SUPPLEMENTARY MATERIAL

Integration of a 3D-printed electrochemical reactor with a tubular membrane photoreactor to promote sulfate-base advanced oxidation processes

Agustina R. de Olivera [a,b,c,1], Carla S. Santos [a,b,1], Ismael F. Mena [c], Miguel A. Montiel [c], Rosa Montes [d], José B. Quintana [d], Rosario Rodil [d], Ana I. Gomes [a,b], Francisca C. Moreira [a,b], Jan Gäbler [e], Lothar Schäfer [e], C. Sáez [c], Manuel A. Rodrigo [c,*], Vítor J.P. Vilar [a,b,*]

[a] *LSRE-LCM – Laboratory of Separation and Reaction Engineering - Laboratory of Catalysis and Materials, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal*

[b] *ALiCE – Associate Laboratory in Chemical Engineering, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal*

[c] *Department of Chemical Engineering. Faculty of Chemical Sciences & Technologies. University of Castilla-La Mancha, Campus Universitario s/n, 13071 Ciudad Real, Spain*

[d] *Aquatic One Health Research Center (iARCUS) & Department of Analytical Chemistry, Nutrition and Food Chemistry. R. Constantino Candeira S/N, IIAA building, Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Spain*

[e] *Fraunhofer Institute for Surface Engineering and Thin Films IST, 38108 Braunschweig, Germany*

[1]The first two authors contributed equally to this work.

*Corresponding authors:

Tel.: +34 639621112; E-mail: Manuel.Rodrigo@uclm.es (Manuel A. Rodrigo)

Tel.: +351 918257824; E-mail: vilar@fe.up.pt (Vítor J.P. Vilar)

Table SM-1 Experimental data (SERPIC-UCLM® cell) *vs.* literature data of distinct electrochemical systems regarding mass transport correlation $k_m A = q\ v_{avg}^b$.

Electrochemical system	v_{avg} (× 10^{-2} m s^{-1})	$k_m A = q\ v_{avg}^b$	References
Customized reactors	0.5 – 10	$k_m A = 1.26\ v_{avg}^{0.48}$	[1][a]
	0.5 – 10	$k_m A = 0.61\ v_{avg}^{0.45}$	[1][b]
	0.5 – 10	$k_m A = 0.43\ v_{avg}^{0.47}$	[1][c]
	1 – 17 [d]	$k_m A = 0.000309\ v_{avg}^{0.386}$	[2][e]
	1 – 17 [d]	$k_m A = 0.00067\ v_{avg}^{0.526}$	[2][f]
	1 – 9[d]	$k_m A = 0.00224\ v_{avg}^{0.492}$	[2][g]
	1 – 16	$k_m A = 0.00236\ v_{avg}^{0.58}$	[3][h]
	1 – 16	$k_m A = 0.0828\ v_{avg}^{0.82}$	[3][i]
	1 – 16	$k_m A = 0.119\ v_{avg}^{0.53}$	[3][j]
MicroFlow Cell	1.3 – 23	$k_m A = (2.29 \pm 0.07) \times 10^{-2}\ v_{avg}^{(0.58 \pm 0.02)}$	[4]
e^- NETmix	10 – 180	$k_m A = (3.99 \pm 0.04) \times 10^{-1}\ v_{avg}^{(0.43 \pm 0.02)}$	[4]
SERPIC-UCLM® cell	1.1 – 7.8	$k_m A = (0.0422 \pm 0.0005)\ v_{avg}^{0.500 \pm 0.003)}$	This work

[a] with Ni foam electrode G100;
[b] with Ni foam electrode G60;
[c] with Ni foam electrode G45;
[d] Data taken from the plot;
[e] With Pt/Ti plate 2D electrode;
[f] With Pt/Ti plate electrode with TP;
[g] With Pt/Ti mesh electrode;
[h] With porous Pt-Ir/Ti plate electrode with TP;
[i] With porous 3D Pt-Ir/Ti fine mesh electrode;
[j] With porous 3D Pt-Ir/Ti felt electrode.

