Liu, Hu and Lo (2019) evaluated the removal of three drugs containing amines in synthetic wastewater (simulating HWW) and found that if an electrolyte support of Na_2SO_4 is used, 59.2-71.4 % of the drugs were removed. While when using an electrolyte support of NaCl, which favors greater indirect oxidation, efficiencies of 75.8 - 99.6 % were achieved. This increase is related to the synergy between hydroxyl radicals (direct oxidation) and active chlorine (indirect oxidation), with direct oxidation being the main

Tecnología y ciencias del agua, ISSN 2007-2422, 15(2), 98-163. DOI: 10.24850/j-tyca-15-02-03

drug removal mechanism, but indirect oxidation considerably increased removal efficiencies. This was also reported by Romero-Soto *et al*. (2018) who found a removal of an antibiotic (chloramphenicol) of 76 % in 12 min with direct oxidation (• OH) and an additional 24 % due to indirect oxidation. Therefore, taking into account that the HWW used in this study had a total chloride concentration of 0.08 ± 0.01 mg/l and a free chloride concentration of 0.065 ± 0.005 mg/l (Table 2) and an electrical conductivity of between 1 494 ± 62 and 2 559 ± 27 µS/cm, both direct and indirect oxidation processes are expected to take place.

In the degradation of drugs, the removal of the parent compound entails a series of transformations to by-products. In the case of CBZ, the main transformation by-product is 10,11-EpoxyCBZ (EP-CBZ). Later transformations include the formation of Acridine-9-carbaldehyde and Acridone that eventually continue their degradation until the rupture of rings reaching simpler compounds and their mineralization (García-Espinoza *et al*., 2018; Mir-Tutusaus *et al*., 2021). However, by-product mineralization requires long electrolysis times and requires much more energy (Oller, Malato, & Sánchez-Pérez, 2011), which indicates that an important part of that 70 % CBZ removal, measured in the present study must be transformed in by-products that have different physic and chemical properties than the parent compound whereby, adsorption and toxicity will differ as well. For example, the main CBZ metabolite EP-CBZ is significantly more toxic than its parent compound CBZ according to Heye *et al*. (2016) and has a reduced adsorption capacity (Malvar *et al*., 2020). Therefore, a biological process should treat the remaining CBZ and by-products, however these last were left out of the scope of this study. This has a series of implications to consider, among the main ones are:

1) the biological process to be applied must be resistant to the toxic by-products that are generated, probably the microorganisms of the biological process require an acclimatization period to be able to remove or bio- transform these by-products; 2) determining which by-products can be formed requires a great deal of work for each molecule, so an indirect way of following the mineralization or transformation of the by-products into simpler and less harmful compounds is through toxicity and total organic carbon (TOC) analysis.

Biofiltration

In this stage, the same biofilter unit previously fed with raw HWW and spiked with CBZ (10 000 µg/l) was fed now with the EO effluent containing an average concentration of 437 ± 33 µg/l of CBZ. By decreasing the influent concentration in the BF (HWW pretreated by EO), desorption of the accumulated CBZ on the biofilter was expected. To accelerate this process initially, the HLR was increased from 0.2030 to 0.4060 m^3/m^2 d. After 11 days of operation, the biofilter effluent reached a maximum concentration of CBZ of 14 450 µg/l, then desorption decreased and reached 4 142 µg/l of residual concentration of CBZ after day 89 (Figure 6a). From day 89 on, the filtration velocity of the EO effluent in the Biofilter unit was reduced significantly by applying again a HLR of 0.2030 m^3/m^2 d. Under these conditions, desorption dropped drastically showing a first effluent concentration removal of CBZ of 360 µg/l, followed by a small period of adsorption/desorption process between days 89 and 103

Tecnología y ciencias del agua, ISSN 2007-2422, 15(2), 98-163. DOI: 10.24850/j-tyca-15-02-03

of the operation period. From day 110 onward, the global (EO + BF) system showed a steady state for CBZ removal efficiency (Figure 6b).

