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Analysis of emerging organic contaminants in environmental solid samples

Review Article

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Abstract: Spreading sewage sludge on agricultural lands has been actively promoted by national authorities as an economic way of recycling. However, as by-product of wastewater treatment, sewage sludge may contain toxic substances, which could be incorporated into agricultural products or be distributed in the environment. Moreover, sediments can be contaminated by the discharge of wastewater effluents into rivers. This article reviews the determination of emerging contaminants (surfactants, flame retardants, pharmaceuticals and personal care products) in environmental solid samples (sludge, soil and sediment). Sample preparation, including extraction and clean-up, as well as the subsequent instrumental determination of contaminants are discussed. Recent applications of extraction techniques, such as Soxhlet extraction, ultrasound assisted extraction, pressurised liquid extraction, microwave assisted extraction and matrix solid-phase dispersion to the analysis of emerging contaminants in environmental solid samples are reviewed. Determination of these contaminants, generally carried out by gas chromatography and liquid chromatography coupled with different detectors, especially mass spectrometry for the identification and quantification of residues, is also summarised and discussed.

Keywords: *Analytical methods • Emerging contaminants • Sediment • Sewage sludge • Soil*

1. Introduction

Emerging contaminants are a heterogeneous group of substances, such as pharmaceuticals, personal care products, flame retardants and surfactants that are commonly derived from households, municipal, agricultural and industrial wastewaters. These products are widely used and often pass through water treatment works unaltered before being discharged into the environment. Moreover, the use in agricultural soil of sewage sludge produced in wastewater treatment plants (WWTPs) is highly encouraged by national authorities, because it is an economic way of recycling nutrients and organic matter contained in sludge while improving the physico-chemical properties and fertility of soil. However, toxic substances present in sludge may be incorporated to soil with this practice raising an environmental concern [1,2].

Emerging contaminants have drawn the attention of the scientific community because of their wide occurrence in the environment that is not commonly monitored due to the lack of regulation. In addition, adverse effects of these substances on humans and animals, such as endocrine disruption activity, carcinogenicity and neurotoxicity among others, have been observed. Therefore, the impact of these compounds on the environment has to be evaluated and this assessment requires the availability of reliable data, thus, adequate analytical methods with sufficiently low detection limits have to be developed.

The analytical procedures used in the determination of emerging contaminants in environmental solid samples involve a sample preparation step that includes sampling, extraction, clean-up and occasionally derivatisation to enhance the analytical response of these compounds. Moreover, the strong adsorption of these contaminants to solid matrices and their occurrence in highly complex mixtures, formed in some cases by many homologues, oligomers and isomers, pose additional difficulties to their analysis. For determination at trace levels, analyses are normally carried out by chromatographic methods

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combined with detection techniques preferably able to confirm analyte identity.

The objective of this work is to review the analytical methods, including sample preparation as well as determination, reported in the last ten years for the analysis of emerging contaminants (surfactants, flame retardants, pharmaceuticals and personal care products) in soil, sediment, and sewage sludge.

2. Surfactants

Surfactants are a diverse group of chemicals employed in a wide variety of applications. They have hydrophobic and hydrophilic groups, which allow sorption to non-polar and polar materials at the same time and to form micelles in solution, giving surfactants their detergency and solubilisation properties. Thus, they are mainly used as components of detergent and cleaner formulations, but also in products such as personal care products, paints, polymers, pharmaceuticals, textiles or pesticides. Synthetic surfactants are some of the chemicals most widely used in the world, being the annual global consumption higher than 13 million tons in 2006, thus, they are emerging contaminants of special interest. As a result of this interest, some reviews and book chapters have been published in the last years about surfactants production and their environmental behaviour and effects [1-4].

Four surfactant classes can be established according to the nature of the hydrophilic group: nonionic, anionic, cationic and amphoteric or zwitterionic surfactants. Nonionic and anionic surfactants represent 86% of the world surfactant consumption; whereas amphoteric surfactants, including betaines and amine oxides, are the surfactants less consumed (3%). No scientific articles have been found in the literature for the analysis of the latter in environmental solid samples and, therefore, they have not been considered in this review.

2.1. Anionic surfactants

Anionic surfactants have a hydrophobic alkyl chain and a sulphonate, sulphate, carboxylate or phosphate group, which makes these compounds to be negatively charged in aqueous solutions. Commercial anionic surfactants contain mixtures of homologues with different alkyl chain lengths and different isomers.

