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# Emerging pollutants in the environment: present and future challenges in biomonitoring, ecological risks and bioremediation

Maria Gavrilesu<sup>1,2</sup>, Kateřina Demnerová<sup>3</sup>, Jens Aamand<sup>4</sup>,  
Spyros Agathos<sup>5</sup> and Fabio Fava<sup>6</sup>

<sup>1</sup>“Gheorghe Asachi” Technical University of Iasi, Department of Environmental Engineering and Management, 73 Prof.dr.docent D. Mangeron Street, 700050 Iasi, Romania

<sup>2</sup>Academy of Romanian Scientists, 54 Splaiul Independentei, RO-050094 Bucharest, Romania

<sup>3</sup>Institute of Chemical Technology Prague, Department of Biochemistry and Microbiology, Technická 3, 166 28 Prague 6, Czech Republic

<sup>4</sup>Geological Survey of Denmark and Greenland (GEUS), Department of Geochemistry, Øster Voldgade 10, 1350 Copenhagen, Denmark

<sup>5</sup>Catholic University of Louvain, Faculty of Bioengineering, Agronomy and Environment, Earth and Life Institute, Place Croix du Sud 2, Box L7.05.19, B-1348 Louvain-la Neuve, Belgium

<sup>6</sup>Alma Mater Studiorum – University of Bologna, Department of Civil, Chemical, Environmental and Materials Engineering, Via Terracini 28, I-40131 Bologna, Italy

Emerging pollutants reach the environment from various anthropogenic sources and are distributed throughout environmental matrices. Although great advances have been made in the detection and analysis of trace pollutants during recent decades, due to the continued development and refinement of specific techniques, a wide array of undetected contaminants of emerging environmental concern need to be identified and quantified in various environmental components and biological tissues. These pollutants may be mobile and persistent in air, water, soil, sediments and ecological receptors even at low concentrations. Robust data on their fate and behaviour in the environment, as well as on threats to ecological and human health, are still lacking. Moreover, the ecotoxicological significance of some emerging micropollutants remains largely unknown, because satisfactory data to determine their risk often do not exist.

This paper discusses the fate, behaviour, (bio)monitoring, environmental and health risks associated with emerging chemical (pharmaceuticals, endocrine disruptors, hormones, toxins, among others) and biological (bacteria, viruses) micropollutants in soils, sediments, groundwater, industrial and municipal wastewaters, aquaculture effluents, and freshwater and marine ecosystems, and highlights new horizons for their (bio)removal. Our study aims to demonstrate the imperative need to boost research and innovation for new and cost-effective treatment technologies, in line with the uptake, mode of action and consequences of each emerging contaminant. We also address the topic of innovative tools for the evaluation of the effects of toxicity on human health and for the prediction of microbial availability and degradation in the environment. Additionally, we consider the development of (bio)sensors to perform environmental monitoring in real-time mode. This needs to address multiple species, along with a more effective exploitation of specialised microbes or enzymes capable of degrading endocrine disruptors and other micropollutants. In practical terms, the outcomes of these activities will build up the knowledge base and develop solutions to fill the significant innovation gap faced worldwide.

Corresponding author: Gavrilesu, M. (mgav@tuiasi.ro, mgav\_ro@yahoo.com)

## Introduction

Over recent decades, the world has experienced the adverse consequences of uncontrolled development of multiple human activities in, for example, industry, transport, agriculture, and urbanisation. The increase in living standards and higher consumer demand have amplified pollution of the air with, for example, CO<sub>2</sub> and other greenhouse gases, NO<sub>x</sub>, SO<sub>2</sub> and particulate matter, of water with a variety of chemicals, nutrients, leachates, oil spills, among others, and of the soil due to the disposal of hazardous wastes, spreading of pesticides, sludge, as well as the use of disposable goods or non-biodegradable materials and the lack of proper facilities for waste [1]. Emerging pollutants (EPs) encompass a wide range of man-made chemicals (such as pesticides, cosmetics, personal and household care products, pharmaceuticals, among others), which are in use worldwide and which are indispensable for modern society [2]. It has been shown that between 1930 and 2000, global production of anthropogenic chemicals increased from 1 million to 400 millions tons per each year [3]. Statistics published by EUROSTAT in 2013 reveal that, between 2002 and 2011, over 50% of the total production of chemicals is represented by environmentally harmful compounds (Table 1). Over 70% of these are chemicals with significant environmental impact [4].

Furthermore, human activities have resulted in contamination of water resources with biological micropollutants, such as viruses and bacteria. Such agents have generated renewed awareness due to their potential pathogenicity and are referred to as emerging or reemerging pathogens. Biological micropollutants, such as enteric bacteria, mycoplasmas, viruses and protozoa, are the source of many waterborne diseases and remain a major cause of death worldwide [5]. A significant proportion of these diseases are caused by classical water related pathogens, but the spectrum of disease is constantly increasing. Diseases which were thought to be controlled may later reemerge, as exemplified by the appearance of *Cryptosporidium*, *Legionella*, rotavirus and hepatitis A virus in water [6].

The aim of this paper is to provide a focus on fostering a new challenge driven approach to R&D needs in the field of biomonitoring, evaluation of the ecological risks, and bioremediation of emerging chemical (pharmaceuticals, endocrine disruptors, hormones, toxins, among others) and biological (bacteria, viruses) micropollutants in soils, sediments, groundwater, industrial and municipal wastewaters, aquaculture effluents, and freshwater and marine ecosystems. It also identifies future challenges for reducing the environmental impacts from emerging micropollutants, with greater emphasis on innovative and advanced tools and technologies for monitoring, prevention and mitigation of environmental and health pressures and risks.