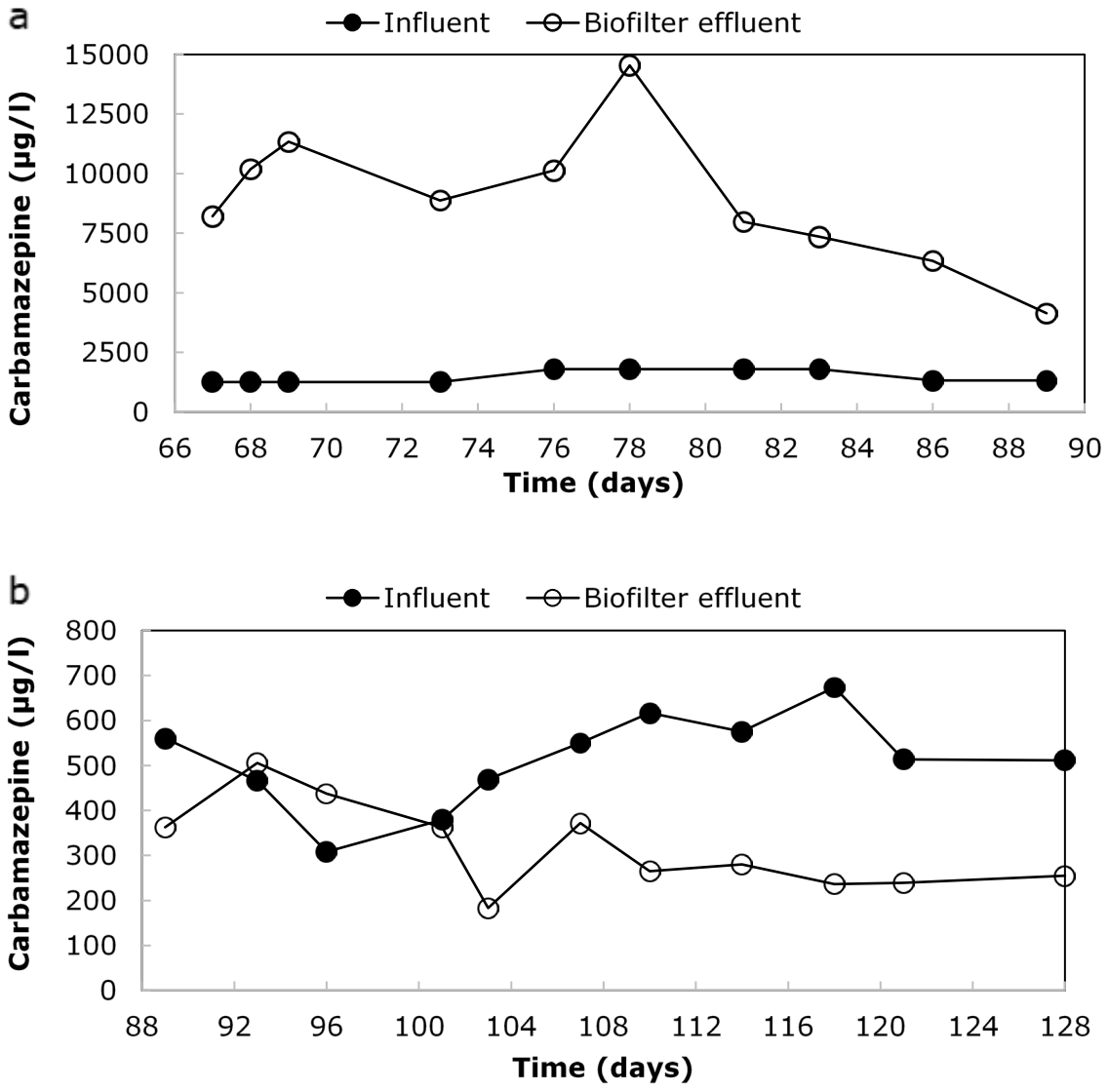

Figure 6. Carbamazepine concentration in electro-oxidation pre-treatment and biofilter: a) with hydraulic surface load of 0.4060 m^3/m^2 d; b) with hydraulic surface load of 0.2030 m^3/m^2 d.

In this period The HWW influent average concentration was 1 830 ± 235 CBZ µg/l. The concentration in the EO effluent was 139 ± 45 CBZ µg/l and the effluent of the BF was 853 ± 203 CBZ µg/l (Figure 7a). This means that there was a removal efficiency of 92 % in EO. Then a negative removal efficiency of -39 % was observed in the biofilter giving a final global removal efficiency of 53 % (Figure 7b) equal to an average value of 976 µg/l removed. This indicated that, in terms of the global removal efficiency, the system EO + BF increased by approximately 40 % the removal efficiency of the BF alone, which passed from 17 to 53 % without and with pre-treatment by EO, respectively.

Tecnología y Ciencias del Agua
OPEN ACCESS
Check for updates

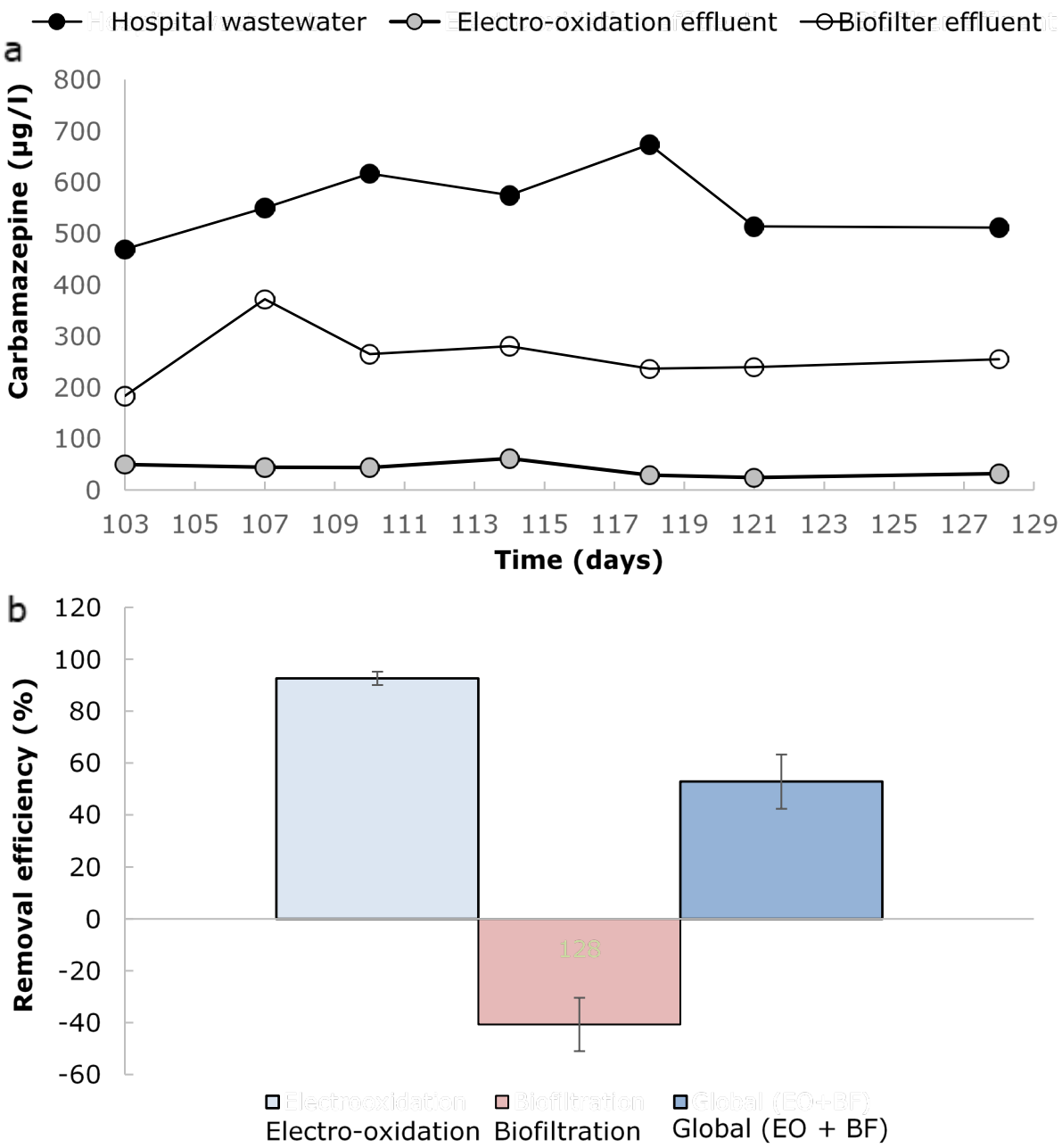

Figure 7. a) Carbamazepine concentration in the raw HWW, the EO effluent and the biofilter effluent; b) removal efficiency of carbamazepine in EO process, biofiltration process and global removal efficiency.

It is worth noting that the removal of CBZ in terms of concentration (976 ± 203 µg/l) achieved in this period is higher than the concentration in most of the reports for HWW, MWW, which are between 0.1 and 5.68 µg/l and even is similar to the concentration in some PHWW (Table 1).

