

Trattamenti innovativi per il riuso degli effluenti dei depuratori

Relatore: ing. Danilo Spasiano, PhD



Politecnico
di Bari

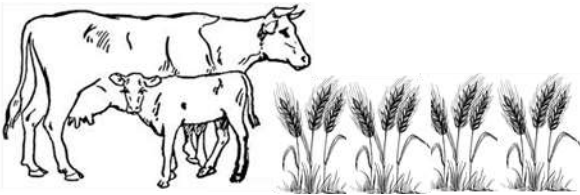


Contaminanti emergenti

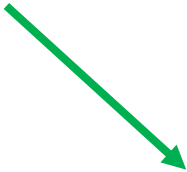
- 1) Sono spesso recalcitranti, ovvero molto resistenti ai processi decomposizione che normalmente avvengono in natura.
- 2) Per le loro caratteristiche di persistenza e, in molti casi, di tossicità sono composti particolarmente nocivi per la salute umana e per l'ambiente.
- 3) Il pericolo consiste nella crescente concentrazione negli ecosistemi terrestri e acquatici.

Qual è l'origine di tali inquinanti?

Allevamento/agricoltura



- Farmaci (antibiotici, antiinfiammatori);
- Metaboliti dei farmaci;
- Pesticidi;
- Erbicidi...



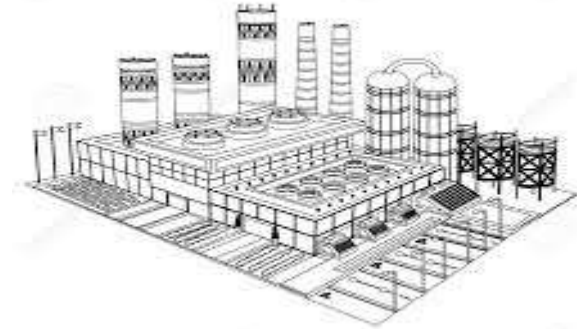
Agglomerati urbani



- Farmaci (antibiotici, antiinfiammatori);
- Metaboliti dei farmaci;
- Prodotti per la cura personale
- Prodotti per la pulizia della casa...



Industrie



- Solventi;
- Ritardanti di fiamma;
- Diossine, IPA, PCB...



Contaminanti emergenti

Concentrazione di inquinanti organici recalcitranti nei liquami (ng/L) e negli effluenti (ng/L) degli impianti di depurazione.

Selected ECs	Asia			North America			Europe		
	Influent	Effluent	Reference	Influent	Effluent	Reference	Influent	Effluent	Reference
Antibiotics									
Amoxicillin	<MQL–6516	<MQL–1670	[1–4]	n.r	<MQL	[5]	<MQL	<MQL–190	[6–8]
Azithromycin	1537–303,500	60.1–980	[1, 9]	61–2500	57–1300	[10]	77–1139	38–784	[11–13]
Ceftazidime	<MQL	<MQL	[1]	–	–	–	–	–	–
Chloramphenicol	<MQL–2430	<MQL–1050	[1, 4, 14, 15]	–	–	–	<MQL–319	<MQL	[16, 17]
Chlortetracycline	2333–15,911	<MQL–1986	[1, 4]	<MQL–310	<MQL–420	[10, 18]	n.r	<MQL	[8]
Ciprofloxacin	15.5–6453	<MQL–524.1	[1, 9, 19, 20]	<MQL–246,100	<MQL–620	[10, 18, 21, 22]	<MQL–13,625	<MQL–5692	[6, 11, 13, 23]
Clarithromycin	26–1854	4.79–637.1	[1, 20]	<MQL–8000	130–7000	[10, 22]	0.4–647	25–359	[11–13]
Clindamycin	23.8–26.6	2.94–4.24	[1]	–	–	–	<MQL–101	10–180	[16, 24]
Enrofloxacin	<MQL	<MQL	[25]	5.9–250	3.5–270	[10, 18]	<MQL–18	<MQL–636	[8, 26]
Erythromycin	111.4–403.3	70–186.6	[1]	–	–	–	<MQL–2130	<MQL–290	[6, 13, 23]
Erythromycin-H ₂ O	226–20,600	194.5–14,400	[1, 4, 20, 27]	<MQL–3900	<MQL–838	[10, 18, 22]	24–6755	15–2841	[11, 12, 17]
Lincomycin	<MQL–19,401	3.92–21,278	[1, 20, 28, 29]	<MQL–360	4.9–510	[10, 18, 21, 30]	<MQL–281	<MQL	[6]
Meropenem	264.8–433.6	27–67.9	[1]	–	–	–	–	–	–
Minocycline	730.9–3808	<MQL	[1]	<MQL	<MQL	[10]	–	–	–
Ofloxacin	54.8–1274	13.3–7870	[4, 20, 25, 31]	470–1000	<MQL–506	[21, 22]	n.r	71–8637	[8]
Oxytetracycline	<MQL–30,049	<MQL–2014	[1, 4, 20, 25]	<MQL–47,000	<MQL–4200	[10, 18, 21]	<MQL–7	<MQL–5	[32]
Sulfamethazine	<MQL–1814	<MQL–260.8	[1, 4, 20, 29]	<MQL–300	<MQL–363	[10, 18, 22]	<MQL–680	<MQL	[13, 16, 32]
Sulfamethoxazole	3.0–1389	<MQL–562	[1, 4, 20, 29, 33]	<MQL–4200	<MQL–1800	[5, 10, 18, 22]	<MQL–11,555	<MQL–544	[6, 11–13, 24, 34]
Tetracycline	<MQL–12,340	<MQL–1536	[1, 4, 20, 25, 27]	<MQL–48,000	<MQL–3600	[10, 18, 22]	<MQL–790	<MQL–850	[8, 13, 32]
Trimethoprim	19.5–570	3.7–772	[1, 14, 19, 20, 27]	<MQL–6796	<MQL–37,000	[5, 10, 18, 21]	<MQL–4342	<MQL–3052	[6, 11–13, 17, 24, 34]
Tylosin	<MQL	<MQL	[1, 4]	<MQL–1500	21–720	[10, 18]	<MQL	<MQL–173	[8, 16]
Vancomycin	962–43,740	<MQL	[1]	–	–	–	n.r	<MQL–8514	[8]
Antimicrobials									
Miconazole	<MQL–597	<MQL	[20, 25]	5.2–43	1.6–27	[10]	<MQL–337.9	<MQL–35.7	[35, 36]
Thiabendazole	<MQL–1.29	<MQL	[20, 25]	6.8–220	6.2–140	[10]	–	–	–
Triclocarban	341.1–8880	8.4–5860	[1, 28, 37]	340–4644	64–617	[10, 38]	97–140	n.r	[39]
Triclosan	1.3–2500	49.1–263.9	[1, 28, 37, 40]	14–6817	3.1–360	[10, 38, 41]	<MQL–5260	<MQL–430	[13, 34, 39]

