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Application of Wastewater and Biosolids in Soil: Occurrence and Fate of Emerging Contaminants

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Abstract Wastewater (WW) for irrigation and application of biosolids in soil is becoming important as it is going to become very common in the near future. By 2050, the world is going to have four billion people living in water-scarce countries, making it a norm of freshwater for the cities and WW for agriculture. Further, biosolids might still be used as green biofertilizers for soils, if they are improved from an ecological point of view. However, application of biosolids in soil is argued because of the amount of organic pollutants that compromise the dynamic equilibrium of the biological systems. Therefore, information on the concentration, behavior, and cycling of organic pollutants as well as their possible degradation pathways is needed to predict, prevent, and remediate these pollutants from different sources including WW and biosolids. Among the group of organic pollutants, emerging contaminants (ECs) enter into the soil with the irrigation water from treated effluents and fertilization by biosolids. Quantification of ECs from WW and biosolids is of main importance to predict the toxic effects of WW effluents and sludge. Moreover, their incorporation into vegetables through irrigation and their magnification through natural food webs have been proved and must be monitored. This review presents information on the different sources of emerging contaminants and linking with the ecological effects they produced by reacting in the environment during various applications of WW and biosolids in soil. The available methods for analysis and quantification of ECs in different matrices, such as WW and biosolids, are also presented.

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Abbreviations

ECs	Emerging contaminants
EDCs	Endocrine-disrupting compounds
GC-MS	Gas chromatography-mass spectrometry
LC-MS	Liquid chromatography-mass spectrometry
LC-MS/MS	Liquid chromatography-tandem mass spectrometry
MEC	Measured environmental concentration
PPCPs	Pharmaceutical and personal care products
PNEC	Predicted no-effect environmental concentration
SPE	Solid phase extraction
VAPs	Value-added products
WWTP	Wastewater treatment plant
WW	Wastewater

1 Introduction

Wastewater (WW) and biosolids accumulate pharmaceuticals and other emerging contaminants (ECs) that may eventually release to the environment. In Canada, for instance, wastewater treatment plants (WWTPs) produce around 4 million tons of dry sludge yearly. These biosolids are rich in nutrients, and hence, they are commonly used to improve soil nutrient content for growing plants in agriculture, parks, and indoors. Many pharmaceutical and personal care products (PPCPs) and endocrine-disrupting compounds (EDCs) have been detected in the discharge from WWTPs indicating their presence in biosolids (Venkatesan and Halden 2014; Sabourin et al. 2012). Therefore, the land use of municipal biosolids may initiate a bioaccumulation and magnification effect of ECs affecting the equilibrium of biological systems from individuals to entire ecosystems.

Synthetic pharmaceuticals are present in sewage effluents mainly due to the input of urine and feces from urban areas. While in developed countries these effluents are discharged into water bodies after a regular treatment, in many developing countries, they are used for irrigation of crops or they reach water bodies without any treatment. Therefore, the input of ECs can be divided into different scenarios. In wastewater treatment plants, some pharmaceuticals, such as antibiotics, are partially eliminated and the final discharge still contains residual concentrations that reach the water bodies (Mohapatra et al. 2013, 2014; Sabourin et al. 2012). Hence, many of these pharmaceuticals are present in natural aquatic systems in small concentrations. Despite this general observation, the basic question remains whether there is some risk to aquatic organisms due to this chronic exposure.

Furthermore, many studies showed the effects of different ECs on the biochemistry, cell structure, growth, reproduction, and mortality of organisms in the environment and on populations and communities in surface water and soil systems (Farré et al. 2010). While much of the information on ECs indicated that they were a minor risk at any scale, there is some evidence that ECs could affect human and environmental health (Pomati et al. 2008). For example, the veterinary use of diclofenac, which is a human pharmaceutical used as an anti-inflammatory treatment, was directly linked to the alarming reduction of vulture populations in certain areas of Asia (Oaks et al. 2004). The veterinary drug, ivermectin, which is used to treat parasitic infections in livestock, has been shown to affect the growth of aquatic invertebrates even with concentrations lower than the ones expected to be measurable in aquatic environments (Garric et al. 2007). Ethinylestradiol, a main ingredient of contraceptive pills, was proven to trigger endocrine-disruptive effects in a fish species (Lange et al. 2001).

Hence, there is an urgent need to increase the understanding of the fate of ECs after application of WW and biosolids in soil and generate innovative methods for the discharge of WW to water streams as well as sludge recycling and reuse. Further, the main problem associated is the quantification of the ECs in WW and biosolids in trace amounts (below ng/L). In the given context, the present review presents a critique on the fate and occurrence of emerging contaminants, source, and ecological effects of these contaminants during various applications of wastewater and biosolids in soil. The wide spectrum of available analytical methods for quantification of emerging contaminants in different complex matrices including wastewater and biosolids is also presented.

2 Land Application of Wastewater and Biosolids

Wastewater and biosolids have been applied on agricultural fields in North America and Europe at least since the 1890s. Following the experience gained with the empirical case studies, various regulatory measures and methods were devised to ensure the safety of human and environmental health. More scientific efforts were invested not only on safety but also on testing the efficiency of the developed procedures (Venkatesan and Halden 2014; Sabourin et al. 2012). However, due to continuous industrial development, there is still concern for new problems that could unexpectedly arise with the application of human and industrial waste. Main concerns include (i) pollution of aquifers due to deficient management, (ii) soil pollution and reduced crop production, (iii) the effect on the market and economies, (iv) epidemiological effects on health, (v) accumulation of heavy metals, and (vi) organic contaminants including

ECs. Thus, it became increasingly important to treat the biosolids and WW before its beneficial application in soil.

With the growing human population, the difference between availability and actual need for water is widening worldwide. Scientists around the globe are working on new ways of conserving water. In this sense, reusing WW for irrigations of crops or ecosystems would help to increase the availability of drinking water. WW is mainly composed of industrial and household runoffs. Urban WW treatment facilities are designed to generate a final liquid product that is supposed to be harmless for the local natural environment causing a negligible impact on human health and local wild communities. However, this is especially difficult when the discharged volume is considerable to the natural local water body as is the case of large cities (Meneses et al. 2010). Moreover, WW can also be seen as a valuable resource from economical point of view since it is rich in nitrogen and phosphorus and such nutrients can increase the productivity of soil (Murray and Ray 2010). However, previous treatment may be required depending on the use of land to be irrigated.

Further, amounts of biosolid waste are constantly growing together with global population increase. Biosolids are composed of almost 50 % of organic matter. Thus, they may be used to improve the physicochemical and biological features of soils that are depleted due to excessive use. They also act as nutrients for the bacterial community and facilitate the aggregate formation and stabilization (Tisdall and Oades 1982). Consequently, important soil physical-chemical properties, such as bulk density, porosity, humidity, and ion exchange capacity, are improved together with the enhancement of the soil community.

The elevated organic matter content of biosolids is an advantage as it can be used to remediate metal polluted areas. This is because they convert metals to less soluble fractions (Brown et al. 2003). Therefore, metal-polluted mining debris, construction fields, landfill cover soils, and eroded land are the targets to be restored. Restoration takes place not because of their ability to bind pollutants but due to the previously mentioned high content of nitrogen and phosphorous that enhances plant growth and ultimately fostering ecosystem sustainability (Brown et al. 2005). As it can be inferred, this implies that biosolids might represent an evolution compared to chemical fertilization since their bioavailable P and chelated Fe content is comparatively higher than standard fertilizers (Lombard et al. 2011).