Linear alkylbenzene sulphonates (LAS), the most widely used anionic surfactants, are complex mixtures of closely related isomers and homologues, with linear alkyl chains ranging from 10 to 14 carbon units attached to an aromatic ring sulphonated at the *para* position. Other commonly used anionic surfactants, although in less extent than LAS, are alkyl sulphates (AS), alkyl ethoxy sulphates (AES) and secondary alkane sulphonates (SAS).

2.1.1. Sample preparation

The application of classical extraction techniques, such as Soxhlet, has declined in the last years in favour of modern extraction techniques like pressurised liquid extraction (PLE) or ultrasound assisted extraction (UAE) (Table 1). Thus, Soxhlet extraction has been used in studies focused in the development of adequate chromatographic methods [6,14] or when different extractive techniques were compared [13,16]. Nevertheless, when comparative extraction studies were accomplished, UAE or PLE were usually chosen instead of classical techniques to carry out surfactants extraction. In general, PLE was the main extractive technique applied using methanol [16,17], methanol:acetone (1:1, v/v) [15,18] or methanol:water (90:10, v/v) [5] as extraction solvents. The amount of sample extracted varied from 5 to 10 g and the methods used different extractive conditions; although a clean-up of the extract through a C_{18} solid-phase extraction (SPE) column was necessary in all of them. With other extractive techniques, a lower amount of sample was used. Thus, Bruno *et al*. [11] employed only 50 mg of sample to extract a mixture of anionic and nonionic surfactants and some metabolites in sludge by subcritical water extraction (SWE), followed by a clean-up with 1 g of graphitised carbon black (GCB) and recoveries higher than 87% were obtained. Villar *et al*. [7,8] used 0.5 g of sample and 5 mL of methanol for the analysis of LAS in sludge by microwave assisted extraction (MAE) or UAE [9] obtaining recoveries from 83 to 102%.

2.1.2. Determination

Table 1 shows the analytical techniques used to determine anionic surfactants in solid environmental samples. There are few studies on anionic surfactants other than LAS [11,14,17,18,35], probably due to their lower potential environmental occurrence and, until recently, the limitation to have selective and sensitive enough analytical techniques for their determination. Nevertheless, as improvements in liquid chromatography-mass spectrometry (LC-MS) occurred, it became one the most powerful tools for surfactant analysis in environmental samples. Thus, its specificity allows the unequivocal identification of homologues and ethoxymers and it has been used in the determination of LAS and their main metabolites, sulphophenyl carboxylate compounds (SPCs) [5,6,10], as well as to evaluate anionic and nonionic surfactants [11,14-17]. Reverse- phase with C_8 or C_{18} bonded silica packing

Table 1. Analysis of surfactants in environmental solid samples.

