MICROcontaminants of interest

- Pharmaceuticals, personal care products

- Endocrine disrupting compounds,

- Flame retardants

- Surfactants

- Pesticides

- Industrial additives

- Microplastics

They can affect water quality and potentially affect drinking water supply, ecosystem and human health.
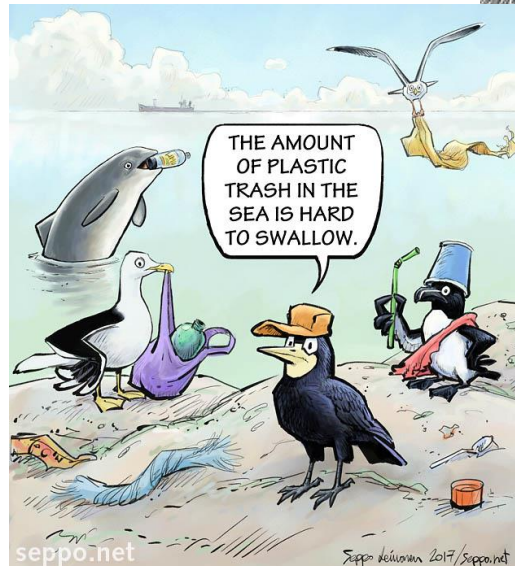Still unknown their potential long-term effects in water compartments

What about Emerging contaminants?

Removal pathways/strategies
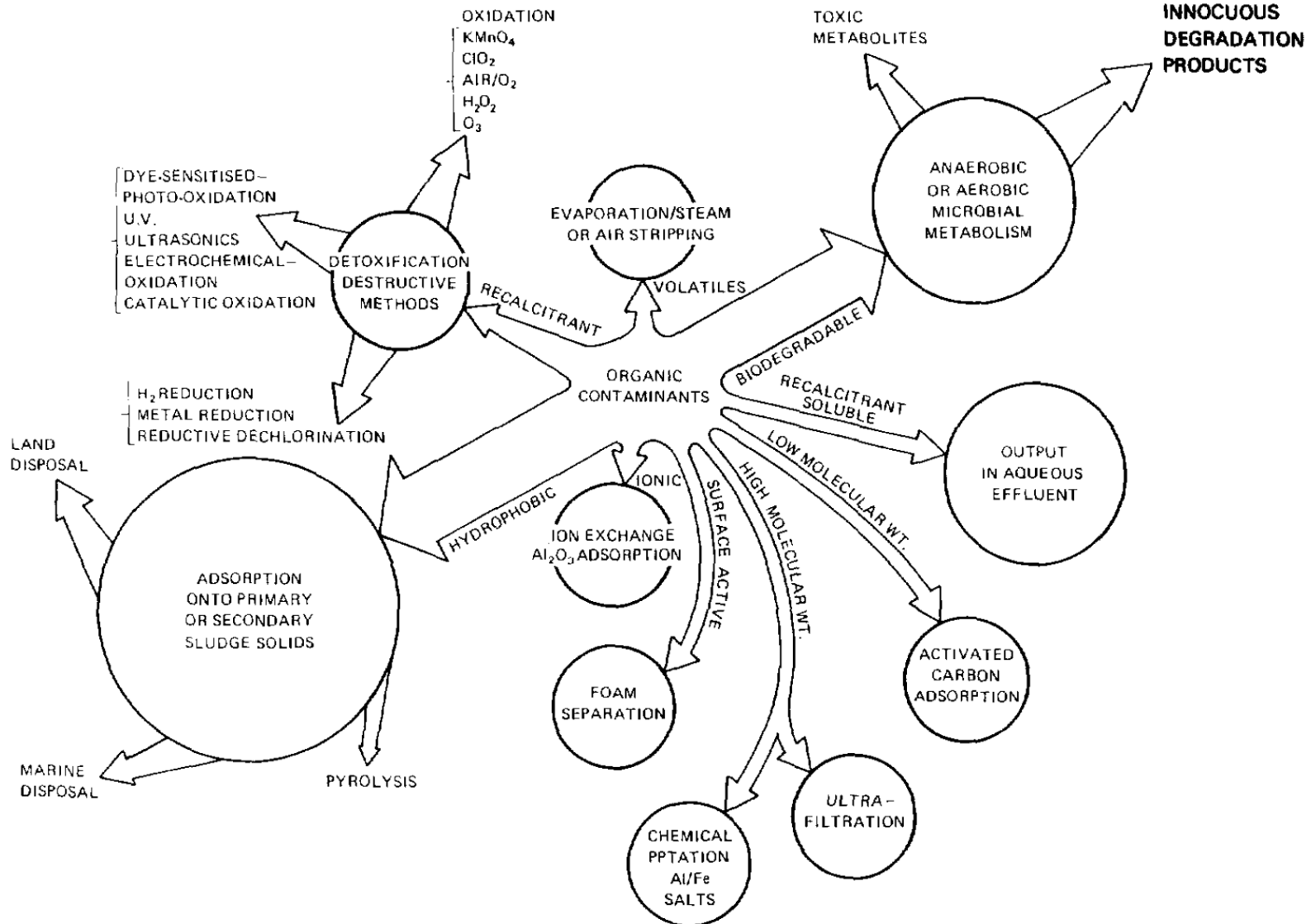
A glimpse to *Biological Processes-*
Advances and challanges

| Treatment process	Advantages	Challenges	references
Activated sludge	Lower capital and investment costs than AOPs Environmental friendly	Low removals for beta-blockers Sludge containing ECs	Verlicchi et al., *STOTEN* 2012
Microalgae reactor	Resource recovery of algal biomass (= fertilizer). High quality effluent and no acute toxicity risk associated with ECs	Removal efficiencies affected by cold seasons. EDCs cannot properly degrade	Matamoros et al., *HazMat* 2015
Constructed wetlands	Low energy demand and low O&M. High removal of estrogens, PCPs, pesticides and pathogens	Risk of clogging. Removals affected by cold seasons. High footprint	Verlicchi et al., *STOTEN* 2014
MBR	Small footprint Effective for removal of biorecalcitrant compounds	Higher O&M costs (energy consumption, membrane fouling, control system…) Removal efficiencies depends on the specific compounds	Verlicchi et al., *STOTEN* 2012; Sim et al 2010

A glimpse to *Chemical Processes-*
Advances and challanges

Treatment process	Advantages	Challenges	references
Coagulation	Reduction of the turbidity. Increased sedimentation rate through suspended solid particle formation	Low removal of Ecs. Large amount of sludge. Addition of coagulants	Verlicchi et al., *STOTEN* 2012
Ozonation	Strong affinity with ECs in presence of H_2O_2 Disinfection and sterilizing effects	High energy demand, generation of oxidative by-products (undesired). Interference of radical scavangers	Kanakaraju et al., *JEME* 2018
AOPs	Higher removal efficiencies for many ECs Short degardation rate	High energy demand, high O&M costs. Generation of undesired by-products. Interference of radical scavangers.	Kanakaraju et al., *JEME* 2018
Fenton and photo-Fenton	Degradation and mineralization of ECs	Decrease of $OH^{\cdot}$ forming chloro and sulfato-Fe(III) complexes or due to scavange of $OH^{\cdot}$ forming $Cl_2^{\cdot}$ and $SO4^{\cdot-}$ in presence of chlorine and sulphate ions.	Le Truong et al., *Wat Res* 2004
Photo-catalysis (TiO_2)	Degardation of recalcitrant compounds High reaction rates by using catalyst Low price and chemical stability of TiO_2 catalist and easier recovery	Dufficulties for large flowrates. High costs for UV lamps and electricity Separation and reuse of photocatalytic particles from slurry suspension	Kanakaraju et al., *JEME* 2018

A glimpse to *Physical Processes-*
Advances and challanges

Treatment process	Advantages	Challenges	references
Micro and ultra-filtration	Pathogen removal	Micropollutant removal efficiencies depend on the the pore size High operation costs	Ahmed et al., *HazMat* 2017
Nanofiltration	Useful for saline water and WWTP effluents	High energy consumption, membrane fouling, disposal issues	Ahmed et al., *HazMat 2017*
Reverse osmosis	Useful for saline water and WWTP effluents High removal of pharmaceuticals, PCPs and EDCs	High energy consumption, membrane fouling, disposal issues	Ahmed et al., *HazMat* 2017

Common Wastewater Treatment
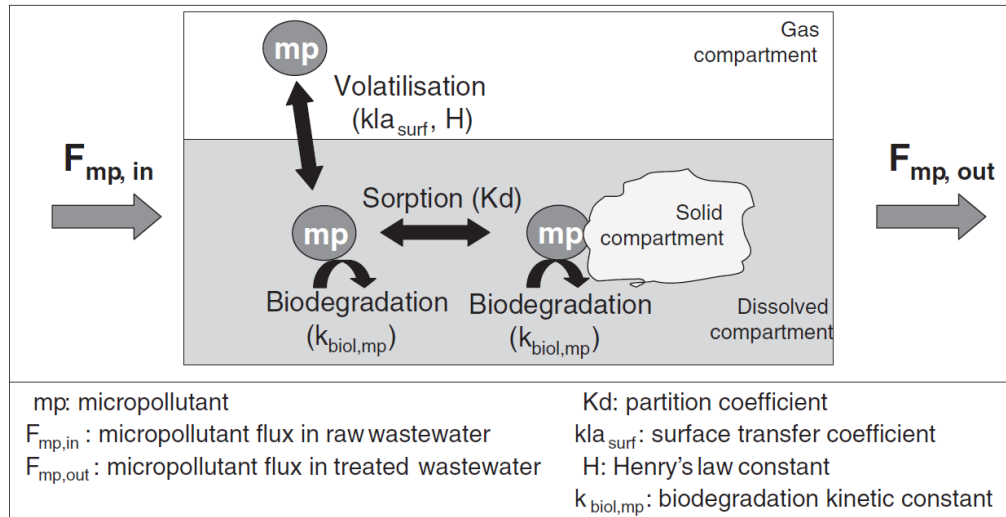
Pomiès et al., STOTEN 2013

- For the highly polar compounds, e.g. most pharmaceuticals and their corresponding metabolites, the most important removal route is **biodegradation** or **mineralization** by microorganisms.

- Removal efficiencies depends on the compounds and also on operational conditions.

- The identification of the degradation products is a challenging task as they are at very low concentrations and in complex matrices which may interfere with detection

Ahmed et al., HazMat 2017

	CAS	MBR
Removal of analgesics non-steroidal anti-inflammatory and anti-pyretics (NSAID) (%)		
Ibuprofen	(37.0–99.1) [16,20,77,110]	(73.0–99.8) [16,20,22,23,61,77,87,114]
Ketoprofen	(11.2–98.0) [20,77]	(3.7–91.9) [20,22,23,77,87]
Naproxen	(9.0–91.0) [20,77,110]	(40.1–99.3) [20,22,23,62,77,87]
Diclofenac	(2.0–51.0) [61,87,118]	(15.0–87.4) [20,22,23,62,77,87]
Acetaminophen	(98.4–100)[20,77]	(95.1–99.9)[20,22,23,61,77,114]
Removal of anti-epileptics and anti-depressant (%)		
Carbamazepine	(NE–9.5) [16,20,77,110]	(−42 to 51.0) [7,16,20,22,23,61,63,76,77,114]
Diazepam	(16.0–17.0) [110]	(67.0) [22,23]
Removal of hormones and endocrine disrupter compounds (EDCs) (%)		
Estrone	(99.0–100)[95]	(76.9–99.4)[22,23,95,112]
17β-estradiol	–	>(99.4) [22,23]
17α-ethynylestradiol	(ND–87.0) [95,110,112]	(ND–93.5) [22,23,95]
Bisphenol A	(96.0) [95]	(88.2–97.0) [22,23,61,95,112]
Removal of lipid regulator and cholesterol lowering drugs (%)		
Bezafibrate	(9.1–97.0) [20,77]	(88.2–95.8) [20,77,87]
Clofibric acid	(26.0–54.2) [16]	(25.0–71.0) [20,77]
Gemfibrozil	(NE–76.0) [20,77]	(32.5–85) [20,77,114]
Removal of antibiotics (%)		
Sulfamethoxazole	(12.0–73.8) [2,110]	(20.0–91.9) [2,7,20,22,23,63,76,77]
Erythromycin	(20–89.0) [2,20,77,110]	(25.2–90.4) [2,20,77]
Removal of beta blockers (%)		
Atenolol	(NE–84.0) [20,77]	(5–96.9) [20,22,23,63,76,77]
Metoprolol	(6.5–65.0) [20,77]	(29.5–58.7) [20,63,77]
Removal of musk fragrances (%)		
Galaxolide	(70.0–92.0) [110]	–
Tonalide	(44.0–90.0) [110]	–
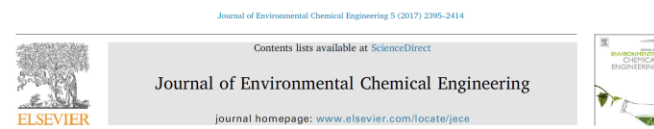
Abreham Tesfaye Besha[a], Abaynesh Yihdego Gebreyohannes[b,*], Ramato Ashu Tufa[c], Dawit Nega Bekele[d], Efrem Curcio[b,c], Lidietta Giorno[b]