Table SM-2 Experimental data (SERPIC-UCLM® cell) *vs.* literature data of distinct electrochemical systems regarding mass transport correlation $Sh = a\, Re^b\, Sc^c\, Le^d$.

Electrochemical system	*Re*	$Sh = a\ Re^b\ Sc^c\ Le^d$	References
Customized reactors	148 – 6109	$Sh = 0.28\ Re^{0.70}\ Sc^{0.33}$	[5][a]
	< 2380	$Sh = 28.4\ Re^{0.23}\ Sc^{0.33}\ Le^{0.33}$	[6][b]
	93 – 371	$Sh = 1.88\ Re^{0.61}\ Sc^{1/3}$	[7][c]
	93 – 371	$Sh = 1.11\ Re^{0.78}\ Sc^{1/3}$	[7][d]
	93 – 371	$Sh = 1.74\ Re^{0.68}\ Sc^{1/3}$	[7][e]
FM01-LC reactor	200 – 1000	$Sh = 0.74\ Re^{0.62}\ Sc^{1/3}$	[8][f]
	187 – 1407	$Sh = 0.617\ Re^{0.489}\ Sc^{0.33}$	[9][g]
	500 – 2200	$Sh = 0.18\ Re^{0.73}\ Sc^{1/3}$	[10][h]
DiaCell® reactor	100 – 2500	$Sh = 0.141\ Re^{0.70}\ Sc^{0.33}$	[11][i]
MicroFlow Cell	100 – 1750	$Sh = (0.45 \pm 0.03)\ Re^{(0.543 \pm 0.008)}\ Sc^{1/3}$	[4]
e^- NETmix	100 – 1750	$Sh = (1.3 \pm 0.1)\ Re^{(0.43 \pm 0.02)}\ Sc^{1/3}$	[4]
SERPIC – UCLM® cell	110 – 790	$Sh = (2.593 \pm 0.060)\ Re^{(0.500 \pm 0.004)}\ Sc^{1/3}$	This work

[a] Parallel plate reactor with Pt/Ti cathode, Ni anode, and without TP;
[b] Rectangular flow cell with nanostructured Ni electrodeposited on a SS plate and without TP;
[c] 3D-printed Filter-Press electrochemical reactor with Ni electrodes and a diamond-shaped 3D-printed TP;
[d] 3D-printed Filter-Press electrochemical reactor with Ni foam electrodes;
[e] 3D-printed Filter-Press electrochemical reactor with square-shaped 3D-printed TP;
[f] With Ni electrodes and TP;
[g] With 316 SS plate electrodes;
[h] With Ni electrodes and without TP;
[i] With BDD as anode and SS as cathode.

Table SM-3. Identification and characteristics of the target CECs and respective limits of quantification in RO_C and NF_C.

Category	Pollutant	Acronym	Chemical composition	Molecular weight (g mol^{-1})	LQ_{ROc}[a] (µg L^{-1})	LQ_{NFc}[a] (µg L^{-1})
Angiotensin II Receptor Blockers	Valsartan	VSTN	$C_{24}H_{29}N_5O_3$	435.52	0.17	0.17
	Irbesartan	ISTN	$C_{25}H_{28}N_6O$	428.53	0.14	0.30
	Losartan	LSTN	$C_{22}H_{23}ClN_6O$	422.91	0.37	1.00
Beta-blocking agents	Atenolol	ATNL	$C_{14}H_{22}N_2O_3$	266.34	0.12	0.18
	Bisoprolol	BSPL	$C_{18}H_{31}NO_4$	325.44	0.05	0.22
Carbamazepine and Metabolites	Carbamazepine	CBZ	$C_{15}H_{12}N_2O$	236.27	0.06	0.05
	10,11 Carbamazepine-epoxide	CBZ-EPX	$C_{15}H_{12}N_2O_2$	252.27	0.12	0.10
Fire Retardants	Melamine	MLN	$C_3H_6N_6$	126.12	1.15	1.00
Herbicides	Diuron	DRN	$C_9H_{10}Cl_2N_2O$	233.1	0.06	0.08
Insect Repellents	N.N-diethyl-meta-toluamide	DEET	$C_{12}H_{17}NO$	191.27	0.04	0.05
Anti-Inflammatory Drugs	Diclofenac	DCF	$C_{14}H_{11}Cl_2NO_2$	318.13	0.51	0.40
Non-ionic X-ray contrast agent	Iopromide	IOP	$C_{18}H_{24}I_3N_3O_8$	791.11	1.06	1.00
Antibiotic	Sulfamethoxazole	SMX	$C_{10}H_{11}N_3O_3S$	253.28	0.08	0.10
Antidepressant	Venlafaxine	VLX	$C_{17}H_{27}NO_2$	277.40	0.07	0.20

