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Review of Endocrine-Disrupting-Compound Removal Technologies in Water and Wastewater Treatment Plants: An EU Perspective

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ABSTRACT: Xenobiotic persistent organic pollutants are ubiquitous in the environment (air, water, soil, biota), and this is the origin of the rising concern about their potential impact. Recent advances in chemical analysis at trace levels and a lack of knowledge about the fate and transport of reference compounds lead to a strong research demand in this area. In this context, special attention is focused on control technologies in water and wastewater involving the application of advanced technologies to minimize their environmental release. After presenting the environmental and sanitary impacts associated with the main classes of persistent xenobiotic compounds, this article focuses on endocrine-disrupting compounds (EDCs), a class of chemicals interfering with the endocrine systems of mammals and lower animals. In the second part of this article, the basic principles of the advanced technologies used for EDC control in water and wastewater are critically discussed with specific reference to their engineering aspects.

1. INTRODUCTION

The demand for fresh water is increasing with the growth in world population. Today, using water only once is a luxury, and sustainable reuse from unconventional sources, including municipal wastewater, is feasible from both technical and economic points of view.¹ To make (waste)water reuse beneficial, conventional wastewater treatment plants (WWTPs) must be designed in such a way that they can achieve removal not only of biodegradable organic matter and pathogens but also of persistent organic (and inorganic) micropollutants present at trace levels to minimize their sanitary and environmental impacts. When treated effluents are released to natural water bodies, a wide range of biopersistent compounds, incompletely degraded or formed as byproducts during conventional biological oxidation, enter aquatic ecosystems.^{2,3} Biopersistent organic micropollutants include endocrine-disrupting chemicals (EDCs), which interfere in vivo with the endocrine systems of various species, thus resulting, for example, in sexual aberrations in fish, mollusks, and mammals living in water bodies that are downstream from WWTPs,^{4,5} among other effects. The hazard from artificial (xenobiotic) persistent chemicals released into the water and soil compartments is unsustainable without the adoption of treatment technologies specifically oriented toward their quantitative removal. Recent advances in chemical analysis [e.g., high-performance liquid chromatography–mass spectrometry (HPLC–MS), gas chromatography–mass spectrometry (GC–MS), gas chromatography–tandem mass spectrometry (GC–MS/MS)] allow for selective detection of the above micropollutants at trace levels (micro- or nanogram or lower) for better substantiation of their sanitary and environmental impacts. On the other hand, basic knowledge about the behavior and fate of xenobiotic compounds in the environment is lacking, also in consideration of the increasing number of new products commercialized on a yearly basis. This complicates the activity of international organizations that have to set new limits as a result of updated reviews of the available information. After an extensive presentation of the

environmental and sanitary impacts related to the presence of the main EDCs in water and wastewater, this article describes basic principles and critically comments on the best available technologies (BATs) for their removal and control.

2. ENVIRONMENTAL AND SANITARY IMPACTS

2.1. Origin and Classes of EDCs. EDCs exert similar effects, even though there are large differences in their chemical structures. Accordingly, wastewater treatment technologies for their control must be specifically targeted toward different EDC classes, and no general treatment pathways can be applied, especially in reference to mixtures of compounds. The increasing number of xenobiotic chemicals introduced onto the market and later potentially released into the environment calls for an increasing research demand on the fate and transport phenomena of new synthetic endocrine-disrupting chemicals. With such a vast number of compounds already known, or suspected, to be EDCs, it is difficult to understand the sanitary impacts and environmental fates of individual compounds. For convenience, different compounds are clustered in homologous classes with similar chemical structures and properties (see Table 1). Pharmaceuticals, personal care products, and pesticides represent three classes of compounds exhibiting significant endocrine disruption. Among other EDC-active pharmaceuticals, a key role is played by natural and synthetic steroid derivatives such as estrogens [estrone (E1), 17 β -estradiol (E2), and 17 α -ethinylestradiol (EE2)], which are widely employed in the treatment of menopause and in the control of fertility.⁶ Phytoestrogens, which promote the growth of plant seed roots, are another class of particular concern.⁷ The activity of these compounds is self-evident because, in most cases,

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Table 1. Main Classes of Compounds with EDC Potential

main classes		selected compounds
pharmaceuticals	steroids	synthetic estrogens [e.g., 17 α -ethinyl estradiol (EE2)], natural estrogens [e.g., estrone (E1), 17 β -estradiol (E2), estriol], phytoestrogens (e.g., isoflavoids, lignans)
	antibiotics	sulfonamides (e.g., sulfamethoxazole sulfadimethoxine), quinolones (e.g., ciprofloxacin, norfloxacin), macrolides (e.g., azithromycin, erythromycin), natural and synthetic tetracycline (e.g., tetracycline, chlortetracycline, oxytetracycline, doxycycline), others (e.g., amoxicillin, trimethoprim)
	analgesics	e.g., acetaminophen, ibuprofen, naproxen
	anti-inflammatory agents	e.g., ketorolac, piroxicam, indomethacin fenamate
	psychotropic agents	antianxiety (meprobamate), antidepressants (fluoxetine), sedatives (diazepam)
	altera	muscle relaxants (e.g., diazepam), antiepileptics (e.g., phenytoin), virility regulators (e.g., sildenafil, vardenafil), lipid regulators (e.g., bezafibrate, gemfibrozil)
personal care products	surfactants	alkylphenols (APs), alkylphenol ethoxylates (APEOs), alkylphenol carboxylates (APECs)
	synthetic fragrances	nitro musks (e.g., trinitro and dinitro benzenes, musk xylene, musk ketone), polycyclic musks [HHCB (e.g., galaxolide), AHTN (e.g., tonalide)]
pesticides	preservatives	parabens (e.g., methyl-, ethyl-, propyl-, and butylparaben)
	insecticides, fungicides, and rodenticides	triazine herbicides, chlorophenoxy herbicides (CPHs), organochlorine insecticides (dichlorophenol derivatives, e.g., 2,4-D, pentachlorophenol (PCP), DDT, hexachlorocyclohexane, or lindane)
miscellaneous industrial chemicals and byproducts	organic oxygen compounds	phthalate, bisphenol A (BPA)
	polycyclic aromatic compounds	polyaromatic hydrocarbons (PAHs), polychlorinated dibenzodioxins (PCDDs) or dioxin, and polychlorinated dibenzofurans (PCDFs), polychlorinated biphenyls (PCBs), brominated flame retardants [e.g., polybrominated biphenyls (PBBs) and polybrominated diphenyl ethers (PBDEs)]
	organometals	organotin (e.g., MBT, DBT, and TBT), organomercury

they are purposely designed to interact with the endocrine system. Surprisingly, other classes of human and animal pharmaceuticals, originally designed to act on different targets, show comparable estrogenic properties. Most anti-inflammatories, antibiotics, antidiabetics, antiepileptics, antihistamine, diuretics, and psychotropic agents are likely EDC candidates.⁸ As an example, an emerging class of compounds that are ubiquitous contaminants in sewage water today consists of antibiotics designed, as are most pharmaceuticals, as biopersistent compounds.⁹ Another major source of concern is personal care products, such as synthetic nitro and polycyclic musk fragrances, which are released unchanged from conventional treatment plants after their ordinary use.¹⁰ Because most of the above chemicals are not readily biodegradable, they become ubiquitous contaminants in wastewater effluents and, sooner or later, end up in surface waters.⁸ Surfactants such as alkylphenol derivatives [e.g., nonylphenol ethoxylates (NPEOs) and alkylphenoxy carboxylates (APECs)] in industrial and domestic detergents and in several personal care products have EDC potential,¹¹ not to mention that the primary biodegradation compounds of alkylphenols are even more harmful than alkylphenols themselves.¹² These latter compounds act as estrogen mimics, and even if their potency is orders of magnitude lower than that of natural estrogens, they are very persistent in the environment.¹³ Bioaccumulation is significant in waterborne organisms and birds, where concentrations of alkylphenol derivatives have been detected at levels exceeding 10–1000 times that of surrounding environment.¹⁴ Polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzodioxins (PCDDs), and polychlorinated dibenzofurans (PCDFs), the associated byproducts from the incomplete combustion of fossil fuels, present a significant sanitary and

environmental hazard. For these compounds, even nanomolar concentrations are environmentally relevant.^{15,16} Potentially hazardous EDCs are also associated with agrochemicals such as organochlorine insecticides [dichlorodiphenyltrichloroethane (DDT), hexachlorocyclohexane, or lindane], triazine herbicides, fungicides, and fertilizers.^{17,18} Although most of these compounds have been banned in developed countries, they are still in use in developing countries, and they are present at relevant concentrations in environmental systems throughout the world.¹⁹ Beyond the listed compounds, a range of other EDCs from different sources enter environmental systems with specific reference to treated sewage effluents. Other chemicals from the manufacturing industry are detected at different levels in sewage systems.²⁰ Some of these compounds come from the plastics industry such as bisphenol A (BPA),^{21,22} being used as plasticizers (phthalates)²³ or as flame retardants such as polybrominated biphenyls (PBBs).²⁴ Although these latter compounds are not strictly bound to the above materials themselves, because they are mostly used as additives, they can easily leach from plastic household goods such as gloves, sponges, baking tins, cellophane wraps, and many more. Another endocrine-disrupting class of chemicals is organo-metal derivatives, such as organotin and organomercury compounds, which are largely used as antifoulants in boat hull paints^{25,26} or as stabilizers in polyvinylchloride (PVC) plastics in the form of mono-, di-, and trialkyl tin (MBT, DBT, and TBT).