## Emerging (micro)pollutants in the environment

Many chemical and microbial agents that were not traditionally considered contaminants can be found in various environmental

compartments and/or in areas where they were never used, mainly due to their persistence during long distance transport. The sources and pathways of these emerging contaminants can be increasingly associated with the waste and wastewaters resulting from industrial, agricultural or municipal activities [7]. Because of their particular characteristics, these pollutants require changes in the conventional approach to pollution prevention and control, although they result from similar domestic, commercial and industrial activities, as conventional contaminants [8]. Chemical micropollutants are often generated through degradation of organic compounds resulting in accumulation of persistent metabolites [9] or from the disposal of products such as pharmaceuticals in the natural environment. The increased appearance of biological pollutants during the production and distribution of drinking water may be related to several factors including changes in human demographic behaviour. Also, changes in agricultural practice towards intensive farming and spreading of manure or sludge on agricultural fields may cause leaching to surface and groundwater and health problems [10,11].

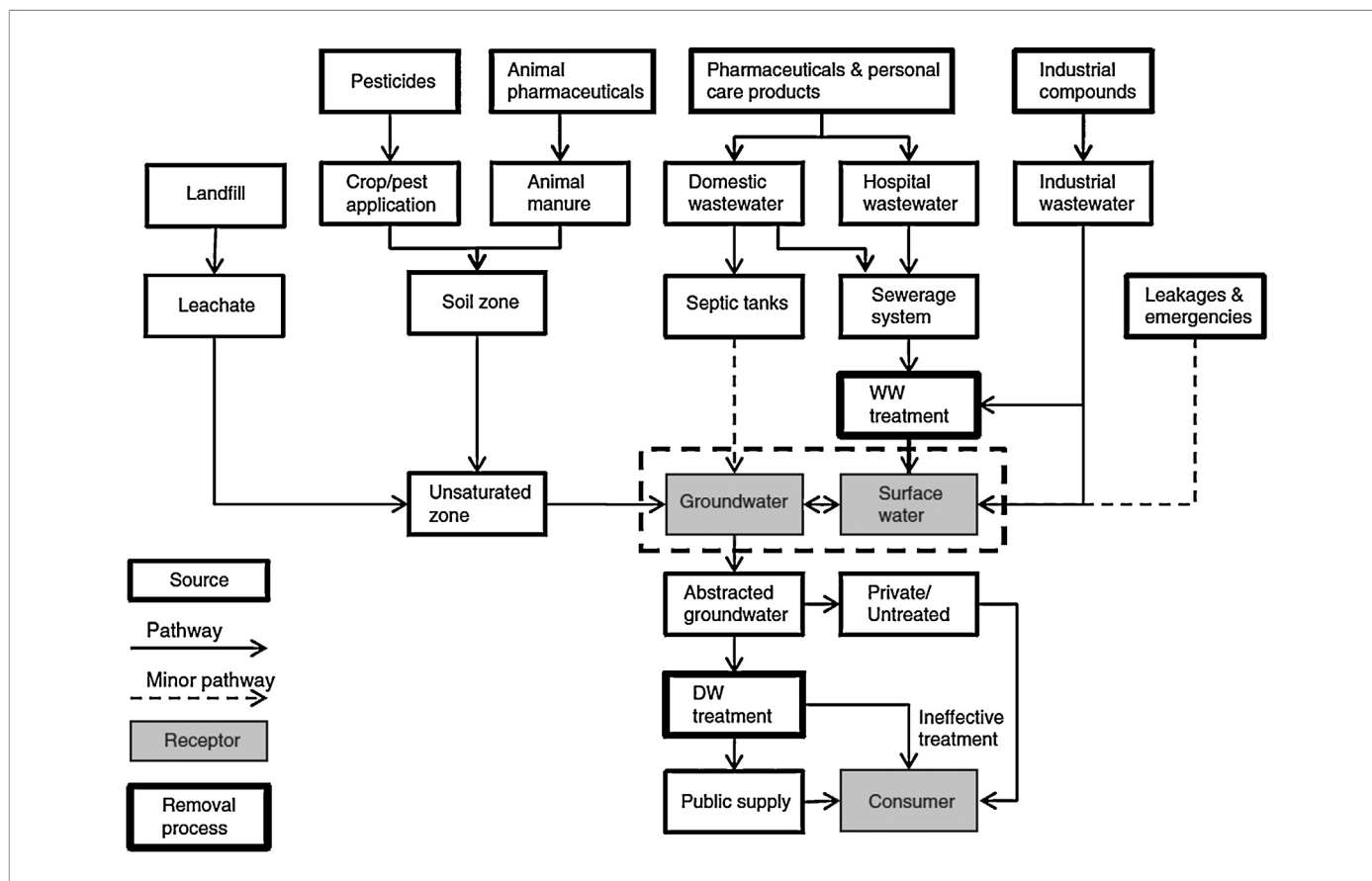
Pesticides continue to be detected in surface and groundwater, although some of them have gradually been banned and replaced by environmentally friendly substitutes [12,13]. Currently, research interest is directed toward pesticide metabolites, often detected in water sources and wastewater effluents at higher concentrations, being also biologically active and toxic [14,15]. Consequently, there is high interest in some categories of environmental contaminants, with particular chemical structures and properties, which interfere with endogenous hormone systems. These contaminants, denoted endocrine disruptors, are poorly inventoried and regulated and insufficient information exists regarding their occurrence, fate and impact in the environment. Also, because many have pharmaceutical, personal care and household uses (hormones, glucocorticoids, analgesics such as ibuprofen, estriol, additives in drugs and cosmetics such as siloxanes and parabens, and household cleansers), more information about their ecotoxicological effects is essential for their analysis and removal. Apart from the above endocrine disruptors, other products such as fire-retardants, heavy metals (cadmium, lead or mercury), widely used industrial chemicals (Bisphenol A) and some pesticides have been shown to impact natural endocrine systems [16–19].

Consequently, endocrine disruptors and their degradation intermediates constitute a topic of extensive research [16,17]. Pertinent studies indicate that toxicity data are not yet available for these compounds, which originate from various sources, among which the most relevant are direct releases into waters, wastewater treatment plants (WWTPs) (effluent and sludge), seepage from septic tanks, landfilling areas, and surface water run-off [20]. Pharmaceuticals, for example, are more concentrated in the wastewater discharged from hospitals, long-term care facilities and other medical facilities [21–23].