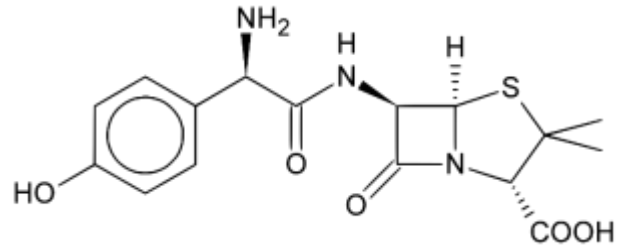


Selected ECs	Asia			North America			Europe		
	Influent	Effluent	Reference	Influent	Effluent	Reference	Influent	Effluent	Reference
NSAIDs									
Acetaminophen	67–147,700	<MQL–2568	[19, 20, 25, 33, 42]	21,000 –500,000	<MQL–62,000	[9, 10, 38]	<MQL –482,687	<MQL –24,525	[6, 13, 17, 34, 43]
Codeine	<MQL–242	<MQL–208	[25, 28]	77–5700	80–3300	[10]	150–32,295	9.7–15,593	[17, 23, 44]
Diclofenac	13–445	<MQL–69.2	[20, 25, 29, 40, 42]	140–2450	<MQL–359	[30, 41, 45]	<MQL–4869	<MQL–5164	[13, 17, 34, 43, 46]
Fenoprofen	<MQL–2260	<MQL–23.4	[25, 42]	<MQL	<MQL–405	[45, 47]	n.r	<MQL–280	[48]
Ibuprofen	34.8–55,975	<MQL–1890	[19, 20, 25, 28]	2500–45,000	16–14,600	[5, 10, 30, 41, 45]	<MQL–83,500	<MQL –24,600	[13, 17, 34, 43, 46]
Indomethacin	<MQL–449.4	<MQL–61.4	[25, 42]	<MQL–640	<MQL–507	[41, 45, 47]	<MQL–297	<MQL	[6]
Ketoprofen	<MQL–286	<MQL–183	[25, 28, 29]	60–150	40–90	[41]	<MQL–5700	<MQL–1620	[6, 13, 17, 48]
Naproxen	<MQL–7762	<MQL–159	[19, 25, 29, 42]	1700–25,000	<MQL–3500	[9, 10, 45, 47, 49]	<MQL –611,000	<MQL –33,900	[6, 13, 17, 34, 43]
Salicylic acid	167–16,900	<MQL–1426	[20, 42]	2820–27,800	<MQL–320	[41, 47]	<MQL –164,400	<MQL –10,100	[6, 17, 34, 43]
Beta-blockers									
Atenolol	<MQL –294,700	<MQL–518.6	[9, 19, 25, 29, 42]	500–2642	<MQL–14,200	[5, 9]	<MQL–33,106	<MQL–7602	[6, 13, 17, 24]
Metoprolol	<MQL–79,500	<MQL–268	[9, 14, 25, 29]	16–154	15–212	[9]	<MQL–4148	<MQL–5762	[6, 13, 17, 23, 24]
Propranolol	<MQL–9.56	<MQL–8.3	[14, 25]	–	–	–	<MQL–1962	<MQL–615	[6, 13, 17, 23, 24]
Anticonvulsants									
Carbamazepine	<MQL–18,500	<MQL–900	[20, 25, 28, 29, 42]	<MQL–440	28–551	[5, 9, 30, 45, 50]	<MQL–3110	<MQL–4596	[6, 13, 17, 24, 34, 46, 51]
Gabapentin	4825.5 –15,359	213–8855	[42]	n.r	1000 ± 900	[52]	6442–25,079	7651 –56,810	[17, 24]
Sulpiride	64.9–15,358.8	70.7–322.4	[14, 42]	n.r	33–137	[53]	113–1100	110–294	[54]
Artificial sweeteners									
Acesulfame	560–13400	5840–9147	[20, 40, 55]	90–2270	600–4330	[56]	12,000 –43,000	15,000 –46,000	[57]
Cyclamate	<MQL–66,400	<MQL–160	[20, 28, 55]	–	–	–	10,000 –65,000	<MQL–450	[57]
Saccharin	9310–389,000	<MQL–2370	[20, 28, 55]	1860–25,100	220–700	[56]	7100–18,000	<MQL–1800	[57]
Sucralose	1100–6520	1300–5490	[20, 28, 40, 55]	17,500–46,100	18,700 –48,900	[56]	2000–9100	2000–8800	[57]
Lipid regulators									
Bezafibrate	16.8–159	<MQL–51.4	[14, 58]	–	65–359	[45]	100–7600	<MQL–4800	[13, 23, 24, 34, 46, 59]
Clofibrac acid	<MQL–65	<MQL–44.9	[14, 20, 25, 29, 42, 58]	<MQL	<MQL–44	[45, 47]	<MQL–265.9	<MQL–91	[6, 17, 23, 34]
Gemfibrozil	<MQL–453.4	<MQL–535.2	[14, 20, 25, 29, 58, 60]	<MQL–36,530	<MQL–1493	[45, 47]	<MQL–17,055	<MQL–5233	[6, 23, 34, 43]



Selected ECs	Asia			North America			Europe		
	Influent	Effluent	Reference	Influent	Effluent	Reference	Influent	Effluent	Reference
Hormones									
Estrone	<MQL–132.5	<MQL–51.2	[29, 42, 61, 62]	8–52	<MQL–56	[5, 38, 41, 47]	2.4–670	<MQL–95	[13, 46, 63]
Estriol	<MQL–802	<MQL–30.2	[29, 42, 61]	<MQL–217	<MQL	[38, 64]	<MQL–660	<MQL–275	[13, 46, 63]
17 α -ethinylestradiol	<MQL–26.1	<MQL–13.1	[61]	<MQL–242	<MQL	[30, 64]	0.4–70	0.5–106	[13, 46]
X-ray contrast media									
Iohexol	63.8–124,966	2100–8700	[20, 37, 40, 42]	n.r	8623–9237	[65]	18,000 \pm 2000	1200 \pm 100	[66]
Iopromide	47.7–12,200	<MQL–7140	[20, 37]	–	–	–	<MQL–7500	<MQL–9300	[13, 59]
Iopamidol	82.8–45,611	<MQL–6520	[20, 37, 42]	–	–	–	4300 \pm 900	4700 \pm 1000	[67]
UV filters									
Octocrylene	<MQL	<MQL–153	[42, 68]	–	–	–	100–1200	<MQL–300	[69]
Oxybenzone	<MQL–2616.8	<MQL–772	[28, 42, 68, 70]	–	–	–	<MQL–7800	<MQL–700	[23, 69]
Stimulant									
Caffeine	759–60,500	13–51,700	[14, 19, 20, 28, 60]	5809–82,882	<MQL–37,200	[5, 9, 38]	102–113,200	30–13,900	[6, 43, 71]
Anti-itching									
Crotamiton	<MQL–1500	<MQL–1000	[25, 42, 72]	–	–	–	<MQL–140	<MQL–100	[51]
Insect repellent									
DEET	124–2341.9	21.6–324.8	[14, 20, 42, 58, 60, 72]	200–42,334	13–1663	[9, 30]	<MQL–6900	n.r	[73]
Plasticizer									
Bisphenol A	55.6–5850	<MQL–123	[25, 72]	595–2469	2–450	[9, 41]	<MQL–2376	16–1840	[46, 73]

Possibili soluzioni



Carboni attivo



Carboni attivo
esausto da rigenerare
o da smaltire

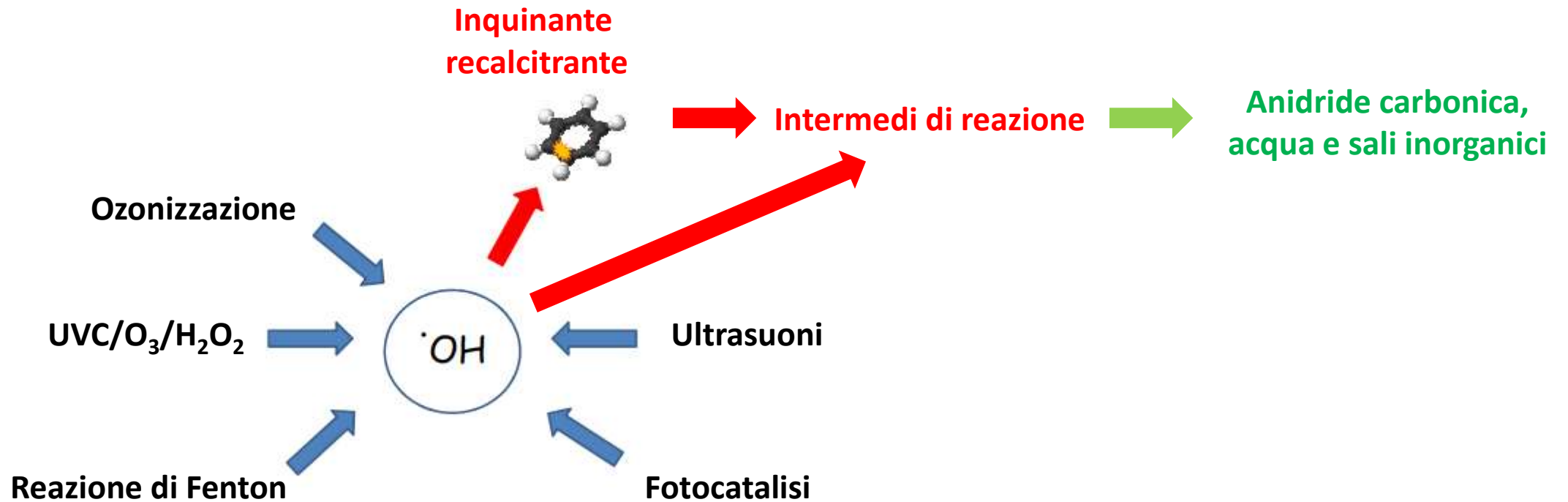
Osmosi inversa



Produzione di un
ritenato da trattare
prima dello
smaltimento

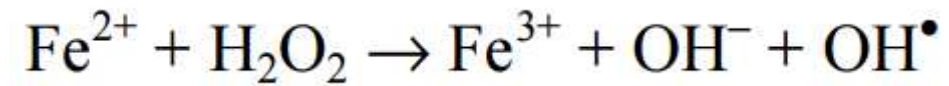
Processi di
rimozione avanzata

Processi di rimozione avanzata



Fenton

Una reazione scoperta (casualmente) nel 1894 da Henry John Horstman Fenton:

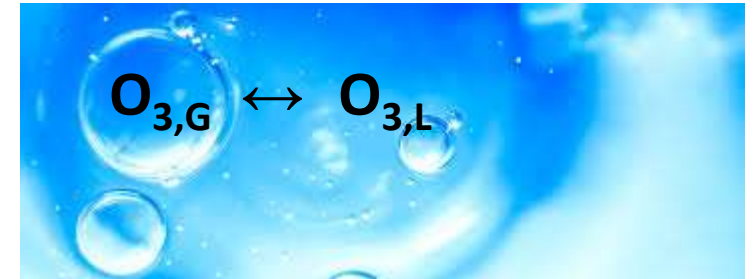
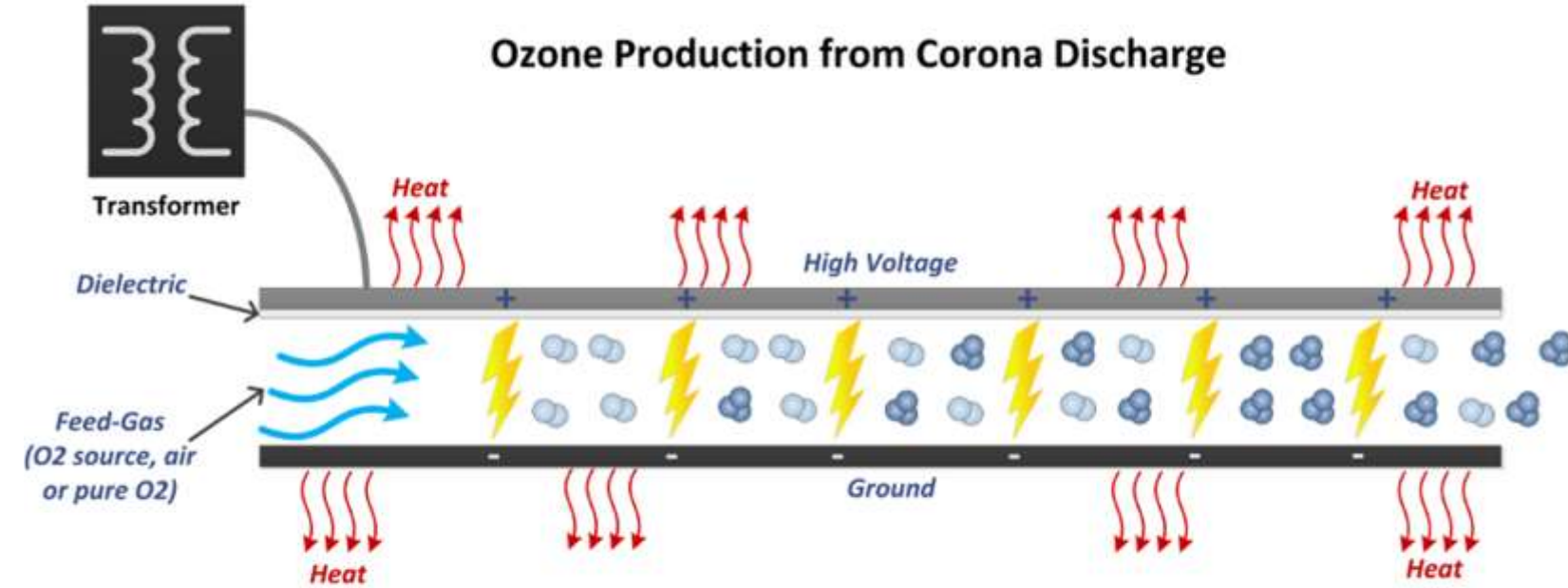


Reazione di Fenton

Si hanno
Elevati consumi di Fe(II), H₂O₂
Produzione di fanghi (Idrossidi di Fe(II) e Fe(III))

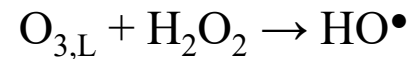
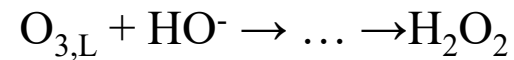
Ozonizzazione

Ozone Production from Corona Discharge



Ozone is formed via an electrical discharge that is diffused over an area using a dielectric to create a corona discharge. Oxygen passed through this corona discharge is converted to ozone.

Se il pH della soluzione è maggiore di 5



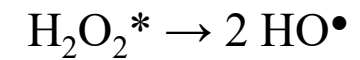
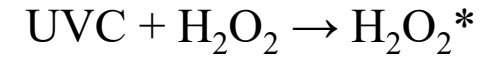
UVC/H₂O₂

Orange County, CA, USA

TROJAN UV
CASE STUDIES

GROUNDWATER REPLENISHMENT SYSTEM

Environmental Contaminant Treatment



Bastano 3-4 mg/L di acqua ossigenata

TrojanUV Solutions
for Water Scarcity:
Treating Trace Contaminants and
Disinfecting with UV in Water Reuse

Processi di rimozione avanzata alternativi

Processi di rimozione convenzionali:

UVC/H₂O₂

O₃

O₃/H₂O₂

O₃/UVC

O₃/H₂O₂/UVC

.....

Tali processi richiedono l'impiego di ozono, acqua ossigenata e radiazione UVC. Consumiamo reagenti la cui produzione richiede un grosso dispendio di energia e risorse.

Negli ultimi anni si stanno studiando altri processi di rimozione avanzata più «ecosostenibili»

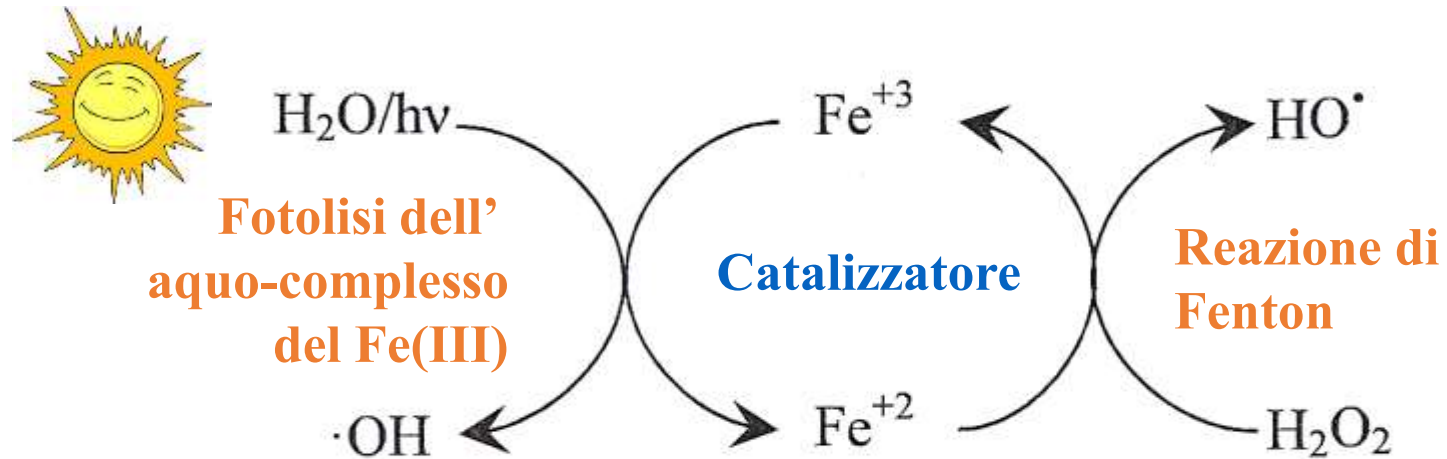
Tali processi sono caratterizzati da un basso consumo di reagenti e da un impiego di fonti di energia rinnovabile.

Un esempio sono i **processi di rimozione avanzata fotocatalitici**

foto-: usano una radiazione... in particolare, la radiazione solare;
-catalitici: usano un catalizzatore.