3. NEED FOR STANDARDIZATION AND ADVANCES IN ANALYTICAL METHODS

Despite extensive data on the potential hazards of artificial chemicals released into the environment, the effects of EDCs on

wildlife and humans are still not fully understood. Correlation between exposure to EDCs and long-term impacts is still a controversial issue.²⁷ In this context, generalization of information implies the adoption of internationally recognized standard protocols and methods for toxicity tests, and in this context, national and international regulatory agencies play an important role. The existing guidelines, fairly standard for a number of years,²⁸ show strong limitations with respect to the definition of reproductive and developmental effects of endocrine disruptors.²⁹ The lack of regulations establishing common directives for EDC manipulation in the European Union (EU) countries leads to difficult comparisons among data produced by different authors, despite the growing amount of data available, which customarily do not lead to additional information on cause–effect relationships. In risk assessment studies, the definition of the threshold and maximum allowable concentrations for single EDCs in any situation is important; otherwise, missing references for nontargeted organisms would lead to the under- or overestimation of risks. Long-term (chronic) effects related to continuous low-level exposure present another concerning issue, together with the risks associated with repeated exposure to mixtures of different byproducts or with the introduction of new commercial compounds in different areas. Market issues are usually assumed as more important than environment and safety.³⁰ Hormones are very active compounds, so a continuous exposure to low concentrations would have more of an effect on immature endocrine systems, thus producing unacceptable consequences. Low-level exposure is also a problem posed by biodegradable EDCs, which are normally metabolized by microorganisms whose metabolites (biodegradation byproducts) might be even more dangerous than the parental compounds once discharged into recipient water bodies. Continuous discharge by WWTPs of nonbiodegradable compounds and/or metabolites can result in a constant and relevant presence of hazardous xenobiotic chemicals.^{16,31} Synergy among substrates plays another important role, as mixtures of different chemicals, already at low concentration, might induce deleterious effects.³² Specifically, the simultaneous low-level presence of several compounds might lead to an increase of the environmentally available dose. Therefore, standard analytical protocols for individual compounds might not be sufficiently effective because they do not consider the synergistic effects of exogenous EDC-active compounds that magnify final effects.³³ EDC-related issues came to light with improvements in analytical techniques allowing for their effective detection at very low concentrations.³⁴ After sample collection, several extraction steps (using solvents and/or solid-phase extraction) and derivatization must be applied prior to quantification.^{35–37} Separation relies on either gas or liquid chromatography, depending on the volatility and thermal stability of the analytes, whereas detection is mainly based on mass spectrometry (MS) or hyphenated methods such as GC–MS/MS or HPLC–MS.^{38,39}

3.1. EU Directives on Water and Wastewater Treatment.

Estrogens are commonly detected in rivers⁴⁰ and, occasionally, in drinking water.⁴¹ The main sources of EDCs entering environmental systems are wastewater treatment plants because conventional installations are not designed to remove EDCs and their degradation byproducts.⁴¹ Hence, exposure to residual biopersistent xenobiotic chemicals present in WWTP effluents can be assumed to be the main source of environmental/sanitary abnormalities in receiving water bodies. Nevertheless, in some international water bodies, EDCs are detected at concentrations beyond the threshold values triggering endocrine disruption in

living organisms;⁴² hence, some authors confirm that fairly good EDC removal is already achieved in conventional WWTPs.^{43,44} Other field investigations point out that removal efficiency varies in relation to the EDC homologue class^{45,46} and specific conditions adopted during the operation of conventional (biological) wastewater treatment plants.⁴⁷ A detailed analysis of these issues is provided in the sections to follow. As mentioned, conventional treatment plants are not effective on wastewater containing recalcitrant compounds. The increasing demand for environmental and sanitary protection calls for further investments to specify the management of endocrine-active compounds. A wide variety of regulatory measures on the use and marketing of hazardous compounds were recently introduced by the EU Commission.⁴⁰ Accordingly, commercialization of new chemicals passes through very stringent sanitary and environmental hazard assessment protocols carried out by the European Chemical Agency (ECHA), after application of the REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals) protocols.⁴⁸ REACH requires that marketed (either manufactured or imported) chemicals in the European Union that might be potentially dispersed in the environment during their use must be registered at ECHA. REACH protocols have already published preliminary lists of substances of very high concern (SVHCs)⁴⁹ including, among others, three EDC-active materials, namely, phthalates such as di-*n*-butyl (DBP), diethylhexyl (DEHP), and benzyl butyl (BBP) phthalates. Starting in June 2011, substances included in the list will be subject to authorization procedures and restrictions on their use. For compounds showing potentially endocrine-disrupting action, the REACH Commission will decide whether these substances should be authorized or not. During the transition period, REACH regulations will set appropriate deadlines for regular updating of the list of SVHCs. REACH regulations underline the importance of finding alternatives to potentially hazardous chemicals already present on the market, including several EDCs that will be kept in use until the introduction of safer alternatives. In the following sections are reported the three important EU regulations referring to the presence of xenobiotic organic micropollutants in water.

*Directive 91/271/CEE*⁵⁰. The objective of this directive is to harmonize different regulations applied in the EU for municipal and industrial wastewater treatment. Among other recommendations, EU members are invited to give indications on their “environmentally sensitive areas”, together with the treatment levels and maximum allowable concentrations for hazardous organics including several EDCs. Each member State arranges indications of the local conditions through individualized implementation programs and publication of a biennial report providing for the Commission an update on the environmental situation.

*Directive 2000/60/CE*⁵¹. This directive sets a general legal framework on the quality of surface waters (river, lakes, internal seawater) and groundwater with the final aim of implementing the following objectives:

- protection of ecosystems for water conservation and long-term sustainable supply,
- control of emissions to minimize the release of priority pollutants to surface water bodies,
- protection of surface and groundwater for quality control and sustainable supply and distribution for different uses, and
- protection of coastal seawater on an international basis with the final aim of reaching natural background levels or zero emissions for pollutants of anthropogenic origin.

Table 2. WWTP Treatment and Corresponding Active Mechanism on EDCs

WWTP technology	active mechanism on EDCs	ref(s)
bioaugmentation	microorganisms/additives	72, 74–79
membrane bioreactors (MBR)	biological degradation/membrane filtration	80–89
sequencing batch reactors	biological degradation	77, 90, 91
advanced oxidation process (AOP)	O ₃ /UV, H ₂ O ₂ /UV, electron beam ultrasound (US), H ₂ O ₂ /us UV/us, H ₂ O ₂ /Fe ²⁺ (Fe ³⁺)/UV (photoassisted Fenton) O ₃ /H ₂ O ₂ , O ₃ /OH [−] , H ₂ O ₂ /Fe ²⁺ (Fenton) H ₂ O ₂ /Fe ³⁺ (Fenton-like), H ₂ O ₂ /Fe ³⁺ - Oxalate Mn ²⁺ /Oxalic acid/O ₃ TiO ₂ /O ₂ /UV (photocatalysis) TiO ₂ /H ₂ O ₂ /UV (photocatalysis) electro-Fenton	94–106
membrane technology	reverse osmosis (RO)/nanofiltration (NF)/ultrafiltration (UF)	107–114, 116–118
sorption	activated carbon (AC)/nonfunctional resins/natural biosorbents	108, 119–122
electrochemical methods	boron-doped diamond electrode (BDDE)	123

The EU Commission has established a preliminary list of priority pollutants (SVHCs) among those showing significant risks for recipient water bodies. The EU Commission reviews this list every four years, after consultation with the Scientific Board on ecological toxicity of each member State and the European Environmental Agency and final approval of the EU Parliament. The EU Commission identifies the treatment levels to reach the proposed maximum allowable concentrations, based on the application of best available technologies.

*EU Decision 2455/2001/CE*⁵². With this directive, the EU Parliament finally promulgated the list of priority pollutants preliminarily indicated in Directive 2000/60/CE.

4. REMOVAL OF ORGANIC MICROPOLLUTANTS FROM WATER AND WASTEWATER

4.1. Analytical and Technological Issues. Recent developments in the analytical methods used for emerging and newly identified contaminants in water and wastewater, recently published in an *Analytical Chemistry* biennial (2007–2008) review,⁵³ indicate the increasing and continuing health concerns associated with the presence of organic micropollutants in the environment. In this review, discussion focused on the hyphenated analytical protocols based on high-performance liquid chromatography associated with mass spectrometry (HPLC–MS), for example, as well as gas chromatography associated with mass spectrometry in high-resolution systems (HRGC–HRMS). Specific reference was made to time-of-flight (TOF) methods,^{54–56} which allow for full-scan benefits (i.e., without side determinations or derivatization) in a single run. In all cases, identification and quantification of target/nontarget analytes that are highly polar, nonvolatile, or of high molecular weight is easily carried out. Still, in most laboratories, detection of EDCs is not an easy task because of the trace levels (micro- or nanogram per liter or even less) of these compounds present in most natural waters and wastewaters. As mentioned, existing wastewater treatment plants (WWTPs) are not designed for the removal of newly identified contaminants such as pharmaceuticals, personal care products, surfactants, flame retardants, industrial additives, and different chemicals purported, in most cases, to be biorecalcitrant and, thus, not metabolized or bioremediated, so that they are discharged untouched from conventional WWTPs. These issues pose a particular challenge to plant designers. Current human activities have a significant sanitary and environmental impact. After release of emerging and newly identified chemicals into the environment, cleanup is extremely difficult, time-consuming, and expensive. Significant research and development is underway to establish methods and

technologies to improve water and wastewater treatment, as well as remediation of contaminated sites. Needless to say, that removal technology must be economically feasible (not entailing excessive costs) and environmentally sound (not negatively impacting the environment). In many cases, challenges have been met, but in others, they are still far from solution and, unfortunately, the latter is the situation for newly identified and biorecalcitrant compounds. Prevention is better than a “cure”, and the development of “clean” production technologies (prevention), on one hand, and more efficient (waste)water treatment technologies (cure), on the other, is the only viable route for environmental and sanitary protection.^{57,58} In the following section, advances in biological, physical, chemical, and physicochemical methods for water and wastewater treatments, aimed at the elimination and control of recalcitrant compounds in water and wastewater, are reviewed with the final aim of providing a comprehensive and updated survey of the best available technologies.

4.2. Treatment Technologies: Destructive and Conservative Methods. The occurrence of EDCs in water and wastewater requires advanced treatments for their control. (See Table 2.) The reference compounds have a wide range of properties, and thus, the removal efficiency of WWTPs varies depending on the specific characteristics of the chemical substrates.⁵⁹ Of course, minor modifications in the operating conditions of conventional plants would be the preferred action from both the technical and economic points of view, but such actions do not always lead to successful results.^{60,61} On these premises, EDC removal and control actions are based on two types of interventions: (a) optimization of the operating conditions of existing plants and (b) upgrading of conventional wastewater treatment installations with new end-of-pipe technologies. In all cases, control technologies can be destructive or conservative toward target pollutants depending on the whether the contaminants are degraded or transferred to (and concentrated in) other phases.⁶² Biodegradation of the organic pollutants in conventional WWTPs occurs under aerobic conditions through biological metabolism and transformation reactions that might play a significant role in the removal of estrogenic compounds as well, because microorganisms present in WWTPs have the potential to utilize steroids as a carbon source in biochemical reactions.^{63,64} It is well-known that, in aerobic treatments, microorganisms utilize oxygen for degradation (oxidation) of the soluble (and microdispersed) organic matter present in the waste stream and convert it into carbon dioxide, water, and energy to produce new cells. Ultimately, the soluble pollutants are converted into insoluble biomass (i.e., sludge) that is partially removed mechanically from

the waste stream and sent to disposal. Facultative oxic/anoxic, nitrifying/denitrifying, and methanogenic bacteria that carry out the degradation of organic materials under mostly anaerobic conditions have been found in many conventional plants.^{65,66} This suggests that, under proper operating conditions, conventional (aerobic) treatment plants should manage biodegradation of steroid derivatives. Accordingly, based on literature data, the biodegradation of EDCs requires (a) a measurable increase of the sludge⁶⁷ and hydraulic retention times (SRT and HRT, respectively); (b) a reduced food-to-microorganism ratio (F/M) in the oxidation ditch;^{68–70} and (c) minor structural adjustments of existing plant configurations, possibly by the introduction of dedicated anoxic or anaerobic zones. Among advanced treatments requiring major infrastructure interventions, membrane bioreactors (MBRs) and integrated fixed activated sludge (IFAS) systems might represent other viable options, as these processes maximize the use of existing facilities⁶⁴ and allow the achievement of higher sludge retention times in smaller tank volumes. Although still a matter of investigation, the amplification (bioaugmentation) of the efficiency of the active biomass (e.g., after acclimation) might be applicable to full-scale installations. Sequencing batch reactor (SBR) methods might also be very promising for EDC removal. EDC degradation based on chemical methods such as advanced oxidation processes (AOPs) and the use of cheap and ready available chemicals such as ozone and hydrogen peroxide, taken alone or synergistically associated with UV radiation, might represent a viable alternative. Regardless of the principle of action, all of the above methods are destructive toward target pollutants, which are degraded into lower-molecular-weight metabolites and/or directly to carbon dioxide or methane depending on the plant environmental conditions. Conservative methods, based on kinetic or thermodynamic unit operations (membrane separation, sorption, ion exchange), might offer additional advantages. In this context, molecular sieving through membrane filtration [i.e., reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF)] might present viable alternatives as polishing steps for the elimination of organic micropollutants from biologically treated wastewater. Sorption technologies based on weak electrostatic (nonselective) retention, such as activated carbon (AC) and nonfunctional polymers (NFPs), or strong electrostatic (selective) retention, such as ion exchange, might also be considered as feasible removal options.