TABLE 1

Production of environmentally harmful chemicals, by environmental impact class in EU-27 (million tons) [4]

	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
<b>Total production of chemicals</b>	330	333	349	351	355	362	338	292	339	347
<b>Environmentally harmful chemicals, total</b>	176	179	191	193	192	194	182	162	184	188
<b>Chemicals with severe chronic environmental impacts</b>	30	31	34	35	36	36	32	30	34	35

**FIGURE 1**

Schematic pathways of some emerging pollutants from sources to receptors [12].  
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Although studies and reviews can be found in the literature on sources, occurrence, environmental behaviour and fate of emerging contaminants [12–14,24,25], the pathway of these pollutants from sources to receptors continues to be an essential subject for advanced research. This is because information is still poor, mainly due to the problems generated by the physico-chemical properties of target compounds, and the complexity of environmental characteristics, among others, which may determine an unexpected behaviour of the emerging pollutants in air, water, or soil [12,16,18,24]. To illustrate this situation, a schematic view of the routes by which some emerging pollutants enter various receptors (groundwater, surface water, consumers) was provided by Stuart *et al.* [12] (Fig. 1). Other studies have been carried out on the pathways of EP, in particular from humans and animals to environmental components [12,24,26,27].

#### Micropollutants in water and WWTPs

Overall, chemical and biological micropollutants are enriched in WWTPs [28], which should make these micropollutants easier to tackle and diminish the rate of their release into the environment. Literature surveys on the occurrence of various EPs in effluents from Sewage Treatment Plants (SPTs) or WWTPs reaching the natural surface waters have discussed an attenuation of their concentration in the natural receptors due to migration or retention by sorption, volatilisation, or dispersion, with transfer from

one environmental compartment to another [1,12,16,18,24,25]. Data on the occurrence and concentrations of some pharmaceuticals in effluents from STPs, WWTPs and surface waters, gathered from a literature survey [24] show that EP concentrations in effluents fluctuate widely (Table 2), most probably due to different doses applied in various regions and inconsistent efficiency of wastewater treatment.

Nevertheless information concerning the nature, variability, transport and fate of these compounds in wastewater and treatment facilities must be improved, because knowledge in this area is still limited. There are few studies devoted to monitoring and understanding the processes involved in conventional or innovative wastewater treatment in eliminating or reducing the concentrations of a large diversity of emerging pollutants at wastewater facilities [29,30].

Several studies on emerging contaminants have focused on surface waters because they are expected to contain significant concentrations from sources such as WWTP discharges, due to a variable potential removal of wastewater treatment for certain groups of EPs [12,14,15]. An interesting analysis has been elaborated by Deblonde *et al.* [25], describing concentrations found in wastewater influents and effluents (after treatment), focusing on phthalates, PCBs, PAHs, Bisphenol A and pharmaceuticals used for human health as well as disinfectants and hormones (Table 3).

TABLE 2

**Data on the occurrence and concentration levels of various emerging pollutants in effluents from WWTP/STP and freshwater rivers, canals [24]** Permission of Elsevier, License number 3278700294358, November 30, 2013.

Compounds	Range in concentration (ng/l)						Lowest PNEC (ng/l)	Percentage of parent compound excreted
	North America		Europe		Asia and Australia			
	Effluent, WWTP/STP	Freshwater-rivers, canals	Effluent, WWTP/STP	Freshwater-rivers, canals	Effluent, WWTP/STP	Freshwater-rivers, canals		
<b>Antibiotics</b>								
Trimethoprim	<0.5–7900	2–212	99–1264	0–78.2	58–321	4–150	1000	≥70
Ciprofloxacin	110–1100	–	40–3353	–	42–720	23–1300	20	≥70
Sulfamethoxazole	5–2800	7–211	91–794	<0.5–4	3.8–1400	1.7–2000	20,000	6–39
<b>Analgesics and anti-inflammatory</b>								
Naproxen	<1–5100	0–135.2	450–1840	<0.3–146	128–548	11–181	37,000	–
Ibuprofen	220–3600	0–34.0	134–7100	14–44	65–1758	28–360	5000	≤5
Ketoprofen	12–110	–	225–954	<0.5–14	–	<0.4–79.6	15.6 × 10 <sup>6</sup>	–
Diclofenac	<0.5–177.1	11–82	460–3300	21–41	8.8–127	1.1–6.8	10,000	6–39
Salicylic acid	47.2–180	70–121	40–190	<0.3–302	9–2098	–	–	6–39
Mefenamic acid	–	–	1–554	<0.3–169	4.45–396	<0.1–65.1	–	–
Acetaminophen	–	24.7–65.2	59–220	12–777	1.8–19	4.1–73	9200	≤5
<b>Antiepileptics</b>								
Carbamazepine	111.2–187	2.7–113.7	130–290	9–157	152–226	25–34.7	25,000	≤5
<b>Beta-blockers</b>								
Propranolol	–	–	30–44	20	50	–	500	<0.5
Atenolol	879	–	1720	314	–	–	10 × 10 <sup>6</sup>	50–90
<b>Blood lipid regulators</b>								
Clofibril acid	ND–33	3.2–26.7	27–120	1–14	154	22–248	12,000	–
Gemfibrozil	9–300	5.4–16	2–28,571	–	3.9–17	1.8–9.1	100,000	–
Bezafibrate	ND–260	–	233–340	16–363	–	–	100,000	40–69

ND—not detected; dashed line—not reported.

It is unlikely that the conventional treatment of wastewater or drinking water will be able to remove estrogens, androgens or detergent components due to the chemical structural stability of these compounds, as well as their low bioavailability, which affects biodegradation. In addition, municipal sewage sludge is also a repository for these emerging pollutants and only recently has there been an effort to assess their occurrence and biotreatment potential [31].