Foto-Fenton

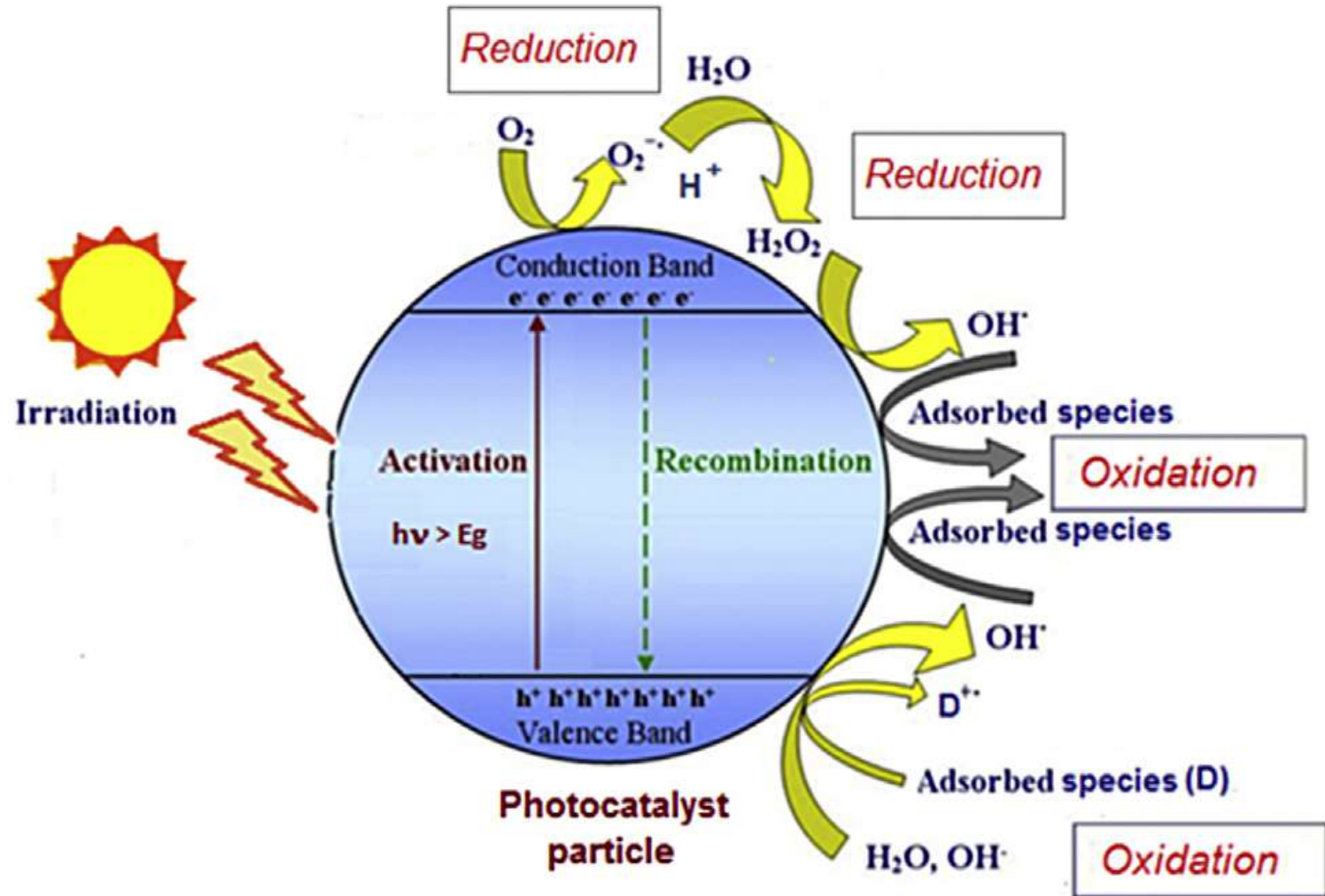
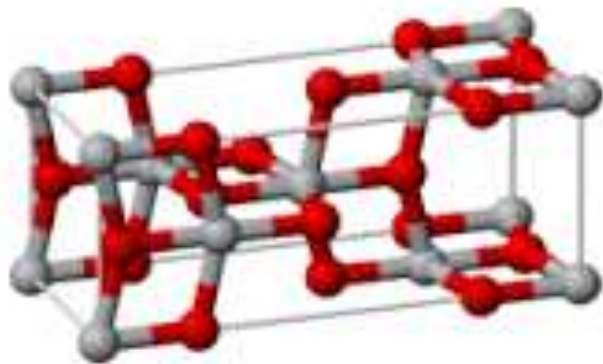


Il ferro è un catalizzatore perché non si consuma!

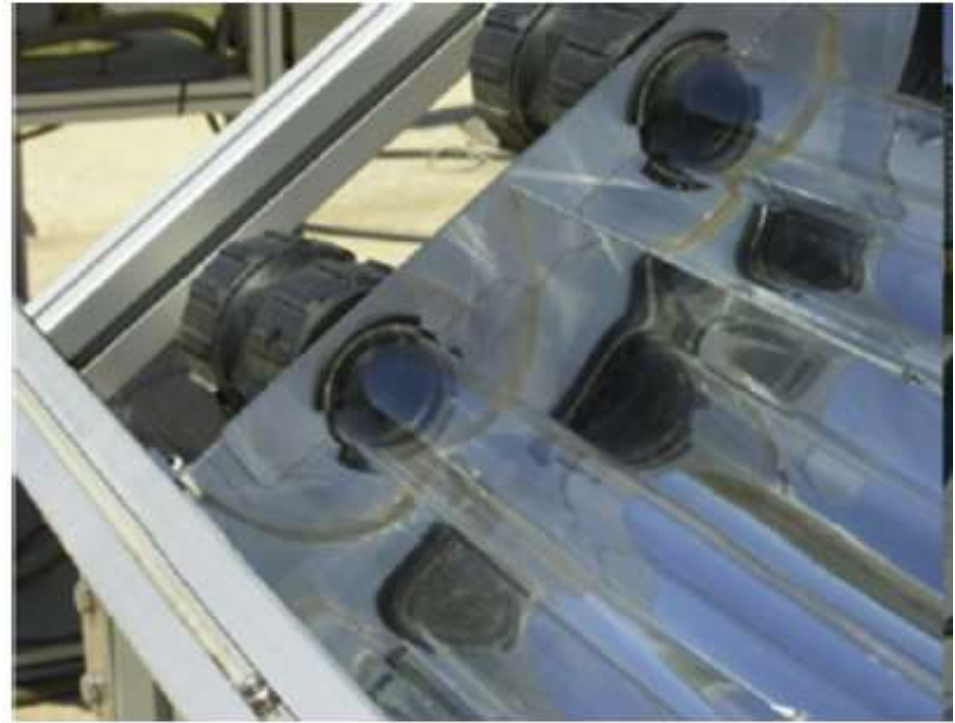
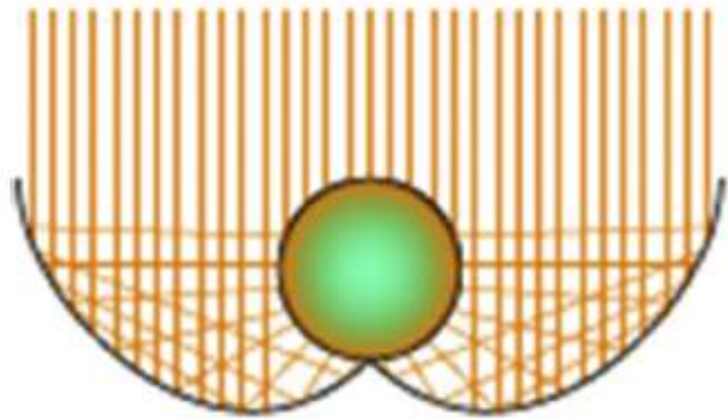
Il processo sfrutta una fonte di energia rinnovabile: la radiazione UV solare.

Biossido di titanio

Molti dei problemi legati all'adozione del foto-Fenton possono essere superati usando il biossido di titanio come catalizzatore e la radiazione solare UV-visibile.