4.2.1. Bioaugmentation. By definition, bioaugmentation refers to those biotechnologies where the use of specifically selected and acclimated microorganisms and/or the addition of additives (e.g., enzymes) leads to the operating enhancement of conventional wastewater treatment facilities, with the final aim of improving effluent quality or lowering the operating and maintenance costs of the plants.⁷¹ Operatively, the implementation of bioaugmentation in conventional treatment plants requires proper seeding (inoculation) with well-acclimated microorganism strains during startup operations or during plant malfunctioning that requires system rehabilitation. Tentative bioaugmentation is commonly adopted through the use of many commercially available products (enzymes) that are applied on a trial-and-error basis because of a lack of theoretical support. The practice of utilizing selected microorganisms to carry out biochemical transformations has long been applied in the fields of agrochemicals (e.g., brewing, dairy) and pharmaceuticals, where the wastewater composition is well-characterized, but it is still not a common practice in municipal wastewater plants. A comprehensive field investigation aimed at determining the degradation efficiency of

more than 55 organic micropollutants, including pharmaceuticals, personal care products, endocrine disruptors, and illicit drugs, was carried out in South Wales, U.K. The removal efficiencies of two conventional biotechnologies, namely, activated sludge and trickling filters, were compared under constant plant operating conditions. Trickling filters led to removal efficiencies exceeding 70%, whereas the corresponding activated sludge system led to higher removal efficiency exceeding 85% for all contaminants investigated.⁷² In both cases, the interest was focused on the microorganism strains responsible for micropollutant degradation. Well-acclimated microbial strains that used steroid substrates as the sole source of carbon in bulk systems were preliminarily cultivated and later introduced into large-scale biological reactors, hence implementing bioaugmentation for EDC removal. Despite the great potential of such an approach, basic knowledge is still lacking.^{73,74} A deeper insight into the identification of the intermediate metabolites (degradation by-products) is required, together with the elucidation of the mineralization mechanisms of steroid substrates in the treatment plants. Efficient and stable atrazine removal was realized after accurate startup operation in a membrane bioreactor (MBR) bioaugmented with genetically engineered microorganisms (GEMs). The removal efficiency exceeded 90% in most cases.⁷⁵ The startup period was the key step of the MBR bioaugmented process, which also determined the operating conditions to follow. Apparently, high initial influent atrazine loadings, high temperature, and large initial density of GEM measurably shortened the startup period, whereas the initial background composition of the influent wastewater had little effect on the startup. The shortest startup period was 2 days, and the longest was 12 days under different operation conditions. A logistical model was adopted to fit the GEM density in the oxidation ditch with atrazine removal performance, thus leading to good correlations.⁷⁶ Another group analyzed wastewater treatment problems by properly isolating aerobic microorganism strains present in a municipal WWTP at constant capacity of the oxidation ditch. The authors estimated that only 5–10% of the existing bacteria effectively contributed to the sewage treatment process whereas the others competed for the available oxygen and nutrients. Accordingly, the authors selected the “working” bacteria to increase their fraction in the mixed liquor, thereby increasing the abatement of organic carbon (lipids, protein, detergents, and hydrocarbons, together with other micropollutants). The problem with some conventional wastewater treatment plants is that they are either overloaded or obsolete before their construction is completed. In other municipal installations, working in an area influenced by organic load shocks from industry contributions, an incremental reduction (>95%) of the 5-day effluent biological oxygen demand (BOD_5) and a measurable reduction (~35%) of the oxygen supply to the oxidation ditch were found. Bioaugmentation by properly inoculated autotrophic organisms facilitated the nitrification/denitrification rates in another installation. These latter reactions were measurably favored by the use of smaller reactors and shorter activated sludge retention times (SRTs). Specifically, operations were carried out after separation of the ammonia digester reject water and accurate classification (enrichment) of the nitrifying strains and denitrifying cultures.⁷⁷ Bioaugmentation was also carried out by using engineered bacteria in a pilot-scale two-stage anoxic/oxic (A/O) process. The experimental results showed that, with chemical oxygen demand (COD) and ammonium nitrogen ($N-NH_4^+$) influent concentrations in the

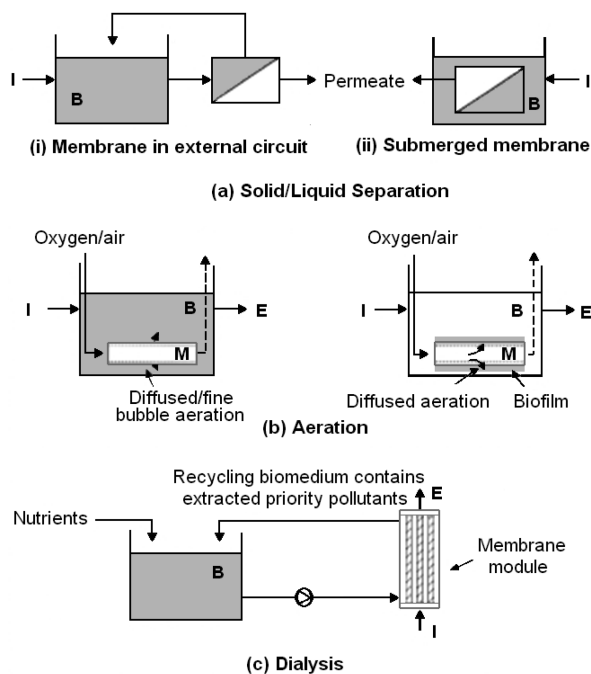


Figure 1. Main features of membrane systems for biological wastewater treatment: B, bioreactor; M, membrane module; I, influent; E, effluent.⁸⁰

range 350–900 and 10–70 mg/L, respectively, the corresponding average effluent concentrations were in the ranges of 80 and 8 mg/L. GC–MS determinations identified 68 persistent organic pollutants in the WWTP effluent that were reduced by almost 50% after bioaugmentation.⁷⁸ Three sets of laboratory-scale reactors applying bioaugmented activated sludge process were operated in parallel to explore treatment possibilities for petrochemical wastewater at low temperatures (13–15 °C). However, massive inoculation did not always lead to successful bioaugmentation, probably because of predation of the specialized bacteria. Bioaugmentation was found to be very promising in the treatment of petrochemical wastewater containing polycyclic aromatic hydrocarbons.⁷⁹

4.2.2. Membrane Bioreactors (MBRs). When bioaugmentation is not feasible in conventional WWTPs by simple modification of the plant operating parameters (e.g., increase of SRT and HRT) for estrogen removal, membrane bioreactors (MBRs) might offer the advantage of increased plant flexibility in more compact installations. MBR technology is considered very promising in wastewater treatment, thus integrating biological degradation with membrane filtration, with specific reference to biopersistent organic substrates. The main advantages of using MBR systems are (a) improved quality of the treated wastewater, (b) more compact plant size, (c) less sludge production, (and d) higher flexibility of plant operations for improved EDC removal by the adoption of variable SRTs and/or HRTs. In these systems, the quality of the final effluent depends strongly on the settling characteristics of the sludge and the hydrodynamic conditions in the sedimentation tank. Accordingly, large-volume sedimentation tanks, offering residence times of several hours, and strict control of the biological unit are necessary to favor sludge settling (granulation), thus minimizing bulking phenomena. The final objective is to obtain adequate solid/liquid separations for optimal performance of the membrane separation to follow. Very often, site-specific and economic constraints limit such options. In most

cases, dual-media filtration, carbon adsorption, or some similar option is needed, with specific reference to those applications leading to wastewater reuse, where the quality of the final effluent is dependent on its final destination. Therefore, a different solid/liquid separation system than conventional secondary sedimentation might represent the most viable solution from both technical and economic points of view. Application of membranes (micro- or ultrafiltration) for biosolids separation might overcome the main disadvantages related to sedimentation tanks in the biological treatment steps. Membranes offer a complete barrier to suspended solids, thus yielding higher effluent quality. This emerging technology offers several advantages over conventional processes allowing, in most cases, for wastewater reuse. Smaller plant sizes, reduced sludge production, and better process reliability are among the main advantages of membrane bioreactors. Membrane-based systems for wastewater treatment can be grouped into three major classes (Figure 1): (1) biosolids separation, (2) biomass aeration, and (3) extraction of selected pollutants. Improved biosolids separation is among the most important advantages, thus promoting full-scale applications in many countries.

In most installations, the membrane can be outer- or inner-skinned, and the permeate is generally extracted by circulating the mixed liquor at high pressure along the membranes installed in the bioreactor. The concentrated mixed liquor at the feed side of the membrane is recycled back to the aeration tank. Continuing progress in membrane manufacturing is leading to full replacement of tertiary treatment by the application of microfiltration or ultrafiltration. This simplified method has been extensively applied at Water Factory 21, Orange County, CA, among the larger wastewater reuse installations operating, with success, since the early 1990s.^{81,82} The higher energy costs to maintain a suitable crossflow velocity through the membranes led to the development of a new system configuration based on the submersion of the membrane modules directly into the bioreactor, just above submerged air diffusers, and withdrawal of the treated water through the membranes.⁸³ Diffusers provide the oxygen necessary for bio-oxidation and the energy to scour the surface of the membrane to remove deposited solids. In one installation, almost-quantitative steroids removal was observed in MBRs, with nitrification and denitrification, upon the application of an average SRT in the range of 12–15 days and a sludge age exceeding 30 days.⁸⁴ In another case, batch experiments confirmed that levels of steroid removal were a factor of 2–3 higher than for conventional activated sludge systems with a solids retention time of 11 days.⁸⁴ However, MBR operations did not lead to satisfactory results, as compared to conventional plants, in two pilot installations that were operated (in parallel) for denitrification at two different SRTs (12 and 25 days) on the same influent wastewater and sludge loading rate (F/M). The authors did not find appreciable differences and concluded that estrogen removal was primarily due to biodegradation rather than mass-transfer phenomena to the sludge phase and/or to membrane separation.^{85,86} Other authors confirmed that the target compounds (17 β -estradiol, estrone, 17 α -ethynilestradiol, and bisphenol A) were, to a certain extent, removed biologically rather than by membrane microfiltration, even after long-term operation that caused gel-layer formation on the membrane surface. It was recognized, however, that migration of the reference pollutants from the liquid to the sludge phase allowed for higher removal yields.⁸⁷ Membrane bioreactors with nano-filtration were adopted for removal of nonylphenol and bisphenol

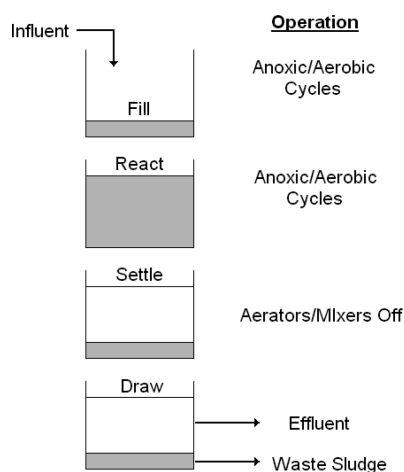


Figure 2. Sketch of the SBR system functions.