Bacteria and enteric viruses are abundant in sewage and the latter have also been detected in the effluents of WWTPs [32]. Because treated wastewater and untreated sewage may eventually drain into water resources, biological micropollutants threaten public health, and the development of new and cost-effective technologies for disinfection of water is therefore needed. It is also acknowledged that the treatment of these pollutant species requires the addition of advanced procedures, such as chemical degradation assisted by specialised microorganisms, or UV light action. Recently it was shown that biologically produced zerovalent silver nanoparticles (bio-Ag<sup>0</sup>) can be a very effective disinfectant which may be used at WWTPs, a technology which deserves further attention [33,34].

#### Micropollutants in freshwater resources

The consequences of micropollutants in aquatic ecosystems are of particular concern, because living organisms present here are subjected to exposure with potential consequences for future generations. The problem becomes more difficult when micropollutants are present in freshwaters (surface and groundwaters) at low (trace) concentrations (nanogram or microgram/L), depending on their source (Fig. 2) [14].

In this case, their detection and removal become difficult but important, because they put at risk the reuse of treated wastewater as well as the sustainability of water cycle management. Also, they are able to pose adverse risks for human health, associated with the development of pathogen resistance, endocrine disruption, and

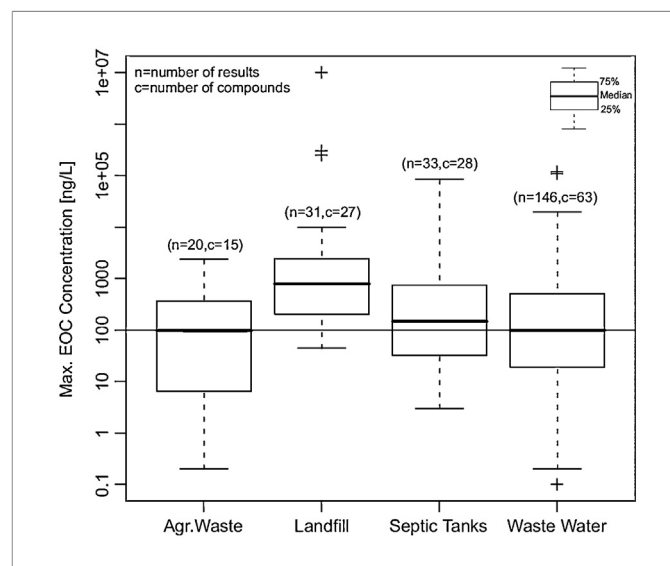


FIGURE 2

Maximum concentration of some emerging contaminants originating from major sources (agricultural waste, landfills, septic tanks, industrial and municipal wastewater) in groundwater (solid horizontal line is the EU drinking water limit for pesticides) [14].

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TABLE 3

**Concentrations of some emerging pollutants ( $\mu\text{g/L}$ ) in influent and effluent of wastewater treatment plants (WWTPs) [25] Permission of Elsevier, License number 3278701010264, November 30, 2013.**

Pharmaceuticals compounds	Molecules	Influent						Effluent						Removal rate (%)
		Means	RSD	Median	Min	Max	n	Means	RSD	Median	Min	Max	n	
<b>Antibiotics</b>	Clarithromycin	0.344					2	0.15					2	56.4
	Ciprofloxacin	0.62	1.48	0.157	0.09	5.524	13	0.234	0.649	0.021	0.007	2.378	13	62.3
	Doxycyclin	0.65	0.94	0.098	0.067	2.48	10	0.420	0.426	0.227	0.038	1.09	9	35.4
	Erythromycin	0.58	0.242	0.56	0.346	0.83	3	0.297	0.237	0.2305	0.109	0.62	4	48.8
	Erythromycin-H <sub>2</sub> O	2.025					2	0.59					2	70.9
	Methronidazole	0.09					1	0.055					1	38.9
	Norfloxacin	0.115	0.056	0.0905	0.066	0.25	12	0.0526	0.0985	0.0195	0.007	0.33	10	54.3
	Ofloxacin	0.482	0.884	0.156	0.007	2.275	6	0.171	0.317	0.0485	0.007	0.816	6	64.5
	Roxithromycin	0.78	0.737	0.81	0.0272	1.5	3	0.472	0.435	0.54	0.008	0.87	3	39.5
	Sulfamethoxazole	0.32	0.248	0.2905	0.02	0.674	10	0.264	0.150	0.243	0.07	0.62	11	17.5
	Sulfapyridin	0.492					1	0.081					1	83.5
	Tetracyclin	48					1	2.375					2	95.1
<b>Antiepileptics</b>	Trimethoprim	0.43	0.401	0.251	0.0535	1.3	15	0.424	0.363	0.32	0.04	1.34	17	1.4
	Carbamazepine	0.732	0.869	0.25	0.0819	1.68	6	0.774	0.789	0.37	0.042	2.1	13	−5.7
	4-Aminoantipyrine	1.517					1	0.676					1	55.4
	Antipyrin	0.04					1	0.027					1	32.5
	Codein	2.8605					2	1.93					2	32.5
<b>Analgesics and anti-inflammatories</b>	Diclofenac	1.039	1.283	0.232	0.16	3.1	6	0.679	0.701	0.55	0.04	2.448	11	34.6
	Ibuprofen	13.482	25.639	3.495	0.0143	22.7	10	3.480	1.489	0.56	0.03	12.6	17	74.2
	Indomethacine	0.136												
	Ketoprofen	0.483	0.286	0.441	0.146	0.94	5	0.333	0.148	0.34	0.125	0.63	9	31.1
	Ketorolac	0.407	0.407				1	0.228					1	44.0
	Naproxen	5.077	8.251	2.363	0.206	23.21	7	0.934	0.873	0.452	0.017	2.62	13	81.6
<b>Lipid regulators</b>	Clofibrac acid	0.215	0.251	0.12	0.026	0.5	3	0.131	0.136	0.12	0.012	0.36	5	39.1
	Fenofibrac acid	0.079					1	0.196	0.161	0.13	0.078	0.38	3	−148.1
	Bezafibrate	1.948	2.320	1.4205	0.05	4.9	4	0.763	0.963	0.13	0.035	2.2	5	60.8
	Gemfibrozil	1.562	1.704	0.71	0.453	3.525	3	0.757	1.068	0.323	0.0112	2.86	6	51.5
	Acebutolol	0.335												
<b>Betablockers</b>	Atenolol	1.080	0.946	0.996	0.03	1.197	4	0.468	0.381	0.345	0.16	1.025	4	56.7
	Celiprolol	0.44					1	0.28					1	36.4
	Metoprolol	1.535	2.290	0.61	0.02	4.9	4	0.679	0.657	0.73	0.019	1.7	5	55.8
	Propanolol	0.198	0.269	0.005	0.036	0.51	3	0.102	0.0712	0.093	0.03	0.18	5	48.5
<b>Diuretics</b>	Sotalol	1.667					2	0.79					2	52.6
	Furosemide	0.413					1	0.166					1	59.8
	Hydrochlorothiazide	2.514					1	1.176					1	53.2
	Amidotrizoic acid	2.5					1	2.494					1	0.2
	Diatrizoate	3.3					1	3.3					1	0.0
<b>Contrast media</b>	Iotalamic acid	1.8					1	1.820					1	−1.1
	Iopromide	9.205					2	2.014	1.40	2.63	0.411	3	3	78.1
	Iomeprol	6.05					2	1.606					2	73.5
	Iohexol	6.7					2	2.706					2	59.6
<b>Cosmetics</b>	Iopamidol	2.3					1	1.9					1	17.4
	Galaxolide	4.281	5.01	2.031	0.79	10.02	3	1.019	0.243	1.08	0.751	1.225	3	76.2
<b>Psycho-stimulants</b>	Tonalide	0.878					2	0.21					2	76.1
	Caffeine	56.634	52.769	52.424	3.69	118	4	1.771	3.620	0.64	0.174	12	10	96.9
<b>Desinfectant</b>	Paraxanthin	26.722					1	0.836					1	96.9
<b>Antidepressants</b>	Triclosan	0.852	0.659	0.317	0.3	1.93	8	0.198	0.161	0.18	0.012	0.219	6	76.8
	Fluoxetin	5.85					1	0.112					2	98.1
<b>Plasticisers</b>	Molecules													
	DEP	19.64	19.64	14.8	0.19	50.7	5	0.68	1.11	0.02	0.0002	2.58	5	96.5
	DBP	12.44	17.59	5.27	0.15	46.8	6	0.52	1.04	0.34	0.0005	2.38	5	95.8
	BBP	9.17	16.1	3	0.01	37.87	5	0.7	1.36	0.076	0.0003	3.13	5	92.4
<b>Phthalates</b>	DEHP	39.68	44.81	23.6	0.13	122	7	3.87	4.91	2.75	0.0016	14.2	8	90.2
	DMP	1.51	1.39	1.24	0.26	3.32	4	0.038	0.066	0.00019	0.00006	0.115	3	97.5
	DIBP	5.98	9.75	1.7	0.04	20.48	4	5.24					2	12.4
	Bisphenol A	2.07	3.1	0.563	0.088	11.8	14	0.6	1.09	0.05	0.006	4.09	15	71.0