Fotoreattori con 'compound parabolic collector'



Effect of advanced oxidation processes on the micropollutants and the effluent organic matter contained in municipal wastewater previously treated by three different secondary methods

Stefanos Giannakis ^a, Franco Alejandro Gamarra Vives ^a, Dominique Grandjean ^b, Anoyo Magnet ^c, Luiz Felipe De Alencastro ^b, César Pulgarin ^{a,*}

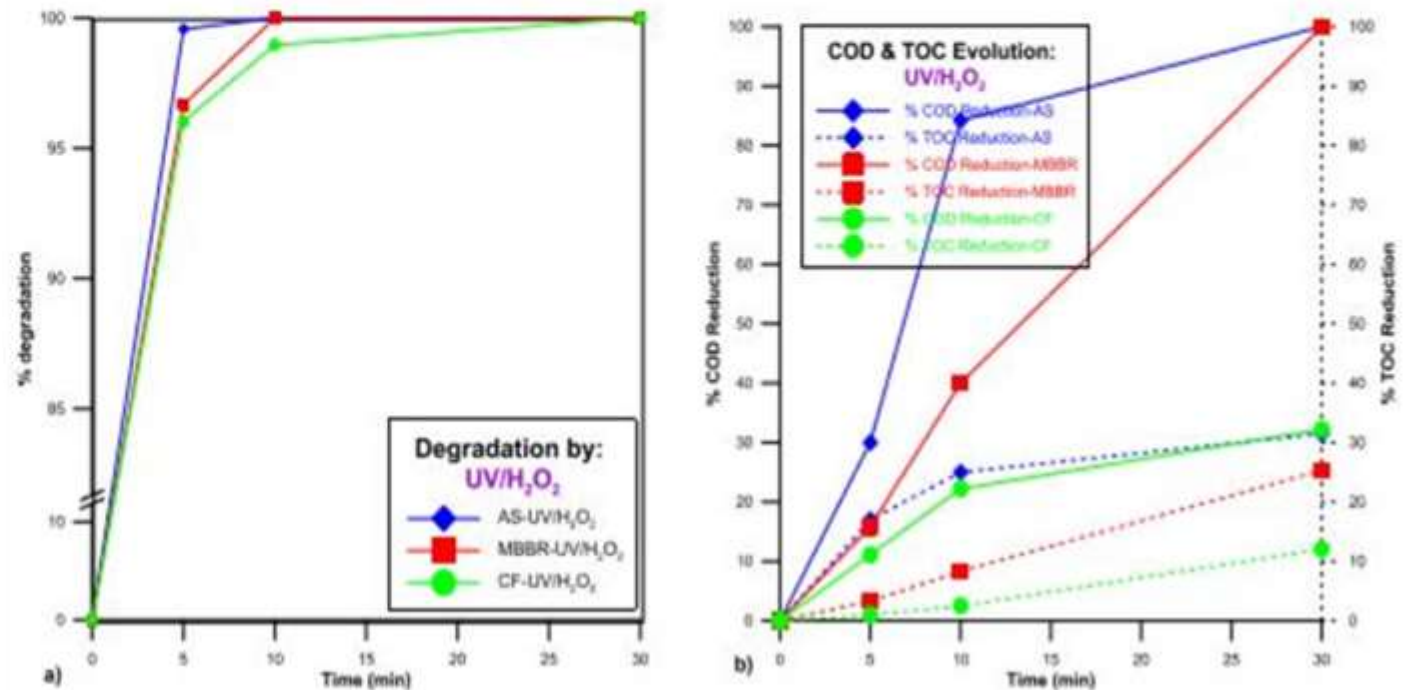
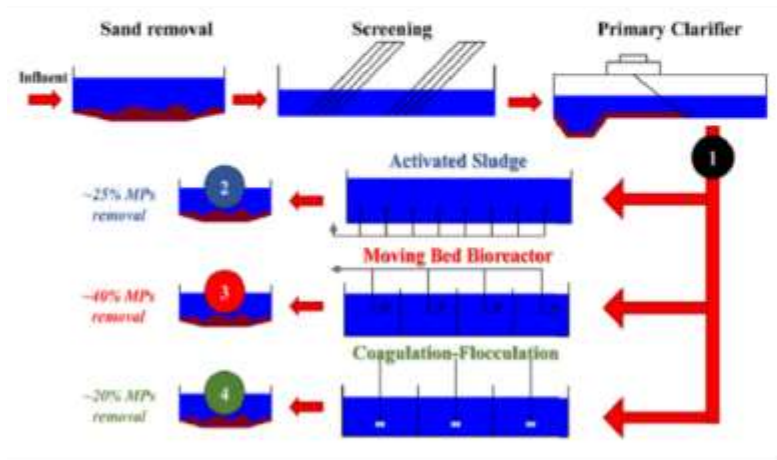
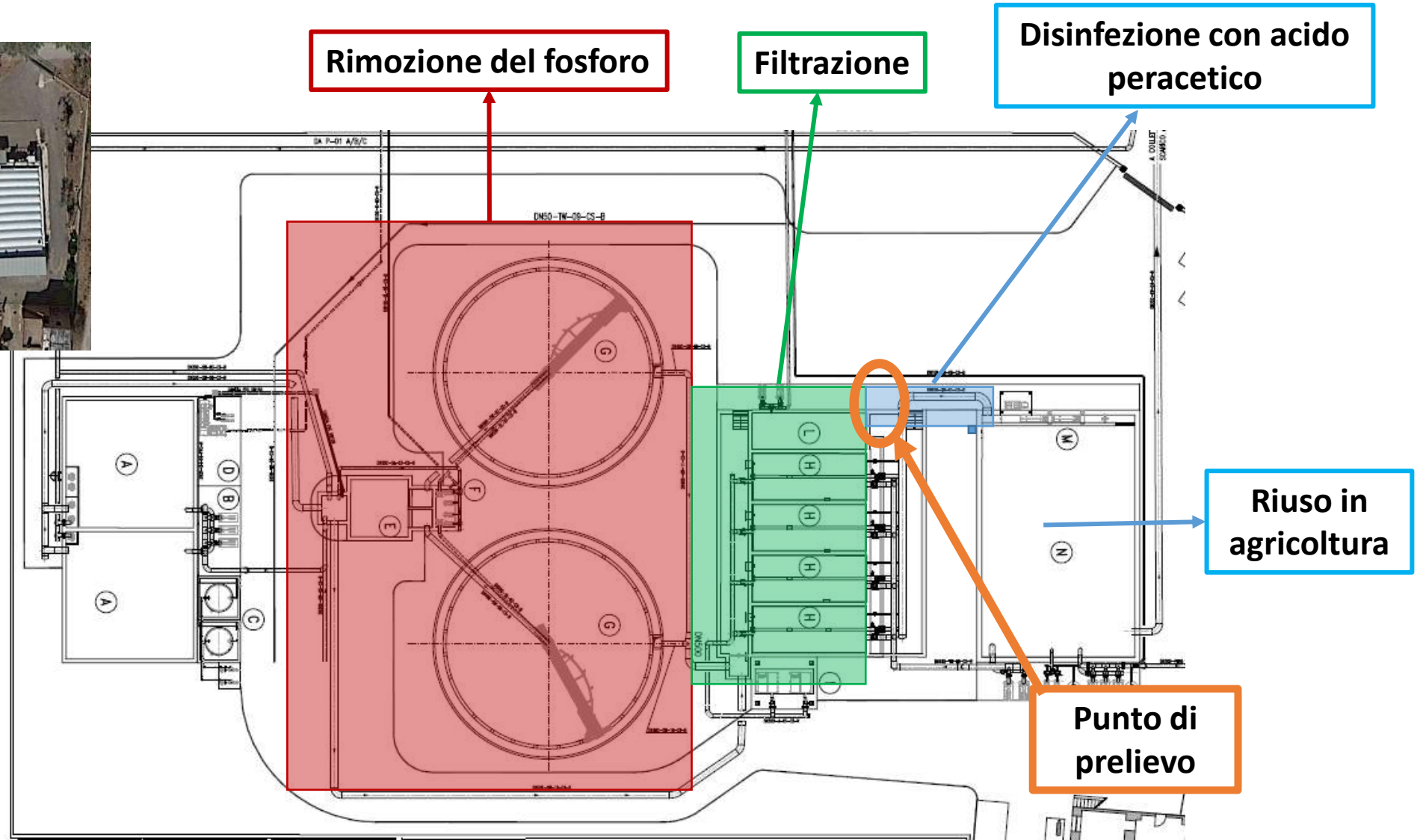


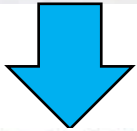
Fig. 3. UV/H₂O₂ treatment results. a) % degradation vs. time. b) % COD & TOC reduction vs. time.

Perché monitorare tutti i contaminanti recalcitranti quando potrebbe bastare monitorare il COD?