Although the improvement of the global CBZ removal was almost 40 %, by including an EO process as a pretreatment, the efficiency in the biofilter decreased because it depends on the phenomenon of adsorption-desorption of the CBZ which was dynamic in the biofilter after the filtrating media was saturated, and final removal efficiency was driven mainly by the HLR and the influent's CBZ concentration, which caused negative efficiencies.

The adsorption capacity of the packing media is the result of a few adsorption mechanisms that can occur simultaneously between packing material and carbamazepine, including pi-pi bonds, hydrophobic interactions, and hydrogen bonds (Aghababaei, Azargohar, Dalai, Soltan, & Niu, 2021). It seems that once the packing media surface had formed a single layer by hydrogen bons, multiple layers may be formed due to stacking of CBZ molecules by pi-pi interaction as proposed by Bizi (2019). Pi-Pi interactions are relatively weak bonds (Muguruma, 2018) that can be easily broken because of cross forces such as changes in hydraulic loads, and changes in concentration and pH. Furthermore, the multilayer behavior is also well supported by the Freunlich model and the SIPS model (a combination of the Freunlich and Langmuir models). To which the adsorption of CBZ in the biofilter was adjusted. This is a behavior that is observable in several adsorbents for CBZ (Décima *et al*., 2021).

Tecnología y ciencias del agua, ISSN 2007-2422, 15(2), 98-163. DOI: 10.24850/j-tyca-15-02-03

Therefore, under the conditions that occur in full scale treatment systems, where the composition or concentration of CBZ is variable, as well as the pH and even the flow rate and therefore the hydraulic load, they can generate the conditions so that the multilayers of CBZ are easily desorbed.

The results observed in this work about the desorption of CBZ are more in concordance with those of authors as Ouarda *et al*. (2018) and Dalahmeh *et al*. (2018) who reported a desorption phenomenon during the treatment in a biological process of an effluent pretreated by EO, than with those reported by Rodríguez-Nava *et al*. (2016), who reported partial removal efficeiency (50 %) of pharmaceuticals (others than carbamazepine) by EO as pre-treatment and 100 % removal by treating the EO effluent by a biological process of activated sludge.

According to these results, it would be important to evaluate a hybrid system where the EO is a post-treatment stage of a biological treatment, to avoid desorption problems. In this sense, Ouarda *et al*. (2018) found that when using an MBR, the removal of CBZ and venlafaxine is very limited (< 10 %), but by submitting the biologically pretreated effluent to EO, it was possible to remove 100 % of EPs in 40 min and with 0.5 A (Nb/BDD).

Macro-pollutants removal using the hybrid process (electro-oxidation followed by biofiltration)

Regarding macro-pollutants (COD and NH_4^+-N), the combined system (EO + Biofilter) showed the following results: EO process did not significantly

remove COD and NH_4^+-N. The removal efficiencies between days 67 and 128 of operation were 2.5 and 16.9 %, respectively (Figure 8). Poor COD removal efficiency was expected, and that can be attributed to refractory organics present in HWW that are partly transformed into less complex and more biodegradable organic molecules which are still being measured as COD. During partial removal of COD in the electrochemical process, effluent biodegradability is often enhanced allowing a subsequent biological step to performed better. For instance, Wang, Hou, Zhang, Qi and Wang (2015) found 48 % of COD removal efficiency in 45 min of electrolysis, applying 75 mA/cm^2, but BOD_5 had a negative removal of 64 %, which enhanced the BOD_5/COD value from 0.05 to 0.27. Unfortunately, in this research BOD_5 was not measured so it was not possible to verify that it increased after EO. However, it was expected that CBZ and other recalcitrant molecules were transformed. Commonly, to mineralize COD with EO as the only treatment process, longer electrolysis time and higher current intensity are required. For example, Ghimire *et al*. (2019) removed 97.6 % COD from domestic wastewater with a seven-hour experiment at 5 V (Pt anode) and reached 10 % COD removal with 0.6 V. Martínez-Huitle, Dos-Santos, De-Araújo and Panizza (2012) found 100 % COD removal in 15 h for dyestuff effluent using a BDD anode, pH 10, 0.25 M $HClO_4$ and 40 mA/cm^2. However, less effective results have been obtained, for example, Can (2014) reached 64.7 % COD removal in 6 h from fruit-industry wastewater with an initial COD of 20 713 mg/l.

Tecnología y ciencias del agua, ISSN 2007-2422, 15(2), 98-163. DOI: 10.24850/j-tyca-15-02-03