DEP: diethyl phthalate; DBP: di-*n*-butyl phthalate; BBP: *n*-butyl benzyl phthalate; DEHP: bis(2-ethylhexyl) phthalate; DMP: dimethyl phthalate; DIBP: diisobutyl phthalate.



TABLE 4

**Emerging contaminants detected in European groundwaters and surface waters as originating from wastewater treatment or other point sources [12]** Permission of Elsevier, License Number 3278710639716, November 30, 2013.

Site	Source	Compounds detected
<b>UK surface water</b>		
England and Wales	Contaminated and control sites	Polychlorinated dibenzo- <i>p</i> -dioxins and dibenzofurans detected in all sediments sampled
Thames in south west London and rural river	WTW	Ibuprofen, paracetamol and salbutamol quantified in all samples. Mefenamic acid (NSAID) in 70% of samples. Propanolol ( $\beta$ -blocker) < LOD
Tyne Estuary	WTW	Clotrimazole, dextropropoxyphene, erythromycin, ibuprofen, propanalol, tamoxifen, trimethoprim quantified Clofibrac acid, diclofenac, mefenamic acid, paracetamol < LOD
Tees, Mersey, Aire river and estuary	Industry-WTW	APEs detected above threshold
Taff&Ely, South Wales	WTW	Trimethoprim, erythromycin, amoxicillin, paracetamol, tramadol, codeine, naproxen, ibuprofen, diclofenac, carbamazepine, gahapentin most frequently detected 41 others detected including illicit drugs
Inland streams	WTW	Ibuprofen, mefenamic acid, diclofenac, propanalol, dextropropoxyphene, erythromycin, trimethoprim, acetyl-sulfamethoxazole, detected Paracetamol, lofepramine not detected
Ouse, West Sussex	WTW	Bisphenol A, oestrone, 17 $\beta$ -oestrodial consistently detected, Propanalol, sulfamethoxazole, carbamazepine, indomethacine, diclofenac variably detected Mebeverine, thioridazine, tamoxifen, meclofenamic acid
UK		Diuron
Stream, Tunbridge Wells	Storm event, fruit growing	Simazine, diuron, NP, endosulfan sulphate, pendimethalin
Thames, 1988–1997		Atrazine, simazine, lindane
<b>European groundwater</b>		
Eastern England	STW	Pharmaceuticals [ $<20$ –max]: ibuprofen (5044), erythromycin (1022), dextropropoxyphene (082), diclofenac (568), mefenamic acid (366), propanolol (215), acetyl-sulfamethoxazole (239), trimethoprim (42)
Berlin, Germany	STW	Pharmaceuticals: clofibrac acid (7300), clofibrac acid derivative (2900), propyphenazone (1465), Phenazone (1250), salicylic acid (1225), primidone (690), gentisic acid (540), <i>N</i> -methylphenacetin (470), diclofenac (380), gemfibrozil (340), ibuprofen (200), fenofibrate (45), ketoprofen (30)
Leipzig, Germany	STW	Bisphenol A (7000), NP (1000), caffeine (–140), carbamazepine (90), tonalide (–6), galoxalide (–2.8)
Halle, Germany	STW	Bisphenol A (–1 to 1136), carbamazepine (–2 to 83), galaxolide (3–19)
Baden-Württemberg, Germany	STW	Maximum concentrations: amidotrizoic acid (1100), carbamazepine (900), diclofenac (590), Sotalol (560), sulfamethoxazole (410), iopamidol (300), anhydro-erythromycin (49), phenazone (25)
France	Regional survey	Hormones (0.4–4): levonorgestrel (4), progesterone (1.6), testosterone (1.4); Pharmaceuticals (0–14): oxazepam (14), carbamazepine (10.4), acetaminophen (10.3), metformin (9.9), diclofenac (9.7), salicylic acid (metabolite) (6.5), atenolol (5.5), sulfamethoxazole (3)