[a] Limit of quantification for reverse osmosis concentrate (LQ_{ROc}) and for nanofiltration concentrate (LQ_{NFc}) determined according to the methodology described in Rodrigues-Silva et al. [12].

Table SM-4. Physicochemical characteristics and native concentrations of target CECs in the feed water for RO and NF membrane system.

Parameters	Units	Influent	
		RO	NF
pH	-	7.2	7.3
Conductivity	µS cm^{-1}	1387	1079
Chemical Oxygen Demand (COD)	mg L^{-1}	120	70
Dissolved Organic Carbon (DOC)	mg L^{-1}	16.2	13.1
Dissolved Inorganic Carbon (DIC)	mg L^{-1}	61.5	50.0
Total Suspended Solids (TSS)	mg L^{-1}	64.5	31.5
Chloride (Cl^-)	mg L^{-1}	132	159
Nitrate (NO_3^-)	mg L^{-1}	5.1	5.8
Nitrite (NO_2^-)	mg L^{-1}	13.8	8.1
Sulfate (SO_4^{2-})	mg L^{-1}	58	57
Phosphate (PO_4^{3-})	mg L^{-1}	14.4	10.6
Ammonium (NH_4^+)	mg L^{-1}	43.6	27.4
Potassium (K^+)	mg L^{-1}	24.1	25.4
Sodium (Na^+)	mg L^{-1}	109	124
Calcium (Ca^{2+})	mg L^{-1}	32.7	28.5
Magnesium (Mg^{2+})	mg L^{-1}	7.0	5.2
Atenolol (ATNL)	µg L^{-1}	<0.12	<0.18
Bisoprolol (BSPL)	µg L^{-1}	0.3	0.6
Carbamazepine (CBZ)	µg L^{-1}	0.5	0.9
CBZ 10,11-epoxide (CBZ-EPX)	µg L^{-1}	<0.12	0.5
DEET (DEET)	µg L^{-1}	0.6	<0.05
Diclofenac (DCF)	µg L^{-1}	0.7	1.8
Diuron (DRN)	µg L^{-1}	<0.06	0.2
Iopromide (IOP)	µg L^{-1}	4.6	3.8
Irbesartan (ISTN)	µg L^{-1}	1.0	2.0
Losartan (LSTN)	µg L^{-1}	0.4	<1.0
Melamine (MLN)	µg L^{-1}	1.8	3.0
Sulfamethoxazole (SMX)	µg L^{-1}	0.4	0.3
Valsartan (VSTN)	µg L^{-1}	1.1	<0.17
Venlafaxine (VLX)	µg L^{-1}	0.3	0.8

Table SM-5. Molar extinction coefficient, quantum yield and rate constants for reaction with $HO^{•}$ and $SO_4^{•-}$ of each target CECs.