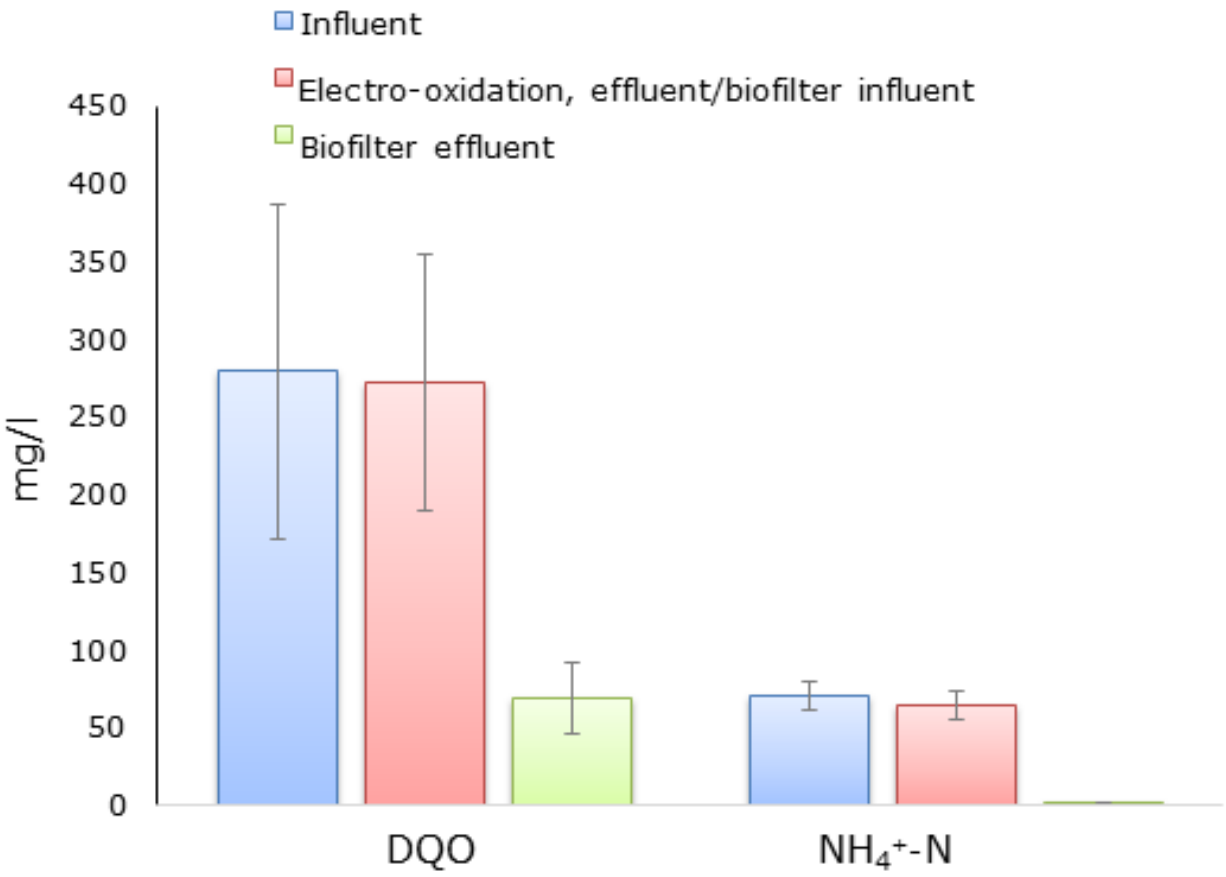

Figure 8. Organic matter and ammoniacal nitrogen removal in the global system (EO + biofilter).

However, the transformation of recalcitrant substances and a partial COD and NH_4^+-N removal in an EO process is beneficial prior to a biological process, so that the latter can continue the biodegradation of organic matter and nutrients and thus avoid unnecessary waste of chemicals and energy (Mantzavinos & Psillakis, 2004; Oller *et al*., 2011). In this study, after EO, the biofiltration process, removed an average of 73.4 % of COD and 98.8 % for NH_4^+-N, which gives a global removal

efficiency (EO + biofilter) of macro-pollutants from day 67 to 128 of operation of 72 ± 13 % removal of COD and 98.90 ± 0.7 % of NH_4^+-N. These results demonstrate the benefit of applying a hybrid system for the removal of emerging pollutants and macro-pollutants, instead of a single biological or advanced oxidation process.

Conclusions

A carbamazepine concentration of 10 000 µg/l did not affect the performance of a biofilter, packed whit mesquite wood chips and volcanic rock on the removal of macro-pollutants treating hospital wastewater (HWW), due to acclimatization of microorganisms and to the characteristics of the filtering bed that protects the microbial community.

The mixed filter bed used in this study (70 % pouzzolane-tezontle, 30 % mesquite wood chips, V:V) showed an adsorption capacity for carbamazepine of 19.84 µg/g.

The biofilter packed with mesquite and volcanic rock and fed with real HWW (spiked with 10 000 µg CBZ/l) presented a removal efficiency of carbamazepine related to biotransformation of 17.2 ± 7.4 %, equivalent to 1 551 ± 664 µg/l of concentration. This is bigger than the concentration in most of the reports for HWW, MWW and pharmaceutical WW effluents, which are between 0.1 and 890 µg/l.

The hybrid treatment using electro-oxidation followed by biofiltration fed with real HWW (spiked with 1 000 µg CBZ/l), enhanced the removal of carbamazepine, reaching up to 53 ± 5 %, and it also enhanced the removal of organic matter and ammoniacal nitrogen

reaching 72 ± 13 % and 99 %, respectively. However, the process of biofiltration presented a desorption phenomenon influenced by changes in concentration and the filtration velocity, leading to negative removal efficiencies in the biological process.

It is recommended to evaluate a hybrid system applying electro-oxidation as a post-treatment after biofiltration to improve CBZ removal by avoiding the desorption process, caused by changes on the initial concentration of the CBZ used to feed the biofiltration unit, and/or due to changes in the HLR.

A very important consideration is the fact that several metabolites will be generated during the breakdown of CBZ. Since by-products can be difficult to measure and monitor, toxicity tests or COT analysis can assist in ensuring that the treatment delivers a safe effluent for organisms at varying levels of trophic complexity. Efforts should be made in this direction not only with CBZ but with any emerging pollutant.

Conflict of interests

The authors declare that they have no conflict of interests.

Acknowledgements

This study was sponsored by Instituto Politécnico Nacional (SIP 20171847; SIP 20170184; SIP 20180337) Also, Javier Navarro-Franco was supported with a scholarship from National Council of Science and Technology (Conacyt). We also appreciate the support of Instituto de Investigaciones Científicas and Facultad de Ciencias Químicas of Universidad Juárez, Durango state, Mexico.

References

Aghababaei, A., Azargohar, R., Dalai, A. K., Soltan, J., & Niu, C. H. (2021). Effective adsorption of carbamazepine from water by adsorbents developed from flax shives and oat hulls: Key factors and characterization. *Industrial Crops and Products*, 170. DOI: 10.1016/j.indcrop.2021.113721

Al-Qaim, F. F., Mussa, Z. H., Yuzir, A., Abdullah, M. P., & Othman, M. R. (2018). Full factorial experimental design for carbamazepine removal using electrochemical process: A case study of scheming the pathway degradation. *Journal of the Brazilian Chemical Society*, 29(8), 1721–1731. DOI: 10.21577/0103-5053.20180047

APHA, American Public Health Association. (1991). Standard methods for the examination of water and wastewater (11th ed.). *American Journal of Public Health and the Nations Health*, 51(6), 940. DOI: 10.2105/AJPH.51.6.940-a

Aubertheau, E., Stalder, T., Mondamert, L., Ploy, M. C., Dagot, C., & Labanowski, J. (2017). Impact of wastewater treatment plant discharge on the contamination of river biofilms by pharmaceuticals and antibiotic resistance. *Science of the Total Environment*, 579, 1387-1398. DOI: 10.1016/j.scitotenv.2016.11.136

Azuma, T., Arima, N., Tsukada, A., Hirami, S., Matsuoka, R., Moriwake, R., Ishiuchi, H., Inoyama, T., Teranishi, Y., Yamaoka, M., Mino, Y., Hayashi, T., Fujita, Y., & Masada, M. (2016). Detection of pharmaceuticals and phytochemicals together with their metabolites in hospital effluents in Japan, and their contribution to sewage treatment plant influents. *Science of the Total Environment*, 548–549, 189-197. DOI: 10.1016/j.scitotenv.2015.12.157