A from landfill leachates. The observed removal of the mentioned chemicals ranged between 70% and 100%. The mass balance indicated that membrane transport played a major role during plant operation, whereas final percolation on granular activated carbon was a further polishing step.⁸⁸ A review of the application of the MBR technology for the removal of endocrine disrupters from different wastewaters is offered by Brice et al.⁸⁹

4.2.3. Sequencing Batch Reactors. Sequencing batch reactors (SBRs) for biological treatment of municipal wastewaters are based on the application of at least two identically equipped tanks with a common inlet that can be switched between them. The tanks work in a flow-through system, with the wastewater inlet positioned at one end and the treated effluent water flowing out the other end. While one tank is in the settling step, the other is in the filling and aeration step (Figure 2). At the tank inlet is positioned a section known as the bioselector, which consists of a series of baffles directing the flow either from side to side of the tank or under and over consecutive baffles. This helps to mix the incoming influent and the returned activated sludge, thus favoring the biological digestion process. Overall, the process includes four stages: (a) fill, (b) reaction, (c) settle, and (d) draw and idle stages. Aeration of the mixed liquor is performed during the first two stages by the use of fixed or floating surface turbines or by blowing air into finely perforated membranes fixed to the floor of the tank. During this period, the inlet valve to the tank is opened, and the mixed liquor from the outlet end of the tank is conveyed to the inlet. This operation favors seeding of the incoming sewage with the suspended active biomass. Aeration times vary according to the plant size and the composition/quantity of the incoming liquor, with typical values ranging from 60 to 90 min. The addition of oxygen to the liquor allows for respiration and BOD₅ oxidation, thus converting biodegradable organics into carbon dioxide, and oxidation of the reduced nitrogen forms to nitrite and nitrate ions (nitrification). Phosphorus compounds are generally removed by the addition of precipitating agents (alum, ferric salts) to the liquor, thus resulting in the formation of insoluble phosphate compounds that settle into the sludge separated at the bottom of the tank. The settling time is usually the same as the duration of the aeration stage. Conditions in the settling tank, especially near the bottom, are suitable for the development of anaerobic bacteria. Many of these latter strains and some of the bacteria that would prefer aerobic environments (facultative aerobic) start to use combined

(oxidized) nitrogen compounds (nitrite, nitrate) instead of pure oxygen for their respiration, thus converting nitrate ions into nitrogen gas (denitrification). As bacteria multiply and die, the sludge within the tank increases, and a waste activated sludge pump removes some of the sludge during the settling stage to a digester for further treatment. The "age" of the biomass within the tank is closely monitored, as it can have a marked effect on the process efficiency. The removal of selected EDCs (estrone, 17 β -estradiol, 17 α -ethynylestradiol, bisphenol A, and 4-*tert*-octylphenol) was investigated by Balest et al.,⁷⁶ using a sequencing batch biofilter reactor with granulation (SBBGR), and the performance was compared to that of conventional anaerobic treatment plants. The SBBGR system was characterized by a high biomass concentration (up to 40 g/L), a high sludge retention time (4 months), and low sludge production. A definite increase (30–50% with respect to the performance of conventional plants) in EDC removal was obtained during the 4-month operation. With specific reference to 17 α -ethynylestradiol, Cluzot et al.⁹⁰ compared conventional plants with MBR and SBR biotechnologies in the removal of the above steroids. Membrane-based and SBR systems appeared to be very promising. Sludge granulation played a significant role in the context of hormone removal in SBR systems.^{91,92}

4.2.4. Transfer of EDCs into the Biomass (Sludge). The presence of biopersistent organics in the sludge can occur either through partitioning between the liquid and contacting solid phases during primary and secondary treatments or, possibly, through direct uptake (incorporation) into the biomass. Generally speaking, the reference compounds are quite recalcitrant to aerobic/anaerobic metabolism and chemically stable to hydrolysis and redox reactions. The objectives of sludge treatment processes are to (a) minimize environmental impacts with associated health hazards and (b) reduce the volume of biosolids with the related economic advantages in the case of disposal. The first objective is obtained through biological (anaerobic digestion), physical (pasteurization), or chemical (lime treatment) means. The second objective is obtained through physical means such as thickening; centrifugation; or, after composting, drainage and evaporation. The final objective is to measurably reduce the water content of the solids to a maximum value exceeding 75% so that the waste will be accepted in most landfills according to EU legislation. Treatment and disposal of biosolids is an increasingly important issue in the EU as a consequence of the introduction of the Wastewater Treatment Directive,⁵⁰ and disposal of biosolids within EU countries consists of recycling to agricultural land or landfilling, either directly or as ash after incineration. Recycling to agricultural land is often the most convenient option from both the economic and practical points of view, as the practice returns nutrients such as carbon, nitrogen, phosphorus, and microelements to soils. The main limitation is presented by the presence of inorganic (metals) and organic (biorecalcitrant compounds) micropollutants including EDCs. The current legislation is very restrictive on this issue.⁹³

Biosolids produced from wastewater treatment plants are known to contain a number of recalcitrant organic micropollutants. Reuse of sewage sludge in agriculture or related areas is based on the premise that procedures are safe from a sanitary point of view and environmentally sound. Within the EU, municipal sludge is not considered as a hazardous waste with related implications for current disposal routes. There is concern, however, about the presence of trace organics with specific reference to those exhibiting endocrine disruption.

4.2.5. Advanced Oxidation. Advanced oxidation processes (AOPs), through the use of cheap chemicals, have been demonstrated as a viable alternative for removing trace estrogens. Few installations are in operation today because of their high operating costs on large-scale installations.⁹⁴ Ozone and hydrogen peroxide are the most diffused oxidants. Ozone has long been used for disinfection of drinking waters, and this was the origin of its application to the degradation of several organic micropollutants, which was initially considered only a side effect of the disinfection reactions. AOPs in wastewater treatment are mainly considered as polishing steps because their performance depends greatly on the bulk organic content of the raw water. Needless to say, in the case of wastewater treatment, higher dosages are necessary to achieve the same removal efficiencies that are normally found in clean water. Ozone can react selectively, as an oxidant in its molecular form (O_3), thus leading to typical ozonation reactions with, for example, double bonds, amines, and phenol derivatives, or nonselectively, after formation of hydroxyl radicals (HO^\bullet).^{95,96} In all cases, depending on the structure of the organic substrate, steroid derivatives can be degraded to lower-molecular-weight compounds (byproducts) of unknown estrogenicity. The synergistic use of ozone with other oxidants (e.g., H_2O_2) or in association with physical means such as UV radiation is justified to reduce the selectivity of action in the hope of amplifying the destruction of trace organics.⁹⁵ The use of UV radiation is energy-intensive, as doses required for the degradation of steroids can exceed, by orders of magnitude (30 mJ/cm^2), the amount needed for disinfection processes, which never exceeds 1 mJ/cm^2 . UV photolysis was investigated by Adams et al.,⁹⁷ who obtained 50–80% removal of the target compounds after application of radiation intensities exceeding the equivalent necessary for typical disinfection operations by 2 orders of magnitude. Therefore, the use of UV radiation for estrogen removal might not be economically feasible in the absence of radical promoters (e.g., metals or metal oxides), provided that these promoters do not, themselves, influence the quality of the final effluent. UV photolysis enhanced (catalyzed) by the presence of TiO_2 (anatase)⁹⁸ or ferrous ions (photoassisted Fenton: $Fe^{2+}/H_2O_2/UV$)⁹⁹ are typical examples. Others metal derivatives such as manganese dioxide and ferrate ions can be used, alone and/or photoassisted by UV radiation, because of their high oxidation potentials.¹⁰⁰ As mentioned, the Fenton process is based on the use of ferrous ions in association with hydrogen peroxide in acidic media (pH 3). This process couples synergistically with the oxidation process to coagulation/flocculation, with the latter process occurring later when the pH is raised to neutralize the final effluent.¹⁰¹ The iron-tetraamidomacrocyclic complex (Fe-TAML) at trace levels (micrograms per liter) was found to be an activator of hydrogen peroxide during oxidation reactions, thus showing rapid degradation of natural and synthetic hormones found in agricultural and municipal effluent streams.¹⁰² The mineral birnessite ($\delta\text{-MnO}_2$), naturally occurring in soils and sediments, was demonstrated to be very efficient toward the oxidation of organic compounds containing phenolic and/or aniline moieties. In this context, Kunde et al. explored the oxidation reaction of bisphenol A and tetrabromobisphenol A (TBBPA), among the most heavily used polymer plasticizers and flame retardants, respectively.^{96,103} This treatment appears to be promising in the degradation of estrogens because of the self-regenerating cycle operated by MnO_2 , thus proving to be cost-effective in the long run. Ferrate ion was investigated as a viable oxidant and coagulant alternative. Although the oxidation potential

of ferrate ions is greater than that of ozone, the acidic conditions of operation strongly limit its use in full-scale installations.^{104,105} Formation of oxidation byproducts after the application of chemicals of a different nature and origin is not always sufficiently highlighted in the literature, and this can pose a real challenge to their extensive application. In this context, the UV/hydrogen peroxide-based technology is most promising, as it leads to a lower formation of oxidation byproducts.¹⁰⁶ Chlorine and chloramines both have the potential to react with various EDCs and personal care compounds. Chlorine gas is a fast-reacting and efficient chemical for phenols and amino functional derivatives, but is nearly nonreactive with ketones and alcohols, which are only partially oxidized. It is also important to note that chlorine oxidation is pH-dependent, with the best performance obtained in acidic media. In a study recently carried out by the American Water Works Association, it was confirmed that the antibiotics sulfamethoxazole, trimethoprim, and erythromycin are among the compounds that exhibit better removal efficiency upon the use of chlorine gas as compared to chloramines.¹⁰⁷