CECs	**ε_{254}[a] (M^{-1} cm^{-1})**	**Φ_{254}[a] (mol Ein^{-1})**	**$k_{SO_4^{•-}}$[b] (M^{-1} s^{-1})**	**$k_{HO^{•}}$[c] (M^{-1} s^{-1})**
VSTN	2.1×10^{3}	Unknown	Unknown	1.0×10^{10}
ISTN	1.5×10^{4}	Unknown	1.2×10^{8}	1.9×10^{8}
LSTN	1.2×10^{4}	1.5×10^{-2}	Unknown	Unknown
ATNL	3.5×10^{2}	6.5×10^{-2}	1.3×10^{10}	7.1×10^{10}
BSPL	Unknown	Unknown	Unknown	Unknown
CBZ	5.8×10^{3}	3.3×10^{-3}	1.92×10^{9}	8.8×10^{9}
CBZ-EPX	Unknown	Unknown	Unknown	Unknown
MLN	Unknown	Unknown	1.0×10^{5}	1.0×10^{4}
DRN	1.6×10^{4}	1.4×10^{-2}	5.2×10^{9}	5.0×10^{9}
DEET	0.9×10^{3}	1.0×10^{-2}	$(1.9 – 0.1) \times 10^{9}$	5.0×10^{9}
DCF	6.8×10^{3}	2.3×10^{-1}	6.7×10^{9}	7.5×10^{9}
IOP	2.2×10^{4}	3.9×10^{-2}	$(1–2) \times 10^{4}$	3.3×10^{9}
SMX	1.3×10^{4}	8.4×10^{-2}	8.8×10^{9}	5.5×10^{9}
VLX	3.8×10^{2}	9.7×10^{-2}	3.5×10^{9}	8.6×10^{9}

[a] Values for molar extinction coefficient (ε_{254nm}) and quantum yield (Φ_{254nm}) were obtained from Allard et al. [13]; Mallegowda et al. [14]; Parry & Young. [15]; Rahmadhani et al. [16]; Wols et al. [17]; Wols & Hofman-Caris. [18]; Starling et al. [19].

[b] Kinetic constants for the reaction with $SO_4^{•-}$ ($k_{SO_4^{•-}}$) were obtained from Canle et al. [20]; Chan et al. [21]; Lian et al. [22]; Liu et al. [23]; Mahdi Ahmed et al. [24]; Matta et al. [25]; Maurino et al. [26]; Mutke et al.[27]; Tay et al. [28].

[c] Kinetic constants for the reaction with $HO^{•}$ ($k_{HO^{•}}$) were obtained from Huber et al. [29]; Lian et al. [22]; Mandal [30]; Maurino et al. [26]; Mutke et al. [27]; Song et al., [31]; Sauter et al. [32].

Table SM-6. Statistical differences (*t*-student test) for operational parameters influencing the treatment of RO_C.

CECs	**1.2 mM PMSA *vs.* 1.2 mM PDS**
	***p*-value**
ATNL	0.0199
BSPL	0.0084
CBZ	0.0693
CBZ-EPX	0.0139
DEET	0.2397
DCF	0.1857
DRN	0.0065
IOP	0.1261
ISTN	0.0045
LSTN	0.0110
MLN	0.3735
SMX	0.0272
VSTN	0.8494
VLX	0.0071

Table SM-7. Statistical analyses (One-way ANOVA) for operational parameters influencing the treatment of NF_C.

CECs	Conditions	One-way ANOVA							
		Mean Diff	**SEM**	***q* Value**	**Prob**	**Alpha**	**Sig**	**LCL**	**UCL**
CBZ-EPX	1.2 mM PDS *vs.* 1.2 mM PMSA	4.09	3.09	1.87	0.43347	0.05	0	-5.39	13.58
	2.4 mM PMSA *vs.*1.2 mM PMSA	32.00	3.09	14.64	0.00011	0.05	1	22.51	41.48
SMX	1.2 mM PDS *vs.* 1.2 mM PMSA	12.06	1.97	8.65	0.00211	0.05	1	6.01	18.11
	2.4 mM PMSA *vs.* 1.2 mM PMSA	21.76	1.97	15.62	0.00008	0.05	1	15.72	27.82
DCF	1.2 mM PDS *vs.* 1.2 mM PMSA	1.17	1.16	1.43	0.59818	0.05	0	-2.38	4.71
	2.4 mM PMSA *vs.* 1.2 mM PMSA	6.15	1.16	7.52	0.00433	0.05	1	2.60	9.69
ISTN	1.2 mM PDS *vs.* 1.2 mM PMSA	0.53	0.04	17.30	0.00004	0.05	1	0.40	0.67
	2.4 mM PMSA *vs.* 1.2 mM PMSA	0.48	0.04	15.67	0.00008	0.05	1	0.35	0.62

Table SM-8. Statistical analyses (Non-parametric ANOVA) for operational parameters influencing the treatment of NF_C.