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CAS *vs.* MBR

DE: Department of Engineering Ferrara

	MBR	MBR-NF	MBR-RO	MBR-PAC	MBR-GAC
Ibuprofen	(73.0–99.8) [16,20,22,23,61,77,87,114]	(99.4–99.8) [61]	(99.4–99.8) [61]	–	–
Ketoprofen	(3.7–91.9) [20,22,23,77,87]	–	–	–	>(98.0) [109,115]
Naproxen	(40.1–99.3) [20,22,23,62,77,87]	(78.0) [76]	–	(87.3) [116]	>(98.0) [109,115]
Diclofenac	(15.0–87.4) [20,22,23,62,77,87]	(87.5–97.0) [61,76]	(88.3–95.9) [61]	>[a](98.0) [111]	>(98.0) [109,115]
Acetaminophen	(95.1–99.9)[20,22,23,61,77,114]	(91.0–99.9) [61,76]	(99.6–99.9) [61]	–	–
Rer Carbamazepine	(−42 to 51.0) [7,16,20,22,23,61,63,76,77,114]	(81.0–93.0) [61,76]	(84.8–99.0) [22,23,61]	(80.0–99.0) [7,68,116]	>(98.0) [109,115]
Diazepam	(67.0) [22,23]	–	>(99) [63]	(80.0–90.0) [68]	–
Estrone	(76.9–99.4)[22,23,95,112]	>(76.0) [112]	>(76.0) [112]	–	–
17β-estradiol	>(99.4) [22,23]	>(71.0) [112]	–	(92.4) [8]	–
17α-ethynylestradiol	(ND–93.5) [22,23,95]	>(71.0) [112]	>(71.0) [112]	(86.7) [8]	–
Bisphenol A	(88.2–97.0) [22,23,61,95,112]	(95.0) [112]	(96.0) [112]	–	–
Bezafibrate	(88.2–95.8) [20,77,87]	–	–	–	–
Clofibric acid	(25.0–71.0) [20,77]	–	–	–	–
Gemfibrozil	(32.5–85) [20,77,114]	–	–	–	–
Removal of antibiotics					
Sulfamethoxazole	(20.0–91.9) [2,7,20,22,23,63,76,77]	(90.0) [76]	>(99.0) [63]	(82.0) [7]	–
Erythromycin	(25.2–90.4) [2,20,77]	–	>(99.0) [63]	>[a](88.0) [111]	–
Atenolol	(5–96.9) [20,22,23,63,76,77]	(85.0) [76]	>(99.0) [63]	–	–
Metoprolol	(29.5–58.7) [20,63,77]	(71.2) [63]	>(99.0) [63]	>[a](99.0) [111]	–

MBBR –
Observed removal efficiencies

- Ibuprofen 94 %

- Naproxen   70-80 %

- Diclofenac 74-85 %

- Clofibric acid   5-28 %

- Ketoprofen   63-73 %

- Carbamazepine 0-1 %

Moving Bed Bioreactors (MBBR)
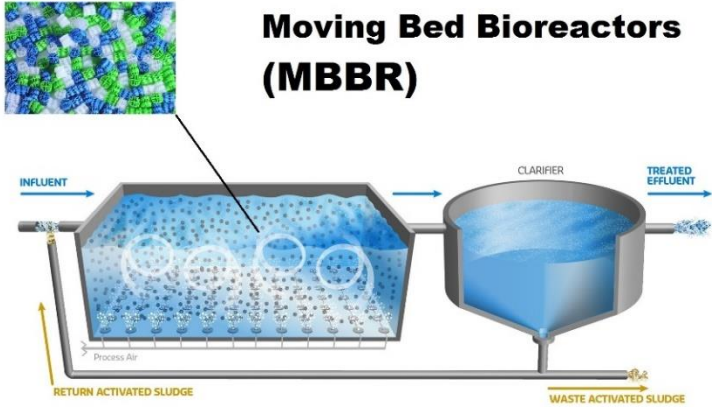
Fungal enzymatic systems

- Increasing number of studies, investigations removal capacity of different fungal species in removing trace organic compounds.

Removal of pharmaceuticals, steroid hormones, phytoestrogens, UV-filters, industrial chemicals and pesticides by *Trametes versicolor*: Role of biosorption and biodegradation

Luong N. Nguyen[a], Faisal I. Hai[a,*], Shufan Yang[a], Jinguo Kang[b], Frederic D.L. Leusch[c], Felicity Roddick[d], William E. Price[b], Long D. Nghiem[a]

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[b] Strategic Water Infrastructure Laboratory, School of Chemistry, University of Wollongong, Wollongong, NSW 2522, Australia
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[d] School of Civil, Environmental and Chemical Engineering, RMIT University, Melbourne, VIC 3001, Australia

The role of sorption processes in the removal of pharmaceuticals by fungal treatment of wastewater

D. Lucas[a], F. Castellet-Rovira[b], M. Villagrasa[a], M. Badia-Fabregat[b], D. Barceló[a,c], T. Vicent[b], G. Caminal[d], M. Sarrà[b], S. Rodríguez-Mozaz[a,*]

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[d] Institut de Química Avançada de Catalunya (IQAC) CSIC, Jordi Girona 18-26, 08034 Barcelona, Spain

Cell Surface Display Fungal Laccase as a Renewable Biocatalyst for Degradation of Persistent Micropollutants Bisphenol A and Sulfamethoxazole

Yingying Chen,[†] Brooke Stemple,[†] Manish Kumar,[‡] and Na Wei*,[†]

[†] Department of Civil and Environmental Engineering and Earth Sciences, University of Notre Dame, 156 Fitzpatrick Hall, Notre Dame, Indiana 46556, United States
[‡] Department of Chemical Engineering, The Pennsylvania State University, University Park, Pennsylvania 16802, United States

Review

Can white-rot fungi be a real wastewater treatment alternative for organic micropollutants removal? A review

Josep Anton Mir-Tutusaus[a], Rim Baccar[b], Glòria Caminal[c], Montserrat Sarrà[a,*]

[a] Departament d'Enginyeria Química Biològica i Ambiental, Escola d'Enginyeria, Universitat Autònoma de Barcelona, 08193, Bellaterra, Barcelona, Spain
[b] ENIS Laboratory of Environmental Engineering and Eco Technology, University of Sfax, BP 1173-3038, Sfax, Tunisia
[c] Institut de Química Avançada de Catalunya (IQAC), CSIC, Jordi Girona 18-26, 08034, Barcelona, Spain

Just a few words on the process

- The term *white-rot fungi* (WRF) refers to a collection of fungal species able to degrade lignin. They include *Trametes versicolor*, *Irpex lacteus*…

- WRF efficiently <u>break down</u> **lignin** to release the more metabolized carbohydrates hemicellulose and cellulose. This is possible due to a combination of extracellular ligninolytic enzymes, organic acids, mediators and accessory enzymes.
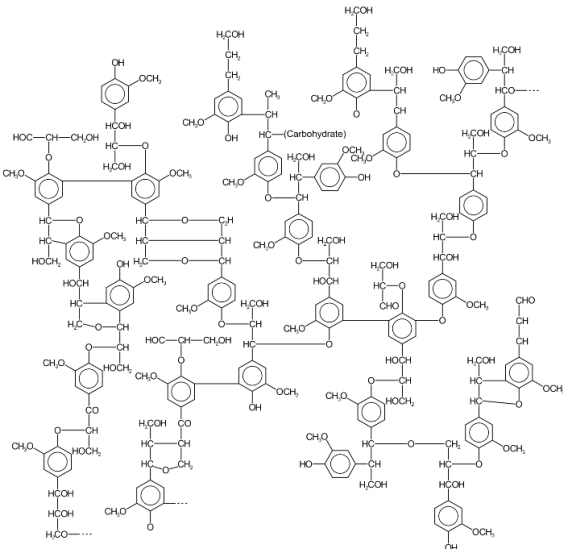
Lignin

Lignin Degrading Enzymes

Mir-Tutusaus et al., 2018

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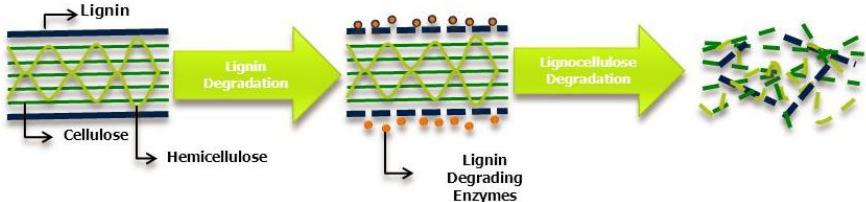
Just a few words on the process

- The main characteristic of this enzimatic cocktail is its non-specificity, due to its action via the generation of radicals. This allows the WRT extracellular enzymes capable of transforming a wide spectrum of compounds, including micropollutants

- WRT secrete lignin modifying enzymes (LMEs) and other compounds for lignid degradation: Laccase, lignin peroxidase (LiP), manganese peroxidase (MnP) and versatile peroxidase (VP).

- Enzyme production depends on the growth medium and culture conditions.

- In addition WRT also produces CytochromeP450, a superfamily of **intracellular** heme-containing monooxygenases, which takes part to detoxification of xenobiotics (among them DCF clofibric acid, carbamazepine, ketoprofen) and adaptation to hostile ecological niches.

Mir-Tutusaus et al., 2018

Bacteria and fungi

- **Bacteria** generally use micropollutants as growth substrates. Difficulties if the contaminants are in low concentrations (bacteria cannot colonize them for degrade them. Degradation of micropollutants in **WRF** is part of a secondary metabolism (cometabolism) as they require a substrate for their growth.

- **Bacteria** are generally less versatile when treating a combination of polltants. **WRF** better suited for these *working* condition.

- Bacteria optimum pH= 7 (tytpical of WWTPs).