Trattamento terziario del depuratore di Gallipoli



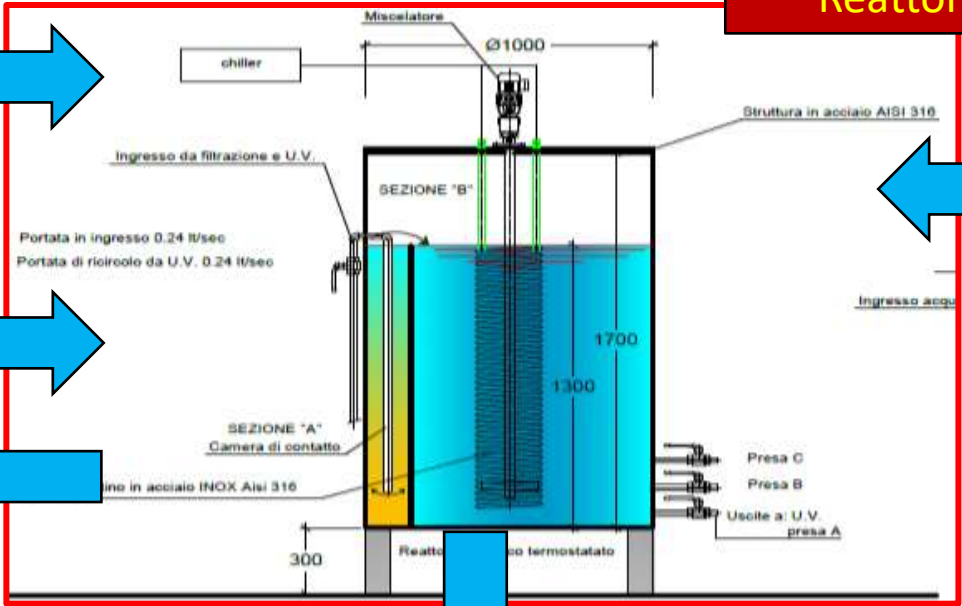
Stazione dosaggio H_2O_2



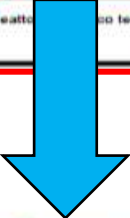
Stazione disinfezione UV



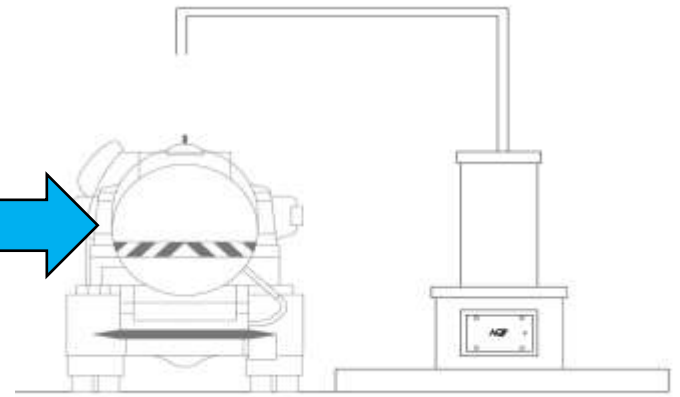
Reattore CSTR



Arrivo dalla filtrazione dell'affinamento



ACCUMULO



Grazie per la cortese attenzione



danilo.spasiano@poliba.it

Concentrazione di inquinanti organici recalcitranti nei fanghi di depurazione (ng/g ST)

Selected ECs	Sludge (ng/g dw)	Reference
Antibiotics		
Amoxicillin	<MQL	[1]
Azithromycin	<MQL-666	[2, 3]
Ceftazidime	–	–
Chloramphenicol	<MQL	[6]
Chlortetracycline	<MQL-1908	[6-8]
Ciprofloxacin	1400-4800	[9, 10]
Clarithromycin	<MQL-537	[2, 6]
Clindamycin	<MQL-6.54	
Enrofloxacin	7.6-11560	[8, 11]
Erythromycin	6-79	[6, 8]
Erythromycin-H ₂ O	–	–
Lincomycin	<MQL-4967	[8, 12, 13]
Meropenem	–	–
Minocycline	1000-2000	
Ofloxacin	1480-5760	[6, 10, 11]
Oxytetracycline	<MQL-3790	[7, 11]
Sulfamethazine	<MQL-54.58	[7]
Sulfamethoxazole	<MQL-84.4	[7, 11, 13]
Tetracycline	<MQL-466	[6, 11]
Trimethoprim	<MQL-13	[1, 2, 12, 13]
Tylosin	31-139	[8]
Vancomycin	<MQL	[8]
Antifungal/antimicrobials		
Miconazole	<MQL-2609	[2, 11, 12, 14]
Thiabendazole	<MQL-10.6	[11, 12]
Triclocarban	362-8460	[2, 11-13]
Triclosan	354-15600	[2, 10, 11, 13]
NSAIDs		
Acetaminophen	<MQL-586	[2, 6, 11, 12]
Codeine	<MQL-79	[11, 13] [2]
Diclofenac	<MQL-133	[2, 6, 11, 16]
Fenoprofen	<MQL	[11]
Ibuprofen	<MQL-3988	[10, 11, 13, 16]
Indomethacin	<MQL-77	[6, 11] [1]
Ketoprofen	<MQL-58.4	[6, 11-13]
Naproxen	<MQL-1022	[10, 11, 16]
Salicylic acid	<MQL-13743	[10, 16]

Selected ECs	Sludge (ng/g dw)	Reference
Beta-blockers		
Atenolol	<MQL-86	[1, 6, 11]
Metoprolol	<MQL-226	[6, 11]
Propranolol	<MQL-849	[2, 6, 11]
Anticonvulsants		
Carbamazepine	<MQL-50	[1, 2, 11, 13]
Gabapentin	–	–
Sulpiride	–	–
Artificial sweeteners		
Acesulfame	<MQL-166	[12, 13, 17]
Cyclamate	66.6-544	[13]
Saccharin	<MQL-19200	[12, 13, 17]
Sucralose	<MQL-1980	[12, 13, 17]
Lipid regulators		
Bezafibrate	17-64	[6]
Clobric acid	< MQL	[6, 11]
Gemfibrozil	< MQL-1192	[10, 11]
Hormones		
Estrone	<MQL-17.5	[16, 18]
Estriol	<MQL-49	[10, 16, 18]
17 α -ethinylestradiol	<MQL-17	[10, 16]
X-ray contrast media		
Iohexol	–	–
Iopromide	80 \pm 4	[20]
Iopamidol	–	–
UV filters		
Octocrylene	1060-9170	[21]
Oxybenzone	<MQL-790	[11, 12, 21]
Anti-itching		
Crotamiton	<MQL-62	[11] [6]
Insect repellent		
DEET	2-6	[6]
Stimulant		
Caffeine	<MQL-805	[2, 6, 11]
Plasticizer		
Bisphenol A	<MQL-4700	[11, 18, 22]



JRC SCIENCE AND POLICY REPORTS

Water Reuse in Europe

Relevant guidelines, needs for and
barriers to innovation

Laura Alcalde Sanz, Bernd Manfred Gawlik

2014

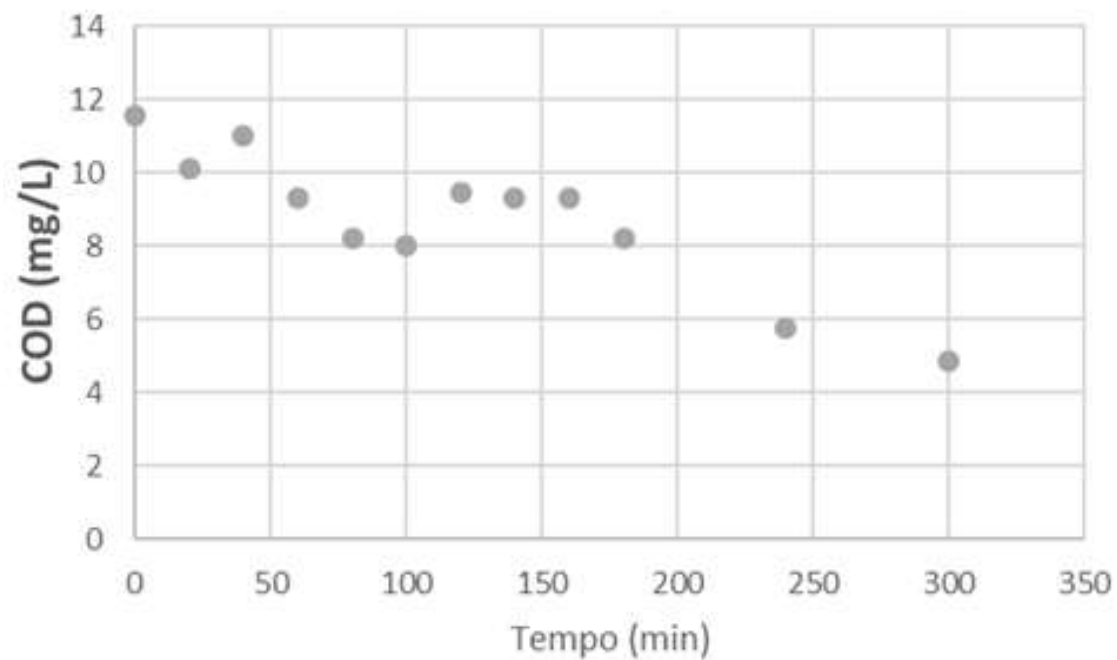
Chemical agents	Adverse effects
Pharmaceuticals and metabolites (antibacterials (sulfamethoxazole), analgesics (acetaminophen, ibuprofen), beta-blockers (atenolol), antiepileptics (phenytoin, carbamazepine), veterinary and human antibiotics (azithromycin), oral contraceptives (ethinyl estradiol))	
Personal care products (triclosan, sunscreen ingredients, fragrances, pigments)	Carcinogenic, teratogenic and/or mutagenic effects, risk for human health (cyanotoxins), bioaccumulation, toxicity to plants.
Household chemicals and food additives (sucralose, bisphenol A (BPA), dibutyl phthalate, alkylphenol polyethoxylates, flame retardants (perfluorooctanoic acid, perfluorooctane sulfonate)	Various effects, often unexplored.
Transformation products (NDMA, HAAs, and THMs)	
Industrial chemicals (PFCs, MTBE, solvents, ...)	Carcinogenic, teratogenic and/or mutagenic effects, risk for human health (cyanotoxins), bioaccumulation, toxicity to plants.
Pesticides, biocides and herbicides (e.g. atrazine, lindane, diuron, fipronil)	
Natural chemicals (hormones, phytoestrogens, geosmin, 2- methylisoborneol)	Various effects, often unexplored.