CECs	Conditions	Mean Rank Diff	Z	Prob	Sig
CBZ	1.2 mM PDS *vs.* 1.2 mM PMSA	3.50	1.56	0.35	0
	2.4 mM PDS *vs.* 1.2 mM PMSA	-1.00	-0.50	1.00	0
DRN	1.2 mM PDS *vs.* 1.2 mM PMSA	0.83	0.37	1.00	0
	2.4 mM PDS *vs.* 1.2 mM PMSA	-3.50	-1.56	0.35	0
LSTN	1.2 mM PDS *vs.* 1.2 mM PMSA	2.50	1.12	0.79	0
	2.4 mM PDS *vs.*1.2 mM PMSA	-2.50	-1.12	0.79	0
IOP	1.2 mM PDS *vs.* 1.2 mM PMSA	2.33	1.17	0.73	0
	2.4 mM PDS *vs.* 1.2 mM PMSA	-1.50	-0.67	1.00	0
MLN	1.2 mM PDS *vs.* 1.2 mM PMSA	0.67	0.33	1.00	0
	2.4 mM PDS *vs.* 1.2 mM PMSA	3.33	1.63	0.31	0
BSPL	1.2 mM PDS *vs.* 1.2 mM PMSA	-1.00	-0.45	1.00	0
	2.4 mM PDS *vs.* 1.2 mM PMSA	-5.00	-2.24	0.01	0
VLX	1.2 mM PDS *vs.* 1.2 mM PMSA	-1.00	-0.45	1.00	0
	2.4 mM PDS *vs.* 1.2 mM PMSA	-5.00	-2.24	0.01	0

References

[1] S. Langlois, F. Coeuret, Flow-through and flow-by porous electrodes of nickel foam. II. Diffusion-convective mass transfer between the electrolyte and the foam, J. Appl. Electrochem. 19 (1989) 51–60, https://doi.org/10.1007/BF01039389.

[2] L.F. Arenas, C.P. de León, F.C. Walsh, Mass transport and active area of porous Pt/Ti electrodes for the Zn-Ce redox flow battery determined from limiting current measurements, Electrochim. Acta. 221 (2016) 154–166, https://doi.org/10.1016/j.electacta.2016.10.097.

[3] A. Abahussain, C. Ponce de Leon, F.C. Walsh, Mass-transfer measurements at porous 3D Pt-Ir/Ti electrodes in a direct borohydride fuel cell, J. Electrochem. Soc. 165 (2018) F198–F206, https://doi.org/10.1149/2.0751803jes.

[4] D.F.S. Morais, B. Lopes, M.M. Dias, V.J.P. Vilar, F.C. Moreira, e^{-} NETmix: A pioneering electrochemical flow reactor with enhanced mass transfer, Chem. Eng. J. 481 (2024) 148244, https://doi.org/10.1016/j.cej.2023.148244.

[5] T.R. Ralph, M.L. Hitchman, J.P. Millington, F.C. Walsh, Mass transport in an electrochemical laboratory filterpress reactor and its enhancement by turbulence promoters, Electrochim. Acta. 41 (1996) 591–603.

[6] F.J. Recio, P. Herrasti, L. Vazquez, C. Ponce De León, F.C. Walsh, Mass transfer to a nanostructured nickel electrodeposit of high surface area in a rectangular flow channel, Electrochim. Acta. 90 (2013) 507–513, https://doi.org/10.1016/j.electacta.2012.11.135.

[7] R.A. Márquez-Montes, V.H. Collins-Martínez, I. Pérez-Reyes, D. Chávez-Flores, O.A. Graeve, V.H. Ramos-Sánchez, Electrochemical engineering assessment of a novel 3D-printed filter-press electrochemical reactor for multipurpose laboratory applications, ACS Sustain. Chem. Eng. 8 (2020) 3896–3905,

https://doi.org/10.1021/acssuschemeng.9b07368.

[8] C.J. Brown, D. Pletcher, F.C. Walsh, J.K. Hammond, D. Robinson, Studies of space-averaged mass transport in the FM01-LC laboratory electrolyser, J. Appl. Electrochem. 23 (1993) 38–43, https://doi.org/10.1007/BF00241573.