  WRF optimum pH = 4,5

Mir-Tutusaus et al., 2018

Enzymatic degradation – Observed removal efficiencies

Compound	Fungus	Duration of the treatment	Reactor	HRT	Matrix	pH	Sterility	Initial concentration		Spiked matrix	Removal (%)	Source
Analgesics and anti-inflammatories												
Acetaminophen	T. versicolor	56 d	FBR	3 d	Flocculated HWW	4.5	No	>20000	ng·L-1	No	>99.3	Mir-Tutusaus et al., 2017
Diclofenac	P. chrysosporium	30 d	stirred tank	24 h	Kirk medium	4.5	Yes	1	mg·L-1	Yes	100	Rodarte-Morales et al., 2011
	P. chrysosporium	50 d	stirred tank	24 h	Kirk medium	4.5	Yes	1	mg·L-1	Yes	>93	Rodarte-Morales et al., 2012a
	P. chrysosporium	100 d	fixed bed	24 h	Kirk medium	4.5	Yes	1	mg·L-1	Yes	100	Rodarte-Morales et al., 2012b
	P. chrysosporium	70 d	stirred tank	–	–	3.7–5.3	Yes	0.9–1.7	mg·L-1	Yes	34–90	Rodarte-Morales et al., 2012b
	T. versicolor	90 d	MBR	48 h	Malt extract-based	5.4	No	300–1500	µg·L-1	Yes	0–60	Yang et al., 2013
	T. versicolor	110 d	MBR	2 d	Malt extract-based	4.5	No	5	µg·L-1	Yes	50	Nguyen et al., 2013
	T. versicolor	26 d	FBR	3.3 d	Veterinary HWW	4.5	No	123	ng·L-1	No	−177	Badia-Fabregat et al., 2015b
	T. versicolor	56 d	FBR	3 d	Flocculated HWW	4.5	No	951	ng·L-1	No	99.8	Mir-Tutusaus et al., 2017
Ibuprofen	P. chrysosporium	30 d	stirred tank	24 h	Kirk medium	4.5	Yes	1	mg·L-1	Yes	100	Rodarte-Morales et al., 2011
	P. chrysosporium	50 d	stirred tank	24 h	Kirk medium	4.5	Yes	1	mg·L-1	Yes	>93	Rodarte-Morales et al., 2012a
	P. chrysosporium	100 d	fixed bed	24 h	Kirk medium	4.5	Yes	1	mg·L-1	Yes	100	Rodarte-Morales et al., 2012b
	P. chrysosporium	70 d	stirred tank	–	–	3.7–5.3	Yes	0.8–1.2	mg·L-1	Yes	65–95	Rodarte-Morales et al., 2012b
	T. versicolor	110 d	MBR	2 d	Malt extract-based	4.5	No	5	µg·L-1	Yes	>95	Nguyen et al., 2013
	T. versicolor	26 d	FBR	3.3 d	Veterinary HWW	4.5	No	212	ng·L-1	No	30	Badia-Fabregat et al., 2015b
	T. versicolor	28 d	FBR	3 d	Flocculated HWW	4.5	No	20	mg·L-1	Yes	100	Mir-Tutusaus et al., 2016
	T. versicolor	56 d	FBR	3 d	Flocculated HWW	4.5	No	>20000	ng·L-1	No	>85.5	Mir-Tutusaus et al., 2017
Ciprofloxacin	T. versicolor	56 d	FBR	3 d	Flocculated HWW	4.5	No	366	ng·L-1	No	47.1	Mir-Tutusaus et al., 2017
	T. versicolor	26 d	FBR	3.3 d	Veterinary HWW	4.5	No	42	ng·L-1	No	100	Badia-Fabregat et al., 2015b
Carbamazepine	P. chrysosporium	50 d	stirred tank	24 h	Kirk medium	4.5	Yes	0.5	mg·L-1	Yes	0–63	Rodarte-Morales et al., 2012a
	P. chrysosporium	100 d	fixed bed	24 h	Kirk medium	4.5	Yes	0.5	mg·L-1	Yes	0–40	Rodarte-Morales et al., 2012b
	P. chrysosporium	70 d	stirred tank	–	–	3.7–5.3	Yes	2.2–1.0	mg·L-1	Yes	5–90	Rodarte-Morales et al., 2012b
	T. versicolor	25 d	FBR	3 d	Defined medium	4.5	Yes	200	µg·L-1	Yes	54	Jelic et al., 2012
	P. chrysosporium	100 d	plate reactor	36 h	Kirk medium	3.5–7.5	No	1	mg·L-1	Yes	80	Zhang and Geißen (2012)
	P. chrysosporium	100 d	plate reactor	36 h	Municipal WW	3.5–7.5	No	1	mg·L-1	Yes	60	Zhang and Geißen (2012)
	T. versicolor	110 d	MBR	2 d	Malt extract-based	4.5	No	5	µg·L-1	Yes	21	Nguyen et al., 2013
	P. chrysosporium	165 d	seepage reactor	2 d	Kirk medium	4.5	No	1	mg·L-1	Yes	80	Li et al., 2015
	P. chrysosporium	160 d	rotating cartridge	3 d	Kirk medium	3–6	No	1	mg·L-1	Yes	70–90	Li et al., 2016
	T. versicolor	12 h	bottle reactor	batch	WWTP effluent	4.5	Yes	350	µg·L-1	Yes	0	Shreve et al., 2016
	T. versicolor	56 d	FBR	3 d	Flocculated HWW	4.5	No	251	ng·L-1	No	61.0	Mir-Tutusaus et al., 2017
X-ray contrast agents												
Iopromide	T. versicolor	8 d	FBR	batch	HWW	4.5	No	419.7	µg·L-1	No	65.4	Gros et al., 2014
	T. versicolor	8 d	FBR	batch	HWW	4.5	Yes	105	µg·L-1	No	87	Gros et al., 2014
Endocrine disruptors												
17α-ethynylestradiol (EE2)	T. versicolor	26 d	FBR	120 h	Defined medium	4.5	Yes	7.3	mg·L-1	Yes	>97	Blánquez et al., 2008
	T. versicolor	110 d	MBR	2 d	Malt extract-based	4.5	No	5	µg·L-1	Yes	90	Nguyen et al., 2013
	T. versicolor	12 h	bottle reactor	batch	WWTP effluent	4.5	Yes	350	µg·L-1	Yes	71.3	Shreve et al., 2016
	P. ostreatus	28 d	trickle bed	46 h - 8	WWTP effluent	7.2–8.3	No	10	ng·L-1	No	50	Kresinová et al., 2017
17β-estradiol (E2)	T. versicolor	26 d	FBR	120 h	Defined medium	4.5	Yes	3–18.8	mg·L-1	Yes	>99	Blánquez et al., 2008
	T. versicolor	110 d	MBR	2 d	Malt extract-based	4.5	No	5	µg·L-1	Yes	>99	Nguyen et al., 2013
	T. versicolor	12 h	bottle reactor	batch	WWTP effluent	4.5	Yes	350	µg·L-1	Yes	>99	Shreve et al., 2016
17β-estradiol-17-acetate	T. versicolor	110 d	MBR	2 d	Malt extract-based	4.5	No	5	µg·L-1	Yes	>95	Nguyen et al., 2013
4-n-nonylphenol	P. ostreatus	28 d	trickle bed	46 h - 8	WWTP effluent	7.2–8.3	No	10	ng·L-1	No	50	Kresinová et al., 2017
Bisphenol A	T. versicolor	90 d	MBR	48 h	Malt extract-based	5.4	No	300–1500	µg·L-1	Yes	40–80	Yang et al., 2013
	T. versicolor	110 d	MBR	2 d	Malt extract-based	4.5	No	5	µg·L-1	Yes	75	Nguyen et al., 2013
	T. versicolor	12 h	bottle reactor	batch	WWTP effluent	4.5	Yes	350	µg·L-1	Yes	61.9	Shreve et al., 2016
	P. ostreatus	28 d	trickle bed	46 h - 8	WWTP effluent	7.2–8.3	No	20	ng·L-1	No	80	Kresinová et al., 2017
Estriol (E3)	T. versicolor	110 d	MBR	2 d	Malt extract-based	4.5	No	5	µg·L-1	Yes	95	Nguyen et al., 2013
Estrone (E1)	T. versicolor	110 d	MBR	2 d	Malt extract-based	4.5	No	5	µg·L-1	Yes	94	Nguyen et al., 2013
	T. versicolor	12 h	bottle reactor	batch	WWTP effluent	4.5	Yes	350	µg·L-1	Yes	83.5	Shreve et al., 2016
	P. ostreatus	28 d	trickle bed	46 h - 8	WWTP effluent	7.2–8.3	No	45	ng·L-1	No	>99	Kresinová et al., 2017

Limitations of WRF

- Need of nutrient addition to guarantee WRF growth

- Immobilization of fungal biomass to avoid growth on the reactor walls and agitators, foaming and increased need of mixing and oxygen supply. It may be by pellets or by carriers

- Competition with microorganisms

- Higher HRT.

Attempts to combine conventional biological process with WRF process.

Mir-Tutusaus et al., 2018

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Comparison

ECs removal efficiency from WWTPs by different biological treatment technologies.

Categories of ECs	ECs	Biological treatment technology			
		Polishing pond (algae)		Fungal reactor	
		Influent ($\mu g\,L^{-1}$)	Removal (%)	Influent ($\mu g\,L^{-1}$)	Removal (%)
Pharmaceuticals					
Analgesics	Carbamazepine	0.03–2.16	40	0.01–0.21	31
	Codeine	0.03–2.16		0.04–84.71	100
	Diclofenac	0.03–2.16	80	0.01–0.21	60
	Ibuprofen	0.03–2.16	50	0.01–0.21	92
	Naproxen	0.03–2.16	75	0.01–0.21	45
	Phenazone			0.01–0.21	45
Anticancer drugs	Acridone			0.04–84.71	100
Serotonin reuptake inhibitors	Citalopram			0.04–84.71	100
Gastroesophageal	Crimetidine			0.01–0.21	100
	Famotidine			0.01–0.21	100
	Ranitidine			0.01–0.21	100
Anxiety remover	Diazepam			0.01–0.21	26
Antidiabetic	Gibenclamide			0.01–0.21	100
NSAIDs	Ketoprofen	0.03–2.16	90	0.01–0.21	50
	Indomethacin			0.01–0.21	62
	Mefanamic acid			0.01–0.21	41
Lipid regulators	Atorvastatin			0.01–0.21	50
	Bezafibrate			0.01–0.21	45
	Gemifibrozil			0.01–0.21	41
Diuretics	Hydrochlorothiazide			0.01–0.21	83
Antibiotics	Azithromycin			0.04–84.71	100
	Ciprofloxacine			0.04–84.71	35
	Erythromycin			0.04–84.71	100
	Sulfathiazole	200	36	0.01–0.21	86
	Sulfapyridine	200	45	0.01–0.21	100
	Sulfamethazine	200	15	0.01–0.21	91
	Sulfamethoxazole	200	20		
	Tetracycline	200	89		
	Oxytetracycline	200	93		
Anti-inflammatory	Acetaminophen			0.04–84.71	100
Stimulants	Butalbital			0.01–0.21	100
	Caffeine	0.03–2.16	60		

Ahmed et al., 2017

Hybrid system=MBR+PAC

- Lab scale experiments

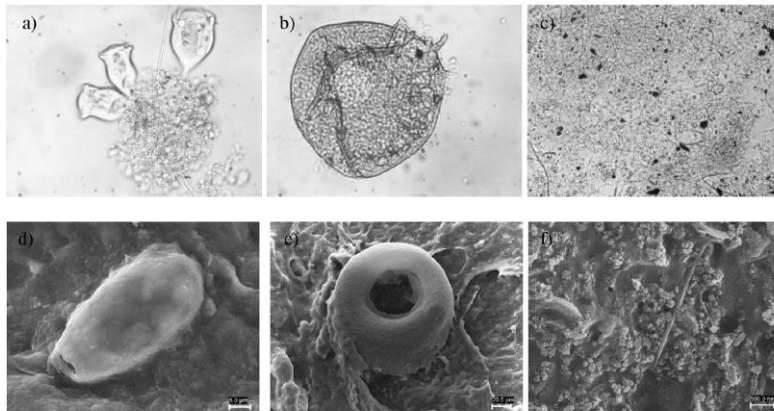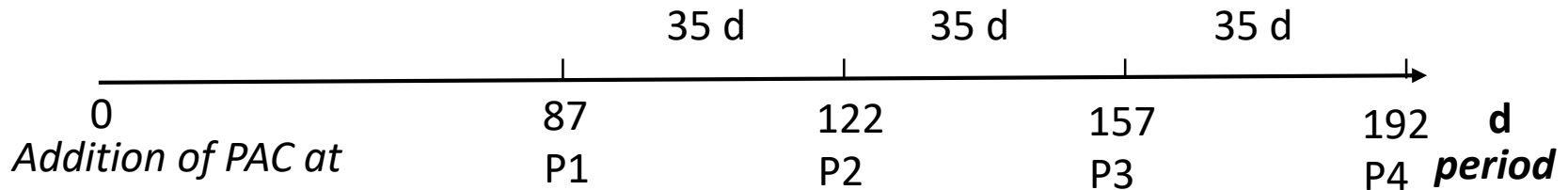- MBR reactors: 30 L (MF; flat sheet; size 0,45 μm); 185 L (UF; hollow fiber; size 0,045 μm). HRT= 24 h.

```
                    35 d        35 d        35 d
  ─────────────────┼───────────┼───────────┼────────────►
  0                 87          122         157          192    d
  Addition of PAC at P1         P2          P3           P4    period
```


**Biomass analysis**: biomass agglomerates not influenced by PAC addition.
Size: 42 μm (UF), 77 μm (MF).
Poorer settleability in UF-MBR, but improved by PAC addition.
Good filterability in all the periods

Fig. 1. Optical microscope observations of: Carchesium polypinum (a), Centropyxis (b), and the PAC integrated in the sludge structure (c) and SEM photographs: Euglypha (d), Arcella (e) and the PAC integrated in the sludge structure (f).