Until date, there are three main steps that can be modified to improve sludge management control at source, initial transport, processing, and final disposal, and reuse to produce value-added products (VAPs). Wastewater sludge reprocessing to VAPs holds the future key to sustainable management. In this perspective, sludge can be transformed not only into biofertilizers but also to other bioproducts, such as pesticides, plastics, surfactants, flocculants, and enzymes, among others (Verma et al. 2005; Ben Rebah et al. 2001). The availability of biopesticides and biofertilizers (different VAPs among others) as effective (in terms of cost-effectiveness) and safer than chemical pesticides is obviously desirable. However, field application of sludge-based biopesticides and biofertilizers is disputable due to the presence of trace organic compounds, including many ECs (e.g., EDCs and PPCPs). The development of sludge treatment or value-added technologies needs to consider the removal of the pollutant as it is closely related to beneficial uses of sludge. Most of the literature has been reported on the fate of trace contaminants in drinking water, surface water, and WW, virtually neglecting sludge which is an essential by-product of wastewater treatment plant. Further, during the process of value addition, there may be formation of more toxic by-products than the parent compound, which needs to be investigated. This propitiates the need to not only produce VAPs from sludge but also to examine the distribution and transformation of ECs in the environment during the process of production and application of VAPs.

3 Source of Contaminants

Wastewater generated by household activities is recognized as the main source of solids and nutrients entering treatment plants. However, its composition and generation process within households is yet to be properly interpreted. The comprehension of how pollutants enter household WW is the key to better manage water resources within an integrative frame.

In recent years, the importance of WW in terms of loads of contaminants entering the wastewater treatment plants has increased. In most of the cities, adoption of strict trade waste monitoring and cleaner production has reduced the total industrial load of heavy metals, such as cadmium, chromium, lead, mercury, nickel, and zinc to the treatment plant to less than 12 % of the overall load (Sörme et al. 2003).

In spite of the information collected so far in the literature, data on ECs in WW and on their origin is limited. The majority of studies on WW have focused on biological oxygen demand (BOD), chemical oxygen demand (COD), nitrogen, and phosphorus. The unknown effects of low concentrations of ECs in the aquatic ecosystem require studies on the occurrence, sources, fate, and transport of these compounds in wastewater treatment to better understand and possibly identify mitigation measures.

Emerging contaminants end up in WW through several pathways including the disposal and use of consumer products, farm runoff, toxic spills, and excretion via the urine and feces of these consuming pharmaceuticals. The human body only metabolizes a percentage of each drug taken, expelling the rest into the municipal wastewater system. Another source is from consumer products, such as soap, shampoo, disinfectant washes, and toothpaste which contains biologically active compounds released to the sewer system and ultimately transported to WWTP (Cabeza et al. 2012). Figure 1 represents typical setup of a WWTP showing wastewater and sludge release and different possible pathways of release/transformation of ECs to the environment.

Municipal facilities to treat WW are designed to reduce organic pollutants load but not for ECs that are present in the WW at concentrations of nanograms per liter or lower. Therefore, many compounds pass through these standard treatment systems remaining unaffected. Emerging contaminants, such as pharmaceuticals, endocrine disruptors, pesticides, iodinated contrast products for X-ray, and personal care products, were detected in WW, groundwater, and surface waters (Mohapatra et al. 2012, 2013). These chemical products can reach the aquatic systems through leaky sewers and septic systems, which can allow contaminants to infiltrate into the groundwater, and pass through wastewater treatment plants to discharge contaminants into receiving waters. The fate and concentrations of many ECs in the environment are mostly unknown, making the design of treatment strategies difficult. From the WWTP effluent, ECs are discharged into surface waters where they may have measurable effects on aquatic life at low concentrations (Haider and Baqri 2000). Once in surface waters, pharmaceuticals have been shown to disturb the natural biochemistry of many aquatic organisms including fish and algae.

Many of the problems associated with the removal of ECs from WW are their low concentrations and chemical diversity, which make detection and analysis difficult. Low concentrations require extremely sensitive analytical equipment while the wide range of distinct chemical compounds necessitates techniques to identify many chemicals at once. The methods for recognition and quantification of several formerly undetected ECs in WW, as many EDCs and PPCPs, showed a large improvement in the last decade together with a fast progress in the analytical techniques (Mohapatra et al. 2013; Gomez et al. 2006). As laboratory procedures are developed and ECs can be accurately quantified, to

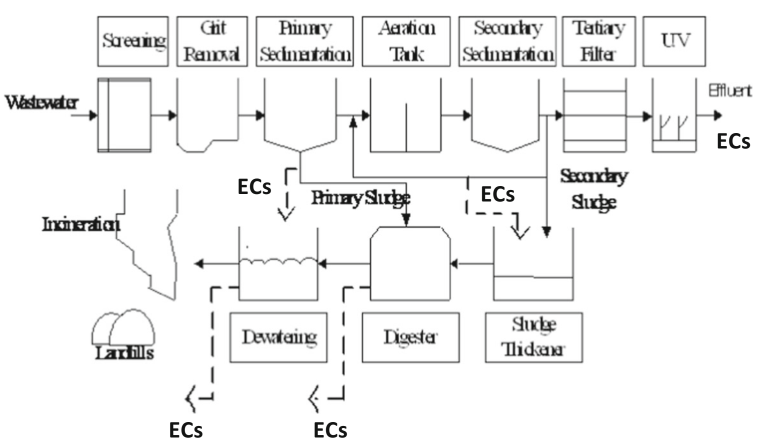

Fig. 1 Typical setup of a WWTP showing wastewater and sludge release. The *arrows with dotted lines* indicate possible pathways of release/transformation of emerging contaminants (*ECs*)

investigate the sources, removal pathways, and fate of ECs in WW and biosolids and its further application in soil becomes important.

4 Methods Used for Analysis of Contaminants

To date, a large number of analytical methods have been developed to quantify ECs in WW and biosolids. They generally use chromatography (gas or liquid) coupled to mass spectrometry (MS) or tandem MS (MS/MS). Nevertheless, analytical studies on ECs need increased sensitivity and selectivity, more than anything due to the complexity of matrices such as WW, WWS, and biosolids. Separation techniques include gas chromatography (GC) and LC, while for detection, MS is the most widely employed technique. Because of the low volatility of many ECs, gas chromatography-mass spectrometry (GC-MS) analysis requires an additional derivatization, which makes sample preparation laborious and time consuming, and also increases the possibility of contamination and errors. As a result, the use of LC-MS and LC-MS/MS is increasing. Farré et al. (2010) compared LC-(ESI)-MS and GC-MS (after derivatization with BF3-MeOH) for monitoring some acidic and very polar analgesics (salicylic acid, ketoprofen, naproxen, diclofenac, ibuprofen, and gemfibrozil) in surface water and WW. Results showed a good correlation between methods, except for gemfibrozil, for which derivatization was not completely achieved in some samples.

The most frequently used equipment in targeted analyses is a triple quadrupole (QqQ), because it provides high selectivity and sensitivity which are often required with complex environmental samples, such as WW and biosolids. In MS/MS techniques, analytes are detected via selected reaction monitoring (SRM) or multiple reaction monitoring (MRM) by measuring known product ions from precursor ions. The disadvantage of MS/MS techniques is that they lead up to biased information on samples, because only the user-defined data obtained through SRMs or MRMs are saved. Studying ECs in WW and biosolids poses several difficulties because of the low concentration of pollutants and the diverse composition of the matrices. Figure 2 presents the scheme of the steps for studying ECs within WW or biosolids. Complete extraction, effective cleanup, and a low threshold detector are needed to successfully quantify ECs in WW and biosolids. Solid phase extraction (SPE) is usually chosen because of the advantages it has over other methods such as (a) low solvent volume needed, (b) easy operation, and (c) easy to reproduce results (Laven et al. 2009). But, further research is needed to compare signals with and without SPE when analyzing ECs in WW.

Another extraction method, Soxhlet, requires much more time and comprises boiling, rinsing, and recovery of solvent. Soxhlet consumes a large volume of organic solvents and is a longer method. As an option to this extraction method, ultrasound is commonly implemented. The cavitation caused by the ultrasonic bath minimizes the time required in Soxhlet extraction methodology. Nevertheless, some researchers indicated that this method was not so easy to reproduce as Soxhlet (Luque-Garcia and Luque de Castro 2003).