Matrix (g)	Analytes (number)	Sample preparation	Determination (Derivatisation)	Recovery (%)	LOD (ng g^{-1})	Levels (ng g^{-1})	Ref.
Soil (10)	LAS (4), SPCs (9)	PLE: MeOH:water (90:10, v/v), 120ºC Clean-up: LiChrolut RP-C_{18}	LC-ESI-MS/MS	52–85	SPCs 0.3-0.8[a]	122–2839 -LAS 4.4-221 -SPCs	[5]
Soil (5)	LAS (4), SPCs (7)	Soxhlet: 150 mL MeOH Clean-up: C_{18}	LC-ESI-MS^n	13-92	0.5-80[a] by MS 2-400[a] by MS^2 20-4000[a] by MS^3	50-15000	[6]
Sludge (0.5)	LAS (4)	MAE: 5mL MeOH	LC-DAD and LC-FL	83-102	250-2500	2.3x10^6-13x10^6	[7]
Sludge (0.5)	LAS (4)	MAE: 5mL MeOH	LC-FL and CE-DAD	85-89	150-200[b]	2.7x10^6-5.5x10^6	[8]
Sludge (0.5)	LAS (4)	UAE: 10 mL MeOH	HPLC-FL	84-97	820-4580	2.4x10^6-12x10^6	[9]
Sludge (2.5)	LAS (4), SPCs (7)	UAE: MeOH Clean-up: isolute ENV+	LC-ESI-MS	58-90	0.4-16	38-427000	[10]
Sludge (0.05)	LAS, DATS, SAS, AS, AES, NPEOs, AEs, NPECs, OP, NP	SWE: 20 mL Carbonate buffer pH 9.4, 200ºC Clean-up: GCB (Carbograph 4)	LC-ESI-MS	>87		240-1.7x10^6	[11]
Sludge	LAS (4)	UAE-clean-up: C_{18}, 0.1 g NaOH +10 mL MeOH	CE-UV-Vis	85-97	930-4830[b]	6000-192000	[12]
Sludge (5)	LAS (4)	MAE: 25 mL MeOH, 105ºC. Soxhlet: 200 mL MeOH UAE: 100 mL MeOH	LC-FL		3.3-5.4	700-13450	[13]
Sludge (10)	AEOs, NPEOs, OPEOs, 4-NP, 4-OP (among other)	Soxtec-50 mL MeOH Clean-up: C_{18}	LC-ESI-MS	69-92	1-20	1300-8500	[14]
Sediment (5)	APEOs, APECs, APs	PLE: MeOH:acetone (1:1, v/v), 50ºC Clean-up: LiChrolute C_{18}	LC-ESI-MS	77–97	1-5	<1-1170	[15]
Sediment (5)	LAS (4), AES (5), AS (5)	Soxhlet: MeOH PLE: MeOH, 125ºC Clean-up: C_{18}	LC-ESI-MS	55–125	1-5	168-1014	[16]
Sediment (4)	LAS, AES, AS, NPEOs, AEOs, SPCs, APECs	PLE: MeOH, 120ºC Clean-up: C_{18}	LC-ESI-MS	70-107	1-10	5370-19970	[17]
Sediment (5)	LAS, CDEAs, NPEOs, NPECs, NP, OP	PLE: MeOH:acetone (1:1, v/v), 50ºC Clean-up: C_{18}	LC-ESI-MS	56-104	1-8	2.8-86940	[18]
Soil (10)	AEOs, ANEOs	PLE: A) MeOH and B) hexane:acetone (1:1, v/v), HAc (75 mmol L^{-1}) and TEA (100 mmol/L), 150ºC Clean-up: Porapak RDX	LC-APCI-MS	27-109	7-43	78-1105	[19]
Soil (5)	APs (3), APEOs (7)	PLE: MeOH, 70ºC Clean-up: Isolute ENV+cartridges	GC-MS (BSTFA/TMCS 1:1,v/v) LC-FL	97-104 96-104	3-38 6-60	100-229000	[20]
Soil (5)	APs, APEOs, AEOs,	PLE: acetone:hexane (1:1, v/v), 60ºC Clean-up: C_{18}	LC-APCI-MS	89-102	0.3-30	37-500	[21]
Sludge (1)	NP, NPECs (2), halogenated NP (2), halogenated NPECs (4)	PLE: acetone:MeOH (1:1, v/v), 75ºC Clean-up: C_{18}	LC-ESI-MS/MS	≤81	0.5-1.5	20-145	[22]
Sludge (0.03-0.3)	NPEOs, NP	MAE (sample + 1g water): hexane:acetone (1:1, v/v), 120ºC	LC-UV	61-91	1820-2860	3600-233500	[23]
Sludge (0.1)	APEOs, AEOs	Coacervative extraction: Acid-induced sodium dodecane sulphonate phase separation	LC-APCI-MS	78-100	90-380	11000-151000	[24]
Sludge (1)	NPEOs, NP	Soxtec (4h): DCM Clean-up: Alumina	LC-UV	54-124	10[a]	<0.01-243	[25]
Sludge (0.2)	NPEOs, OPEOs, APECs, AP	Shaking: 10 mL MeOH:acetone (1:1, v/v) Clean-up: Silica gel	LC-ESI-MS/MS	51-89	6-60	12-289544	[26]
Sludge (0.1-0.4)	OP, NP, NPEOs (2)	UAE: hexane:DCM (1:1, v/v) (x2) +DCM:acetone (1:1, v/v) (x1) Clean-up: Florisil	GC-ESI-MS	47-108	300-1700	300-199000	[27]
Sediment (1)	NP, OP, NPEO (1), NPECs (2)	Soxhlet: DCM Clean-up: SAX cartridges+Silica gel	GC-MS (BF_3-MeOH; BSTFA)	≤110	3-40	5-1820	[28]
Sludge (0.1), Sediment (2)	NPEOs, NP	MAE: 20 mL hexane+1 mL water, 120ºC Clean-up: MISPE	LC-FL LC-ESI-MS/MS	60-110		2300-107500	[29]
Soil, sludge, sediment (2)	NPEOs, NP	SAESC: 5 mL water:MeOH (30:70, v/v) Clean-up: C_{18}	LC-FL	26-94	60-520		[30]

Continued **Table 1.** Analysis of surfactants in environmental solid samples.