PAC increases the strength of the floc structure, allows the formation of a biofilm around it and favor the development of some Protozoans able to improve effluent quality and amoebas (able to enhance nitrogen removal)
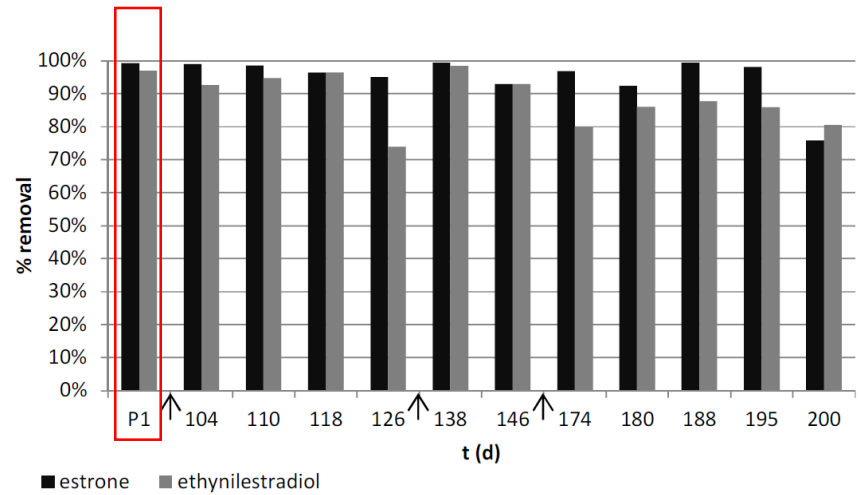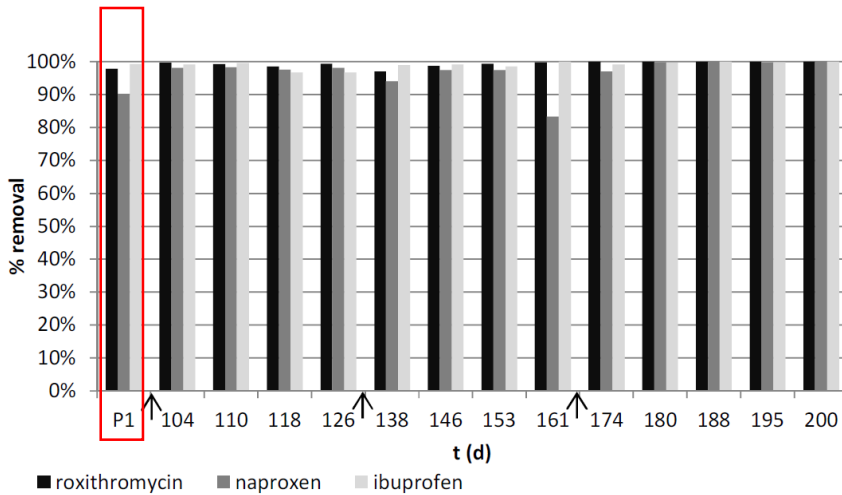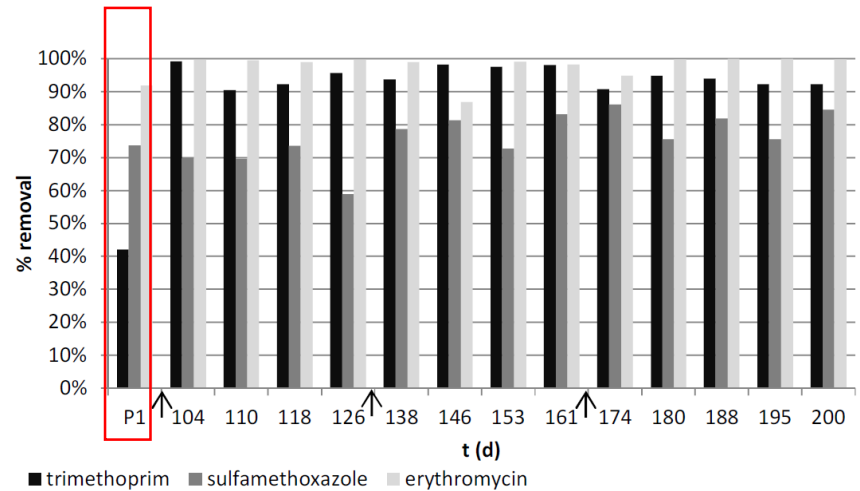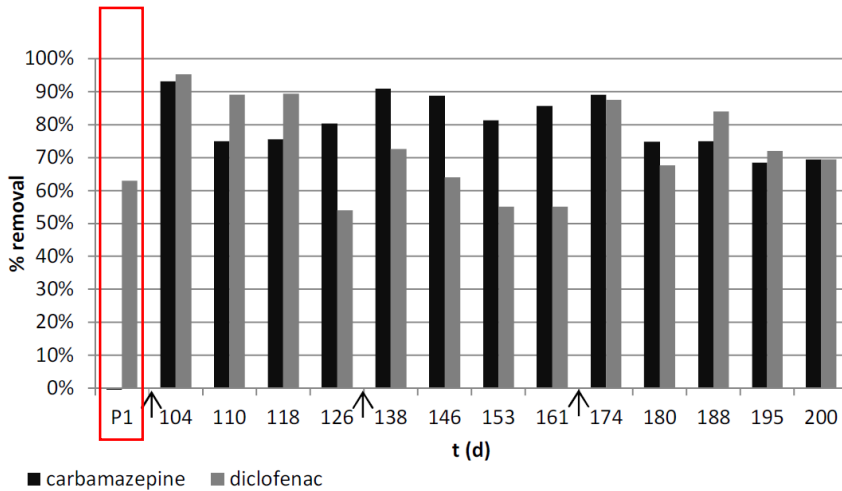
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Hybrid system=MBR+PAC
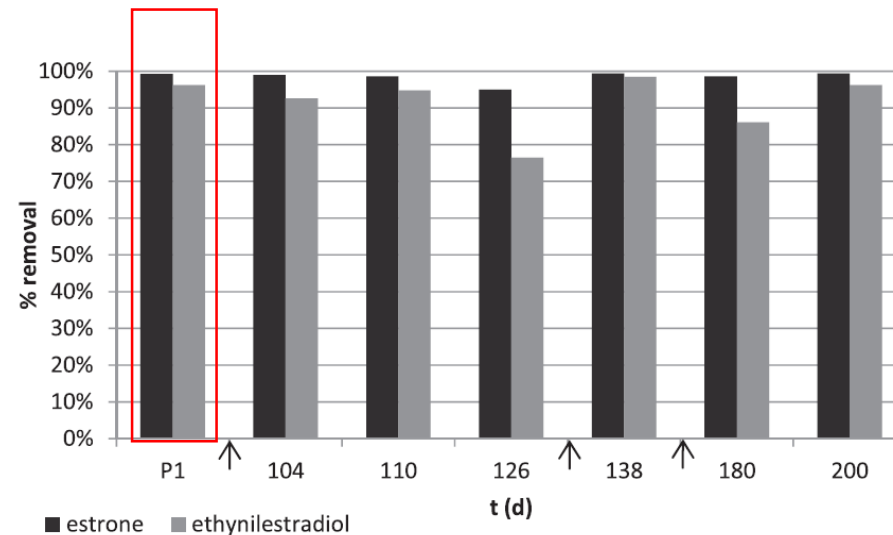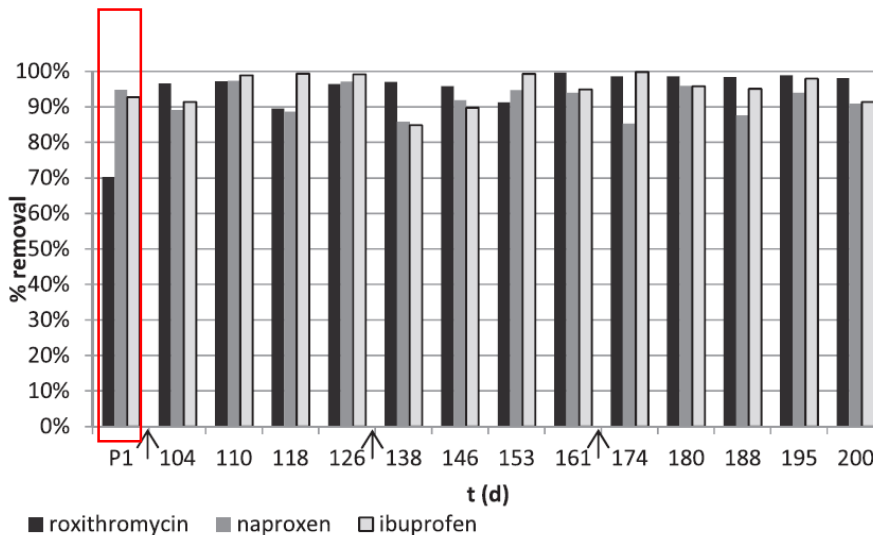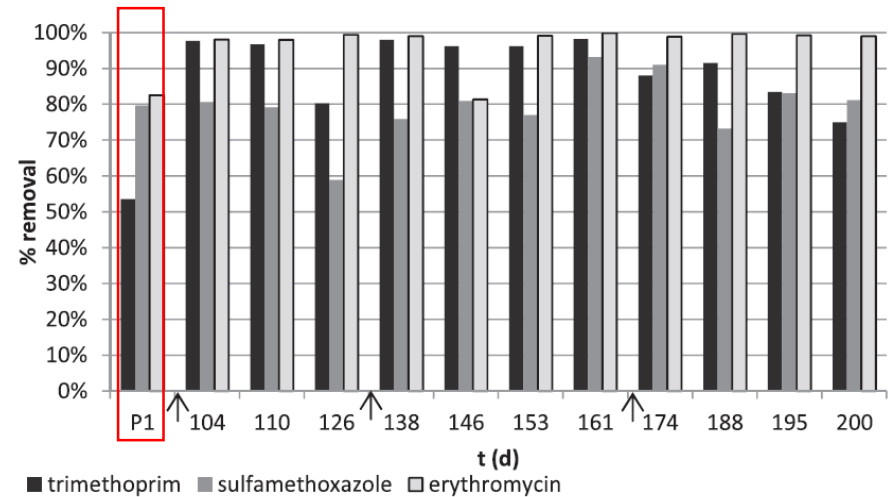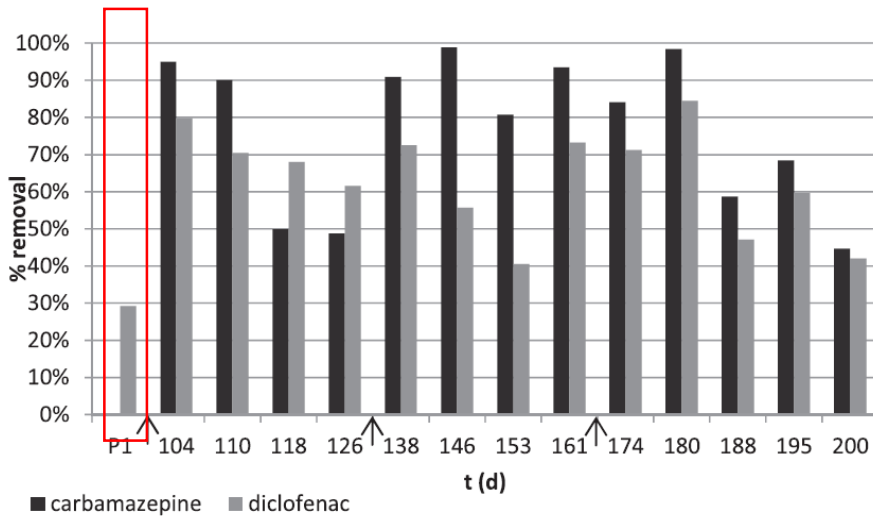
P1= no PAC added
PAC addition = 250 mg PAC/L

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Hybrid system=MBR+PAC

Ultrafiltration membranes

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Hybrid system=MBR+PAC
Analysis of the removal pathways

Fig. 3. OMPs removal in the MF$_{MBR}$ and UF$_{MBR}$ before PAC addition (P1) and 7 days after the first PAC addition (P2).

Table 3
Effect of the biotransformation, sorption and type of membrane on the removal of the selected OMPs (↑↑: 75−100%, ↑:40−75%, ↓:20−40%, ↓↓:0−20%).

	Biotransformation	Sorption onto sludge	Sorption onto PAC	Effect of the membrane
IBP	↑↑	↓↓	↓↓	↓↓
NPX	↑↑	↓↓	↓↓	↓↓
DCF	↓	↓↓	↑	↓
TMP	↑	↓↓	↓	↓↓
SMX	↑↑	↓↓	↓↓	↓↓
ERY	↑↑	↓↓	↓↓	↓↓
ROX	↑	↓↓	↓	↓
CBZ	↓↓	↓↓	↑↑	↓↓
E1	↑↑	↓	↓↓	↓↓
EE2	↑↑	↓	↓↓	↓↓

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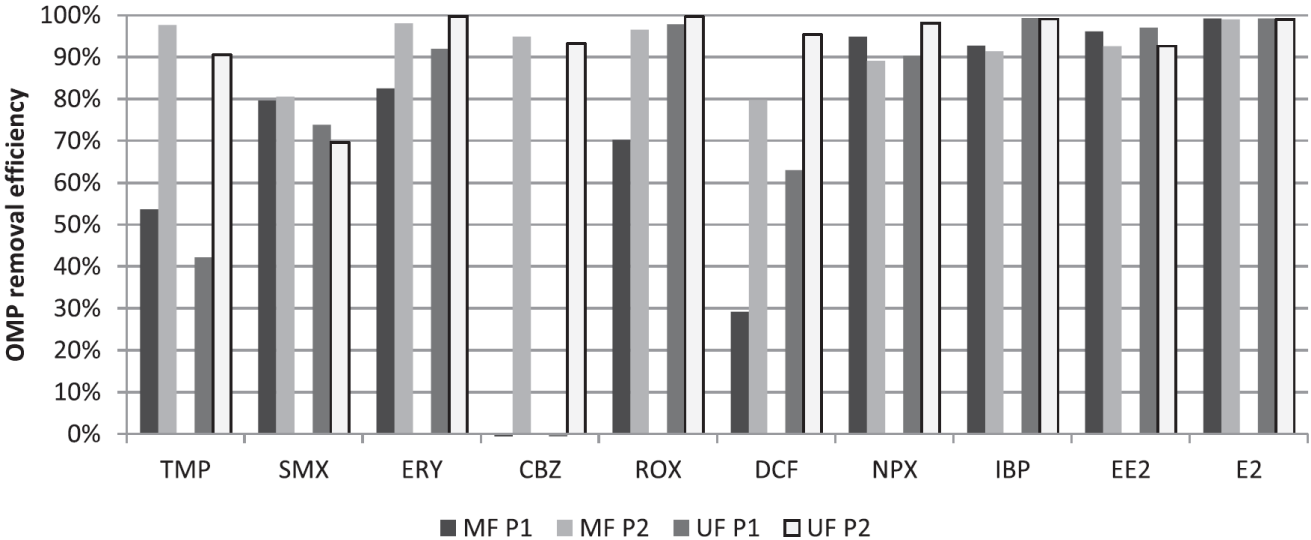
Hybrid system=MBR+PAC
Analysis of the removal pathways

Fig. 3. OMPs removal in the MF_{MBR} and UF_{MBR} before PAC addition (P1) and 7 days after the first PAC addition (P2).

- CBZ: improvement after PAC addition, no influence of the membrane size

- Hormones, IBU, NPX: no influence of membrane size nor PAC addition in the removal.

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Hybrid system=MBR+PAC
Analysis of the solid phase
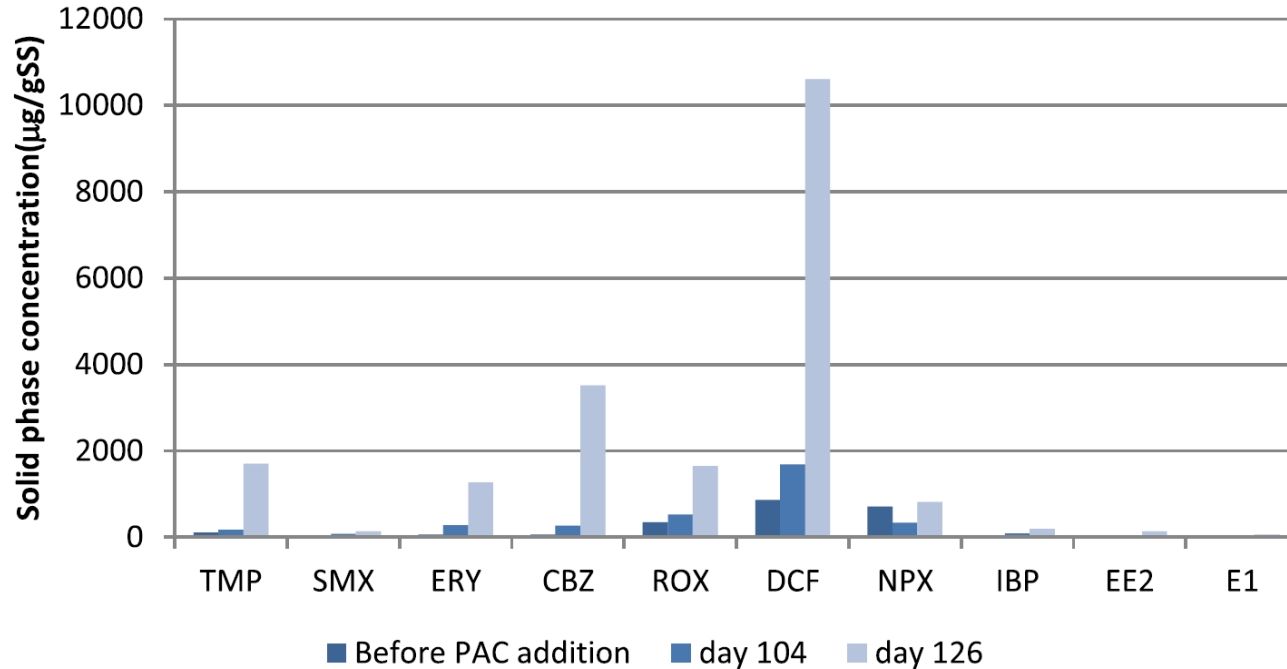
Fig. 4. OMPs concentration in the solid phase in the MF_{MBR}.