Microbiological assays are commonly used to determine the presence of drugs in biological samples, but these methods are not applicable to soil sediments or sludge matrices since they are not sensitive and specific (Diaz-Cruz et al. 2003). In such cases, immunoanalytical techniques are better suited to track organic pollutant traces in the nature, due to their easier sample preparation, high sensitivity, and low-cost chromatographic and mass spectrometric methods. Still, the selectivity of the antibodies applied in a given immunoassay allows only a single EC species detection. Therefore, for screening of different ECs, several repetitions with different antibodies are needed. Analyses of polychlorinated alkanes are difficult due to their intrinsically complex industrial formulations. For instance, estrogens in WWTPs have been a largely investigated class of contaminants; even so, their concentration in sludge was never well addressed because of analytical artefacts of poor selectivity and poor detection limits (Richardson and Ternes 2011).

Small particles that present large surfaces (0.8–1.7 m^2 g), negative charges, and interstitial spaces are physical features of biosolids that facilitate strong sorption of charged chemicals, consequently complicating the analysis of the chemical composition of biosolids. Moreover, the addition of conditioners, such as lime, iron chloride, and positively charged polyacrylamide, also interferes with the analysis. For instance, Rogers (1996) indicated the partition of lipophilic compounds to primary slime during first precipitation which is correlated with K_{ow} octanol-water partition. In order to have a reference, he indicated that log K_{ow} <2.5 presents a small sorption probability, log K_{ow} >2.5 and <4.0 has an intermediate sorption probability,

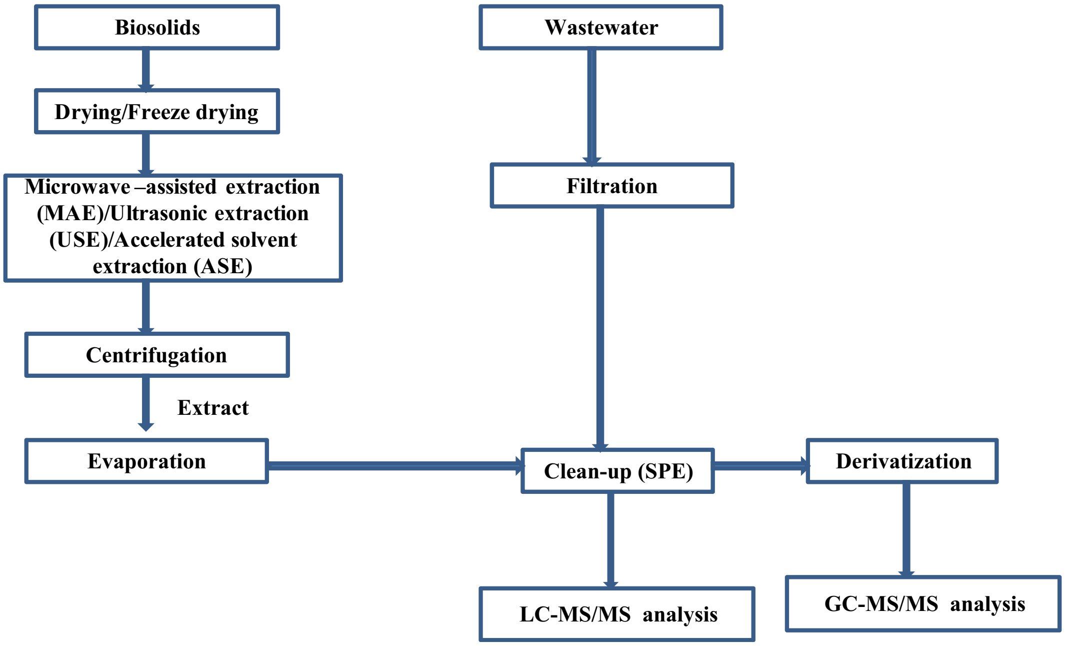

Fig. 2 Analytical procedure schematic diagram for analysis of emerging contaminants (ECs) in wastewater and biosolids

while log K_{ow} >4.0 would generate an elevated sorption probability. All these factors should be considered during the method development for quantification of ECs in complex matrices such as biosolids. The main inconvenience, in quantification of ECs in WW and biosolids, was the matrix influence on the measured concentration of the analyte. This may be solved with the addition of standards. The development of different analytical procedures for quantification of ECs in various matrices, such as WW and biosolids, shows the way to study their occurrence and fate.

5 Fate of Contaminants in Land and Groundwater

Entrance of ECs into groundwater can be classified as local sources or dispersed sources. The first originates from discrete locations and is dumped into water bodies. They generate a pollution plume upstream that can be monitored and easily located. Usual examples are industrial effluents, wastewater treatment facilities, and stormwater overflows as well as open air mining, waste landfill facilities, and septic containers. Wastewater sources are considered as one of the most important point sources of ECs in the aquatic environment (Glassmeyer et al. 2005). Figure 3 represents the schematic presentation of daily mass flow of ECs in different unit operations of wastewater treatment plants. Many researchers studied the fate of ECs from WW to groundwater and polluted surface water bodies. Old landfill areas were also proven to liberate ECs into groundwater for many years even after closure, continuing to pollute

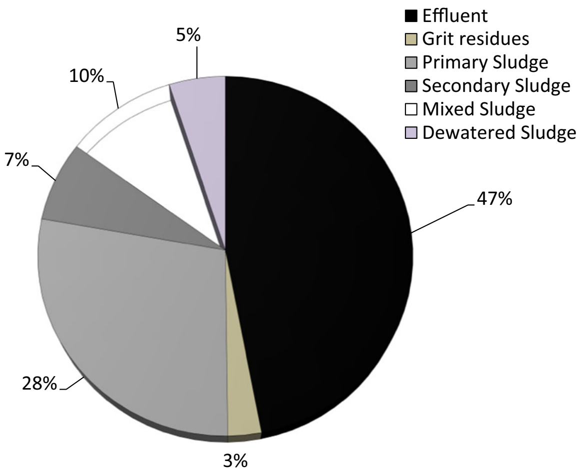

Fig. 3 A schematic presentation of daily mass flow of ECs in different unit operations of wastewater treatment plants. Quantities of ECs in these streams are expressed relative to those observed in the influent (in %) (data from Alidina et al. 2014; Mohapatra et al. 2014; Du et al. 2014; Luo et al. 2014; Camacho-Muñoz et al. 2014; Li et al. 2013; Cabeza et al. 2012; Shaaban and Goreki 2012; Mohapatra et al. 2011; Rosal et al. 2010; Diaz-Cruz et al. 2009; Terzic et al. 2008; Petrovic et al. 2003)

groundwater due to inappropriate design and construction of the different isolated layers, poor waste management options, and unsuited locations. However, the present landfill design and management practices in some regions of Europe and North America follow strict regulations. Unfortunately, there are currently poor functioning regulations in many developing countries in regard to groundwater preservation from such pollution sources. The combination of these facts together with an increasing use of pharmaceuticals in the last decades has indicated the possibility of ECs polluting groundwaters that are used without previous treatment in many regions around the globe. Diffuse pollution, on the other hand, is introduced to the environment along large areas instead of punctual sources. These sources include the irrigation or runoff of biosolids or excrement in agricultural areas or urban areas, leaching and percolation of sewage treatment facilities, and spray settlement.

Some literature reported the higher concentration of perfluorochemicals and polychlorinated alkanes in waters and their migration to groundwater (Clarke and Smith 2011). Sarmah et al. (2006) studied the presence and ecological storage of antibiotics used for animal treatment. They indicated that several antibiotics were present in groundwater due to fertilization with cattle excrement. Buerge et al. (2011) pointed out the presence of saccharin in Swiss wells from a fast bio-mineralizing soil, at amounts as high as 260 ng/L, which were related to fertilization with pig excrement. Table 1 presents concentration of ECs in WWTP influent and their percentage decrease in effluent that ultimately act as source of these contaminants in groundwater.