4.2.6. Membrane Technology. Among other conservative technologies for the abatement of organic micropollutants, reverse osmosis (RO) and nanofiltration (NF) have been found to be very promising.^{108,109} RO membranes, working at the molecular level (10–50-Å range), led to quantitative separation (>90%) of organic macromolecules from the liquid phase, whereas the larger-pore-sized (50–100-Å range) NF membranes did not perform equally well.^{110,111} However, the more-energy-intensive RO makes the technology is less convenient than NF technology. The retention of organics on membranes occurs through a combination of mechanisms associated with size exclusion (molecular sieve) and sorption (weak electrostatic interactions at the liquid–solid interface). Reference mechanisms are strictly related to each other, thus influencing the overall membrane rejection efficiency, which, in turn, determines the separation performance of the organic macromolecules from the liquid phase. The performance of specific membranes toward different organic substrates can be selective and chemically specific.¹¹² Understanding the membrane separation mechanisms and their relationships to the chemical structures of the organic compounds is essential during the design and control of RO/NF installations. Mass-transfer phenomena, that is, diffusion through the membranes with separation accomplished by sieving effect, is claimed to be the controlling mechanism in the case of RO membranes, and accordingly, EDC rejection of neutral compounds usually increases with the molar mass of the organic substrate.¹⁰⁹ Separation based on weak electrostatic (van der Waals) interactions (i.e., dipole–dipole, ion–dipole, hydrogen bonding, etc.) is claimed to be the controlling mechanism in the case of NF technology, whereas charged and higher-molecular-weight organics are rejected by strong electrostatic interactions (ion exchange) at the membrane surface.¹¹² Sorption mechanisms also include hydrophilic/hydrophobic interactions of the pollutants at the membrane surface,¹¹³ with the extent of such phenomena quantified by the logarithm of the EDC octanol–water partition coefficient ($\log K_{ow}$), which is easily determined for specific organic substrates.¹¹⁴ During membrane separation, surface depositions onto membranes can control the pore size distribution and, thereby, the overall membrane rejection. On one hand, such phenomena might improve the separation performance^{109,110} of the membranes, but on the other hand, it might irreversibly foul the membranes with adverse effects on their separation efficiency.^{111,115} Figure 3 shows the main

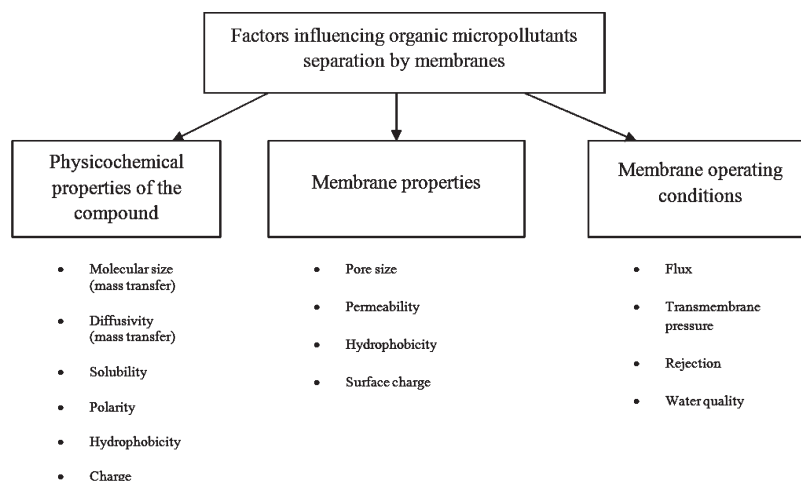


Figure 3. Factors influencing rejection of micropollutants during membrane filtration (from ref 116).

factors controlling micropollutant performance during membrane separation.

Polyamide NF/RO cationic membranes were used for rejection of DBPs and other pharmaceutical compounds.¹¹⁷ Under acidic conditions, negatively charged compounds were rejected (>90%) at the charged (sulfonate and/or carboxylate) surface functional groups of the membrane,¹¹⁸ regardless of other physicochemical properties of the compounds. At higher pH, the increased negative surface charge associated with the sulfonate and carboxylate groups of the membrane, as well as dissociation of the organic substrates into the anionic form, led to stronger membrane rejections toward DBP molecules.¹¹⁹ This occurred because the higher pH measurably affected the solute–water hydrophobic/hydrophilic interactions of the organic substrates and, therefore, their fugacity in the liquid phase.

4.2.7. Sorption. Activated carbon (AC) and nonfunctional resins (NFRs), as well as natural biosorbents (wood, chitin), are the reference materials for the separation of biopersistent organic compounds from liquid and gaseous phases. It is known that sorption is controlled by mass-transfer phenomena at the liquid–solid interface, with retention depending on the properties of both the sorbent and the sorbate (pollutant) molecule. Strong (Coulomb) and weak (van der Waals) electrostatic interactions and the relative hydrophobic/hydrophilic properties between the sorbent and sorbate play the most relevant roles. In this case, diffusion of the organic substrates across the solid phase and/or the liquid film around the particles is claimed to be the rate-determining step controlling the sorption kinetics.^{109,120} On these premises, EDC retention of the above sorbents might be based on a combination of steric factors (e.g., size exclusion) and electrostatic factors, both allowing for fairly selective separations among organic substrates, depending on their relative dimensions and charge densities.¹²¹ Based on field experience, the main limitations to the extensive application of this technology in large-scale systems is represented by the site competition resulting from the massive copresence of natural organic matter (NOM; i.e. humic and fulvic acids), as well as pore blockage (fouling) of the sorbent materials resulting from the presence of residual xenobiotic organics (e.g., filming compounds such as surfactants) in the influent (waste)water that can measurably reduce retention performance.¹²² This is the case reported in a literature example where the amount of 17 β -estradiol sorbed onto granular

activated carbon was measurably reduced (by 3 orders of magnitude) by the massive copresence of other biorefractory organics in natural waters and secondary treated wastewater.¹²³ Another issue that has to be taken into account in the case of sorption is that pollutants are concentrated from a diluted liquid phase (wastewater) into a concentrated solid phase (the sorbent) that must be disposed of properly (e.g., landfilled) under conditions of environmental safety. In all cases, the environmental problems are different between a diluted liquid phase and a more concentrated solid phase.

4.2.8. Electrochemical Methods. Anodic degradation (oxidation) of EDCs, namely, 17 β -estradiol (E2) and bisphenol A (BPA), by the use of a boron-doped diamond electrode (BDDE) was investigated at the laboratory scale. Cyclic voltammetry experiments were carried out to evaluate the electrochemical process response to E2 and BPA degradation as a function of the applied voltammetry cycles. Apparently, electro-oxidation reaction was controlled by the applied current density, which was evaluated and discussed at three different levels. Electrolysis at high anodic potential caused quantitative oxidation of EDCs with formation of CO₂. The effects of operating conditions in the electrolytic bath [e.g., pH, background solutions (Na₂SO₄, NaNO₃, and NaCl)] were discussed in terms of electro-generated inorganic oxidants such as S₂O₈²⁻, H₂O₂, and ClO⁻. Better performance of the BDDE anode was found on a comparative basis with respect to, for example, Pt and amorphous graphite under similar experimental conditions.¹²⁴

CONCLUSIONS

Today, using water only once is an unaffordable luxury, and sustainable reuse from unconventional sources, including municipal wastewater, is of paramount importance for social and economic purposes. To make water reuse beneficial, however, wastewater treatment plants (WWTPs) must be designed so as to accomplish removal of not only biodegradable organic matter and pathogens but also biopersistent trace organics, with the final aim of minimizing their release to receiving waters with related sanitary and environmental impacts. Among other organic micropollutants, endocrine disruptors induce a particular sanitary impact on mammals and lower animals with problems related to reproduction. Therefore, their quantitative removal from conventionally treated wastewater is urgent, also in consideration of

the increasing worldwide application of water reuse policies to supplement available water resources for different socioeconomic purposes, including drinking. Revisited biological treatments for wastewaters, either aerobic or anaerobic, appear to be promising in light of bioaugmentation protocols of culture strains that might need preliminary acclimation (and the use of specific enzymes) at the bench scale before introduction into the full-scale biological reactors of wastewater treatment plants. Bioaugmentation can be coupled with proper rearrangement of plant operating conditions in terms of hydraulic and sludge retention times (HRT and SRT) with the final aim of maximizing the degradation of biopersistent organics. However, basic knowledge related to a deeper understanding of the diversity of microorganisms and enhancement of their activity might be a viable and economical way to quantitatively metabolize steroids to lower-molecular-weight substrates or eventually to carbon dioxide and water. In this context, literature examples make reference to several substrates, including petrochemicals, agrochemicals such as atrazine, and estrogens, and in this context, significant full-scale applications have been reported. As mentioned, enhancement of the operating parameters of conventional biological plants, namely, sludge retention time (SRT) and hydraulic retention time (HRT) in the oxidation ditch, or upgrading the configurations of the existing installations, such as by the synergistic introduction of anaerobic and anoxic zones, leads to a definite improvement in removal performance toward the estrogenic compounds. Wherever costs and space are not a problem, the application of advanced biotechnologies based on the use of membrane bioreactors (MBRs), integrated fixed-film activated sludge (IFAS), and sequencing batch reactors (SBRs) might represent viable options. Several literature examples on medium- to large-scale installations have been reported in the literature with almost exclusive reference to estrogens and agrochemicals (atrazine). The main limitations are associated with the deposition of filming compounds hindering mass-transfer phenomena at the liquid–solid interface, although the above solutions allow for the use of the existing infrastructures. Biological processes have the most favorable technical/economic balance whenever organics are readily biodegradable and not toxic. Dedicated physical, chemical and/or physicochemical methods [e.g., membrane separation (RO, NF), advanced oxidation (AOP), and sorption (AC, nonfunctional synthetic resins)] must be preferred in case of new installations. In this latter context, the action of the technology on the target pollutants, which in the cases of reference compounds are represented by pharmaceuticals (antibiotics and estrogenic compounds) as well as on phenol derivatives, must be taken into consideration. Chemical processes based on advanced oxidation, as “destructive” toward target organics, degrade the substrates to lower-molecular-weight compounds or, incidentally, to carbon dioxide and water. Although advanced oxidation by direct use of cheap chemicals such as ozone and/or hydrogen peroxide has been found to be very effective in the removal of trace concentrations, the extensive application of the reference technology is strongly limited by the quite high operating costs (chemicals and energy consumption) of full-scale installations. The adoption of catalyzed AOPs [i.e., those assisted by the use of metals such as Fe^{2+} (Fenton), ferrate ions, or oxides (MnO_2) or by the use of physical means such as UV (photochemical degradation), where the latter can be performed with or without the presence of activators (TiO_2)] has been proposed with alternate success. On these premises, the use of AOPs is usually justified as a polishing step toward the removal

of estrogenic compounds. Finally, the use of inexpensive oxidants such as chlorine or sodium hypochlorite (breakpoint chlorination) shows the formation of chlorine derivatives that strongly impact the receiving water bodies and, consequently, are ubiquitous in tap water. Although high EDC removal efficiency is achieved by the use of sorbents (AC, synthetic resins, and coagulation), the massive copresence of other organic substrates, including natural organic matter (NOM, humic/fulvic derivatives), usually presents dramatic limitations to the operating performance of sorbents toward organic micropollutants in conventionally treated wastewater. Needless to say, physical and physicochemical methods (membrane separation, sorption), as “conservative” toward target pollutants, change the problem from one of a dilute liquid phase (wastewater) to a more concentrated liquid (retentate) or solid-phase (exhausted sorbent) problem, respectively, with problems related to the safe management and disposal of the resulting wastes (concentrated effluents or the exhausted sorbents), for which proper management (disposal or regeneration) must be attentively evaluated as the final disposal might be unsustainably expensive. Literature examples in this context make reference to dyes and related derivatives.