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Hybrid system=MBR+PAC
Lessons learned

- Reactor performance was excellent in terms of organic matter degradation and nitrification (efficiencies > 95%) in both MBRs, independently of the PAC addition. Partial denitrification was observed during the operation with PAC.
- The properties of the sludge and the effluent quality were enhanced after PAC addition.
- NPX, IBP and hormones were removed mainly by biotransformation, while to guarantee good removal efficiencies for TMP, CBZ and DZP the addition of PAC was essential. ERY and ROX were removed partially by biotransformation and by sorption onto the PAC.
- The degree of removal by PAC could be related to the log D of the compound, while the saturation of PAC depended on the ionic charge of the OMP.
- The type of membrane only influenced the removal of DCF and ROX, which might be related to the adsorption/biotransformation processes occurring in the cake layer.
- PAC addition was beneficial for membrane fouling prevention

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Advanced treatment processes

Review

Advanced oxidation process-mediated removal of pharmaceuticals from water: A review

Devagi Kanakaraju [a,*], Beverley D. Glass [b], Michael Oelgemöller [c]
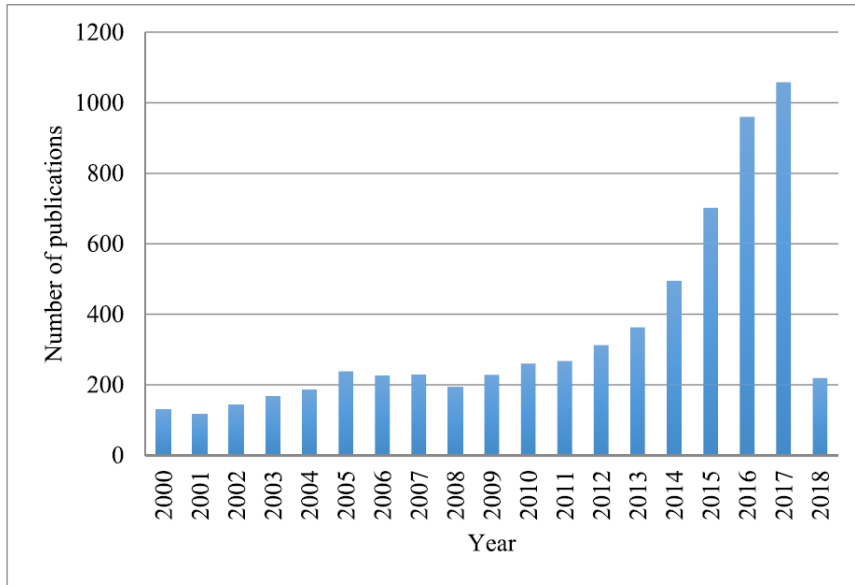
Statistics of publications (2000-2018) on applications of AOPs for pharmaceutical removal (Scopus database search for «AOPs» and «pharmaceuticals» in all subject areas).

- Which is the level of investigations? Lab, pilot full scale investigations?
- Lessons learned?

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AOPs: current investigations

Non-photochemical processes

Fenton, ozonation, ultrasound, sonolysis, electrochemical, radiation

Photochemical processes

UV oxidation (UV and UV/H_2O_2), photo-Fenton, photocatalysis

Hybrid processes

Sono-photolysis, photocatalytic ozonation, sono-biphotocatalysis, photoelectrocatalysis, electro-peroxone, sono-Fenton

AOPs

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Ozonation

Pharmaceuticals	Water matrix	Significant findings
Antibiotics, steroid hormone, lipid regulator, antineoplastic, non-steroidal anti-inflammatory drug, and psychostimulant	Synthetic wastewater, surface water, and effluents of municipal wastewater treatment plant	Specific ozone doses ranging from 0.82 to 2.55 mg O_3/mg DOC resulted in >99.9% removal for most of the studied pharmaceuticals. The increased toxicity for aqueous solutions of acidic pharmaceuticals at a specific ozone dose of 2.24 mg O_3/mg DOC was due to formation of more toxic by-products.
Indomethacin	Ultrapure water	Ozone doses of 2, 10, 20 and 35 mg/L resulted in complete indomethacin (25 μM) degradation within 7 min in contrast to poor mineralization (TOC), despite extending the reaction time to 30 min.
Propranolol	Milli-Q water	Complete removal of propranolol was achieved in 8 min. Total organic carbon (TOC) removal did not increase above 5%, despite increased contact time of 60 min. Low dose ozone was inefficient to improve biodegradability of ozonated samples.
Tetracycline	Deionized water	Direct ozonation showed complete degradation of tetracycline with H_2O_2 concentrations with *tert* butyl alcohol (HO• radical scavenger) showing no effect on the degradation rate. Only 35% of COD removal was attained after 90 min ozonation.
Carbamazepine, diclofenac, sulfamethoxazole, and trimethoprim	Milli-Q water	Carbamazepine, diclofenac and trimethoprim degraded completely when a lower dose of ozone was applied, 1.6 mg/L, 2.3 mg/L and 2.8 mg/L, respectively. However, sulfamethoxazole consumed a higher dose, 4.5 mg/L and longer time to achieve complete degradation due to the formation of highly reactive by-products.
Amoxicillin	Distilled water and ultrapure water	The pseudo-first order reaction rates for amoxicillin by ozonation at pH 3, pH 7 and pH 10 were 0.064 min^{-1}, 0.321 min^{-1} and 1.970 min^{-1}, respectively, with pH 10 being the optimum one.
Salicylic acid	Deionized water	Salicylic acid removal was observed to be more significant and rapid at pH 4 compared to pH 8 and pH 10. At pH 4 and in the presence of 1 mg/L of ozone, about 95% of salicylic acid was removed.
Ibuprofen, acetyl sulfamethoxazole and metoprolol	Secondary effluent from wastewater treatment plant	Effect of pHs (6.5, 7.0 and 7.5) at a constant temperature, 20°C in the presence of organic matter on the ozonation treatment with an initial concentration of 1.5 mg/L showed that metoprolol degraded at the fastest rate followed by acetyl sulfamethoxazole and ibuprofen at all pHs.

Ozonation

Treatment scheme	Operation conditions	Ozone dose	Efficiencies	Energy and costs
Secondary effluent – sand filtration (SF) or ultrafiltration (UF) - ozone/H_2O_2 – BAC.	pH: 6.9; Alkalinity: 90 mg $CaCO_3 \cdot L^{-1}$; BAC 1.4 m bed depth; Residence time: 5 min; 3.5 mg $H_2O_2 \cdot L^{-1}$.	5 mg $O_3 \cdot L^{-1}$	O_3/H_2O_2 + BAC PPCPs$_{Removal}$ = 95% (Except benzophenone). TOC$_{Removal}$ = 33%.	UF required higher costs compared to SF. SF require higher O_3 doses for suitable disinfection levels
1) NF at VRF 5,10, and 20; 2) NF of treated WW at VRF 60 and O_3; 3) O_3 treated WW and NF at VRF 60.	Membranes nominal area 7.9 m^2; pH:6.1 to 6.9; T: 20.7–24.6 °C.	5 mg $O_3 \cdot L^{-1}$	PPCPs$_{Removal}$: 1) VRF 5, 10, 20 were 39, 18 and 20%, respectively; 2) NF + O_3:99%; 3) O_3 + NF:99%	———————
1) Ozone – SF; 2) PAC – UF; 3) PAC – SF.	pH: 7.2 (±0.4); T: 17.1 (±3.5) °C; DOC: 7.3 (± 1.9)mg$\cdot L^{-1}$; TSS: 14.8 (±5.3) mg$\cdot L^{-1}$;	5.7 mg $O_3 \cdot L^{-1}$ (Average)	PPCPs$_{Removal}$: 1) >70%; 2) >70% (13 mg PAC$\cdot L^{-1}$ and UF);Toxicity$_{Reduction}$: 1) 75%; 2) 84%(PAC-UF);Estrogenic$_{Reduction}$: 1) 89%; 2) 77% (PAC-UF).	Electricity (kWh$\cdot m^{-3}$): 1) 0.117; 2) 0.9 (15 mg PAC$\cdot L^{-1}$-UF); 3) 0.08 (15 mg PAC$\cdot L^{-1}$-SF);Total cost ($€\cdot m^3$): 1) 0.176; 2) 0.803 (15 mg PAC$\cdot L^{-1}$-UF); 3) 0.161 (15 mg PAC$\cdot L^{-1}$-SF).
Biological activated sludge: 1) Ozone – SF; 2) PAC – SF.	pH: 7.5; DOC: 9.4 mg$\cdot L^{-1}$; 20 mg PAC$\cdot L^{-1}$	6.58 mg $O_3 \cdot L^{-1}$	Toxicity reduction was verified for five different species. Ozonation slightly increased the adverse effects on species but sand filtration reduce these effects.	———————

Ozonation

Treatment scheme	Operation conditions	Ozone dose	Efficiencies	Energy and costs
Denitrification-pre-ozonation-dissolved air flotation and sand filtration-ozone and biological activated carbon (BAC)	T: 22 °C; pH: 6.7; DOC: 6.5–8.1 mg·L^{-1}; BAC: Residence time 18 min	Pre-ozonation: 2 mg O_3·L^{-1};3.9–6.5 mg O_3·L^{-1}	PPCPs$_{removal}$: >90% (for a wide range); Estrogenic$_{Reduction}$: >95%; Non-specific Toxicity$_{Reduction}$: up to 70%; DOC$_{removal}$: up to 50%.	_____
Biological treatment-ozonation-sand filtration	pH: 8.3; DOC: 5.4–5.9 mg·L^{-1} Median discharge: 6190 m^3·day^{-1};	2.2–5.9 mg O_3·L^{-1}	Toxicity reduction verified with ozonation linked to sand filtration.	_____
Secondary effluent-ozonation-sand filtration	pH: 7.0; T: 20 °C; DOC: 2.4–4.8 mg·L^{-1};TCC: 3.3–8.4 × 10^6 cells·mL^{-1}.	0.8–5.2 mg O_3·L^{-1}	PPCPs$_{removal}$: 100% (for higher ozone doses); TCC$_{reduction}$: 0.5–1.5 log units.	_____
Secondary effluent-ozonation-sand filtration	pH: 7.0; T: 17 °C; DOC: 5.4 mg·L^{-1};	3.2 mg O_3·L^{-1}	PPCPs$_{removal}$: 100% (except compounds such as atenolol, benzotriazole (>85%)).	Energy consumption: 0.035 kWh·m^{-3}; 0.01–0.015 kWh·m^{-3} (O_2 production)
Conventional activated sludge-sand filtration-ozonation	Residence time: 27 min; DOC: 3.7 mg·L^{-1}; pH: 7	3 mg O_3·L^{-1}	PPCPs$_{removal}$: >80% (most of the target compounds).	_____
Activated sludge-ozonation-sand filtration	DOC: 5.8 mg·L^{-1} Fr: 5000–5500 m^3·day^{-1}; Residence time: 3–10 min.	3 mg O_3·L^{-1}	Estrogenic$_{reduction}$: 99.5%; Non-specific Toxicity$_{Reduction}$: up to 76%. Photosyntesis inhibition$_{reduction}$: 89%.	_____
Conventional activated sludge and ozonation	48 m^3·day^{-1} Residence time: 8–8.8 min; pH:7 DOC: 7 mg·L^{-1} T:16 °C; SS: 15 mg·L^{-1}	0.5–5 mg O_3·L^{-1}	PPCPs$_{removal}$: ~100% (except iopromide (40%)); E. coli$_{inactivation}$: inefficient in the presence of higher SS (even with 5 mg O_3·L^{-1}).	_____

Ozonation

Treatment scheme	Operation conditions	Ozone dose	Efficiencies	Energy and costs
Biofiltration-ozonation-soil aquifer treatment (SAT)	Fr: 120 $m^3 \cdot day^{-1}$ Residence time: 6–7 min (ozonation); 5 min (biofiltration); 22 day (SAT) DOC: 10.2 $mg \cdot L^{-1}$	10 mg $O_3 \cdot L^{-1}$	$DOC_{removal}$: 88%; $PPCPs_{removal}$: ~100% (except iopromide (52%) and primidone (65%)).	_____