However, most ECs studies concentrated on surface water and WW, while wells have received less attention. During the past 10 years, some literature studies reported pharmacological products and EDCs in water (Mohapatra et al. 2010, 2011, 2014; Murray et al. 2010; Díaz-Cruz and Barceló 2008) indicated a list of priority micro-pollutants in different types of waterbeds. Nevertheless, extensive revisions are still needed regarding with the presence of the most used ECs in groundwater. Stuart et al. (2012) presented a revision on the threat posed by ECs in British groundwater while Lapworth et al. (2012) extensively reviewed the presence of ECs from cradle to grave in the northern hemisphere.

The European Water Framework Directive (WFD) (2000/60/EC) and Groundwater Directive (2006/118/EC) set a list of environmental goals to protect freshwater and the depending natural communities. Therefore, list of threshold contaminant concentrations were set as environmental health endangering limits. The release of ECs into the environment is of a particular concern because they may affect ecological or human health. Although previous references stated that studied ECs amounts are under toxicity limits in the ground waterbeds due to natural mitigating effects and dilution, still many are discovered at concentration which may pose life risks (>100 ng/L). The combined toxicity of multiple contaminants is not well understood. In addition, there are a number of specific pollutants that have a global footprint, and are frequently detected in groundwater resources. Due to the presence of ECs in all environmental compartments, including soil and groundwater, it becomes important to study the toxic effect of these contaminants.

6 Ecological and Toxic Effect of Emerging Contaminants

The toxicity of every compound in relation to each organism is set by the dose. It can be defined as acute if the reaction is immediately observable as symptoms like nausea, breathing difficulty, skin rash, vomiting, dizziness, and death. Monitoring and hazard evaluation is applied to add on the evaluation of the danger posed by drinking water. The prediction of eventual negative responses of exposed organisms is carried out by means of in vivo experiments or clinical cases.

A revision of potential effects of pesticide combinations was performed by Carpy et al. (2000) while Relyea (2009) focused their impacts on aquatic systems. Borgert et al. (2001) on the other hand, suggested a pool of criteria to be taken into account when evaluating information and interpreting chemical relations for a wide range of compounds, such as drugs, pesticides, industrial chemicals, food additives, and natural products. With a similar goal, Eljarrat and Barcelo (2003) proposed a factor to compare toxic effects. This allowed to compare the toxic effect of different combinations of chemicals and tested its usefulness by comparing dioxins and related compounds. Similarly, Pomati et al. (2008) studied the reaction of human and fish cell-cultures for the commonly used pain relievers, anticonvulsants and antibiotics at environmental levels. All these works indicated that drug combinations at

Table 1 Concentration of emerging contaminants (ECs) in WWTP influent and their percentage decrease in effluent

ECs	Influent concentration	Decrease (%) in effluent	Reference
Acetylsalicylic acid	3.1 μg/L	88	Heberer (2002)
Alkylphenol ethoxylates	–	99	Petrovic et al. (2003)
Acetaminophen	27,000 ng/L	100	Du et al. (2014)
Atenolol	1400 ng/L	84	Du et al. (2014)
Bisphenol A	1.68 μg/L	76	Mohapatra et al. (2011)
Bezafibrate	5.3 μg/L	83	Stumpf et al. (1999)
Caffeine	230 μg/L	99	Heberer (2002)
Carbamazepine	420 ng/L	38	Mohapatra et al. (2013)
Ciprofloxacin	0.37 μg/L	80	Alder et al. (2001)
Clofibric acid	1.2 μg/L	51	Heberer (2002)
Codeine	300 ng/L	99	Du et al. (2014)
Cyclophosphamide	0.14 μg/L	94	Steger-Hartmann et al. (1997)
Diclofenac	3.02 μg/L	98	Heberer (2002)
Dimethylaminophenazone	1.1 μg/L	38	Ternes (1998)
17α-Ethinylestradiol	0.01 μg/L	99	Johnson et al. (2002)
Fenofibric acid	1.03 μg/L	64	Stumpf et al. (1999)
Fragrances	154 μg/L	99	Simonich and Begley (2000)
Gemfibrozil	0.9 μg/L	69	Stumpf et al. (1999)
Ibuprofen	4.1 μg/L	90	Stumpf et al. (1999)
Indomethacin	1.1 μg/L	83	Ternes (1998)
Ketoprofen	0.6 μg/L	69	Stumpf et al. (1999)
Metoprolol	6.5 μg/L	83	Ternes (1998)
Naproxen	1.3 μg/L	78	Ternes (1998)
Phenazone	0.3 μg/L	34	Ternes (1998)
Propranolol	8.9 μg/L	96	Ternes (1998)
Sucralose	62,000 ng/L	28	Du et al. (2014)
Sulfamethoxazole	2800 ng/L	81	Du et al. (2014)
Warfarin	2.3 ng/L	–	Du et al. (2014)

nanograms per liter concentrations were able to impair cell reproduction, and in the case of hydrophilic compounds, it was most likely to affect aquatic communities.

Stuer-Lauridsen et al. (2000) modeled the expected amounts of some pharmaceuticals to be found in the environment by dividing the consumed quantities by the WW volume produced per inhabitant and then added a dilution factor of 10 and bibliographic information of K_{OW} and TD_{50}. They indicated the scarcity of data related to the ecotoxic effects that allowed the estimation of the expected amounts, while the results for ibuprofen, paracetamol, and acetylsalicylic acid were over the limit of no effect. Schulman et al. (2002) evaluated the hazard posed to human health by drugs related to the abovementioned groups, and those have been widely reported to be present in WWTPs' effluent, surface water, drinking water, and groundwater. They have taken into account the toxic potential and pharmacological nature, exposition potential, and transport and fate of the considered drugs and concluded that there was no human risk at the present environmental levels. However, recent studies pointed out that in spite of the progress achieved in water treatment processes and their capability to reduce EC concentrations, the reports of their presence in all types of waters indicated that ECs can still bypass the treatments and reach the water beds in important quantities. Moreover, when these WWTPs remove ECs, they get transformed into other by-products depending on process conditions, which could be potentially more toxic. Dry climate environments are proven to be especially sensitive to groundwater pollution by ECs because the water recharge cycling of these areas facilitates chemical concentration (Cabeza et al. 2012). In these scenarios, the forced artificial recharge reduces the natural mitigation and dilution ability of the system finally impacting on the water, reducing the sustainability of this practice in such areas. This problem has to be immediately addressed since artificial recharge is nowadays the main water resource management option in deserts worldwide. Moreover, a demand of irrigation with WW and fertilization with biosolids for agriculture is increasing in the developing countries, when taking into account the fact that much of the fruits and vegetables available in the market in the developed countries are imported from these areas. The problem is of global concern since all humans are exposed to this threat. In this sense, there is an agreement that these agricultural practices increase the exposure of humans due to the direct uptake by crops. For instance, chlorinated flame retardants (TCEP and TCPP) were the most bioconcentrated in leaves and seeds (Eggen et al. 2013) of meadow fescue (used as cattle food). Moreover, Calderón-Preciado et al. (2011) correlated the presence of medication in irrigation WW and irrigated crops. They estimated an average of 9.8 μg of pollutants, reaching each consumer through marketed fruits and vegetables weekly (taking into account 27 agrochemicals). Also, bioconcentration in several cereals and vegetables as tomatoes and beans has been reported by Eggen and Lillo (2012). While pumpkin and zucchini plants were reported to remediate the polluted soils through accumulation in roots and only low quantities would reach the fruits (Reinhold and Aryal 2011), cucumber does uptake carbamazepine when irrigated with wastewater (Shenker et al. 2011). The varying ECs capture capacity among vegetable species which may be partially explained by the different amounts of lipids contained in the roots that facilitate an interaction with lipophilic compounds (Wu et al. 2012). Since the presence of ECs in vegetables depends on the interaction of each particular EC,