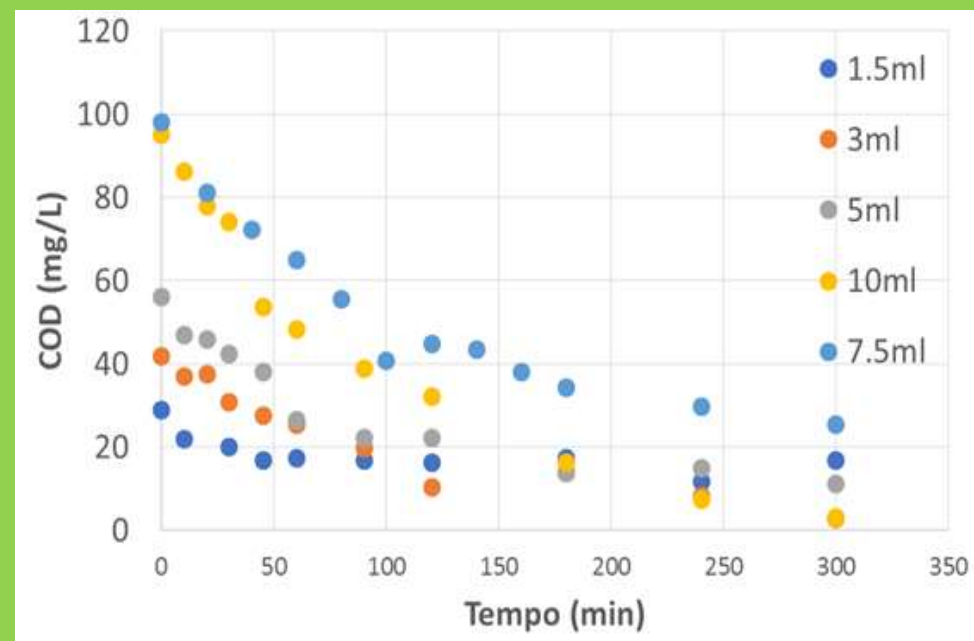
Dives in Misericordia Church in Rome (left); Cité de la Musique et des Beaux-Arts in Chambéry (right).

Risultati sperimentali

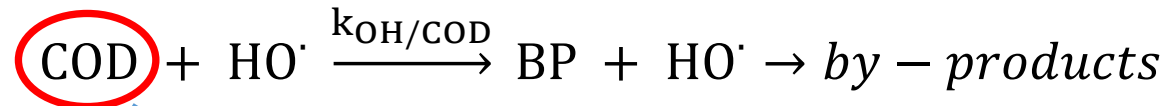
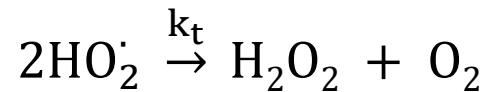
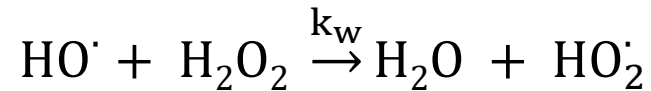
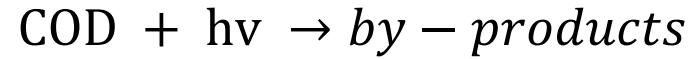
NO H₂O₂



CON H₂O₂



Modellazione del processo UV/H₂O₂



Schema di reazioni

Viene considerato al pari di uno pseudo-componente

Dopo aver fatto le ipotesi di stato stazionario sulle specie radicaliche (HO[·] and HO₂[·]) e dopo aver fatto un po' di passaggi matematici...

Modellazione del processo UV/H₂O₂ (2)

$$\frac{d[\text{H}_2\text{O}_2]}{dt} = -F[\text{H}_2\text{O}_2] - F[\text{H}_2\text{O}_2] \frac{k_{\text{OH},\text{H}_2\text{O}_2}[\text{H}_2\text{O}_2]}{k_{\text{OH},\text{H}_2\text{O}_2}[\text{H}_2\text{O}_2] + k_{\text{OH},\text{COD}}[\text{COD}]}$$

$$\frac{d[\text{COD}]}{dt} = -F[\text{COD}] - 2F[\text{H}_2\text{O}_2] \frac{k_{\text{OH},\text{COD}}[\text{COD}]}{k_{\text{OH},\text{H}_2\text{O}_2}[\text{H}_2\text{O}_2] + k_{\text{OH},\text{COD}}[\text{COD}]}$$

Dove:

$$k_{\text{OH},\text{H}_2\text{O}_2} = 2.7 \cdot 10^{-4} \text{mM}^{-1} \text{s}^{-1} \text{ (Buxton et al., 1988)}$$

$$F[\text{H}_2\text{O}_2] = \varphi_{\text{H}_2\text{O}_2}^{254} \cdot \frac{I_0^{254}}{V_{\text{TOT}}} \cdot (1 - \exp(-2.3 \cdot L \cdot A_{\text{TOT}})) \cdot g_{\text{H}_2\text{O}_2}$$