Matrix (g)	Analytes (number)	Sample preparation	Determination (Derivatisation)	Recovery (%)	LOD (ng g^{-1})	Levels (ng g^{-1})	Ref.
Sludge (0.1)	QACs (10)	Acid-induced CPE	LC-ESI-MS	91-100	40-75	100-34000	[31]
Sediment (5), sludge (1)	QACs (12)	Soxhlet: 150 mL MeOH acidified	LC-MS/MS	67-95	0.6-5[a]	22000-103000	[32]
Sediment (10)	BACs	PLE: ACN:water (60:40, v/v), 100ºC Clean-up: on-line SPE-polymeric reverse-phase cartridges	LC-ESI-MS	79-85	0.2	22-206	[33]
Sediment (0.1)	QACs (12)	UAE: 30 mL acidic MeOH Clean-up: LLE-water +anion exchange resin	LC-ESI-ToF MS	98-118	0.1-2.6[a]	1800-74000	[34]

[a]LOQ; [b]ng mL^{-1}

are the stationary phases most commonly used in the analyses. Usually LC-MS analysis of anionic surfactants is performed with electrospray ionisation (ESI) under negative ion-mode; nevertheless, for the simultaneous detection of anionic and cationic surfactants, analyses can be performed in positive or negative mode depending on the compounds to be determined [11,14] or in mixed-mode to achieve a simultaneous detection of the compounds [17]. Eichhorn *et al*. [5] reported the first analytical method based on liquid chromatography tandem mass spectrometry (LC–MS/MS) for the quantitative determination of LAS, including their major degradation products, SPCs, in sludge-amended soil. This method allowed the detection and identification of low concentrations of SPCs in environmental samples of high complexity, with the limits of quantification (LOQ) between 0.3 and 0.8 ng g^{-1}. Andreu and Picó [6] used liquid chromatography multiple stage mass spectrometry (LC-MS^n) and the MS^2 and MS^3 allowed the unequivocal detection and quantification of LAS and their degradation products in soil. However, detectors other than mass spectrometry (MS), such as fluorescence (FL) or diode array detectors (DAD), have also been used to evaluate LAS in sludge [7-9,13]. It should be noted that higher limits of detection (LOD) were obtained by Villar *et al*. [7-9] compared to those reported by other authors [10-13]. Nevertheless, these concentrations are close to the limit values of 2600 mg kg^{-1} established in the third draft of the future European Union (EU) Directive for total LAS in sludge for land application [36]. Another technique used to determine LAS in sludge was capillary electrophoresis (CE), which has been described as a good and quick technique for the analysis of ionic compounds using small sample amounts and low consumption of solvent, but with low concentration sensitivity. Recently, Villar *et al*. [8] and Alzola *et al*. [12] have determined LAS in sludge by CE with DAD. Dialkyltetralin sulphonates (DATS) are reaction by-products of LAS that can be present at levels from 3 to 10% in the LAS derived from an $AlCl_3$ process described as less than 5% from total LAS production in 2005 [37]. Nevertheless, although DATS are minor components in LAS formulations, these by-products seem to be more resistant to biodegradation than LAS and they are present at higher concentration in sewage-contaminated groundwater [38]. The determination of DATS in sludge was included in the multiresidue analysis of anionic and nonionic surfactants developed by Bruno *et al*. [11].

2.2. Nonionic surfactants

Nonionic surfactants have a balance between the hydrophobic and hydrophilic groups and are not ionised in aqueous solutions. The most important nonionic surfactants are: alcohol ethoxylates (AEs), alkylphenol ethoxylates (APEOs), fatty acid alkanolamides (FAA), n-methylglucamides (NMG) and alkylpolyglycosides (APG). AEs, containing an ethylene oxide chain attached to the hydroxyl group, are formed by compounds differing in the chain length (between C_8 to C_{18} units are the most common) and in the number of ethylene oxide units (indicated by a subscript). APEOs are based on p-octyl-, nonyl-, and dodecylphenol poly(ethylene glycol) ethers. Although parent APEOs are not classified at highly toxic substances, some of their metabolites have been reported to have endocrine disruption activity at low concentrations in different aquatic organisms [2]. Thus, the hydrophilic ethoxylate chain of nonylphenol polyethoxylates (NPEOs) is shortened during wastewater treatment to the corresponding nonylphenol monoethoxylate (NP1EO) or diethoxylate (NP2EO) and further biodegraded to completely deethoxylated nonylphenol (NP), which has been listed as a priority substance in the Water Framework Directive [39].