Table 2 Pharmaceutical compounds measured in WW or environment in the most populated countries in nanograms per liter except where others are indicated

ECs	Spain	Italy	UK	Germany	France	India	China	USA	Mexico	Brazil
CBZ	3090	265	4596	3200	600	28.3	1090	60	203	[a]234
Diazepam	60	10	–	–	–	–	8	[3]0.43		
Ibuprofen	19,000	–	424	0.3	10	–	[2]400	–	4700	500
Naproxen	16,000	5220	703	–	10	–	[2]17	[3]0.9	11,377	500
Diclofenac	3400	5450	142	1500	400	0.051–0.6 μg/g[1]	[2]130	[3]1.1	2338	700
Iopromide	6600	–	–	–	10	–	[3]90			
Sulfamethoxazole	800	317	10	0.5	[b]544	[3]25	[5]193	[2]120	[2]300	[b]106
Trimethoprim	620		3052	1	[c]31	[4]83	[5]200	[3]0.8		[b]484
Metoprolol	400	400	130	2.3	25	[2]950 μg/L	[3]20			[a]28
Triclosan						5160	[3]40	[3]3	1587	
Reference	Carballa et al. (2008); Gros et al. (2010)	Al-Aukidy et al. (2012)	Kasprzyk-horden et al. (2009)	Ternes (2007)	Vulliet and Cren-Olive (2011); Golet et al. (2001); [c]Tamtam et al. (2008)	Ramaswamy et al. (2011); [1]Oaks et al. (2004); [2]Larsson et al. (2007); [3]Diwan et al. (2013); [4]Rao et al. (2008)	Zhou et al. (2011); [2]Wang et al. (2010); [3]Yu et al. (2011); [4]Xu et al. (2007); [5]Sui et al. (2010)	Thacker (2005); [2]Yang and Carlson (2004); [3]Benotti et al. (2009)	Chavez et al. (2011); [2]Brown et al. (2006)	Stumpf et al. (1999); [a]Thomas et al. (2014); [b]Locatelli et al. (2011)

Table 3 Biological effects of ECs detected in the environment on plants, invertebrates, and vertebrates

Group	Pollutant	Effect	LOEC concentration	References
Oncorhynchus mykiss *Cyprinus carpio* (fishes)	Carbamazepine Diclofenac Metoprolol	Gill damage Liver damage	5–20 μg/L	Triebskorn et al. (2007)
Danio rerio (zebra fish)	Carbamazepine Clofibric ac. Diclofenac	Embryos and larvae mortality	25,000 μg/L 70,000 μg/L 4000 μg/L	Ferrari et al. (2003)
Chironomus riparius (midge)	Carbamazepine		70 to 210 mg/L	Oetken et al. (2005)
P subcapitata (microalga)	Clofibric ac. Diclofenac	Growth reduction	75 mg/L 10 mg/L	Ferrari et al. (2003)
Lactuca sativa (macrophyte)	Metoprolol + other 10	Emerging seedlings	>100 μg/L	Larsson et al. (2007)
Brachionus calyciflorus (rotifer)	Carbamazepine Clofibric ac. Diclofenac	Reproduction Reduction	25 mg/L 246 mg/L 1000 mg/L	Ferrari et al. (2003)
Ceriodaphnia dubia (crustacean)	Carbamazepine Clofibric ac. Diclofenac	Reproduction Reduction	52 mg/L 640 mg/L 1000 mg/L	Ferrari et al. (2003)
Perna perna (mussel)	Triclosan	Larval development	0.135 mg/L	Sanzi Cortez et al. (2012)

LOEC lowest observed effect concentration

the soil and the plant species, it is clear that monitoring ECs in crops should be implemented as a regular procedure by national agencies of food quality control.

As previously stated, the dilution factor is a relation between the amount of water and the presence of ECs. Therefore, not only the volume of available water is important but also the amount of EC dumped into the environment. In this sense, it is clear that the most populated areas would be hot spots of ECs input to the environment. They are China, India, the EU, the USA, Indonesia, and Brazil. Among them, the presence of ECs in WW and biosolids has been extensively reported (Table 2). There are several reports of ECs that trigger deleterious reactions in European fish species at environmentally reported concentrations (Ternes 2007). Table 3 provides some examples of different animal and plant species that show adverse reactions to ECs. The lowest observed effect concentrations (LOECs) are 10 to 100 times less than the acute standard tests with the water fly, *Daphnia magna* (Ferrari et al. 2003), or *Danio rerio*. Therefore, chronic tests with native species in early developmental stages and mixtures of ECs are needed.

The procedures implemented to evaluate and manage the risks from drinking polluted groundwater based on research information are not enough as of date. Social, legal, economic, and political issues need to be taken into account for setting accurate guidelines to prevent and reduce groundwater pollution. Consequently, each country must provide different regulatory frames which, in the near future, could cause inconveniences among countries sharing a single river basin or any other types of water reservoir.

Further, other factors, such as global warming, can affect the proper management of wastewater and solid wastes which ultimately change the effect of different treatment methods for removal of ECs from these sources. The ecosystem will be negatively affected if the receiving water body for wastewater effluent has a higher temperature due to global warming, adding cost and energy to the process for cooling down the effluent before discharge. Macdonald et al. (2005) presented a review on climate change in the Arctic and its impact on contaminant pathways and interpretation of temporal trend data. They concluded that the risk of contaminants to arctic ecosystems cannot be fully understood by studying isolated components and rapid transport of a contaminant to the Arctic in air may or may not be followed by entry into food webs. Further, a report by Snyder et al. (2012) on climate change impacts on emerging contaminants showed that climate change and the consequent impact to drought and precipitation conditions severed the shortage of freshwater which put pressure on water utilities to adopt new technologies to treat and deliver water resources, ultimately treating the contaminants.

7 Conclusions and Future Challenges

Field utilization of wastewater and biosolids is a useful practice to restore organic matter and reuse, to ameliorate physicochemical and biological features of soils, to facilitate resettlement of plants, and to restore altered communities. Nevertheless, it is important to pay attention to the possible accumulation and magnification of ECs and other pollutants that come from the application of WW and biosolids, since such pollutants can trigger adverse effects even at low concentrations.

Wastewater and biosolids are possible vehicles facilitating the entrance of ECs into the ecosystems. Wastewater treatment facilities produce millions of tons of sludge annually. As sludge is enriched in minerals and organic compounds useful for growing plants, it is commonly used as a natural fertilizer enhancing the soil qualities. ECs have been detected in crops, and therefore, human populations would be chronically exposed to them. Furthermore, there are several reports indicating adverse effects of ECs on natural populations of plants and animals at environmental concentrations. Since a large list of organic compounds, including pharmaceuticals, have been detected in wastewater derived from WWTPs, doubts on the safety of biosolids in regard to ECs are increasing. Therefore, the adoption of monitoring protocols and the constant innovation of treatment techniques are the key for future drinking water and safe fertilization using WW and biosolids.

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References

AI-Aukidy, M., Verlicchi, P., Jelic, A., Petrovic, M., Barcelo, D. (2012). Monitoring release of pharmaceuticals compounds: occurrence and environmental risk assessment of two WWTP effluents and their receiving bodies in the PO Valley, Italy. *Science of The Total Environment, 438*, 15–25.

Alder, A.C., McArdell, C.S., Golet, E.M., Ibric, S., Molnar, E., Nipales, N.S., & Giger, W. (2001). Occurrence and fate of fluoroquinolone, macrolide, and sulfonamide antibiotics during wastewater treatment and in ambient waters in Switzerland. In: C.G. Daughton, T.M. Jones-Lepp (Eds.), *Pharmaceuticals and personal care products in the environment, scientific and regulatory issues* (pp. 56–69). USA: American Chemical Society Symposium Series 791.