Barbosa-Ferreira, M., Souza, F. L., Muñoz-Morales, M., Sáez, C., Cañizares, P., Martínez-Huitle, C. A., & Rodrigo, M. A. (2020). Clopyralid degradation by AOPs enhanced with zero valent iron. *Journal of Hazardous Materials*, 392(January), 122282. DOI: 10.1016/j.jhazmat.2020.122282

Bizi, M. (2019). Activated carbon and the principal mineral constituents of a natural soil in the presence of Carbamazepine. *Water* (Switzerland), 11(11). DOI: 10.3390/w11112290

Calderón, A., Meraz, M., & Tomasini, A. (2019). Pharmaceuticals present in urban and hospital wastewaters in Mexico City. *Journal of Water Chemistry and Technology*, 41(2), 105-112. DOI: 10.3103/s1063455x19020073

Can, O. T. (2014). COD removal from fruit-juice production wastewater by electrooxidation electrocoagulation and electro-Fenton processes. *Desalination and Water Treatment*, 52(1-3), 65-73. DOI: 10.1080/19443994.2013.781545

Carraro, E., Bonetta, S., & Bonetta, S. (2017). Hospital wastewater: Existing regulations and current trends in management. In: Verlicchi, P. (ed.). *Hospital wastewaters. The handbook of environmental chemistry*. Vol. 60. Springer, Cham. DOI: 10.1007/698_2017_10

Carrillo-Parra, A., Hapla, F., Mai, C., & Garza-Ocañas, F. (2011). Durabilidad de la madera de *Prosopis laevigata* y efecto de sus extractos en hongos que degradan la madera. *Madera y Bosques*, 17(1), 7-21. DOI: 10.21829/myb.2011.1711151

Chettiar, M., & Watkinson, A. P. (1983). Anodic oxidation of phenolics found in coal conversion effluents. *The Canadian Journal of Chemical Engineering*, 61(4), 568-574. DOI: 10.1002/cjce.5450610411

Clara, M., Strenn, B., & Kreuzinger, N. (2004). Carbamazepine as a possible anthropogenic marker in the aquatic environment: Investigations on the behaviour of Carbamazepine in wastewater treatment and during groundwater infiltration. *Water Research*, 38(4), 947-954. DOI: 10.1016/j.watres.2003.10.058

Comninellis, C., & Chen, G. (eds.). (2010). *Electrochemistry for the Environment*. New York, USA: Springer-Verlag. DOI: 10.1007/978-0-387-68318-8

Cunningham, V. L., Perino, C., D'Aco, V. J., Hartmann, A., & Bechter, R. (2010). Human health risk assessment of carbamazepine in surface waters of North America and Europe. *Regulatory Toxicology and Pharmacology*, 56(3), 343-351. DOI: 10.1016/j.yrtph.2009.10.006

Dalahmeh, S., Ahrens, L., Gros, M., Wiberg, K., & Pell, M. (2018). Potential of biochar filters for onsite sewage treatment: Adsorption and biological degradation of pharmaceuticals in laboratory filters with active, inactive and no biofilm. *Science of the Total Environment*, 612, 192-201. DOI: 10.1016/j.scitotenv.2017.08.178

De-Almeida, C. A. A., Oliveira, M. S., Mallmann, C. A., & Martins, A. F. (2015). Determination of the psychoactive drugs carbamazepine and diazepam in hospital effluent and identification of their metabolites. *Environmental Science and Pollution Research*, 22(21), 17192-17201. DOI: 10.1007/s11356-015-4948-y

Décima, M. A., Marzeddu, S., Barchiesi, M., Di Marcantonio, C., Chiavola, A., & Boni, M. R. (2021). A review on the removal of carbamazepine from aqueous solution by using activated carbon and biochar. *Sustainability* (Switzerland), 13(21). DOI: 10.3390/su132111760

Drogui, P., Blais, J., & Mercier, G. (2007). Review of electrochemical technologies for environmental applications. *Recent Patents on Engineering*, 1(3), 257-272. DOI: 10.2174/187221207782411629

Dvory, N. Z., Livshitz, Y., Kuznetsov, M., Adar, E., Gasser, G., Pankratov, I., Lev, O., & Yakirevich, A. (2018). Caffeine *vs*. carbamazepine as indicators of wastewater pollution in a karst aquifer. *Hydrology and Earth System Sciences*, 22(12), 6371-6381. DOI: 10.5194/hess-22-6371-2018

Dwivedi, K., Morone, A., Chakrabarti, T., & Pandey, R. A. (2018). Evaluation and optimization of Fenton pretreatment integrated with granulated activated carbon (GAC) filtration for carbamazepine removal from complex wastewater of pharmaceutical industry. *Journal of Environmental Chemical Engineering*, 6(3), 3681-3689. DOI: 10.1016/j.jece.2016.12.054

Dzionek, A., Wojcieszyńska, D., & Guzik, U. (2016). Natural carriers in bioremediation: A review. *Electronic Journal of Biotechnology*, 23, 28-36. DOI: 10.1016/j.ejbt.2016.07.003

Fontmorin, J. M., Siguié, J., Fourcade, F., Geneste, F., Floner, D., Soutrel, I., & Amrane, A. (2014). Combined electrochemical treatment/biological process for the removal of a commercial herbicide solution, U46D®. *Separation and Purification Technology*, 132, 704-711. DOI: 10.1016/j.seppur.2014.06.024

Freedman, D. E., Riley, S. M., Jones, Z. L., Rosenblum, J. S., Sharp, J. O., Spear, J. R., & Cath, T. Y. (2017). Biologically active filtration for fracturing flowback and produced water treatment. *Journal of Water Process Engineering*, 18, 29-40. DOI: 10.1016/j.jwpe.2017.05.008

García-Espinoza, J. D., Mijaylova-Nacheva, P., & Avilés-Flores, M. (2018). Electrochemical carbamazepine degradation: Effect of the generated active chlorine, transformation pathways and toxicity. *Chemosphere*, 192, 142-151. DOI: 10.1016/j.chemosphere.2017.10.147

García-Gómez, C., Drogui, P., Zaviska, F., Seyhi, B., Gortáres-Moroyoqui, P., Buelna, G., Neira-Sáenz, C., Estrada-Alvarado, M., & Ulloa-Mercado, R. G. (2014). Experimental design methodology applied to electrochemical oxidation of carbamazepine using Ti/PbO2 and Ti/BDD electrodes. *Journal of Electroanalytical Chemistry*, 732, 1-10. DOI: 10.1016/j.jelechem.2014.08.032