FAA has little application in laundry detergents but they can be added to give stability to the foam produced by shampoo, liquid soaps and some personal care products. NMG are used as co-surfactants in powder and liquid detergent formulations. Finally, APG usually consist of an alkyl chain and sugar derivatives made

from vegetable oils and starch. There is growing interest in these surfactants of natural origin because they could replace traditional petroleum surfactants [40,41].

2.2.1. Sample preparation

In general, most of the analytical methods reported for the analysis of nonionic surfactants in environmental solid samples use modern extractive techniques (Table 1) and MAE is perhaps one of the most used for the extraction of these compounds. For this reason, Sanchez-Prado *et al*. [42] reviewed the application of MAE to the determination of surfactants, among other emerging pollutants. Together with MAE, UAE and PLE are techniques usually used to extract nonionic surfactants from solid environmental samples, often together with other emerging contaminants. Although alkyl phenols (APs) and APEOs have been extracted by shaking [43], there is an interest in developing selective and sensitive methods for the extraction of these contaminants. Recently, Llorca-Pórcel *et al*. [44] developed a method for the analysis of 4-nonylphenols, among other compounds with estrogenic properties, by means of UAE and stir bar sorptive extraction (SBSE) with *in situ* derivatisation. No recovery assays were done in this study because the method accuracy was determined by analysis of a certified reference material that contained only chlorophenols.

However, PLE seems to be the extraction technique most commonly used when only nonionic surfactants are determined [15,19-22]. A field study designed by Jiménez-Díaz *et al*. [20], to determine APs and APEOs in agricultural soils using PLE with methanol, and a clean-up and pre-concentration of the extracts by SPE using ENV+ cartridges, allowed them to study the behaviour of these compounds in agricultural soils. Using PLE as extractive technique, Krogh *et al*. [19] developed a method to analyse alcohol polyethoxylates (AEOs) and alkylamine ethoxylates (ANEOs) in soil contaminated from the use of these surfactants as adjuvants in pesticide formulations to enhance their effectiveness. Nevertheless, classical techniques, such as Soxhlet or Soxtec [25,28], UAE [27] and shaking [26], continue to be widely used procedures. Croce *et al*. [46] carried out the comparison of five extraction techniques for the determination of NP and NPEOs in river sediments. In this study, all the methods gave reliable results but the small amount of solvent and reduced extraction time are important advantages of PLE and MAE techniques. The effect of four different pre-treatments (untreated, freeze-dried and dried at 40 ºC or 100 ºC) were evaluated by Fernández-Sanjuan *et al*. [27] for the determination of APs and NPEOs in sludge. The results showed that freeze-drying is the recommended sample pre-treatment to prevent possible losses of octylphenol (OP), NP and NP1EO. The development of rapid, simple and selective extractive methods for the analysis of these compounds in sludge has been a main objective [24,29,30]. With this aim, the method developed by Cantero *et al*. [24] used acid-induced sodium dodecane sulphonate phase separation to extract APEOs and AEOs from sludge samples, with recoveries between 78 and 100% and LODs between 90 and 380 ng g^{-1}. Nuñez *et al*. [29] described the preparation and evaluation of several NP molecularly imprinted polymers (MIPs) for the selective extraction and clean-up of NP and NPEOs in solid samples and the method was successfully applied to the analysis of various sludge samples.

2.2.2. Determination

The chemical complexity of APEOs and AEOs, which are mixtures of numerous isomers and oligomers, needs a quite sophisticated analytical methodology for their isolation, identification and quantification that is generally based on their determination by LC-MS or gas chromatography-mass spectrometry (GC-MS). C_{18} bonded silica packing is the stationary phase commonly used in the LC analyses and 5% phenyl- 95% methylpolysiloxane columns are often employed in GC-MS analysis. A review was published in 2002 on sample preparation methods for APEOs and their degradation products in environmental matrices [46] due to the interest of environmental analytical chemistry on these nonionic surfactants because of their questionable environmental acceptability.