Alidina, M., Hoppe-Jones, C., Yoon, M., Hamadeh, A. F., Li, D., & Drewes, J. E. (2014). The occurrence of emerging trace organic chemicals in wastewater effluents in Saudi Arabia. *Science of the Total Environment, 478*, 152–162.

Ben Rebah, F., Tyagi, R. D., & Prévost, D. (2001). Acid and alkaline treatment for enhancing the growth of Rhizobia in sewage sludge. *Canadian Journal of Microbiology, 47*, 467–474.

Benotti, M. J., Vanderford, R. A., Holady, J. C., Stanford, B. D., & Snyder, S. A. (2009). Pharmaceuticals and endocrine disrupting compounds in U.S. drinking water. *Environmental Science and Technology, 43*, 597–603.

Borgert, C. J., Price, B., Wells, C., & Simon, G. S. (2001). Evaluating interaction studies for mixture risk assessment. *Human and Ecological Risk Assessment, 7*, 259–306.

Brown, J.N., Peake, B.M., Robinson, D., Schmid, O. (2003). Partitioning of chemical contaminants in urban stormwater. 3rd South Pacific Conference on Stormwater and Aquatic Resource Protection, Auckland, New Zealand: New Zealand Water and Wastes Association.

Brown, A. E., Zhang, J., McMahon, T. A., Western, A. W., & Vertessy, R. A. (2005). A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology, 310*, 28–61.

Brown, K. D., Kulis, J., Thomson, B., Chapman, T. H., & Mawhinney, D. B. (2006). Occurrence of antibiotics in hospital, residential, and dairy effluent, municipal wastewater, and the Rio Grande in New Mexico. *Science of the Total Environment, 366*, 772–783.

Buerge, I. J., Keller, M., Buser, H.-R., Müller, M. D., & Poiger, T. (2011). Saccharin and other artificial sweeteners in soils: estimated inputs from agriculture and households, degradation, and leaching to groundwater. *Environmental Science and Technology, 45*, 615–621.

Cabeza, Y., Candela, L., Ronen, D., & Teijon, G. (2012). Monitoring the occurrence of emerging contaminants in treated wastewater and groundwater between 2008 and 2010. The Baix Llobregat (Barcelona, Spain). *Science of Total Environment*, 239–240, 32–39.

Calderón-Preciado, D., Matamoros, V., & Bayona, J. M. (2011). Occurrence and potential crop uptake of emerging contaminants and related compounds in an agricultural irrigation network. *Science of the Total Environment, 412–413*, 14–19.

Camacho-Muñoz, D., Martin, J., Santos, J. A., & Aparicio, I. (2014). Concentration evolution of pharmaceutically active compounds in raw urban and industrial wastewater. *Chemosphere, 111*, 70–79.

Carballa, M., Omil, F., Lema, J. M. (2008). Comparision of predicted and measured concentration of selected pharmaceuticals, fragrances and hormones in Spanish sewage. *Chemosphere, 72*, 1118–1123.

Carpy, S. A., Kobel, W., & Doe, J. (2000). Health risk of low dose pesticides mixtures: a review of the 1985–998 literature on combination toxicology and health risk assessment. *Journal of Toxicology and Environmental Health, Part B, 3*, 1–25.

Chavez, A., Maya, C., Gibson, R. & Jiménez, B. (2011). The removal of microorganisms and organic micropollutants from wastewater during infiltration to aquifers after irrigation of farmland in the Tula Valley, Mexico. *Environmental Pollution, 159*, 1354–1362.

Clarke, B. O., & Smith, S. R. (2011). Review of 'emerging' organic contaminants in biosolids and assessment of international research priorities for the agricultural use of biosolids. *Environment International, 37*, 226–247.

Díaz-Cruz, M. S., & Barceló, D. (2008). Trace organic chemicals contamination in ground water recharge. *Chemosphere, 72*, 333–342.

Diaz-Cruz, M. S., Alda, M. J. L., & Barcelo, D. (2003). Environmental behavior and analysis of veterinary and human drugs in soils, sediments and sludge. *TrAC, Trends in Analytical Chemistry, 22*, 340–351.

Diaz-Cruz, M. S., Garcia-Galon, M. J., Gurrea, P., & Jelic, A. (2009). Analysis of selected emerging contaminants in sewage sludge. *TrAC, Trends in Analytical Chemistry, 28*, 1263–1275.

Diwan, V. S., Lundborg, C., & Tamhankar, A. J. (2013). Seasonal and temporal variation in release of antibiotics in hospital wastewater: estimation using continuous and grab sampling. *PLoS ONE, 8*(7), e68715. doi:10.1371/journal.pone.0068715.

Du, B., Price, A. E., Scott, W. C., Kristofoco, L. A., et al. (2014). Comparison of contaminants of emerging concern removal, discharge, and water quality hazards among centralized and on-site wastewater treatment system effluents receiving common wastewater influent. *Science of the Total Environment, 466–467*, 976–984.

Eggen, T., & Lillo, C. (2012). Antidiabetic II drug metformin in plants: uptake and translocation to edible parts of cereals, oily seeds, beans, tomato, squash, carrots, and potatoes. *Journal of Agricultural and Food Chemistry, 60*(28), 6929–6935.

Eggen, T., Heimstad, E. S., Stuanes, A. O., & Norli, H. R. (2013). Uptake and translocation of organophosphates and other emerging contaminants in food and forage crops. *Environmental Science and Pollution Research International, 20*(7), 4520–4531.

Eljarrat, E., & Barcelo, D. (2003). Priority lists for persistent organic pollutants and emerging contaminants based on their relative toxic potency in environmental samples. *Trends in Analytical Chemistry, 22*, 655–665.

Farré, M., Pérez, S., Gonclaves, C., Alpendurada, M. F., & Barceló, D. (2010). Green analytical chemistry in the determination of organic pollutants in the aquatic environment. *Trends in Analytical Chemistry, 29*, 1347–1362.

Ferrari, B., Paxéus, N., Giudice, R. L., Pollio, A., & Garric, J. (2003). Ecotoxicological impact of pharmaceuticals found in treated wastewaters: study of carbamazepine, clofibric, and diclofenac. *Ecotoxicology and Environmental Safety, 55*, 359–370.

Garric, J., Vollat, B., Duis, K., Péry, A., Junker, T., Ramil, M., Fink, G., & Ternes, T. A. (2007). Effects of the parasiticide ivermectin on the cladoceran Daphnia magna and the green alga Pseudokirchneriella subcapitata. *Chemosphere, 69*, 903–910.

Glassmeyer, S. T., Furlong, E. T., Kolpin, D. W., Cahill, J. D., Zaugg, S. D., Werner, S. L., Meyer, M. T., & Kryak, D. D. (2005). Transport of chemical and microbial compounds from known wastewater discharges: potential for use as indicators of human fecal contamination. *Environmental Science and Technology, 39*, 5157–5169.

Golet, E. M., Alder, A. C., Hartmann, A., Ternes, T. A., & Giger, W. (2001). Trace determination of fluoroquinolone antibacterial agents in urban wastewater by solid-phase extraction and liquid chromatography with fluorescence detection. *Analytical Chemistry, 73*(15), 3632–3638.

Gomez, M. J., Petrovic, M., Fernadez-Alba, A. R., & Barceló, D. (2006). Determination of pharmaceuticals of various therapeutic classes by solid-phase extraction and LC-MS/MS analysis in hospital effluent wastewater. *Journal of Chromatography A, 1114*, 224–233.

Gros, M., et al. (2010) Removal of pharmaceuticals during wastewater treatment and environmental risk assessment using hazard indexes. *Environment international, 36*(1),15–26

Haider, S., & Baqri, S. S. R. (2000). Beta-adrenoceptor antagonists reinitiate meiotic maturation in Clarias batrachus oocytes. *Comparative Biochemistry and Physiology a-Molecular & Integrative Physiology, 126*, 517–525.