Fenton and photo-Fenton processes

	Pharmaceuticals	Water matrix	Significant findings
Photo-Fenton	Amoxicillin	Distilled water	Complete and rapid oxidation was attained for amoxicillin in the presence potassium ferrioxalate complex within 5 min, while for $FeSO_4$ 15 min was required in experiments using a solar simulator.
Solar photo-Fenton	Ofloxacin and trimethoprim	Ultrapure water	Comparison of solar photo-Fenton between acidic pH (pH 2.8–2.9) and neutral (unadjusted pH 7) showed that complete degradation of ofloxacin and trimethoprim was attained likewise at the acidic pH but at a slower rate. Poor DOC removal was observed for both conditions.
Solar photo-Fenton	Nalidixic acid	Demineralized water, saline water, synthetic industrial effluent, real industrial effluent	Although complete degradation was obtained for nalidixic acid, degradation and mineralization was slower in saline water and synthetic industrial effluent with a compound parabolic collector.
Solar photo-Fenton	5-Fluorouracil	Ultrapure water	Solar simulated Fenton-like treatment ($Fe^{3+}/S_2O_8^{2-}$) resulted in a higher degradation rate and dissolved organic carbon (DOC) removal than Fe^{3+}/H_2O_2 for the degradation of 5-fluorouracil. The degradation rate and DOC removal under $Fe^{3+}/S_2O_8^{2-}$ was 0.04 min^{-1} and 40%, respectively while for Fe^{3+}/H_2O_2 system the values were 0.024 min^{-1} and 25%.
Photo-Fenton	Antipyrine	Aqueous solution	Ferrioxalate induced photo-Fenton reaction with UVA-LED was effective to degrade antipyrine as a result of the production of more $HO^{\bullet}$ radicals in the system. The complete degradation of antipyrine was obtained after 2.5 min, while 93% of TOC removal was recorded after 60 min ($[H_2O_2]o = 100$ mg/L, $[Fe]o = 2$ mg/L and $[H_2C_2O_4]o = 100$ mg/L, pH = 2.8).
Solar and artificial UV photo-Fenton	Oxacillin	Deionized water	Based on the applied factorial design, removal of oxacillin (203 μmol/L) was found to be optimum when the concentration of Fe^{2+}, H_2O_2 and applied light power were 90 μmol/L, 10 mmol/L and 30 W, respectively.
Photo-Fenton	15 pharmaceuticals (in combination with other micro pollutants)	Municipal wastewater treatment plant	The highest percentage of micro pollutant degradation at 83% was achieved in the presence of UV (254 nm) using 30 mg/L H_2O_2 and 2 mg/L Fe(III) at natural pH.
Solar photo-Fenton	Mixtures of 15 emerging contaminants (ECs)	Synthetic water, simulated effluent wastewater, real effluent wastewater	Mild solar photo-Fenton (Fe = 5 mg/L, H_2O_2 = 50 mg/L) was efficient to degrade mixtures of 15 ECs (pharmaceuticals, personal care products, pesticides) without any pH adjustments. But, toxicity level increased, with the degradation products formed in real effluent wastewater.
Solar photo-Fenton	Carbamazepine, ibuprofen, ofloxacin, flumequine, sulfamethoxazole	Municipal wastewater treatment plant effluent	Solar photo-Fenton using Fe: ethylenediamine-disuccinic acid (1:2) resulted in >96% removal of pharmaceuticals within 45 min while Fe:citrate (1:5) produced 94% removal after 96 min at neutral pH using nanofiltration concentrated sample.
Photo-Fenton	Ciprofloxacin	Milli-Q water	Photo-Fenton degradation of low and high concentrations of ciprofloxacin in the presence of different iron sources (iron citrate, iron oxalate and iron nitrate) and pH (2.5, 4.5 and 6.5) gave different results. For a high

UV-based processes

	Pharmaceuticals	Water matrix	Significant findings
UV and UV/peroxide processes			
UV and UV/H_2O_2	41 APIs (10 analgesics, 4 antiarrhythmic agents and 12 antibiotics and 15 others)	Municipal treatment plant	The removal efficiencies by UV and UV/H_2O_2 were highly dependent on the type of pharmaceutical, while H_2O_2 addition during the treatment enhanced the API removal up to 90% as well as DOC removal.
UV/H_2O_2 and UV	Sulfamethoxazole, sulfamethazine, sulfadiazine, trimethoprim, bisphenol A, and diclofenac	Milli-Q water, lake water and wastewater treatment plant effluent	Photolysis rate of all the bioactive compounds using low pressure UV photolysis (254 nm) differed at pHs tested, while efficiency of UV/H_2O_2 on the tested bioactive compounds was as follows: diclofenac > sulfamethoxazole > sulfamethazine > sulfadiazine > bisphenol A ≈ trimethoprim.
UV	Sulfasalazine, sulfapyridine and 5-aminosalicyclic acid	Milli-Q water	Sulfasalazine was resistant to direct UV (254 nm) photolysis while sulfapyridine demonstrated the fastest degradation due to its high molar absorption coefficient, 15241 M^{-1} cm^{-1}.
UV/H_2O_2 and UVC	Amoxicillin	Distilled deionized water	Degradation of amoxicillin by direct UV and UV/H_2O_2 with a low pressure Hg lamp (254 nm) showed that the degradation of 100 μM of amoxicillin (pH 7, 20 °C) followed first-order kinetics and the degradation rate increased with the H_2O_2 concentration. An addition of 10 mM H_2O_2 improved the degradation rate up to six-fold when compared to direct UV.
UV	Ketoprofen, carprofen and diclofenac acid	Ultrapure water and methanol	The photolysis kinetics of ketoprofen, carprofen and diclofenac acid followed pseudo-first order kinetics. Degradation of diclofenac acid was much slower compared to carprofen and ketoprofen. The predicted toxicity revealed that the transformation products of ketoprofen were more toxic than the parent API.
UVC/H_2O_2 and UVC/ $S_2O_8^{2-}$	17α-ethinyl estradiol, 17β-estradiol, azithromycin, carbamazepine, dexamethasone, erythromycin and oxytetracycline	Ultrapure water	In the presence of natural organic matter in the UVC/H_2O_2 system, the degradation rates (k_{app}) of azithromycin, carbamazepine, dexamethasone and 17α-ethinyl estradiol were enhanced between 3% and 11%, while an inhibitory effect resulted in the case of 17β-estradiol, erythromycin and oxytetracycline.
UVC/H_2O_2	Diclofenac	Ultra-pure water	Diclofenac completely degraded in solution within 2 min under UVC/H_2O_2 compared to UVA/TiO_2, which took 156 min to achieve similar degradation. A much higher mineralization (TOC) rate constant, 3.92×10^{-4} s^{-1} was obtained from the UVC/H_2O_2 treatment.
UV	Sulfamethoxazole and ibuprofen	Deionized water	The direct photolysis (UV 254 nm) of sulfamethoxazole and ibuprofen at pH 3 and pH 7.55 followed pseudo-first order kinetics. The initial reaction rate of the neutral sulfamethoxazole at pH 3 was 0.9149 min^{-1} higher than anionic sulfamethoxazole at pH 7.55, 0.3558 min^{-1} in contrast to ibuprofen, where the initial reaction rate was higher for its anionic form at pH 7.55 (0.0263 min^{-1}) than its neutral form at pH 3 (0.0043 min^{-1}).

Sonolysis

Pharmaceuticals	Water matrix	Significant findings
Ciprofloxacin	Deionized water	Degradation of ciprofloxacin at frequency 544 kHz (pH 7, 25 °C) fitted pseudo-first-order degradation with a half-life of 102 min. Addition of t-butanol (0.45, 4.5 and 45 mM) slowed down the degradation of ciprofloxacin confirming that t-butanol acts as a radical scavenger and the degradation of ciprofloxacin occurred due to the HO$^\bullet$ radical.
Diclofenac and carbamazepine	Milli-Q water and urban wastewater treatment plant	Degradation of diclofenac and carbamazepine followed first-order kinetics. The reaction rates were observed to increase with increasing power density from 100 to 400 W/L.
Piroxicam	Ultrapure water, bottled water and surface water	The reaction rates of piroxicam (640 μg/L) at power density of 20, 36 and 60 W/L were 0.1157 min^{-1}, 0.1695 min^{-1} and 0.1967 min^{-1}, respectively.
Ibuprofen	Ultrapure water	Application of single ultrasonic frequencies, 20 kHz, 40 kHz, 200 kHz, 572 kHz and 1130 kHz to ibuprofen (50 μM) resulted in 0.033 min^{-1}, 0.035 min^{-1}, 0.038 min^{-1}, 0.234 min^{-1} and 0.090 min^{-1}, respectively, indicating increasing degradation with frequency. Addition of zero-valent iron markedly increased ibuprofen degradation even at low single frequencies, 20, 40 and 200 kHz.
Oxacillin	Distilled water	Sonochemical process (275 KHz) efficiently degraded oxacillin (47.23 μmol/L) and eliminated antimicrobial activity in the presence and absence of additives (calcium carbonate and mannitol).
Diclofenac	Milli-Q water	The optimum conditions, initial concentration, pH and frequency ultrasound for DCF degradation was found to be 30 μM, 3.0 and 861 kHz, respectively. Addition of Fe-containing additives improved diclofenac elimination in particular with paramagnetic iron oxide nanoparticles. Mineralization occurred after 60 min of sonolysis in all cases.

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Electrochemical oxidation

Pharmaceuticals	Water matrix	Significant findings
Diclofenac, sulfamethoxazole, iopromide and 17-alpha-ethinyl estradiol	Deionized water and hospital wastewater treatment plant	When the degradation rates of the four APIs in synthetic wastewater and real wastewater was compared, higher rates were obtained for the latter when current conditions I = 0.9 A, initial concentration, C_o = 0.5 mg/L and flow rate = 500 L/h were used. This was attributed to the consumption of less oxidative species by organic matter present in real wastewater compared to those present in synthetic wastewater.
Carbamazepine	Demineralized water, tap water and treated wastewater	Comparison of carbamazepine degradation in tap water, demineralized water and treated municipal wastewater using Nb/BDD anode and 14 mM of NaCl showed that electrolysis resulted better performance in demineralized water (for pH 2 > pH7 > pH 10) followed by tap water and treated municipal wastewater.
Not stated	Wastewater samples from a pharmaceutical manufacturing plant	BDD-electro oxidation resulted in constant COD decrease in samples numbered as 55 to 61 with COD ranging from 5000 to 60,000 mgO_2/dm^3 when the applied electric charge was increased from 5 to 50 A h/dm^3 at a constant temperature (25 °C).

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Radiation

Pharmaceuticals	Water matrix	Significant findings
Carbamazepine	Deionized water	The increase of peroxymonosulfate concentration (mole ratio of peroxymonosulfate to carbamazepine from 10:1 to 30:1) increased the degradation of carbamazepine from 80% to 100% within 10 min of treatment time.
Carbamazepine	Ultrapure water	TOC reduction in carbamazepine solution decreased with increasing H_2O_2 concentrations (0−200 mM) at varying irradiation doses. Carbamazepine solution containing 50 mM H_2O_2 produced highest TOC removal at 41% when the irradiation dose was 20 kGy.
Carbamazepine	River water and ultrapure water	Addition of sulfite ion (SO_3^{2-}) prior to the electron beam radiation led to 85.4% of carbamazepine (75 mg/L) degradation in pure water. Sulfite radical ($^{\bullet}SO_3^{-}$), e_{aq}^{-} and $O^{\bullet-}$ were concluded to be a contributing active species for carbamazepine degradation in the presence of Na_2SO_3.
Nineteen pharmaceutical compounds	Wastewater sample from WWTP	A 5 kGy radiation dose effectively decomposed low initial levels of pharmaceutical compounds (<50 ng/L). The extent of the degradation of the pharmaceuticals was found to be dependent on the type and concentration of the compound.
Fluoxetine	Ultrapure water	Electron beam irradiation yielded 90% degradation of fluoxetine at radiation dose of 0.5 kGy whereas doses above 2.5 kGy led to a below detection limit.
Piperacillin	Distilled water, synthetic wastewater	The initial value of the calculated radiation chemical yield for the degradation of piperacillin was 0.26 μmol/J. Comparison of electron-beam mediated antimicrobial inactivation in aqueous solution and synthetic wastewater revealed that the adsorbed dose and degradation products affected the findings.