García-Sánchez, L., Gutiérrez-Macías, T., & Estrada-Arriaga, E. B. (2019). Assessment of a *Ficus benjamina* wood chip-based aerated biofilter used for the removal of metformin and ciprofloxacin during domestic wastewater treatment. *Journal of Chemical Technology and Biotechnology*, 94(6), 1870-1879. DOI: 10.1002/jctb.5962

Garcia-Segura, S., Ocon, J. D., & Chong, M. N. (2018). Electrochemical oxidation remediation of real wastewater effluents — A review. *Process Safety and Environmental Protection*, 113, 48-67. DOI: 10.1016/j.psep.2017.09.014

Garzón-Zúñiga, M. A., & Buelna, G. (2011). Treatment of wastewater from a school in a decentralized filtration system by percolation over organic packing media. *Water Science and Technology*, 64(5), 1169-1177. DOI: 10.2166/wst.2011.425

Garzón-Zúñiga, M. A., Sandoval-Villasana, A. M., & Moeller-Chávez, G. E. (2011). Decolorization of the AO24 azo dye and reduction of toxicity and genotoxicity in trickling biofilters. *Water Environment Research*, 83(2), 107-115. DOI: 10.2175/106143010x12780288627977

Garzón-Zúñiga, M., Lessard, P., Aubry, P., & Buelna, G. (2005). Nitrogen elimination mechanisms in an organic media aerated biofilter treating pig manure. *Environmental Technology*, 26(4), 361-372. DOI: 10.1080/09593332608618552

Garzón-Zúñiga, M. A., Vigueras-Cortés, J. M., Zamora-Acevedo, A. E. (2021). *Patente No. MX/a/2017/015629. Título No. 387824. Nombre: Biofiltro empacado con roca volcánica acondicionada con material orgánico para el tratamiento de aguas residuales*. Ciudad de México, México: Instituto Politécnico Nacional.

Ghimire, U., Jang, M., Jung, S. P., Park, D., Park, S. J., Yu, H., & Oh, S. E. (2019). Electrochemical removal of ammonium nitrogen and cod of domestic wastewater using platinum coated titanium as an anode electrode. *Energies*, 12(5). DOI: 10.3390/en12050883

Gurung, K., Ncibi, M. C., Shestakova, M., & Sillanpää, M. (2018). Removal of carbamazepine from MBR effluent by electrochemical oxidation (EO) using a Ti/Ta2O5-SnO2 electrode. *Applied Catalysis B: Environmental*, 221, 329-338. DOI: 10.1016/j.apcatb.2017.09.017

Hai, F. I., Li, X., Price, W. E., & Nghiem, L. D. (2011). Removal of carbamazepine and sulfamethoxazole by MBR under anoxic and aerobic conditions. *Bioresource Technology*, 102(22), 10386-10390. DOI: 10.1016/j.biortech.2011.09.019

Heye, K., Becker, D., Lütke-Eversloh, C., Durmaz, V., Ternes, T. A., Oetken, M., & Oehlmann, J. (2016). Effects of carbamazepine and two of its metabolites on the non-biting midge *Chironomus riparius* in a sediment full life cycle toxicity test. *Water Research*, 98, 19-27. DOI: 10.1016/j.watres.2016.03.071

Hmani, E., Samet, Y., & Abdelhédi, R. (2012). Electrochemical degradation of auramine-O dye at boron-doped diamond and lead dioxide electrodes. *Diamond and Related Materials*, 30, 1-8. DOI: 10.1016/j.diamond.2012.08.003

Jelic, A., Gros, M., Ginebreda, A., Cespedes-Sánchez, R., Ventura, F., Petrovic, M., & Barcelo, D. (2011). Occurrence, partition and removal of pharmaceuticals in sewage water and sludge during wastewater treatment. *Water Research*, 45(3), 1165-1176. DOI: 10.1016/j.watres.2010.11.010

Klančar, A., Trontelj, J., Kristl, A., Justin, M. Z., & Roškar, R. (2016). Levels of Pharmaceuticals in Slovene municipal and hospital wastewaters: A preliminary study. *Arhiv Za Higijenu Rada i Toksikologiju*, 67(2), 106-115. DOI: 10.1515/aiht-2016-67-2727

Komtchou, S., Dirany, A., Drogui, P., & Bermond, A. (2015). Removal of carbamazepine from spiked municipal wastewater using electro-Fenton process. *Environmental Science and Pollution Research*, 22(15), 11513-11525. DOI: 10.1007/s11356-015-4345-6

Kumari, V., & Tripathi, A. K. (2019). Characterization of pharmaceuticals industrial effluent using GC–MS and FT-IR analyses and defining its toxicity. *Applied Water Science*, 9(8), 1-8. DOI: 10.1007/s13201-019-1064-z

Lawrence, J. R., Swerhone, G. D. W., Wassenaar, L. I., & Neu, T. R. (2005). Effects of selected pharmaceuticals on riverine biofilm communities. *Canadian Journal of Microbiology*, 51(8), 655-669. DOI: 10.1139/w05-047

Lema, J. M., & Martinez, S. S. (2017). *Innovative wastewater treatment & resource recovery technologies: Impacts on energy, economy and environment*. IWA Publishing. Recovered from https://books.google.com.mx/books?id=aNYoDwAAQBAJ

Lester, Y., Mamane, H., Zucker, I., & Avisar, D. (2013). Treating wastewater from a pharmaceutical formulation facility by biological process and ozone. *Water Research*, 47(13), 4349-4356. DOI: 10.1016/j.watres.2013.04.059

Li, S. W., & Lin, A. Y. C. (2015). Increased acute toxicity to fish caused by pharmaceuticals in hospital effluents in a pharmaceutical mixture and after solar irradiation. *Chemosphere*, 139, 190-196. DOI: 10.1016/j.chemosphere.2015.06.010

Liu, Y. J., Hu, C. Y., & Lo, S. L. (2019). Direct and indirect electrochemical oxidation of amine-containing pharmaceuticals using graphite electrodes. *Journal of Hazardous Materials*, 366(August 2018), 592-605. DOI: 10.1016/j.jhazmat.2018.12.037

Malvar, J. L., Santos, J. L., Martín, J., Aparicio, I., & Alonso, E. (2020). Approach to the dynamic of carbamazepine and its main metabolites in soil contamination through the reuse of wastewater and sewage sludge. *Molecules* (Basel, Switzerland), 25(22). DOI: 10.3390/molecules25225306

Mantzavinos, D., & Psillakis, E. (2004). Enhancement of biodegradability of industrial wastewaters by chemical oxidation pre-treatment. *Journal of Chemical Technology and Biotechnology*, 79(5), 431-454. DOI: 10.1002/jctb.1020