Heberer, T. (2002). Occurrence, fate, and removal of pharmaceutical residues in the aquatic environment: a review of recent research data. *Toxicology Letters, 131*, 5–17.

Johnson, D.J., Brain, R.A., Richards, S.M., Wilson, C.J., Mabury, S.A., Lam, M., Sibley, P.K., & Solomon, K.R. (2002). Ecotoxicology of pharmaceutical mixtures in aquatic microcosms part IV: responses in freshwater fish. SETAC Platform Presentation 064, SETAC NA 23rd Annual Meeting 16–20 November 2002.

Kasprzyk-Hordern, B., Dinsdale, R. M., & Guwy, A. J. (2009). The removal of pharmaceuticals, personal care products, endocrine disruptors and illicit drugs during wastewater treatment and its impact on the quality of receiving waters. *Water research, 43*(2), 363–380.

Lange, R., Hutchinson, T. H., Croudace, C. P., Siegmund, F., Schweinfurth, H., Hampe, P., et al. (2001). Effects of the synthetic estrogen 17α-ethinylestradiol on the life-cycle of the fathead minnow (Pimephales promelas). *Environmental Toxicology and Chemistry, 20*, 1216–1227.

Lapworth, D. J., Baran, N., Stuart, M. E., & Ward, R. S. (2012). Emerging contaminants in groundwater: a review of sources, fate and occurrence. *Environmental Pollution, 163*, 287–303.

Larsson, D. G. J., de Pedro, C., & Paxeus, N. (2007). Effluent from drug manufactures contains extremely high levels of pharmaceuticals. *Journal of Hazardous Materials, 148*, 751–755.

Laven, M., Alsberg, T., Yu, Y., Adolfsson-Erici, M., & Sun, H. (2009). Serial mixed mode cation and anion exchange solid phase extraction for separation of basic, neutral and acidic pharmaceuticals in wastewater and analysis by high performance liquid-chromatography-quadrupole time-of-flight mass spectrometry. *Journal of Chromatography A, 1216*, 49–62.

Li, X., Zheng, W., & Kelly, W. R. (2013). Occurrence and removal of pharmaceutical and hormone contaminants in rural wastewater treatment lagoons. *Science of the Total Environment, 445–446*, 22–28.

Locatelli, M. A. F., Sodre, F. F., & Jardim, W. F. (2011). Determination of antibiotics in Brazilian surface waters using liquid chromatography–electrospray tandem mass spectrometry. *Archives of Environmental Contamination and Toxicology, 60*, 385–393.

Lombard, K., Neill, M. O., Ulery, A., Mexal, J., Onken, B., & Sammis, T. (2011). Fly ash and composted biosolids as a source of Fe for hybrid poplar: a greenhouse study. *Applied and Environmental Soil Science*. doi:10.1155/2011/475185.

Luo, Y., Guo, W., Ngo, H. H., Nghiem, L. D., et al. (2014). A review on the occurrence of micropollutants in the aquatic environment and their fate and removal during wastewater treatment. *Science of the Total Environment, 473–474*, 619–641.

Luque-Garcia, J. L., & Luque de Castro, M. D. (2003). Ultrasound: a powerful tool for leaching. *Trends in Analytical Chemistry, 22*, 41–47.

Macdonald, R. W., Harner, T., & Fyfe, J. (2005). Recent climate change in the Arctic and its impact on contaminant pathway and interpretation of temporal trend data. *Science of the Total Environment, 342*, 5–86.

Meneses, M., Pasqualino, J. C., & Castells, F. (2010). Environmental assessment of urban wastewater reuse: treatment alternatives and applications. *Chemosphere, 81*, 266–272.

Mohapatra, D. P., Brar, S. K., Tyagi, R. D., & Surampalli, R. Y. (2010). Physico-chemical pre-treatment and biotransformation of wastewater and wastewater sludge—fate of bisphenol A. *Chemosphere, 78*(8), 923–941.

Mohapatra, D. P., Brar, S. K., Tyagi, R. D., & Surampalli, R. Y. (2011). Parameter optimization of ferro-sonication pre-treatment process for degradation of BPA and biodegradation from wastewater sludge using response surface model. *Journal of Hazardous Materials, 189*, 100–107.

Mohapatra, D. P., Brar, S. K., Tyagi, R. D., Picard, P., & Surampalli, R. Y. (2012). Carbamazepine in municipal wastewater and wastewater sludge: ultrafast quantification by laser diode thermal desorption-atmospheric pressure chemical ionization coupled with tandem mass spectrometry. *Talanta, 99*, 247–255.

Mohapatra, D. P., Brar, S. K., Tyagi, R. D., Picard, P., & Surampalli, R. Y. (2013). A comparative study of ultrasonication, Fenton's oxidation and ferro-sonication treatment for degradation of carbamazepine from wastewater and toxicity test by yeast estrogen screen (YES) assay. *Science of the Total Environment, 447*, 280–285.

Mohapatra, D. P., Brar, S. K., Tyagi, R. D., Picard, P., & Surampalli, R. Y. (2014). Analysis and advanced oxidation treatment of a persistent pharmaceutical compound in wastewater and wastewater sludge-carbamazepine. *Science of the Total Environment, 470–471*, 58–75.

Murray, A., & Ray, I. (2010). Wastewater for agriculture: a reuse-oriented planning model and its application in peri-urban China. *Water Research, 44*, 1667–1679.

Murray, K. E., Thomas, S. M., & Bodour, A. A. (2010). Prioritizing research for trace pollutants and emerging contaminants in the freshwater environment. *Environmental Pollution, 158*, 3462–3471.

Oaks, J. L., Gilbert, M., Virani, M. Z., Watson, R. T., Meteyer, C. U., Rideout, B. A., et al. (2004). Diclofenac residues as the cause of vulture population decline in Pakistan. *Nature, 427*, 630–633.

Oetken, M., Nentwig, G., Loffler, D. (2005). Effects of pharmaceuticals on aquatic invertebrates. Part I. The antiepileptic drug carbamazepine. *Archives of Environmental Contamination and Toxicology, 49*, 353–361.

Petrovic, M., Gonzalez, S., & Barcelo, D. (2003). Analysis and removal of emerging contaminants in wastewater and drinking water. *Trends in Analytical Chemistry, 22*, 685–696.

Pomati, F., Orlandi, C., Clerici, M., Luciani, F., & Zuccato, E. (2008). Effects and interactions in an environmentally relevant mixture of pharmaceuticals. *Toxicological Sciences, 102*, 129–137.

Ramaswamy, B. R., Shanmugam, G., Velu, G., Rengarajan, B., & Larsson, D. J. (2011). GC-MS analysis and ecotoxicological risk assessment of triclosan, carbamazepine and parabens in Indian Rivers. *Journal of Hazardous Materials, 186*, 1586–1593.

Rao, R. N., Venkateswarlu, N., & Narsimha, R. (2008). Determination of antibiotics in aquatic environment by solid-phase extraction followed by liquid chromatography–electrospray ionization mass spectrometry. *Journal of Chromatography A, 1187*, 151–164.

Reinhold D., & Aryal, N. (2011). Mitigation of emerging pollutants by plants. *Water Practice Technology*, *6*(4), 20pp.

Relyea, R. A. (2009). A cocktail of contaminants: how pesticide mixtures at low concentrations affect aquatic communities. *Oecologia, 159*, 363–376.

Richardson, S. D., & Ternes, T. A. (2011). Water analysis: emerging contaminants and current issues, 2011 review. *Analytical Chemistry, 83*, 4614–4648.

Rogers, H. R. (1996). Sources, behaviour and fate of organic contaminants during sewage treatment and in sewage sludges. *Science of the Total Environment, 185*, 3–26.