APEs: alkyl phenol ethoxylates; LOD: limit of detection; NSAID: non-steroidal anti-inflammatory drug; STW: Sewage Treatment Work; WTW: wastewater treatment work.

chronic toxicity [35]. The uptake, mode of action, and biological endpoints of each emerging contaminant must be researched and documented to establish a correlation between contaminant and consequence.

A successful approach to the problem of emerging contaminants should be highly interdisciplinary [36]. Drinking water resources such as groundwater are often contaminated by extremely low concentrations of pesticides in the nanogram to microgram/L range, but still above the EU limit values. Surveys of groundwater contaminants detected in several European areas show that most of these EPs can be associated with the impact of WWTP or other point sources (Table 4), more significantly than recognised hitherto [12,37,38].

Moreover, European monitoring programmes discriminate among the most frequently detected EP in groundwater (Fig. 3) [12]. The risk to groundwater posed by the presence of these EPs, and consequently to drinking water, is clear. Development of new technologies for treatment of drinking water resources to below the EU threshold limit is urgent.

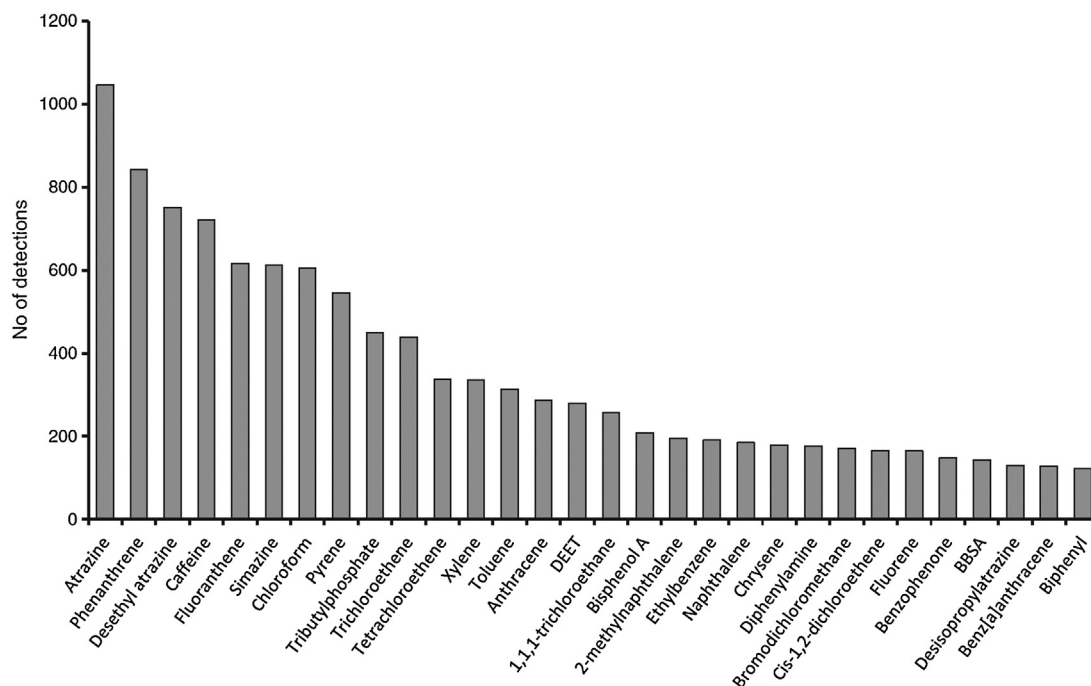
## (Bio)monitoring and ecological risk assessment for emerging pollutants

### *R&D for impact and risk assessment*

The relevance of emerging and new chemical and biological agents and their impact on soil, water and ecosystems can be addressed by the following research challenges:

- identification and preparation of comprehensive lists of emerging contaminants;
- characterisation of interactions and physical/chemical fate of such chemicals/biological emerging pollutants in soil, sediment and water ecosystems;
- assessment of the functioning of the water/soil system in the presence of emerging pollutants.

Establishing action plans for emerging and reemerging infectious agents is an additional need worldwide. There is little toxicological information for the majority of the chemicals in use, predominantly with regard to long-term, low-level exposure. Current challenges which the environment is facing are often hidden so that long-term threats or intermittent exposure can restructure

**FIGURE 3**

The most frequently detected compounds in European groundwater included in the Environmental Agency database (DEET = *N,N*-dimethyl-toluamide; BASA = *N*-buthylbenzene sulphonamide; BBSA = *N*-buthylbenzene sulphonamide) [12]. With permission of the publishers.

ecosystems and often lead to a decrease in biodiversity and a loss of important functions and services [39,40]. In this context, a major problem lies in the identification of future hazardous or potentially dangerous chemicals and biological agents hazardous or potential dangerous. An inventory of the available information in terms of persistence, fluxes, toxicity, endocrine disruption potential of both individual compounds and complex mixtures is lacking.