Martín-de-Vidales, M. J., Millán, M., Sáez, C., Pérez, J. F., Rodrigo, M. A., & Cañizares, P. (2015). Conductive diamond electrochemical oxidation of caffeine-intensified biologically treated urban wastewater. *Chemosphere*, 136, 281-288. DOI: 10.1016/j.chemosphere.2015.05.077

Martínez-Huitle, C. A., Dos-Santos, E. V., De-Araújo, D. M., & Panizza, M. (2012). Applicability of diamond electrode/anode to the electrochemical treatment of a real textile effluent. *Journal of Electroanalytical Chemistry*, 674, 103-107. DOI: 10.1016/j.jelechem.2012.02.005

Mazumder, S., Falkinham, J. O., Dietrich, A. M., & Puri, I. K. (2010). Role of hydrophobicity in bacterial adherence to carbon nanostructures and biofilm formation. *Biofouling*, 26(3), 333-339. DOI: 10.1080/08927010903531491

McBean, E., Salsali, H., Bhatti, M., & Huang-Jeanne, J. (2018). Beta-blockers and antidepressants: Contributions to municipal wastewaters from hospitals and residential areas. *Journal of Environmental Science and Public Health*, 2(3), 144-159. DOI: 10.26502/jesph.96120034

Miao, X. S., & Metcalfe, C. D. (2003). Determination of carbamazepine and its metabolites in aqueous samples using liquid chromatography - Electrospray tandem mass spectrometry. *Analytical Chemistry*, 75(15), 3731-3738. DOI: 10.1021/ac030082k

Mir-Tutusaus, J. A., Jaén-Gil, A., Barceló, D., Buttiglieri, G., Gonzalez-Olmos, R., Rodriguez-Mozaz, S., Caminal, G., & Sarrà, M. (2021). Prospects on coupling UV/H2O2 with activated sludge or a fungal treatment for the removal of pharmaceutically active compounds in real hospital wastewater. *Science of the Total Environment*, 773, 145374. DOI: 10.1016/j.scitotenv.2021.145374

Muguruma, H. (2018). Biosensors: Enzyme immobilization chemistry. In: *Encyclopedia of interfacial chemistry: Surface science and electrochemistry*. Ámsterdam, The Netherlands: Elsevier. DOI: 10.1016/B978-0-12-409547-2.13486-9

Oller, I., Malato, S., & Sánchez-Pérez, J. A. (2011). Combination of advanced oxidation processes and biological treatments for wastewater decontamination. A review. *Science of the Total Environment*, 409(20), 4141-4166. DOI: 10.1016/j.scitotenv.2010.08.061

Ouarda, Y., Tiwari, B., Azaïs, A., Vaudreuil, M. A., Ndiaye, S. D., Drogui, P., Tyagi, R. D., Sauvé, S., Desrosiers, M., Buelna, G., & Dubé, R. (2018). Synthetic hospital wastewater treatment by coupling submerged membrane bioreactor and electrochemical advanced oxidation process: Kinetic study and toxicity assessment. *Chemosphere*, 193, 160-169. DOI: 10.1016/j.chemosphere.2017.11.010

Palo, P., Domínguez, J. R., González, T., Sánchez-Martin, J., & Cuerda-Correa, E. M. (2014). Feasibility of electrochemical degradation of pharmaceutical pollutants in different aqueous matrices: Optimization through design of experiments. Journal of Environmental Science and Health - Part A Toxic/Hazardous Substances and Environmental Engineering, 49(7), 843-850. DOI: 10.1080/10934529.2014.882652

Punyapalakul, P., & Sitthisorn, T. (2010). Removal of ciprofloxazin and carbamazepine by adsorption on functionalized mesoporous silicates. *World Academy of Science, Engineering and Technology*, 69, 546-550.

Rodríguez-Nava, O., Ramírez-Saad, H., Loera, O., & González, I. (2016). Evaluation of the simultaneous removal of recalcitrant drugs (bezafibrate, gemfibrozil, indomethacin and sulfamethoxazole) and biodegradable organic matter from synthetic wastewater by electro-oxidation coupled with a biological system. *Environmental Technology* (United Kingdom), 37(23), 2964-2974. DOI: 10.1080/09593330.2016.1172669

Romero-Soto, I. C., Dia, O., Leyva-Soto, L. A., Drogui, P., Buelna, G., Díaz-Tenorio, L. M., Ulloa-Mercado, R. G., & Gortáres-Moroyoqui, P. (2018). Degradation of Chloramphenicol in synthetic and aquaculture wastewater using electrooxidation. *Journal of Environmental Quality*, 47(4), 805-811. DOI: 10.2134/jeq2017.12.0475

Servos, M. R., Bennie, D. T., Burnison, B. K., Jurkovic, A., McInnis, R., Neheli, T., Schnell, A., Seto, P., Smyth, S. A., & Ternes, T. A. (2005). Distribution of estrogens, 17β-estradiol and estrone, in Canadian municipal wastewater treatment plants. *Science of the Total Environment*, 336(1-3), 155-170. DOI: 10.1016/j.scitotenv.2004.05.025

Shama, S., & Iffat, N. (2016). *Role of the biofilms in wastewater treatment. Microbial biofilms. Importance and applications*. DOI: 10.5772/63499

Silva, C. P., Jaria, G., Otero, M., Esteves, V. I., & Calisto, V. (2019). Adsorption of pharmaceuticals from biologically treated municipal wastewater using paper mill sludge-based activated carbon. *Environmental Science and Pollution Research*, 26(13), 13173-13184. DOI: 10.1007/s11356-019-04823-w

Sosa-Hernández, D. B., Vigueras-Cortés, J. M., & Garzón-Zúñiga, M. A. (2016). Mesquite wood chips (Prosopis) as filter media in a biofilter system for municipal wastewater treatment. *Water Science and Technology*, 73(6), 1454-1462. DOI: 10.2166/wst.2015.595

Sreejon, D., Nillohit-Mitra, R., Jing, W., Adnan, K., Tulip, C., & Madhumita, B. R. (2017). Micropollutants in wastewater: Fate and removal processes, physico-chemical wastewater treatment and resource recovery. In: *Physico-chemical wastewater treatment and resource recovery*. Vol. I (Issue tourism, p. 13). DOI: 10.5772/65644

Metcalf & Eddy, Inc., Tchobanoglous, G., Burton, F. L., & Stensel, H. D. (2023). Wastewater Engineering: Treatment and Reuse (4a ed.). New York, USA: McGraw-Hill Education.