[9] E.P. Rivero, F.F. Rivera, M.R. Cruz-Díaz, E. Mayen, I. González, Numerical simulation of mass transport in a filter press type electrochemical reactor FM01-LC: Comparison of predicted and experimental mass transfer coefficient, Chem. Eng. Res. Des. 90 (2012) 1969–1978, https://doi.org/10.1016/j.cherd.2012.04.010.

[10] M. Griffiths, C.P. De León, F.C. Walsh, Mass transport in the rectangular channel of a filter-press electrolyzer (the FM01-LC reactor), AIChE J. 51 (2005) 682–687, https://doi.org/10.1002/aic.10311.

[11] J.L.C. Santos, V. Geraldes, S. Velizarov, J.G. Crespo, Characterization of fluid dynamics and mass-transfer in an electrochemical oxidation cell by experimental and CFD studies, Chem. Eng. J. 157 (2010) 379–392, https://doi.org/10.1016/j.cej.2009.11.021.

[12] F. Rodrigues-Silva, C.S. Santos, J.A. Marrero, R. Montes, J.B. Quintana, R. Rodil, O. C. Nunes, M.C.V.M. Starling, C.C. Amorim, A.I. Gomes, V.J.P. Vilar, Continuos UV-C/H_2O_2 and UV-C/Chlorine applied to municipal secondary effluent and nanofiltration retentate: Removal of contaminants of emerging concern, ecotoxicity, and reuse potential, Chemosphere. 361 (2024) 142355, https://doi.org/10.1016/j.chemosphere.2024.142355.

[13] S. Allard, J. Criquet, A. Prunier, C. Falantin, A. Le Person, J. Yat-Man Tang, J.-P. Croué, Photodecomposition of iodinated contrast media and subsequent formation of toxic iodinated moieties during final disinfection with chlorinated oxidants, Water Res. 103 (2016) 453–461, https://doi.org/10.1016/j.watres.2016.07.050.

[14] S.M. Mallegowda, H.N. Deepakumari, H.D. Revanasiddappa, Spectrophotometric determination of valsartan using p-chloranilic acid as π-acceptor in pure and in dosage forms, J. Appl. Pharm. Sci. 3 (2013) 113–116, https://doi.org/10.7324/JAPS.2013.30122.

[15] E. Parry, T.M. Young, Comparing targeted and non-targeted high-resolution mass spectrometric approaches for assessing advanced oxidation reactor performance, Water Res. 104 (2016) 72–81, https://doi.org/10.1016/j.watres.2016.07.056.

[16] Q. Rahmadhani, F. Armin, H. Rivai, Overview on determination of irbesartan levels in pharmaceutical preparation and biological matrices, Int. J. Pharm. Sci. Med. 6 (2021) 1–11, https://doi.org/10.47760/ijpsm.2021.v06i05.001.

[17] B.A. Wols, D.J.H. Harmsen, J. Wanders-Dijk, E.F. Beerendonk, C.H.M. Hofman-Caris, Degradation of pharmaceuticals in UV (LP)/H_2O_2 reactors simulated by means of kinetic modeling and computational fluid dynamics (CFD), Water Res. 75 (2015) 11–24, https://doi.org/10.1016/j.watres.2015.02.014.

[18] B.A. Wols, C.H.M. Hofman-Caris, Review of photochemical reaction constants of organic micropollutants required for UV advanced oxidation processes in water, Water Res. 46 (2012) 2815–2827, https://doi.org/10.1016/j.watres.2012.03.036.

[19] M.C.V.M. Starling, P.P. Souza, A. Le Person, C.C. Amorim, J. Criquet, Intensification of UV-C treatment to remove emerging contaminants by UV-C/H_2O_2 and UV-C/$S_2O_8^{2-}$: Susceptibility to photolysis and investigation of acute toxicity, Chem. Eng. J. 376 (2019) 120856, https://doi.org/10.1016/j.cej.2019.01.135.