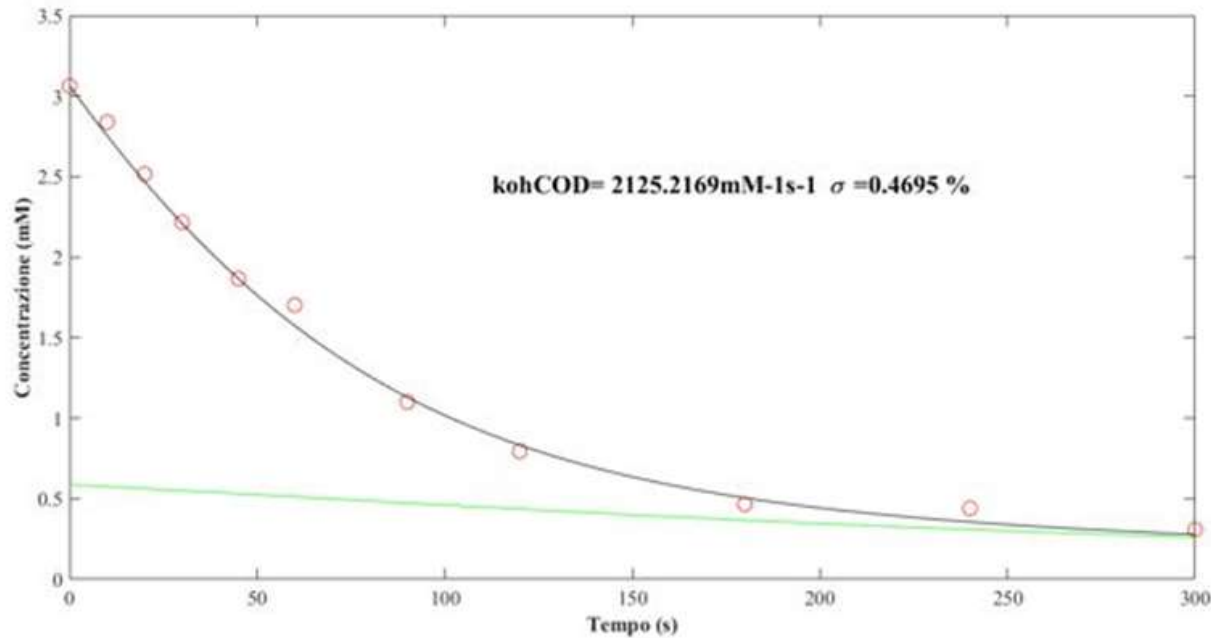
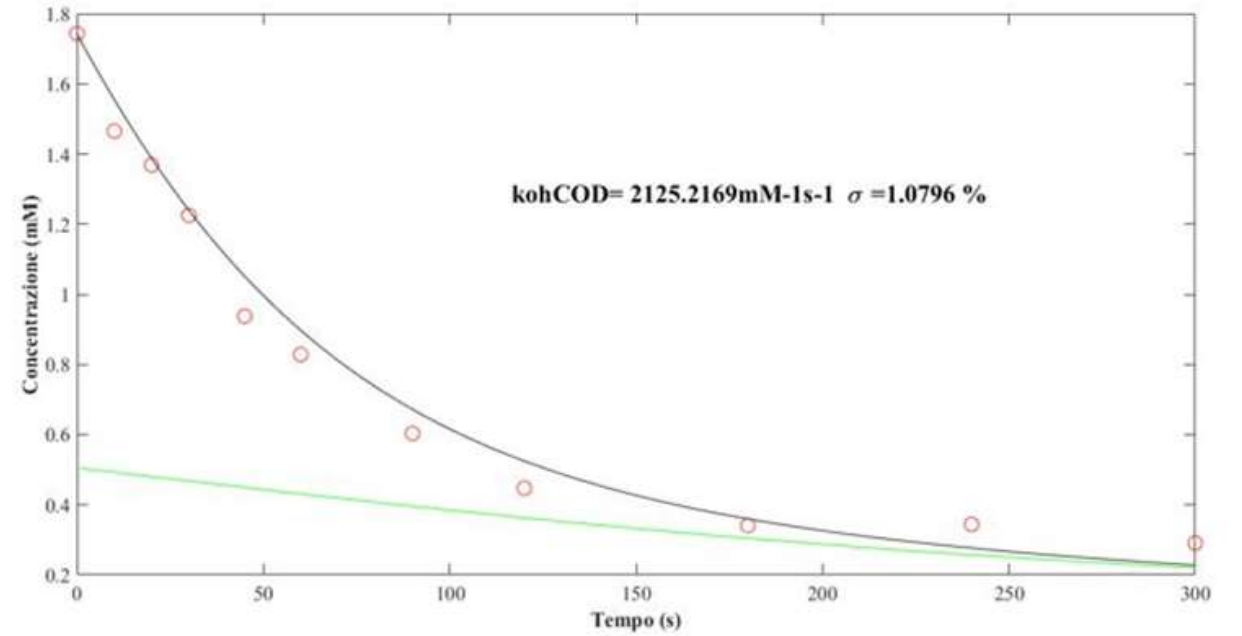
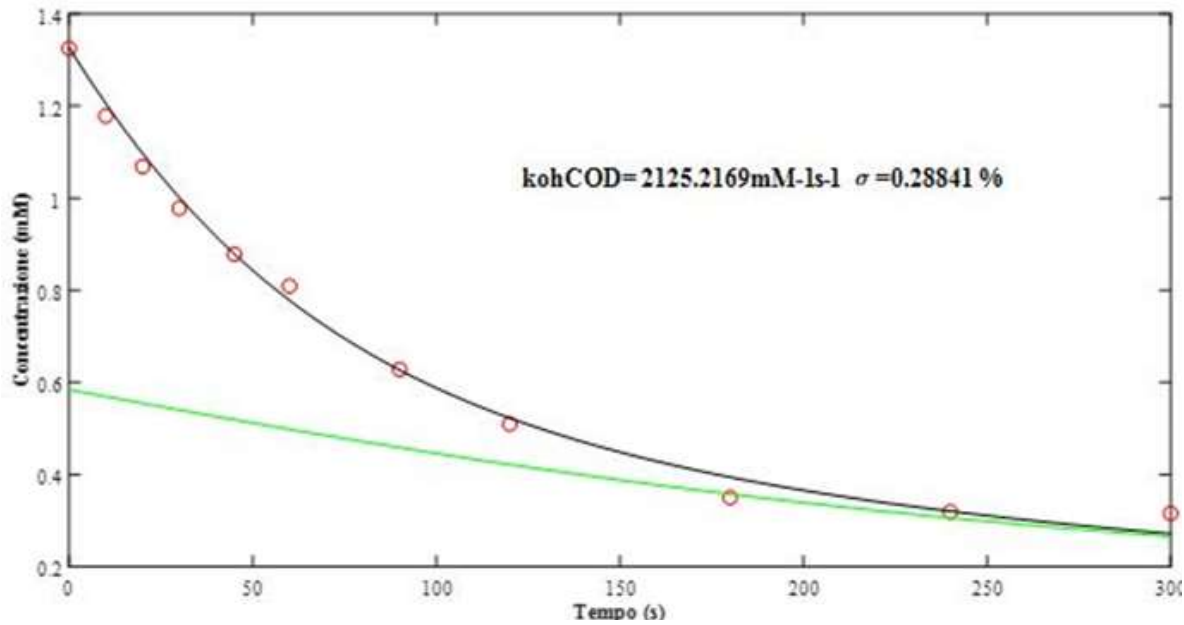
$$F[\text{COD}] = \varphi_{\text{COD}}^{254} \cdot \frac{I_0^{254}}{V_{\text{TOT}}} \cdot (1 - \exp(-2.3 \cdot L \cdot A_{\text{TOT}})) \cdot g_{\text{COD}}$$

$$A_{\text{TOT}} = (\varepsilon_{\text{H}_2\text{O}_2}^{254}[\text{H}_2\text{O}_2] + \varepsilon_{\text{COD}}^{254}[\text{COD}])$$

$$g_{\text{H}_2\text{O}_2} = \frac{\varepsilon_{\text{H}_2\text{O}_2}^{254}[\text{H}_2\text{O}_2]}{A_{\text{TOT}}}$$

$$g_{\text{COD}} = \frac{\varepsilon_{\text{COD}}^{254}[\text{COD}]}{A_{\text{TOT}}}$$

Parametro incognito

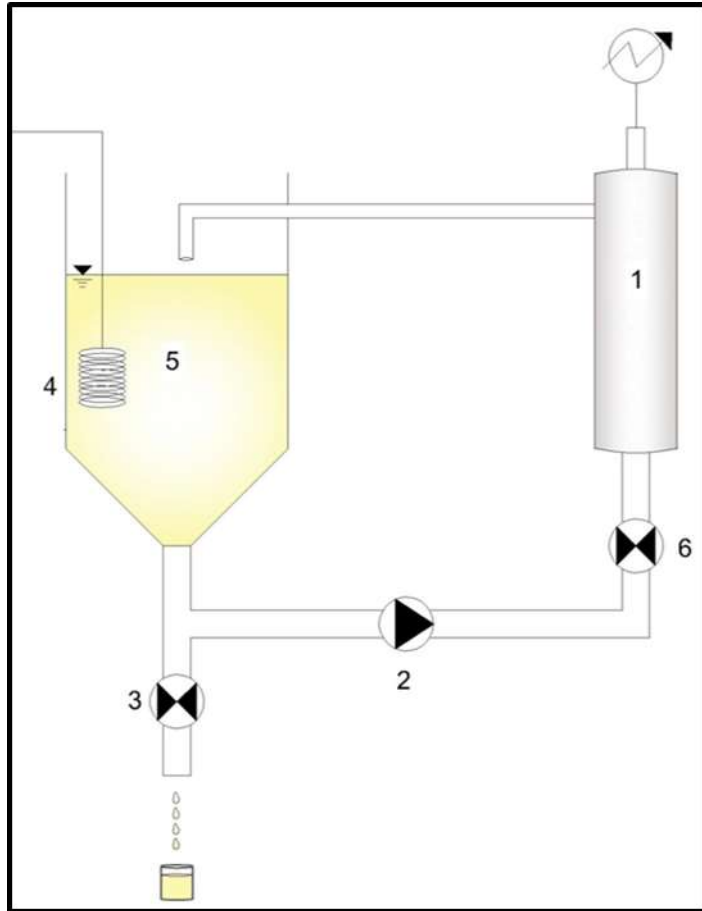


$$k_{OH,COD} = 2125 \text{ mM}^{-1} \cdot \text{s}^{-1}$$

La linea continua nera rappresenta la concentrazione teorica del COD totale, ovvero la somma del COD relativo ai composti inizialmente disciolti nell' effluente del depuratore (**linea verde**) ed il COD relativo alla presenza di H₂O₂

$$[\text{COD}]_{t,\text{total}} = [\text{COD}]_t + [\text{H}_2\text{O}_2]_t \cdot 0.48 \cdot \frac{34}{32}$$

Apparato sperimentale



- 1 Lampada UV
- 2 Pompa di ricircolo
- 3 Valvola per prelievi
- 4 Raffreddamento
- 5 Vasca di ricircolo
- 6 Valvola di regolazione