Although the literature on the fate of these substances appears to be extensive, data about their environmental effects at the realistic low concentrations at which they exist in different media are limited, especially when exposure to these compounds could occur. Hence, the development of new technologies for remediation and disinfection of water resources to drinking water standards is an ongoing challenge. In several cases, regulations to impose long-term impact assessment of the exposure to low levels of chemical compounds in the environment are missing, because important classes of these compounds have not yet been studied in detail. This has been mainly attributable to the lack of appropriate standards for instrumental analysis techniques in the case of low concentrations of micropollutants in environmental components [1,16]. To understand the full range of potential contaminant effects, it is important to measure and monitor pollutant concentrations at the emission source, within the environmental compartments as well as in living organisms (invertebrates, fish, among others) [41,42]. Currently, some groups of physico-chemical treatment methods could be applied, coupled with toxicity tests after each stage of treatment, to remove one or more classes of

toxic compounds, despite the time and necessary costs for these tests.

Online monitoring would have the advantage that it can improve the reliability of monitoring data, but involves expensive equipment and relative high maintenance costs [43,44]. An efficient option now being applied refers to passive sampling methods, such as Polar Organic Chemical Integrative Samplers (POCIS), which can sample water over a long period, providing time weighted average (TWA) concentrations [45,46].

Understanding the causes of ecosystem harm or effects resulting from chronic exposure to a pollutant is not an easy task and one which requires innovative approaches. Also, there is a growing agreement that chemical data alone are not sufficient to assess the potential risks of all emerging pollutants, and those analyses of pollution-induced biological and biochemical effects are desirable to evaluate the impact of chemical pollutants on human health.

#### *Biomonitoring and biosensors*

Biomonitoring tools (e.g. bioassays, biomarkers, microbial community analyses) have great potential for increasing confidence in the risk assessment of both regulated and emerging chemical pollutants. Sensors developed to determine several analytes in parallel are useful tools in environmental monitoring and screening.

The comprehensive term 'biosensor' denotes a system capable of detecting the presence of a substrate by using biological components, which then provides a quantifiable signal [47]. Recently, there has been an expansion of studies and research on biosensing



techniques and devices for environmental monitoring and similarly for genetic engineering and sensor cell development. For example, it is assumed that many endocrine disruptors can bind to the oestrogen receptor (ER) as agonists or antagonists. Therefore, the chemical binding capacity of ER would be a factor in screening or testing the potential toxicity of these substances on the environment and biosensors for endocrine disruptors have been developed, taking advantage of this property [48,49]. Moreover, molecular self-assembly, inspired by nature, has been proposed to synthesise nanostructures with distinctive functions, because current detection methods for pathogenic bacteria, protozoa, viruses, or helminths proved to be sometimes inaccurate, but also costly in terms of resources and time [50]. The self-assembly technique makes possible organised, patterned nanostructures which can involve biomaterials (proteins, lipids, nucleic acids), without external control and directions, which can then be applied to the development of amperometric immunosensors [51,52].

Because monitoring of multiple species would be recommended in a real-time parallel procedure, the current tendency is to develop large-scale biosensor clusters, especially if highly miniaturised signal transduction elements are necessary. Genomics is a new tool in recognising and understanding the molecular pathways disturbed by emerging pollutants, and is able to relate them to both the whole organism and population level effects. Technologies such as DNA microarrays are successfully applied in ecotoxicogenomics, an emerging field in ecotoxicology, to understand the effects of pollutants at the molecular level [53]. Furthermore, the bioavailability of nanoparticles in environmental compartments can be investigated by developing molecular biomarkers as detection tools for emerging contaminants. This is essential for risk assessment and decision making for remediation of contaminated soils and sediments. Measuring the concentration levels of polluting compounds through techniques which

allow the determination of contamination bioaccessibility as well as the prediction of microbial degradation and availability in the environment is a crucial part of environmental (bio)monitoring [54].

Quantifying the bioavailability of organic contaminants in soil and sediment is crucial for risk assessment and decision making for contaminated land remediation. It would therefore be highly opportune to develop techniques that can directly predict microbial bioavailability and the environmental degradation potential of these contaminants.

### Innovative approaches in bioremediation of emerging pollutants

Environmental hazards and risks that occur as a result of accumulated toxic chemicals or biological micropollutants could be reduced or eliminated through the application of various (bio)-technologies [1]. These could take the form of treatment/remediation of historic pollution, disinfection of water resources addressing chemical and biological agents resulting from changed human demographic behaviour, breakdown of public health measures and current industrial/agricultural practices through pollution prevention and control [55,56].

Thanks to biotechnological solutions some of these pollutants can be readily degraded or removed. Studies have demonstrated that these solutions involve the action of microbes, plants and animals under specific conditions that address both abiotic and biotic factors, so as to achieve contaminant mineralisation, transformation or immobilisation [1,57–59]. For example, the combination of biological processes with adsorption on solids in the treatment of wastewaters can provide 45–99% removal efficiency of EDCs (Endocrine Disrupting Chemicals) from influent [16].

Monitoring and managing the biological aspects of bioremediation require the characterisation of the fate and behaviour of the compounds of interest in the environment to update the choice of