[20] M.C. López, M.I. Fernández, S. Rodríguez, J.A. Santaballa, S. Steenken, E. Vulliet, Mechanisms of direct and TiO_2-photocatalysed UV degradation of phenylurea herbicides, ChemPhysChem. 6 (2005) 2064–2074,

https://doi.org/10.1002/cphc.200500004.

[21] T.W. Chan, N.J.D. Graham, W. Chu, Degradation of iopromide by combined UV irradiation and peroxydisulfate, J. Hazard. Mater. 181 (2010) 508–513, https://doi.org/10.1016/j.jhazmat.2010.05.043.

[22] L. Lian, B. Yao, S. Hou, J. Fang, S. Yan, W. Song, Kinetic study of hydroxyl and sulfate radical-mediated oxidation of pharmaceuticals in wastewater effluents, Environ. Sci. Technol. 51 (2017) 2954–2962, https://doi.org/10.1021/acs.est.6b05536.

[23] X. Liu, T. Zhang, Y. Zhou, L. Fang, Y. Shao, Degradation of atenolol by UV/peroxymonosulfate: Kinetics, effect of operational parameters and mechanism, Chemosphere. 93 (2013) 2717–2724, https://doi.org/10.1016/j.chemosphere.2013.08.090.

[24] M. Mahdi Ahmed, S. Barbati, P. Doumenq, S. Chiron, Sulfate radical anion oxidation of diclofenac and sulfamethoxazole for water decontamination, Chem. Eng. J. 197 (2012) 440–447, https://doi.org/10.1016/j.cej.2012.05.040.

[25] R. Matta, S. Tlili, S. Chiron, S. Barbati, Removal of carbamazepine from urban wastewater by sulfate radical oxidation, Environ. Chem. Lett. 9 (2011) 347–353, https://doi.org/10.1007/s10311-010-0285-z.

[26] V. Maurino, M. Minella, F. Sordello, C. Minero, A proof of the direct hole transfer in photocatalysis: The case of melamine, Appl. Catal. A Gen. 521 (2016) 57–67, https://doi.org/10.1016/j.apcata.2015.11.012.

[27] X.A.M. Mutke, P. Swiderski, F. Drees, O. Akin, H. V. Lutze, T.C. Schmidt, Efficiency of ozonation and sulfate radical – AOP for removal of pharmaceuticals, corrosion inhibitors, x-ray contrast media and perfluorinated compounds from reverse osmosis concentrates, Water Res. 255 (2024) 121346,

https://doi.org/10.1016/j.watres.2024.121346.

[28] K.S. Tay, N.A. Rahman, M.R. Bin Abas, Chemical oxidation of N,N-diethyl-m-toluamide by sulfate radical-based oxidation: Kinetics and mechanism of degradation, Int. J. Environ. Sci. Technol. 10 (2013) 103–112, https://doi.org/10.1007/s13762-012-0081-3.

[29] M.M. Huber, S. Canonica, G.Y. Park, U. Von Gunten, Oxidation of pharmaceuticals during ozonation and advanced oxidation processes, Environ. Sci. Technol. 37 (2003) 1016–1024, https://doi.org/10.1021/es025896h.

[30] S. Mandal, Reaction rate constants of hydroxyl radicals with micropollutants and their significance in advanced oxidation processes, J. Adv. Oxid. Technol. 21 (2018) 178–195, https://doi.org/10.26802/jaots.2017.0075.

[31] W. Song, W.J. Cooper, B.M. Peake, S.P. Mezyk, M.G. Nickelsen, K.E. O'Shea, Free-radical-induced oxidative and reductive degradation of N,N′-diethyl-m-toluamide (DEET): Kinetic studies and degradation pathway, Water Res. 43 (2009) 635–642, https://doi.org/10.1016/j.watres.2008.11.018.

[32] D. Sauter, A. Dąbrowska, R. Bloch, M. Stapf, U. Miehe, A. Sperlich, R. Gnirss, T. Wintgens, Deep-bed filters as post-treatment for ozonation in tertiary municipal wastewater treatment: Impact of design and operation on treatment goals, Environ. Sci. Water Res. Technol. 7 (2021) 197–211, https://doi.org/10.1039/d0ew00684j.