Rosal, R., Rodriguez, A., Perdigo-Melon, J., Petre, A., et al. (2010). Occurrence of emerging pollutants in urban wastewater and their removal through biological treatment followed by ozonation. *Water Research, 44*, 578–588.

Sabourin, L., Duenk, P., Bonte-Gelok, S., Payne, M., & Lapen, D. R. (2012). Uptake of pharmaceuticals, hormones and parabens into vegetables grown in soil fertilized with municipal biosolids. *Science of the Total Environment, 431*, 233–236.

Sanzi Cortez, F., Pereira, C. D. S., Santos, A. R., Cesar, A., Choueri, R. B., Martini, G. A., & Bohrer-Morela, M. B. (2012). Biological effects of environmentally relevant concentrations of the pharmaceutical triclosan in the marine mussel Perna perna (Linnaeus, 1758). *Environmental Pollution, 168*, 145–150.

Sarmah, A. K., Meyer, M. T., & Boxall, A. B. A. (2006). A global perspective on the use, sales, exposure pathways, occurrence, fate and effects of veterinary antibiotics (Vas) in the environment. *Chemosphere, 65*, 725–759.

Schulman, S. J., Sargent, E. V., & Naumann, B. D. (2002). A human health risk assessment of pharmaceuticals in the aquatic environment. *Human and Ecological Risk Assessment, 8*, 657–680.

Shaaban, H., & Goreki, T. (2012). Fast ultrahigh performance liquid chromatographic method for the simultaneous determination of 25 emerging contaminants in surface water and wastewater samples using superficially porous sub-3 μm particles as an alternative to fully porous sub-2 μm particles. *Talanta, 100*, 80–89.

Shenker, M., Harush, D., Ben-Ari, J., & Chefetz, B. (2011). Uptake of carbamazepine by cucumber plants—a case study related to irrigation with reclaimed wastewater. *Chemosphere, 82*(6), 905–910.

Simonich, S. L., Begley, W. M. (2000). Trace analysis of fragrance materials in wastewater and treated wastewater. *Environmental Science and Technology, 34*, 959–965.

Snyder, S. A., Tan, Y., Udy, J. W., Bartkow, M. E., Merel, S., Roig, B., & Thomas, O. (2012). Climate change impacts on emerging contaminants. *Encyclopedia of Sustainability Science and Technology*. doi:10.1007/978-1-4419-0851-3_261.

Sörme, L., Lindqvist, A., & Söderberg, H. (2003). Capacity to influence sources of heavy metals to wastewater treatment sludge. *Environmental Management, 31*, 421–428.

Steger-Hartmann, T., Kummerer, K., & Hartmann, A. (1997). Biological degradation of cyclophosphamide and its occurrence in sewage water. *Ecotoxicology and Environmental Safety, 36*, 174–179.

Stuart, M. E., Lapworth, D. J., Crane, E., & Hart, A. (2012). Review of risk from potential emerging contaminants in UK groundwater. *Science of the Total Environment, 416*, 1–21.

Stuer-Lauridsen, F., Birkved, M., Hansen, L. P., et al. (2000). Environmental risk assessment of human pharmaceuticals in Denmark after normal therapeutic use. *Chemosphere, 40*, 783–793.

Stumpf, M., Ternes, T. A., Wilken, R. D., & Rodrigues, S. V. (1999). Polar drug residues in sewage and natural waters in the state of Rio de Janeiro, Brazil. *Science of the Total Environment, 225*, 135–141.

Sui, Q., Huang, J., Deng, S. (2011). Seasonal variation in the occurrence and removal of pharmaceuticals and personel care products in different biological wastewater treatment processes. *Environmental Science and Technology, 45*, 3341–3348.

Tamtam, F., Mercier, F., LeBot B., Eurin, J., Dinh, Q. T., Clément, M., & Chevreuil, M. (2008). Occurrence and fate of antibiotics in the Senie River in various hydrological conditions. *Science of The Total Environment, 393*, 84–95.

Ternes, T. A. (1998). Occurrence of drugs in German sewage treatment plants and rivers. *Water Research, 32*, 3245–3260.

Ternes, T. A. (2007). Analytical methods for the determination of pharmaceuticals in aqueous environmental samples. *Trends in Analytical Chemistry, 20*, 419–434.

Terzic, S., Senta, I., Ahel, M., & Gros, M. (2008). Occurrence and fate of emerging wastewater contaminants in Western Balkan Region. *Science of the Total Environment, 399*, 66–77.

Thacker, P. D. (2005). Pharmaceutical data eludes environmental researchers. *Environmental Science and Technology, 39*, 193A–194A.

Thomas, K. V., Araujo da Silva, F. M., Langford, K. H., Leao de Souza, A. D., Nizzeto, L., & Waichman, A. V. (2014). Screening for selected human pharmaceuticals and cocaine in the urban streams of Manaus, Amazonas, Brazil. *Journal of the American Water Resources Association, 50*(2), 302–308.

Tisdall, J. M., & Oades, J. M. (1982). Organic matter and water-stable aggregates in soils. *Journal of Soil Science, 33*, 141–163.

Triebskorn, R., Casper, H., Scheil, V., & Schwaiger, J. (2007). Ultrastructural effects of pharmaceuticals (carbamazepine, clofibric acid, metoprolol, diclofenac) in rainbow trout (Oncorhynchus mykiss) and common carp (Cyprinus carpio). *Analytical and Bioanalytical Chemistry, 387*, 1405–1416.

Venkatesan, A. K., & Halden, R. U. (2014). Brominated flame retardants in U.S. biosolids from the EPA national sewage sludge survey and chemical persistence in outdoor soil mesocosms. *Water Research, 55*, 133–142.

Verma, M., Brar, S. K., Barnabé, S., Tyagi, R. D., Valéro, J. R., & Surampalli, R. (2005). Wastewater sludge as a potential raw material for antagonistic fungus (Trichoderma sp.): role of pre-treatment and solids concentration. *Water Research, 39*, 3587–3596.

Vulliet, E., & Cren-Olive, C. (2011). Screening of pharmaceuticals and hormones at the regional scale, in the surface and groundwater to human consumption. *Environmental Pollution, 159*, 2929–2934.

Wang, L., Ying, G., Zhao, J., Yang, X., Chen, F., Tao, R., Liu, S., & Zhou, L. (2010). Occurrence and risk assessment of acidic pharmaceuticals in the Yellow River, Hai River and Liao River of north China. *Science of the Total Environment, 408*, 3139–3147.

Wu, C., Spongberga, A. L., Wittera, J. D., & Sridharc, B. B. M. (2012). Transfer of wastewater associated pharmaceuticals and personal care products to crop plants from biosolids treated soil. *Ecotoxicology and Environmental Safety, 85*, 104–109.

Xu, W., Zhang, G., Zou, S., Li, X., & Liu, Y. (2007). Determination of selected antibiotics in the Victoria Harbour and the Pearl River, South China using high-performance liquid chromatography-electrospray ionization tandem mass spectrometry. *Environmental Pollution, 145*(3), 672–679.

Yang, S., & Carlson, K. H. (2004). Solid-phase extraction-high-performance liquid chromatography-ion trap mass spectrometry for analysis of trace concentrations of macrolide antibiotics in natural and waste water matrices. *Journal of Chromatography A, 1038*(1-2), 141–155.

Yu, Y., Huang, Q., Wang, Z., Zhang, K., Tang, C., Cui, J., Fenga, J., & Peng, X. (2011). Occurrence and behavior of pharmaceuticals, steroid hormones, and endocrine-disrupting personal care products in wastewater and the recipient river water of the Pearl River Delta, South China. *Journal of Environmental Monitoring, 13*, 871–878.

Zhou, X. F., Dai, C. M., Zhang, Y. L., Surampalli, R., & Zhang, T. C. (2011). A preliminary study on the occurrence and behavior of carbamazepine (CBZ) in aquatic environment of Yangtze River Delta, China. *Environmental Monitoring and Assessment, 173*, 45–53.