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REFERENCES

- (1) Postel, S. L. Entering an era of water scarcity: The challenges ahead. *Ecol. Appl.* **2000**, *10* (4), 941–948.
- (2) Campbell, C. G.; Borglin, S. E.; Green, F. B.; Grayson, A.; Wozei, E.; Stringfellow, W. T. Biologically directed environmental monitoring, fate, and transport of estrogenic endocrine disrupting compounds in water: A review. *Chemosphere* **2006**, *65*, 1265–1280.
- (3) Nelson, J.; Bishay, F.; van Roodseelaar, A.; Ikononou, M.; Law, F. C. P. The use of in vitro bioassays to quantify endocrine disrupting chemicals in municipal wastewater treatment plant effluents. *Sci. Total Environ.* **2007**, *374* (1), 80–90.
- (4) Mills, L. J.; Chichester, C. Review of evidence: Are endocrine-disrupting chemicals in the aquatic environment impacting fish populations? *Sci. Total Environ.* **2005**, *343* (1–3), 1–34.
- (5) Fossi, M. C.; Casiniand, S.; Marsili, L. Potential toxicological hazard due to endocrine-disrupting chemicals on Mediterranean top predators: State of art, gender differences and methodological tools. *Environ. Res.* **2007**, *104* (1), 174–182.
- (6) Whitehead, S. A.; Rice, S. Endocrine-disrupting chemicals as modulators of sex steroid synthesis. *Best Pract. Res. Clin. Endocrinol. Metab.* **2006**, *20* (1), 45–61.
- (7) Liu, Z. H.; Kanjo, Y.; Mizutani, S. A review of phytoestrogens: Their occurrence and fate in the environment. *Water Res.* **2010**, *44* (2), 567–577.
- (8) Ternes, T. A.; Joss, A., Eds. *Human Pharmaceuticals, Hormones and Fragrances: The Challenge of Micropollutants in Urban Water Management*; IWA Publishing: London, U.K., 2006.
- (9) Ghosh, G. C.; Okuda, T.; Yamashita, N.; Tanaka, H. Occurrence and elimination of antibiotics at four sewage treatment plants in Japan and their effects on bacterial ammonia oxidation. *Water Sci. Technol.* **2009**, *59* (4), 779–786.
- (10) Ternes, T. A.; Joss, A.; Siegrist, H. Scrutinizing pharmaceuticals and personal care products in wastewater treatment. *Environ. Sci. Technol.* **2004**, *38* (20), 392–399.
- (11) Muncke, J. Exposure to endocrine disrupting compounds via the food chain: Is packaging a relevant source? *Sci. Total Environ.* **2009**, *407* (16), 4549–4559.

- (12) Gong, Y.; Wu, J.; Huang, Y.; Shen, S.; Han, X. Nonylphenol induces apoptosis in rat testicular Sertoli cells via endoplasmic reticulum stress. *Toxicol. Lett.* **2009**, *186* (2), 84–95.
- (13) Hao, R.; Li, J.; Zhou, Y.; Cheng, S.; Zhang, Y. Structure–biodegradability relationship of nonylphenol isomers during biological wastewater treatment process. *Chemosphere* **2009**, *75* (8), 987–994.
- (14) Sonnenschein, C.; Soto, A. M. An updated review of environmental estrogen and androgen mimics and antagonists. *J. Steroid Mol. Biol.* **1998**, *65* (1–6), 143–150.
- (15) Sidhu, S.; Gullett, B.; Striebig, R.; Klosterman, J.; Contreras, J.; DeVito, M. Endocrine disrupting chemical emissions from combustion sources: Diesel particulate emissions and domestic waste open burn emissions. *Atmos. Environ.* **2005**, *39* (5), 801–811.
- (16) Pagnout, C.; Rast, C.; Veber, A. M.; Poupin, P.; Féraud, J. F. Ecotoxicological assessment of PAHs and their dead-end metabolites after degradation by *Mycobacterium* sp. strain SNP11. *Ecotoxicol. Environ. Saf.* **2006**, *65* (2), 151–158.
- (17) Chen, D.; Zhang, X.; Mai, B.; Sun, Q.; Song, J.; Luo, X.; Zeng, E. Y.; Hale, R. C. Polychlorinated biphenyls and organochlorine pesticides in various bird species from northern China. *Environ. Pollut.* **2009**, *157* (7), 2023–2029.
- (18) Ottinger, M. A.; Wu, J. M.; Hazelton, J. L.; Abdelnabi, M. A.; Thompson, N.; Quinn, M. L., Jr.; Donoghue, D.; Schenck, F.; Ruscio, M.; Beavers, J.; Jaber, M. Assessing the consequences of the pesticide methoxychlor: Neuroendocrine and behavioral measures as indicators of biological impact of an estrogenic environmental chemical. *Brain Res. Bull.* **2005**, *65* (3), 199–209.
- (19) Porter, W. P.; Jaeger, J. W.; Carlson, I. H. Endocrine, Immune, and Behavioral Effects of Aldicarb (Carbamate), Altrazine (Triazine) and Nitrate (Fertilizer) Mixtures at Groundwater Concentrations. *Toxicol. Ind. Health* **1999**, *15*, 133–151.
- (20) Sánchez-Avila, J.; Bonet, J.; Velasco, G.; Lacorte, S. Determination and occurrence of phthalates, alkylphenols, bisphenol A, PBDEs, PCBs and PAHs in an industrial sewage grid discharging to a Municipal Wastewater Treatment Plant. *Sci. Total Environ.* **2009**, *407* (13), 4157–4167.
- (21) Staples, C. A.; Dorn, P. B.; Klecka, G. M.; O'Block, S. T.; Harris, L. R. A review of the environmental fate, effects and exposures of bisphenol A. *Chemosphere* **1998**, *36* (10), 2149–2173.
- (22) Ben-Jonathan, N.; Hugo, E. R.; Brandebourg, T. D. Effects of bisphenol A on adipokine release from human adipose tissue: Implications for the metabolic syndrome. *Mol. Cell. Endocrinol.* **2009**, *304* (1–2), 49–54.
- (23) Fromme, H.; Kuchler, T.; Otto, T.; Pilk, K.; Muller, J.; Wenzel, A. Occurrence of phthalates and bisphenol A and F in the environment. *Water Res.* **2002**, *36* (6), 1429–1438.
- (24) Eriksson, P.; Jakobsson, E.; Fredriksson, A. Brominated flame retardants: A novel class of developmental neurotoxicants in our environment? *Environ. Health Perspect.* **2001**, *109* (9), 903–908.
- (25) Smith, B. S. Male characteristics on female mud snails caused by antifouling bottom paints. *J. Appl. Toxicol.* **1981**, *1* (1), 22–25.
- (26) Horiguchi, T. Masculinization of female gastropod mollusks induced by organotin compounds, focusing on mechanism of actions of tributyltin and triphenyltin for development of imposex. *Environ. Sci.* **2006**, *13* (2), 77–87.
- (27) Chang, H. S.; Choo, K. H.; Lee, B.; Choi, S. J. The methods of identification, analysis, and removal of endocrine disrupting compounds (EDCs) in water. *J. Hazard. Mater.* **2009**, *172* (1), 1–12.
- (28) Kimmel, C. A.; Makris, S. L. Recent developments in regulatory requirements for developmental toxicology. *Toxicol. Lett.* **2001**, *120* (1–3), 73–82.
- (29) Matthiessen, P.; Johnson, I. Implications of research on endocrine disruption for the environmental risk assessment, regulation and monitoring of chemicals in the European Union. *Environ. Pollut.* **2007**, *146* (1), 9–18.
- (30) Ankley, G. T.; Brooks, B. W.; Huggett, D. B.; Sumpton, J. P. Repeating History: Pharmaceuticals in the Environment. *Environ. Sci. Technol.* **2007**, *41*, 8211–8217.
- (31) Ruiz, P.; Faroon, O.; Moudgal, C. J.; Hansen, H.; De Rosa, C. T.; Mumtaz, M. Prediction of the health effects of polychlorinated biphenyls (PCBs) and their metabolites using quantitative structure–activity relationship (QSAR). *Toxicol. Lett.* **2008**, *181* (1), 53–65.
- (32) Sun, L.; Zha, J.; Wang, Z. Effects of binary mixtures of estrogen and antiestrogens on Japanese medaka (*Oryzias latipes*). *Aquat. Toxicol.* **2009**, *93* (1), 83–9.
- (33) Porter, W. P.; Jaeger, J. W.; Carlson, I. H. Endocrine, immune and behavioural effects of aldicarb (carbamate), atrazine (triazine) and nitrate (fertilizer) mixtures at groundwater concentrations. *J. Toxicol. Ind. Health* **1999**, *15* (1–2), 133–150.
- (34) Kawaguchi, M.; Ishii, Y.; Sakui, N.; Okanouchi, N.; Ito, R.; Inoue, K.; Saito, K.; Nakazawa, H. Stir bar sorptive extraction with in situ derivatization and thermal desorption–gas chromatography–mass spectrometry in the multi-shot mode for determination of estrogens in river water samples. *J. Chromatogr. A* **2004**, *1049* (1–2), 1–8.
- (35) Kawaguchi, M.; Inoue, K.; Yoshimura, M.; Sakui, N.; Okanouchi, N.; Ito, R.; Yoshimura, Y.; Nakazawa, H. Trace analysis of phenolic xenoestrogens in water samples by stir bar sorptive extraction with in situ derivatization and thermal desorption–gas chromatography–mass spectrometry. *J. Chromatogr. A* **2004**, *1041* (1–2), 19–26.
- (36) Gerecke, A. C.; Tixier, C.; Bartels, T.; Schwarzenbach, R. P.; Müller, S. R. Determination of phenylurea herbicides in natural waters at concentrations below 1 ng L^{−1} using solid-phase extraction, derivatization, and solid-phase microextraction–gas chromatography–mass spectrometry. *J. Chromatogr. A* **2001**, *930* (1–2), 9–19.
- (37) Regueiro, J.; Becerril, E.; Garcia-Jares, C.; Llompart, M. Trace analysis of parabens, triclosan and related chlorophenols in water by headspace solid-phase microextraction with in situ derivatization and gas chromatography–tandem mass spectrometry. *J. Chromatogr. A* **2009**, *1216* (23), 4693–4702.
- (38) Liscio, C.; Magi, E.; Di Carro, M.; Suter, M. J.-F.; Vermeirssen, E. L. M. Combining passive samplers and biomonitors to evaluate endocrine disrupting compounds in a wastewater treatment plant by LC/MS/MS and bioassay analyses. *Environ. Pollut.* **2009**, *157* (10), 2716–2721.
- (39) Fatoki, O. S.; Vernon, F. Phthalate esters in rivers of the Greater Manchester area, U.K. *Sci. Total Environ.* **1990**, *95*, 227–232.
- (40) Clark, L. B.; Rosen, R. T.; Hartmann, T. G.; Louis, J. B.; Suffet, I. H.; Lippincott, R. L.; Rosen, J. D. Determination of alkylphenol ethoxylates and their acetic acid derivatives in drinking water by particle beam liquid chromatography/mass spectrometry. *Int. J. Environ. Anal. Chem.* **1992**, *47*, 167–180.
- (41) Jackson, J.; Sutton, R. Sources of endocrine-disrupting chemicals in urban wastewater, Oakland, CA. *Sci. Total Environ.* **2008**, *405* (1–3), 153–160.
- (42) Lopez de Alda, M. J.; Barceló, D. Review of analytical methods for the determination of estrogens and progestins in waste waters. *Fresenius' J. Anal. Chem.* **2001**, *371*, 437–447.
- (43) Janex-Habibi, M.; Huyard, A.; Esperanza, M.; Bruchet, A. Reduction of endocrine disruptor emissions in the environment: The benefit of wastewater treatment. *Water Res.* **2009**, *43* (6), 1565–1576.
- (44) Schilirò, T.; Pignata, C.; Rovere, R.; Fea, E.; Gilli, G. The endocrine disrupting activity of surface waters and of wastewater treatment plant effluents in relation to chlorination. *Chemosphere* **2009**, *75* (3), 335–340.
- (45) Nakada, N.; Tanishima, T.; Shinohara, H.; Kiri, K.; Takada, H. Pharmaceutical chemicals and endocrine disruptors in municipal wastewater in Tokyo and their removal during activated sludge treatment. *Water Res.* **2006**, *40*, 3297–3303.
- (46) Fernandez, M. P.; Buchanan, I. D.; Ikonou, M. G. Seasonal variability of the reduction in estrogenic activity at a municipal WWTP. *Water Res.* **2008**, *42* (12), 3075–3081.
- (47) Liu, Z.; Kanjo, Y.; Mizutani, S. Removal mechanisms for endocrine disrupting compounds (EDCs) in wastewater treatment—Physical means, biodegradation, and chemical advanced oxidation: A review. *Sci. Total Environ.* **2009**, *407* (2), 731–748.