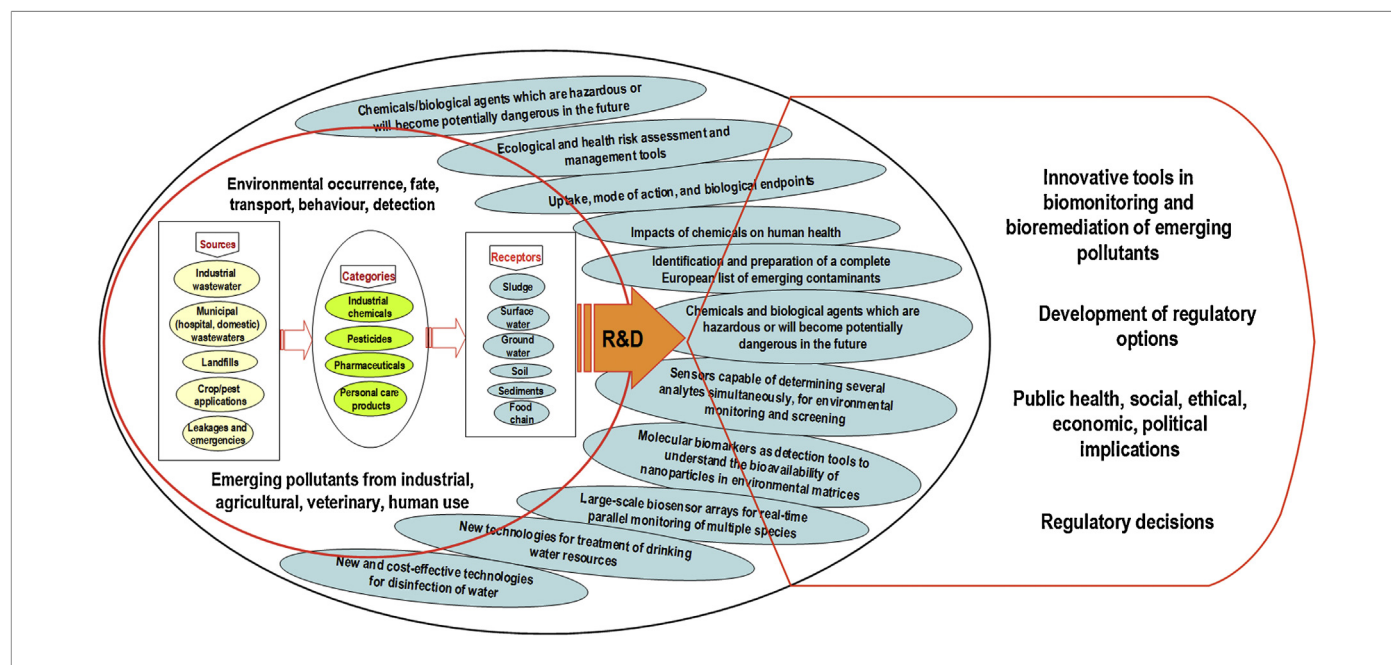


FIGURE 4

R&D needs for emerging pollutants in the environment considering sources, biomonitoring, ecological risks and bioremediation.

bioremediation strategy. However, at present it is difficult to suppose that the environmental impacts of trace chemicals would be minimised or removed, mostly as a consequence of insufficient information being available. This highlights the importance of a consistent link between R&D needs for the assessment and treatment of emerging pollutants and the tools, equipment and know-how which contributes to the fulfilment of these needs. Such an integrated approach should take into consideration the entire lifecycle of the pollutants, from the source of emission to their removal through treatment and remediation techniques, without neglecting the impacts and risks they may pose to the environment and human health (Fig. 4).

Pollution control in the aquatic environment can be achieved by applying the well-established activated sludge wastewater treatment. However, biological processes carried out in conventional treatment systems (activated sludge) showed a low efficiency in removing EDCs from wastewater, even in WWTP units with multiple biological treatment units [57].

Membrane bioreactors (MBRs) are regarded as feasible options in relation to conventional treatment plants, because they have proved to be efficient in removing recalcitrant compounds that cannot be eliminated or biodegraded in activated sludge systems. Some studies have shown that the elimination of EDCs in MBRs before disinfection may result in removal effectiveness of 96% for cholesterol, stigmastanol and coprostanol in municipal wastewater, compared to 85% efficiencies obtained in a conventional treatment plant, with influents of similar loadings. However, if the sludge retention time (SRT) is extended, MBR performance for the removal of several compounds may diminish [16,60].

Isolation of activated sludge bacteria capable of degrading endocrine disruptors can provide great opportunities to effectively remove these compounds, which are sometimes difficult to degrade even by advanced treatment processes such as hydrolysis or photocatalysis. White rot fungi and their oxidative enzymes are also attractive candidates to decontaminate waters containing EDCs, such as the ubiquitous plasticiser Bisphenol A [61,62]. The development of innovative/advanced packed or fluidised bed bioreactors or MBRs is also necessary for a more effective exploitation of such specialised microbes or enzymes.

The growing outbreaks of infectious waterborne diseases are a challenge to both the water and public health sector. The development of new (bio) technologies for water disinfection and monitoring biological micropollutants is therefore urgent. Novel concepts for the removal of such agents and of potential usefulness for the biotreatment of water and wastewater are starting to emerge [63,64]. The recently demonstrated co-metabolism of estrogenic compounds during nitrification (including the action of ammonia oxidising Archaea) might also be applicable to the

removal of other micropollutants such as pharmaceuticals and personal care products (PPCPs), while recruitment of other heterotrophic bacteria seems to be necessary to further degrade the intermediate metabolites of these micropollutants produced by the action of aerobic nitrifiers [63,65].

Scientifically validated and innovative processes and tools are further necessary to tackle these matters and the public and decision makers' needs in terms of chemicals and pathogens impacts on environment and human health.

## Concluding remarks

Ensuring the elimination of emerging contaminants of environmental concern requires future studies and research to develop robust (bio)remediation processes elaborated on a sustainable basis. Our analysis shows that emerging contaminants continue to cause new and serious challenges to water, air, soil, natural resources, ecosystems and human health. It is also evident that the production of new chemicals extends and often goes beyond the power of current safety monitoring and risk assessment methods, as well as of existing preventative and remediation technologies.

Some issues should be addressed so as to generate a synergistic effect between the environmental influence on fate and (bio)availability of chemical (organic and inorganic) contaminants and the selection and performance of the most appropriate bioremediation processes, as well as of complementary techniques that support the effective operation and monitoring of a bioremediation approach. Considering the current situation and based on our study, it is clear that several interconnected factors must be taken into account: contaminant concentration; contaminant/contamination characteristics and category; scale and level of contamination; the risk intensity generated for health or the environment; the opportunity to be applied *in situ* or *ex situ*; the later use of the site; and available resources. Moreover, the removal of pollutants from any given environment would be made more predictable by applying multidisciplinary techniques. The results of R&D efforts will lead to future regulations, entailing their occurrence, bioremediation targets and their potential environmental and health risks.

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