Kanakaraju et al., JEMA 2018

Other AOPs

	Pharmaceuticals	Water matrix	Significant findings
Combined AOPs			
Ozone/TiO$_2$ solar photocatalysis	Mixtures of four pharmaceuticals (atenolol, hydrochlorothiazide, ofloxacin and trimethoprim)	Distilled water and simulated synthetic secondary effluent solution	Four APIs, atenolol, hydrochlorothiazide, ofloxacin and trimethoprim sequentially treated, by ozonation and solar photocatalytic oxidation revealed that initial ozonation step led to poor removal of TOC (10%), while subsequent solar TiO$_2$ photocatalysis improved the TOC removal to 80% and 60% in distilled water and secondary effluent, respectively.
Ultrasound/Fenton oxidation (sono-Fenton)	Ibuprofen	Distilled water and effluent from municipal wastewater treatment plant	Coupling of Fenton with ultrasound (20 kHz) enhanced the degradation of ibuprofen in the presence of 6.4 mM whereby 95% removal was achieved within 60 min and mineralization was also improved under the same conditions.
Ultrasound and ozonation	Diclofenac, sulfamethoxazole and carbamazepine	Distilled water	The combined ultrasound/ozonation process positively enhanced the degradation of three APIs in single and mixed solutions at an ozone flow of 3.3 g/h after 20 min of treatment time when compared to ozonation alone at the same flow.
Sonolysis and photolysis (UV/H$_2$O$_2$)	Diclofenac, paracetamol, salicylic acid, chloramphenicol etc.	Synthetic pharmaceutical wastewater	Sonophotolysis resulted in the highest TOC removal of 91% in the presence of 900 mg/L H$_2$O$_2$, 80 W ultrasonic power and UV (253.7 nm). Two factors, ultrasound power and initial concentration of H$_2$O$_2$ were concluded as having the most effect based on the three-level Box−Behnken experimental design performed.
Sono-photocatalysis with TiO$_2$, sono-photoFenton and sono-biphotocatalysis with TiO$_2$ and Fe^{2+}	Ibuprofen	Milli-Q water	Sono-biphotocatalysis produced the highest mineralization rate (DOC removal of 98%) with more efficient consumption of H$_2$O$_2$. Initial degradation rate was 3.50×10^{-3} mM/min.
Photocatalytic ozonation	Diclofenac and amoxicillin	Aqueous solution (not specified) and urban wastewater	Complete mineralization (TOC abatement) was achieved with TiO$_2$ photocatalytic ozonation for amoxicillin and diclofenac after 30 min and 120 min, respectively.
Ozone/TiO$_2$/UVB, UVB/ TiO$_2$, O$_3$/UVB and single systems (UV, O$_3$)	Mixtures of nine pharmaceuticals	Water (not specified)	Ozone/TiO$_2$/UVB (313 nm) yielded the highest TOC removal of 95% within 120 min for the pharmaceutical mixtures (each 10 ppm).
Electro-peroxone	Venlafaxine	Milli Q water, secondary effluent from wastewater treatment plant	Compared to single ozonation and electrolysis treatment, electro-peroxone efficiently degraded 20 mg/L of venlafaxine within 3 min of reaction time, when the applied current was increased from 50 mA to 300 mA and the O$_3$ concentration was fixed at 40 mg/L.
Ozone and ultrasound	Amoxicillin	Distilled water and ultrapure water	Coupling of ozonation and ultrasound resulted in a higher pseudo-first-order degradation rate of 2.5 min^{-1} at pH and higher TOC removal (45%) than single ozonation treatment with 1.97 min^{-1} at similar pH.

Kanakaraju et al., JEMA 2018

Lessons learned from AOPs studies

AOPs investigations on pharmaceutical removal generally deal with:

- Degradation kinetics by investigating the effect of oprational parameters,

- Mineralization measurements using macroparameters such as TOC, DOC, COD

- Toxicity of the effluent

- Profiling or identification of degradants

Challenges for future AOPs studies

- Identify transformation products and effluent toxicity levels as transformation products may pose a higher toxicity than the corresponding parent compounds,

- Test AOPs with real water/wastewater

- Due to presence of a mixture of compounds whose concentration may vary, define and choose a reliable AOP protocol to ensure its effectiveness

- Refer to mixture of pharmaceuticals and not to a single compounds

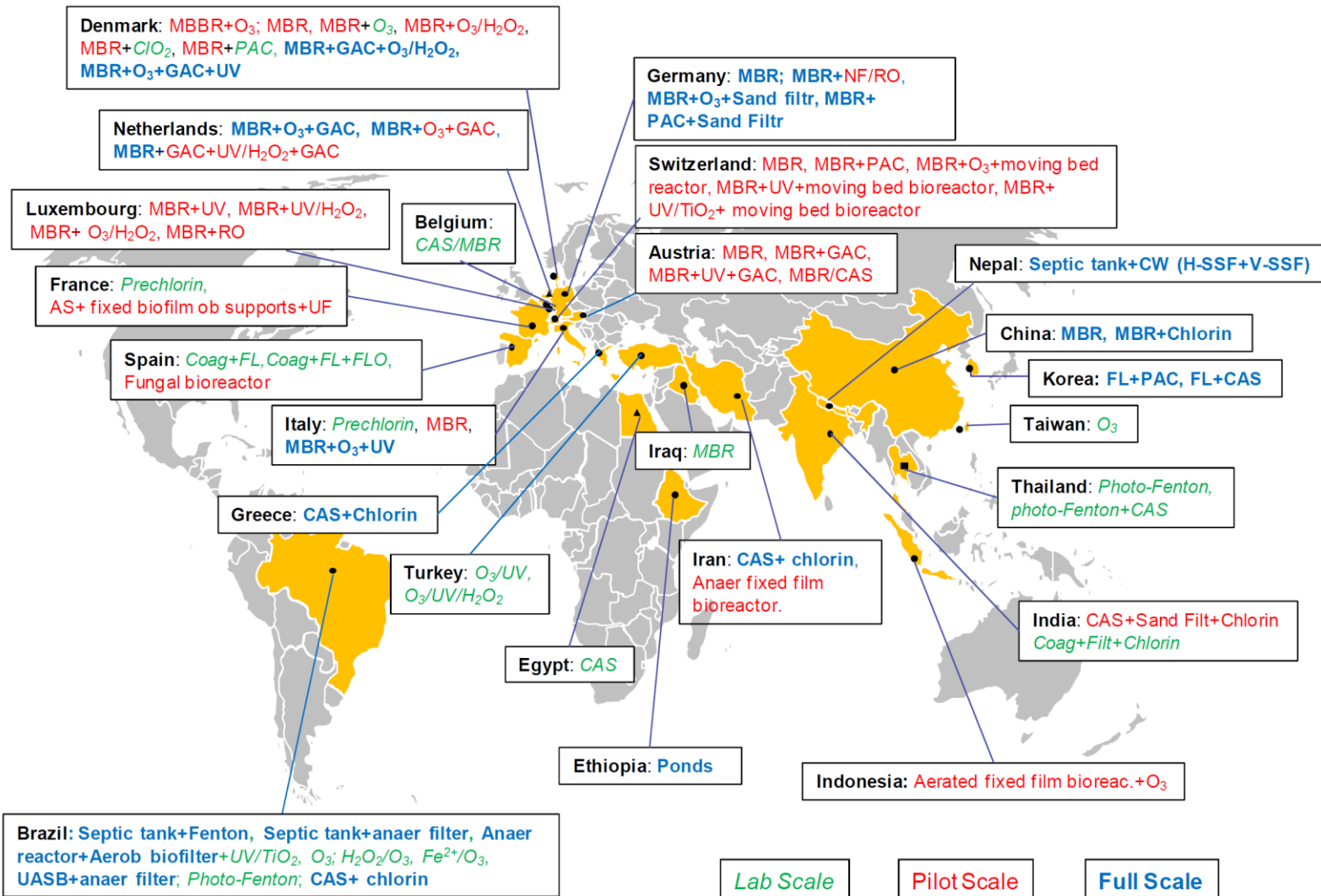# Hospital effluent: treatment and management

Verlicchi et al., 2015 *STOTEN*

Denmark: MBBR+O$_3$; MBR, MBR+O$_3$, MBR+O$_3$/H$_2$O$_2$, MBR+ClO$_2$, MBR+PAC, **MBR+GAC+O$_3$/H$_2$O$_2$, MBR+O$_3$+GAC+UV**

Netherlands: **MBR+O$_3$+GAC, MBR+O$_3$+GAC, MBR**+GAC+UV/H$_2$O$_2$+GAC

Luxembourg: MBR+UV, MBR+UV/H$_2$O$_2$, MBR+ O$_3$/H$_2$O$_2$, MBR+RO

Belgium: *CAS/MBR*

France: *Prechlorin*, AS+ fixed biofilm ob supports+UF

Spain: *Coag+FL,Coag+FL+FLO*, Fungal bioreactor

Italy: *Prechlorin*, MBR, **MBR+O$_3$+UV**

Greece: **CAS+Chlorin**

Germany: **MBR; MBR+NF/RO, MBR+O$_3$+Sand filtr, MBR+ PAC+Sand Filtr**

Switzerland: MBR, MBR+PAC, MBR+O$_3$+moving bed reactor, MBR+UV+moving bed bioreactor, MBR+ UV/TiO$_2$+ moving bed bioreactor

Austria: MBR, MBR+GAC, MBR+UV+GAC, MBR/CAS

Nepal: **Septic tank+CW (H-SSF+V-SSF)**

China: **MBR, MBR+Chlorin**

Korea: **FL+PAC, FL+CAS**

Taiwan: *O$_3$*

Thailand: *Photo-Fenton, photo-Fenton+CAS*

Iraq: *MBR*

Iran: **CAS+ chlorin**, Anaer fixed film bioreactor.

India: CAS+Sand Filt+Chlorin *Coag+Filt+Chlorin*

Turkey: *O$_3$/UV, O$_3$/UV/H$_2$O$_2$*

Egypt: *CAS*

Ethiopia: **Ponds**

Indonesia: Aerated fixed film bioreac.+O$_3$

Brazil: **Septic tank+Fenton, Septic tank+anaer filter, Anaer reactor+Aerob biofilter**+*UV/TiO$_2$*, *O$_3$; H$_2$O$_2$/O$_3$, Fe^{2+}/O$_3$,* **UASB+anaer filter**; *Photo-Fenton*; **CAS+ chlorin**

Lab Scale   Pilot Scale   **Full Scale**

Fig SD-1. World map of the investigations on dedicated treatment for hospital effluent between 1995-2015

40

Hospital effluent: treatment and management

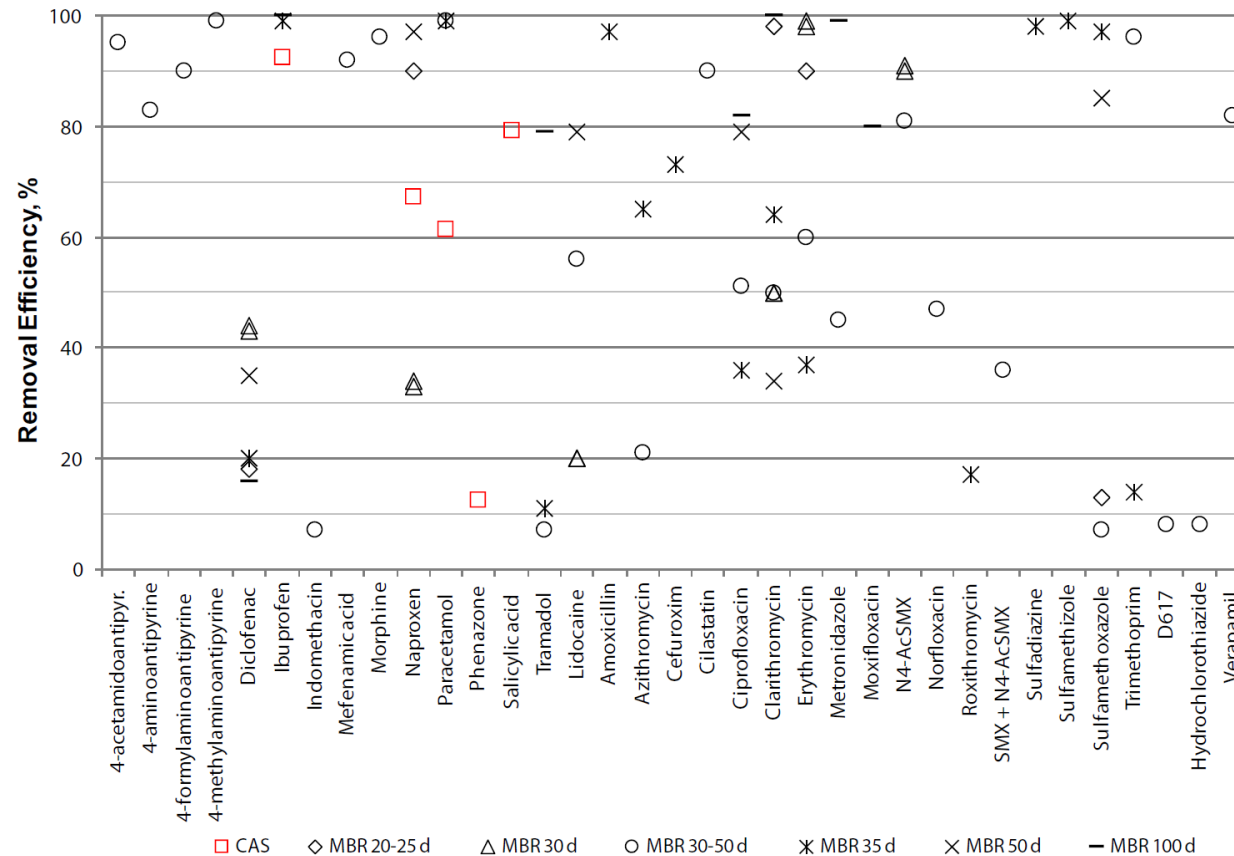P. Verlicchi et al. / Science of the Total Environment 514 (2015) 467–491