- (48) Regulation (EC) No. 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH), establishing a European Chemicals Agency. OJEC L396, 30 Dec 2006; pp 1–849.
- (49) Candidate List of Substances of Very High Concern for Authorization; European Chemicals Agency: Helsinki, Finland, 2010. http://echa.europa.eu/chem_data/authorisation_process/candidate_list_table_en.asp (Accessed April 2011).
- (50) Council Directive 91/271/EEC of the Council of the European Community of 21 May 1991 concerning urban wastewater treatment. OJEC L 135/40, 30 May 1991.
- (51) Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for the Community action in the field of water policy. OJEC L 327/1, 22 Dec 2000; 1–73.
- (52) Decision 2455/2001/EC of the European Parliament and of the Council of 20 November 2001 establishing the list of priority substances in the field of water policy and amending Directive 2000/60/EC. OJEC L 331/1, 15 Dec 2001.
- (53) Richardson, S. D. Water Analysis: Emerging Contaminants and Current Issues. *Anal. Chem.* **2009**, 81 (12), 4645–4677.
- (54) Hernandez, F.; Sancho, J. V.; Ibanez, M.; Grimalt, S. Investigation of pesticide metabolites in food and water by LC-TOF-MS. *Trends Anal. Chem.* **2008**, 27 (10), 862–872.
- (55) Williamson, L. N.; Bartlett, M. G. Quantitative liquid chromatography/time-of-flight mass spectrometry. *Biomed. Chromatogr.* **2007**, 21 (6), 567–576.
- (56) Ibanez, M.; Sancho, J. V.; McMillan, D.; Rao, R.; Hernandez, F. Rapid non-target screening of organic pollutants in water by ultraperformance liquid chromatography coupled to time-of light mass spectrometry. *Trends Anal. Chem.* **2008**, 27 (5), 481–489.
- (57) Talley, J. W., Ed. *Bioremediation of Recalcitrant Compounds*; CRC-Lewis Press: Boca Raton, FL, 2005.
- (58) Tarr, M. A. *Chemical Degradation Methods for Wastes and Pollutants: Environmental and Industrial Applications*; Marcel Dekker Inc: New York, 2003.
- (59) Nakada, N.; Tanishima, T.; Shinohara, H.; Kiri, K.; Takada, H. Pharmaceutical chemicals and endocrine disruptors in municipal wastewater in Tokyo and their removal during activated sludge treatment. *Water Res.* **2006**, 40 (17), 3297–3303.
- (60) Johnson, A. C.; Sumpter, J. P. Removal of endocrine-disrupting chemicals in activated sludge treatment works. *Environ. Sci. Technol.* **2001**, 35 (24), 4697–4703.
- (61) Teske, S. S.; Arnold, R. G. Removal of natural and xenoestrogens during conventional wastewater treatment. *Rev. Environ. Sci. Biotechnol.* **2008**, 7 (2), 107–124.
- (62) Petruzzelli, D.; Volpe, A.; Di Pinto, A. C.; Passino, R. Conservative technologies for environmental protection based on the use of reactive polymers. *React. Funct. Polym.* **2000**, 45, 95–107.
- (63) Pickering, A. D.; Sumpter, J. P. Comprehending endocrine disruptors in aquatic environments. *Environ. Sci. Technol.* **2003**, 37, 331A–336A.
- (64) Koh, Y. K. K.; Chiu, T. Y.; Boobis, A.; Cartmell, E.; Scrimshaw, M. D.; Lester, J. N. Treatment and removal strategies for estrogens from wastewater. *Environ. Technol.* **2008**, 29 (3), 245–267.
- (65) Moharikar, A.; Purohit, H. J.; Kumar, R. Microbial population dynamics at effluent treatment plants. *J. Environ. Monit.* **2005**, 7, 552–558.
- (66) Dytczak, M. A.; Londry, K. L.; Oleszkiewicz, J. A.; Transformation of estrogens in nitrifying activated sludge under aerobic and alternating anoxic/aerobic conditions. In *Proceedings of the 79th Water Environment Federation Technical Conference (WEFTEC)*; Water Environment Federation: Alexandria, VA, 2006; pp 1509–1520.
- (67) Stasinakis, A. S.; Kordoutis, C. I.; Tsiouma, V. C.; Gatidou, G.; Thomaidis, N. S. Removal of selected endocrine disruptors in activated sludge systems: Effect of sludge retention time on their sorption and biodegradation. *Bioresour. Technol.* **2010**, 101 (7), 2090–2095.
- (68) Servos, M. R.; Bennie, D. T.; Burnison, B. K.; Jurkovic, A.; McInnis, R.; Neheli, T.; Schnell, A.; Seto, P.; Smyth, S. A.; Ternes, T. A. Distribution of estrogens, 17- β estradiol and estrone in Canadian municipal wastewater treatment plants. *Sci. Total Environ.* **2005**, 336, 155–170.
- (69) Ternes, T.; Kreckel, P.; Mueller, J. Behaviour and occurrence of estrogens in municipal sewage treatment plants—II. Aerobic batch experiments with activated sludge. *Sci. Total Environ.* **1999**, 225, 91–99.
- (70) Clara, M.; Strenn, B.; Gans, O.; Martinez, E.; Kreuzinger, N.; Kroiss, H. Removal of selected pharmaceuticals, fragrances and endocrine disrupting compounds in a membrane bioreactor and conventional wastewater treatment plants. *Water Res.* **2005**, 39, 4797–4807.
- (71) Balest, L.; Mascolo, G.; Di Iaconi, C.; Lopez, A. Removal of endocrine disrupter compounds from municipal wastewater by an innovative biological technology. *Water Sci. Technol.* **2008**, 58 (4), 953–956.
- (72) Kasprzyk-Hordern, B.; Dinsdale, R. M.; Guwy, A. J. 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 Res.* **2009**, 43 (2), 363–380.
- (73) Shi, J. H.; Suzuki, Y.; Lee, B. D.; Nakai, S.; Hosomi, M. Isolation and characterization of the ethynylestradiol biodegrading microorganism *Fusarium proliferatum* strain HNS-1. *Water Sci. Technol.* **2002**, 45 (12), 175–179.
- (74) Jones, P. Designed Experiment Optimizes Method for Removing Endocrine Disrupters. *Environ. Sci. Eng. Mag.* **2008**, No. Mar 31, 70–72.
- (75) Baugh, C. L. Technical Discussion #3: Bio-Augmentation for Waste Water Treatment; Custom Biologicals, Inc. (CBI): Deerfield Beach, FL. www.custombio.com/OldSite/wastewater-treatment/files/02%20wp%20tech%20discussion.pdf (Accessed March 2011).
- (76) Liu, C.; Huang, X.; Wang, H. Start-up of a membrane bioreactor bioaugmented with genetically engineered microorganism for enhanced treatment of atrazine containing wastewater. *Desalination* **2008**, 231 (1–3), 12–19.
- (77) Benson, L.; Daigger, G. T.; Murthy, S. N.; Constantine, T.; Katehis, D.; Bailey, W. F.; Sadick, T. E., Jr. (D.C. Water & Sewer Authority). Method for nitrogen removal and treatment of digester reject water in wastewater using bioaugmentation. U.S. Patent 7,404,897, 2008.
- (78) Zhao, L. J.; Ma, F.; Guo, J. B.; Zhao, Q. L. Petrochemical wastewater treatment with a pilot-scale bioaugmented biological treatment system. *J. Zhejiang Univ.* **2007**, 8 (11), 1831–1838.
- (79) Guo, J.; Ma, F.; Jiang, K. Bioaugmentation combined with biofilm process in the treatment of petrochemical wastewater at low temperatures. *J. Water Resour. Protect.* **2008**, 1, 1–65.
- (80) Visvanathan, C.; Ben Aim, R.; Parameshwaran, K. Membrane Separation Bioreactors for Wastewater Treatment. *Crit. Rev. Environ. Sci. Technol.* **2000**, 30 (1), 1–48.
- (81) Mills, W. R. Update on Water Reuse in Southern California. Presented at the *Symposium on Water Reuse for the Community and Industry—Latest Developments and Future Directions*, Sydney, Australia, August 1, 1996.
- (82) Muller, E. B.; Stouthamer, A. H.; van Verseveld, H. W.; Eikelboom, D. H. Aerobic domestic wastewater treatment in a pilot plant with complete sludge retention by cross-flow filtration. *Water Res.* **1995**, 29 (4), 1179–1189.
- (83) Visvanathan, C.; Yang, B.-S.; Muttamara, S.; Maythanukhraw, R. Application of air backflushing technique in membrane bioreactor. *Water Sci. Technol.* **1997**, 36 (12), 259–266.
- (84) Joss, A.; Andersen, H.; Ternes, T.; Richle, P. R.; Siegrist, H. Removal of estrogens in municipal wastewater treatment under aerobic and anaerobic conditions: Consequences for plant optimization. *Environ. Sci. Technol.* **2004**, 38, 3047–3055.
- (85) Ivashechkin, P.; Corvini, P. F. X.; Dohmann, M. Behaviour of endocrine disrupting chemicals during the treatment of municipal sewage sludge. *Water Sci. Technol.* **2004**, 50 (5), 133–140.
- (86) Weber, S.; Leuschner, P.; Kampfer, P.; Dott, W.; Hollender, J. Degradation of estradiol and ethinyl estradiol by activated sludge and by a defined mixed culture. *Appl. Microbiol. Biotechnol.* **2005**, 67, 106–112.