Tejeda, A., Barrera, A., & Zurita, F. (2017a). Adsorption capacity of a volcanic rock -used in constructed wetlands- for carbamazepine removal, and its modification with biofilm growth. *Water* (Switzerland), 9(9). DOI: 10.3390/w9090721

Tejeda, A., Torres-Bojorges, Á. X., & Zurita, F. (2017b). Carbamazepine removal in three pilot-scale hybrid wetlands planted with ornamental species. *Ecological Engineering*, 98, 410-417. DOI: 10.1016/j.ecoleng.2016.04.012

Thirugnanasambandham, K., & Ganesamoorthy, R. (2019). Dual treatment of milk processing industry wastewater using electro fenton process followed by anaerobic treatment. *International Journal of Chemical Reactor Engineering*, 17(12), 1-10. DOI: 10.1515/ijcre-2019-0074

Tian, Y., Xia, X., Wang, J., Zhu, L., Wang, J., Zhang, F., & Ahmad, Z. (2019). Chronic toxicological effects of carbamazepine on daphnia magna straus: Effects on reproduction traits, body length, and intrinsic growth. *Bulletin of Environmental Contamination and Toxicology*, 103(5), 723-728. DOI: 10.1007/s00128-019-02715-w

Torres, F. G., Dioses-Salinas, D. C., Pizarro-Ortega, C. I., & De-la-Torre, G. E. (2021). Sorption of chemical contaminants on degradable and non-degradable microplastics: Recent progress and research trends. *Science of the Total Environment*, 757, 143875. DOI: 10.1016/j.scitotenv.2020.143875

Tran, N. H., Urase, T., & Kusakabe, O. (2009). The characteristics of enriched nitrifier culture in the degradation of selected pharmaceutically active compounds. *Journal of Hazardous Materials*, 171(1-3), 1051-1057. DOI: 10.1016/j.jhazmat.2009.06.114

Trellu, C., Ganzenko, O., Papirio, S., Pechaud, Y., Oturan, N., Huguenot, D., van Hullebusch, E. D., Esposito, G., & Oturan, M. A. (2016). Combination of anodic oxidation and biological treatment for the removal of phenanthrene and tween 80 from soil washing solution. *Chemical Engineering Journal*, 306, 588-596. DOI: 10.1016/j.cej.2016.07.108

Tuson, H. H., & Weibel, D. B. (2013). Bacteria-surface interactions. *Soft Matter*, 9(18), 4368-4380. DOI: 10.1039/C3SM27705D.Bacteria-surface

Vader, J. S., Van Ginkel, C. G., Sperling, F. M. G. M., De-Jong, J., De-Boer, W., De-Graaf, J. S., Van Der Most, M., & Stokman, P. G. W. (2000). Degradation of ethinyl estradiol by nitrifying activated sludge. *Chemosphere*, 41(8), 1239-1243. DOI: 10.1016/S0045-6535(99)00556-1

Valdés, M. E., Huerta, B., Wunderlin, D. A., Bistoni, M. A., Barceló, D., & Rodriguez-Mozaz, S. (2016). Bioaccumulation and bioconcentration of carbamazepine and other pharmaceuticals in fish under field and controlled laboratory experiments. Evidences of carbamazepine metabolization by fish. *Science of the Total Environment*, 557-558, 58-67. DOI: 10.1016/j.scitotenv.2016.03.045

Vanderford, B. J., & Snyder, S. A. (2006). Analysis of pharmaceuticals in water by isotope dilution liquid chromatography/tandem mass spectrometry. *Environmental Science and Technology*, 40(23), 7312-7320. DOI: 10.1021/es0613198

Verlicchi, P., Al Aukidy, M., & Zambello, E. (2015). What have we learned from worldwide experiences on the management and treatment of hospital effluent? - An overview and a discussion on perspectives. *Science of the Total Environment*, 514, 467-491. DOI: 10.1016/j.scitotenv.2015.02.020

Verlicchi, P., Galletti, A., Petrovic, M., & Barceló, D. (2010). Hospital effluents as a source of emerging pollutants: An overview of micropollutants and sustainable treatment options. *Journal of Hydrology*, 389(3-4), 416-428. DOI: 10.1016/j.jhydrol.2010.06.005

Wang, C. R., Hou, Z. F., Zhang, M. R., Qi, J., & Wang, J. (2015). Electrochemical oxidation using BDD anodes combined with biological aerated filter for biotreated coking wastewater treatment. *Journal of Chemistry*, 2015. DOI: 10.1155/2015/201350

Wang, S., & Wang, J. (2018). Degradation of emerging contaminants by acclimated activated sludge. *Environmental Technology* (United Kingdom), 39(15), 1985-1993. DOI: 10.1080/09593330.2017.1345989

Wunder, D. B., Bosscher, V. A., Cok, R. C., & Hozalski, R. M. (2011). Sorption of antibiotics to biofilm. *Water Research*, 45(6), 2270-2280. DOI: 10.1016/j.watres.2010.11.013

Zamora-Acevedo, Á. E. (2016). *Evaluación de la eficiencia de un sistema de biofiltración con cama mixta de material orgánico e inorgánico para el tratamiento de aguas* (thesis Master's degree). Instituto Politécnico Nacional, Ciudad de México.

Zhang, X., Song, Z., Hao-Ngo, H., Guo, W., Zhang, Z., Liu, Y., Zhang, D., & Long, Z. (2020). Impacts of typical pharmaceuticals and personal care products on the performance and microbial community of a sponge-based moving bed biofilm reactor. *Bioresource Technology*, 295(October 2019), 122298. DOI: 10.1016/j.biortech.2019.122298

Zhang, Y., Geißen, S. U., & Gal, C. (2008). Carbamazepine and diclofenac: Removal in wastewater treatment plants and occurrence in water bodies. *Chemosphere*, 73(8), 1151-1161. DOI: 10.1016/j.chemosphere.2008.07.086

Zhang, Y., Zhu, H., Szewzyk, U., Lübbecke, S., & Uwe Geissen, S. (2017). Removal of emerging organic contaminants with a pilot-scale biofilter packed with natural manganese oxides. *Chemical Engineering Journal*, 317, 454-460. DOI: 10.1016/j.cej.2017.02.095

Zhu, X., Ni, J., Wei, J., Xing, X., Li, H., & Jiang, Y. (2010). Scale-up of BDD anode system for electrochemical oxidation of phenol simulated wastewater in continuous mode. *Journal of Hazardous Materials*, 184(1-3), 493-498. DOI: 10.1016/j.jhazmat.2010.08.062