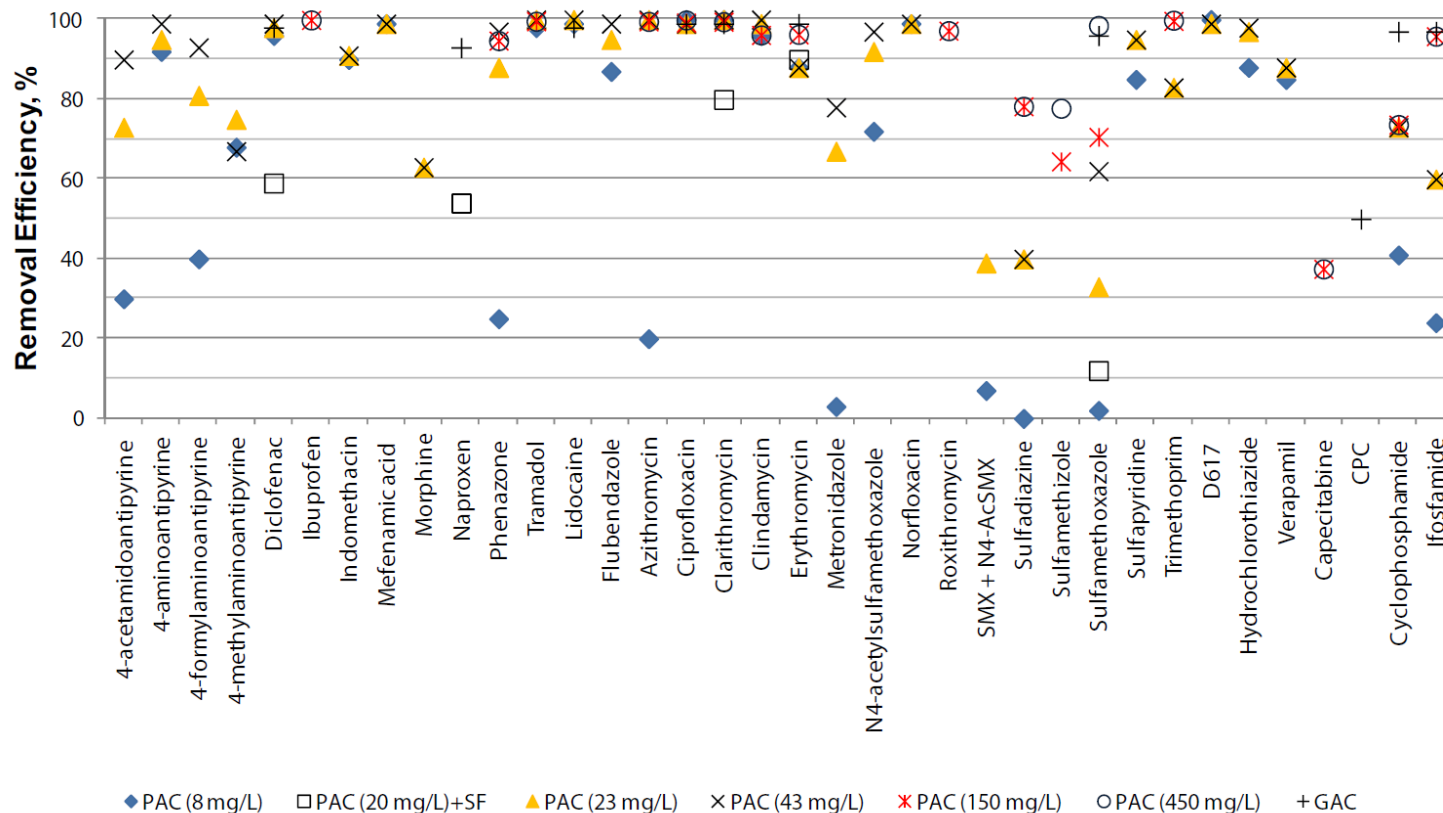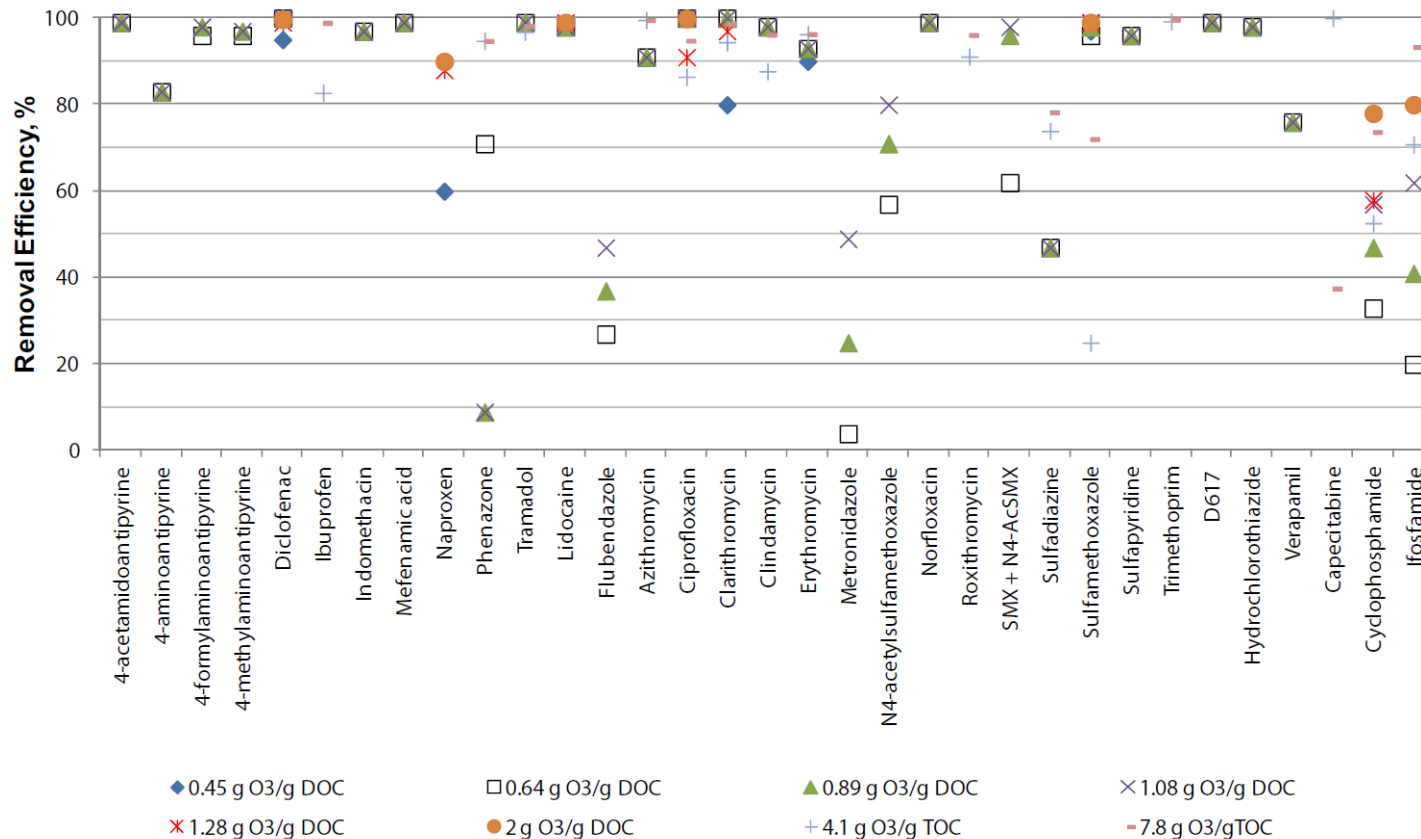**Fig. 2.** Observed removal efficiencies for a group of selected compounds in MBRs and CAS operating at different SRTs.
Data from: Kosma et al., 2010; Kovalova et al., 2012; PILLS Report, 2012, Nielsen et al., 2013; Beier et al., 2011; Kohler et al, 2012.

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Fig. 4. Observed removal efficiencies for a group of selected PhCs in HWW by PAC and GAS systems.
Data from: Kovalova et al., 2013; PILLS Report, 2012; Nielsen et al., 2013; Lenz et al., 2007b.

Verlicchi et al., 2015 *STOTEN*

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Fig. 6. Observed removal efficiencies for a group of selected PhCs in HWW by ozonation.
Data from: PILLS Report, 2012; Kovalova et al., 2013; Nielsen et al., 2013; Lenz et al., 2007b.
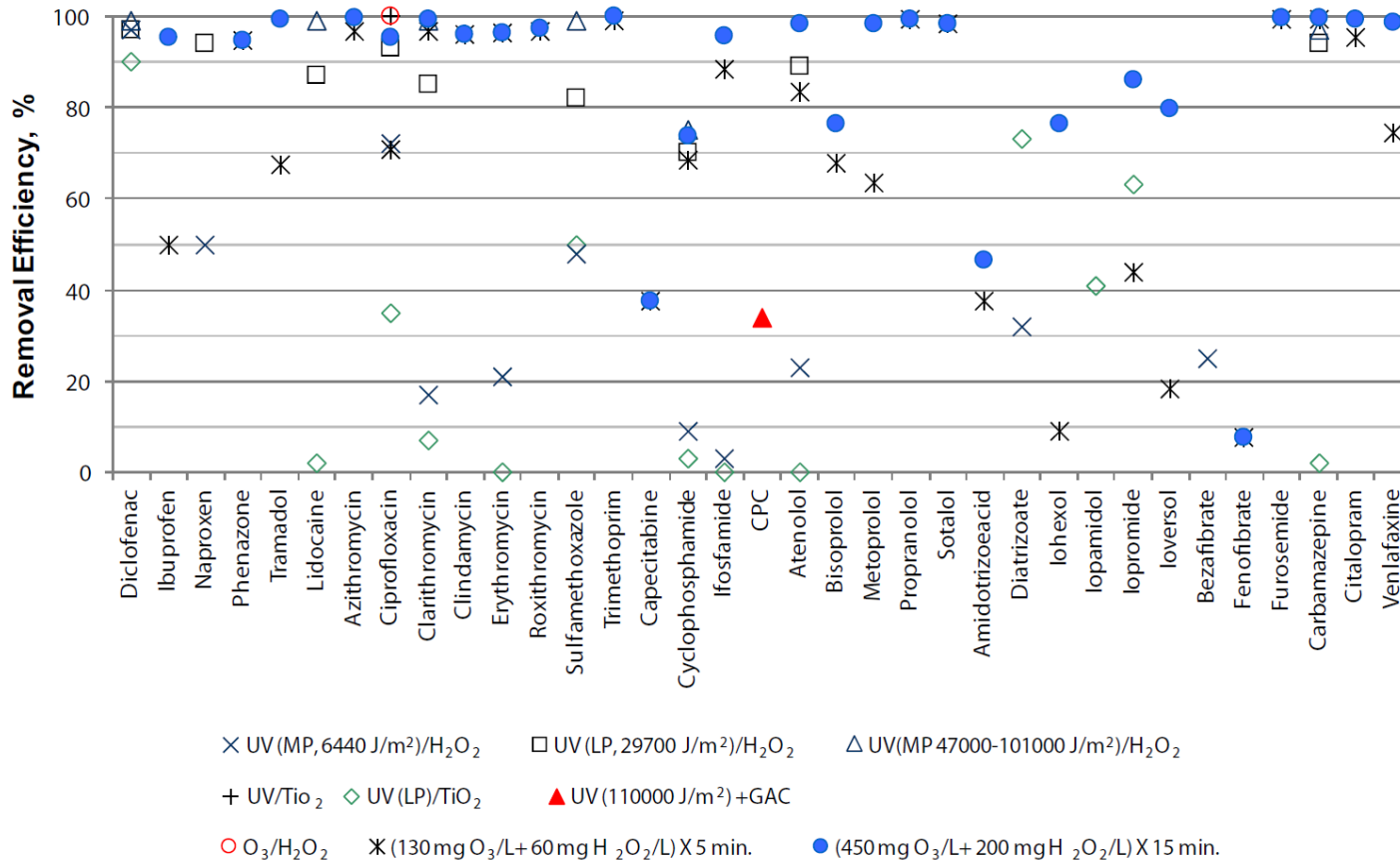
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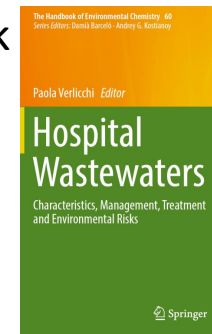
Know thy unknowns

DE: Department of Engineering Ferrara

Fig. 1 What is known and what is unknown referring to hospital effluent characterization, treatment and management (adapted from [5])
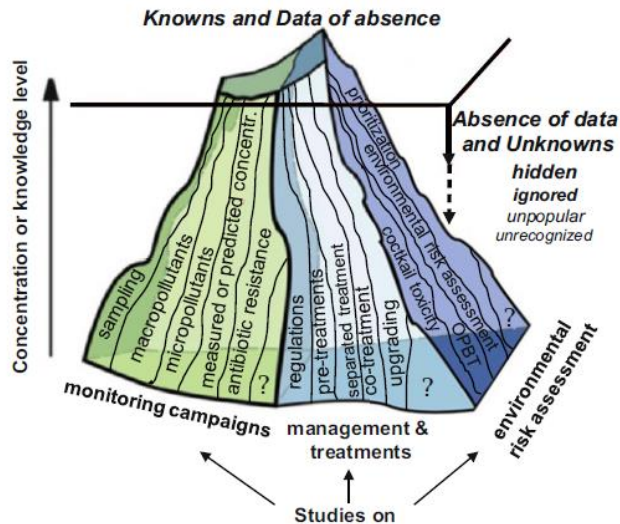
Verlicchi, 2018 Preface
Springer's book

The Handbook of Environmental Chemistry 60
Series Editors: Damià Barceló · Andrey G. Kostianoy

Paola Verlicchi *Editor*

Hospital Wastewaters
Characteristics, Management, Treatment and Environmental Risks

Springer

"There are known knowns. These are things we know that we know. There are known unknowns. That is to say, there are things that we know we don't know. But there are also unknown unknowns. There are things we don't know we don't know."
Donald Rumsfeld

There is the need/hope to reduce the unknowns size and enlarge knowns size!

Grazie per l'attenzione

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