- (87) Kikuta, T.; Urase, T. Removal of endocrine disruptors in membrane separation activated sludge process. *Desalination* **2005**, *178*, 107–113.
- (88) Wintgens, T.; Gallenkemper, M.; Melin, T. Endocrine disrupter removal from wastewater using membrane bioreactor and nanofiltration technology. *Desalination* **2002**, *146* (1–3), 387–391.
- (89) Brice, R.; Silver, N.; Church, N.; Couper, S. Removal of viruses and endocrine disruptors across the MBR process. Presented at the NZWWA Conference, Christchurch, New Zealand, 2006. www.awtwater.com/data/media/documents/Publication%20conference%202006/Removal%20of%20viruses%20and%20endocrine%20disrupters%20across%20the%20MBR%20process.pdf (Accessed March 2011).
- (90) Clouzot, L.; Marrot, B.; Doumenq, P.; Roche, N. 17 α -Ethinylestradiol: An endocrine disrupter of great concern. Analytical methods and removal processes applied to water purification. A review. *Environ. Prog.* **2008**, *27* (3), 386–393.
- (91) Ramadori, R.; Di Iaconi, R.; Lopez, A.; Passino, R. An innovative technology based on aerobic granular biomass for treating municipal and/or industrial wastewater with low environmental impact. *Water Sci. Technol.* **2006**, *53* (12), 321–329.
- (92) Di Iaconi, C.; Ramadori, R.; Lopez, A. Aerobic granulation during the start up period of a periodic biofilter. In *Aerobic Granular Sludge: Selected Proceedings of the 1st IWA-Workshop on Aerobic Granular Sludge, September 2004, Munich, Germany*; Bathe, S., de Kreuk, M. K., McSwain, B. S., Schwarzenbeck, N., Eds.; Water and Environmental Management Series (WEMS); IWA Publishing: London, U.K., 2005.
- (93) Eriksson, E. Organic substances in sewage sludge intended for agricultural land. What do we know and where are the knowledge gaps? http://www.naturvardsverket.se/upload/30_global_meny/02_aktuellt/yttranden/Sa_har_vill_vi_aterfora_mer_fosfor_till_kretsloppet/Bil2-5_Rev_Organic_substances_in_sewage_sludge_intended_for_agricultural%20land.pdf (Accessed March 2011).
- (94) Madsen, P. B.; Johansen, N. H.; Andersen, H. R.; Kaas, P. Removal of Endocrine Disruptors and Pathogens. Advanced Photo Oxidation Processes at Hørsholm WWTP. Presented at the IWA World Water Congress 2006, Beijing, China, Sep 10–14, 2006. http://pbconsult.dk/DK/infodown_dk/Outline_Paper_for_IWA_Beijing_2006.pdf (Accessed March 2011).
- (95) Von Gunten, U. Ozonation of drinking water: zPart I. Oxidation kinetics and product formation. *Water Res.* **2003**, *37*, 1443–1467.
- (96) Haag, W. R.; Yao, C. C. D. Rate constants for reaction of hydroxyl radicals with several drinking water contaminants. *Environ. Sci. Technol.* **1992**, *26*, 1005–1013.
- (97) Adams, C.; Wang, Y.; Loftin, K.; Meyer, M. Removal of antibiotics from surface and distilled water in conventional water treatment process. *J. Environ. Eng.* **2002**, *128*, 253–260.
- (98) Benotti, M. J.; Stanford, B. D.; Wert, E. C.; Snyder, S. A. Evaluation of a photocatalytic reactor membrane pilot system for the removal of pharmaceuticals and endocrine disrupting compounds from water. *Water Res.* **2009**, *43*, 1513–1522.
- (99) Vogelpohl, A.; Sievers, M.; Geilssen, S. V., Eds. Oxidation Technologies for Water and Wastewater Treatment IV. *Water Sci. Technol.* **2007**, *55* (12).
- (100) Rosenfeldt, E.; Linden, K. G. Degradation of Endocrine Disrupting Chemicals Bisphenol A, Ethinylestradiol, and Estradiol during UV Photolysis and Advanced Oxidation Processes. *Environ. Sci. Technol.* **2004**, *38*, 5476–5483.
- (101) Petruzzelli, D.; Boghetich, G.; Petrella, M.; Dell'Erba, A.; L'Abbate, P.; Sanarica, S. Advanced oxidation as a pretreatment of industrial landfill leachate. *Global NEST J.* **2007**, *9* (1), 51–56.
- (102) Shappell, N. W.; Vrabell, M. A.; Madse, P. J.; Harrington, G.; Billey, L. O.; Hakk, H.; Larsen, G. L.; Beach, E. S.; Horwitz, C. P.; Ro, K.; Hunt, P. G.; Collins, T. J. Destruction of estrogens using Fe-TAML/peroxide catalysis. *Environ. Sci. Technol.* **2008**, *42* (4), 1296–1300.
- (103) Kunde, L.; Weiping, L.; Gan, J. Oxidative Removal of Bisphenol A by Manganese Dioxide: Efficacy, Products, and Pathways. *Environ. Sci. Technol.* **2009**, *43* (10), 3860–3864.
- (104) Lee, Y.; Yoon, J.; Von Gunten, U. Kinetics of the oxidation of phenols and phenolic endocrine disruptors during water treatment with ferrate (Fe(VI)). *Environ. Sci. Technol.* **2005**, *39*, 8978–8984.
- (105) Jiang, J. Q.; Yin, Q.; Zhou, J. L.; Pearce, P. Occurrence and treatment trials of endocrine disrupting chemicals (EDCs) in wastewaters. *Chemosphere* **2005**, *61*, 544–550.
- (106) Scruggs, C.; Hunter, G.; Snyder, E.; Long, B.; Snyder, S. EDCs in wastewater: What's the next step? *Water Environ. Technol.* **2005**, *17* (3), 24–31.
- (107) Snyder, S.; Westerhoff, P.; Song, R.; Levine, B.; Long, B. American Water Works Association Research Foundation (AWWARF) Project #2758: Evaluation of Conventional and Advanced Treatment Processes to Remove Endocrine Disruptors and Pharmaceutically Active Compounds. http://enpub.fulton.asu.edu/pwest/awwarf_project_EDC.htm (Accessed March 2011).
- (108) Yoon, Y.; Westerhoff, P.; Snyder, S. A.; Wert, E. C. Nanofiltration and ultrafiltration of endocrine disrupting compounds, pharmaceuticals and personal care products. *J. Membr. Sci.* **2006**, *270*, 88–100.
- (109) Nghiem, L. D.; Schafer, A. I.; Elimelech, M. Removal of natural hormones by nanofiltration membranes: Measurement, modeling and mechanisms. *Environ. Sci. Technol.* **2004**, *38*, 1888–1896.
- (110) Huang, C. H.; Sedlak, D. L. Analysis of estrogenic hormones in municipal wastewater effluent and surface water using enzyme-linked immunosorbent assay and gas chromatography/tandem mass spectrometry. *Environ. Toxicol. Chem.* **2001**, *20*, 133–139.
- (111) Nghiem, L. D.; Manis, A.; Soldenhoff, K.; Schafer, A. I. Estrogenic hormone removal from wastewater using NF/RO membranes. *J. Membr. Sci.* **2004**, *242*, 37–45.
- (112) Schafer, A. I.; Nghiem, D. L.; Waite, T. D. Removal of the natural hormone estrone from solution using nanofiltration and reverse osmosis. *Environ. Sci. Technol.* **2003**, *37*, 182–188.
- (113) Nghiem, D. L.; Schafer, A. I.; Waite, T. D. Adsorptive interactions between membranes and trace contaminants. *Desalination* **2002**, *147*, 269–274.
- (114) Lopez, A.; Petruzzelli, D. Interaction of Toxic Organics with Subsoils Components. In *Migration and Fate of Pollutants in Soils and Subsoils*; Petruzzelli, D., Helfferich, F. G., Eds.; NATO-ASI Series G2, Ecological Sciences; Springer-Verlag: Berlin, 1993; Vol. 32, pp 93–110.
- (115) Drewes, J. E.; Xu, P.; Oedekoven, M.; Bellona, C.; Kim, T.; Amy, G.; Heberer, T. Viability of reverse osmosis membranes in removing emerging organic micropollutants in indirect potable reuse applications. Presented at the AWWA Membrane Technology Conference & Exposition, Phoenix, AZ, Mar 7–9, 2005.
- (116) Bolong, N.; Ismail, A. F.; Salim, M. R.; Matsuura, T. A review of the effects of emerging contaminants in wastewater and options for their removal. *Desalination* **2009**, *239*, 229–246.
- (117) Kimura, K.; Toshima, S.; Amy, G.; Watanabe, Y. Rejection of neutral endocrine disrupting compounds (EDCs) and pharmaceutical active compounds (PhACs) by RO membranes. *J. Membr. Sci.* **2004**, *245*, 71–78.
- (118) Bellona, C.; Jörg, E.; Drewes, J. E.; Xu, P.; Amy, G. Factors affecting the rejection of organic solutes during NF/RO treatment—a literature review. *Water Res.* **2004**, *38*, 2795–2809.
- (119) Tanninen, J.; Nyström, M. Separation of ions in acidic conditions using NF. *Desalination* **2002**, *147*, 295–299.
- (120) Crittenden, J. C.; Sanongraj, S.; Bulloch, J. L.; Hand, D. W.; Rogers, T. N.; Speth, T. F.; Ulmer, M. Correlation of aqueous phase adsorption isotherms. *Environ. Sci. Technol.* **1999**, *33*, 2926–2933.
- (121) Eisenman, G. The molecular basis of ionic selectivity in macroscopic systems. In *Mass Transfer and Kinetics of Ion Exchange*; Liberti, L., Helfferich, F. G., Eds.; M. Nijhoff Publishers Co.: The Hague, The Netherlands, 1983; pp 121–155.
- (122) Newcombe, G.; Drikas, M.; Hayes, R. Influence of characterised natural organic material on activated carbon adsorption: II. Effect on pore volume distribution and adsorption of 2-methylisoborneol. *Water Res.* **1997**, *31* (5), 1065–1073.
- (123) Pelekani, C.; Snoeyink, V. L. Competitive adsorption in natural water: Role of activated carbon pore size. *Water Res.* **1999**, *33*, 1209–1219.
- (124) Yoshihara, S.; Murugananthan, M. Decomposition of various endocrine-disrupting chemicals at boron-doped diamond electrode. *Electrochim. Acta* **2009**, *54*, 2031–2038.