These compounds, widely used in consumer products and industrial applications, are continuously discharged into WWTPs and their presence in sludge has been the focus of many studies. Thus, sludge has been the main matrix evaluated in the analysis and occurrence of nonionic surfactants, whereas there is scarce information regarding the environmental concentration of these compounds in soil and sediments. Some of the advances in the analysis of nonionic surfactants in environmental solid samples are summarised in Table 1. Andreu *et al*. [21] applied LC-MS to analyse OP, NP, APEOs and AEs in soils treated with sewage sludge from WWTPs, showing the presence of these compounds at concentrations between 37-500 ng g^{-1}. The method developed by Isobe and Takada [28] to determine degradation products of APEOs in sediment employed GC-MS. In this method, the extract was fractionated through an anion exchange column into nonionic and anionic fractions and the APs fraction was directly subjected to GC-MS, whereas the NP1EO fraction was derivatised with N,O-bis(trimethylsilyl) trifluoroacetamide (BSTFA) and the mixture of

nonylphenoxy acetic acid (NP1EC) and nonylphenoxy monoethoxy acetic acid (NP2EC) was methylated with boron trifluoride (BF_3) in methanol before GC-MS analysis, obtaining LODs between 3 and 40 ng g^{-1}.

Due to the endocrine disruption capacity of 4-*tert*-OP, NP, NP1EO, and NP2EO, these compounds have been evaluated in some works together with other potential endocrine disrupting compounds (EDCs), such as bisphenol A (BPA), estrogens, phthalates, polycyclic aromatic hydrocarbons (PAHs), triclosan or polychlorinated biphenyls (PCBs) [43,47-55]. When different groups of compounds were evaluated, analyses were usually done by GC-MS with a derivatisation step using BSTFA [49,51-53,55] or without derivatisation [56,57]. Recently, gas chromatography tandem mass spectrometry (GC-MS/MS), more selective and sensitive than GC-MS, was applied in the determination of phenolic compounds and estrogens in sediments [48]. Nevertheless, Céspedes *et al*. [51] and Langford *et al*. [43] used LC-MS in their studies for the determination of 27 alleged EDCs in sediment samples, focused in the assessment of the total estrogenic activity of the samples by the recombinant yeast assay, and in the determination of alkylphenolic surfactants and PBDEs in sludge, respectively. Petrovic *et al*. [47] developed a new method for the analysis of EDCs in sediments, based on a PLE-on column switching system, for an integrated sample clean-up, and LC-MS that allowed the simultaneous analysis of the compounds in less than 2 h, showing a significant improvement in comparison to the method reported previously. In general, LC-MS is the analytical technique usually chosen when only surfactants are evaluated (Table 1).

Petrovic *et al*. [22] reported a LC-MS/MS method for quantitative analysis of NP, nonylphenol ethoxy carboxylates (NPECs) and their brominated and chlorinated derivatives. The method was applied to study the occurrence of halogenated alkylphenolic compounds derived from drinking water treatment plants and it was found that the flocculation sludge accumulated hydrophobic halogenated compounds and their precursors; hence, NP, brominated and chlorinated NPs were found in flocculation sludge in concentrations of 150, 105, and 145 ng g^{-1}, respectively.

2.3. Cationic surfactants

Cationic surfactants are mainly used in fabric softeners, hair conditioners and other hair care products and they are also important ingredient in disinfectants. According to CESIO surfactants statistics for Western Europe, during 2005 about 9% of the total surfactants consumed were cationic surfactants [47]. The most common cationic surfactants are quaternary ammonium compounds (QACs), which contain a hydrophobic tail linked to a positively charged quaternary nitrogen atom. Due to their positive charge, they have a strong affinity for the negatively charged particles in sludge, soil and sediments. As a result of their low consumption, few studies have been found in the scientific literature on the presence of cationic surfactants in solid environmental samples, in comparison to those reported on other surfactants (Table 1).

2.3.1. Sample preparation

The extraction of cationic surfactants from solid matrices is difficult because they are strongly adsorbed by hydrophobic and electrostatic interactions. They are mixtures of homologues and, due to the low concentration expected, preconcentration methods are generally required. Different methods have been reported for the extraction and purification of QACs from sediment and sludge (see Table 1). Soxhlet, using acidified methanol as solvent, was used by Martinez-Carballo *et al*. [32] for the extraction of QACs from sediment and sludge. Merino *et al*. [31] carried out the extraction from sludge samples using the acid-induced cloud-point extraction (CPE) technique on the basis of the formation of extractant-analyte mixed aggregates. In this study, different variables affecting efficiency of the extraction technique were optimised and recoveries from 91 to nearly 100% of QACs were obtained, pointing out that the formation of extractant-analyte mixed aggregates, using CPE, is a valuable strategy for the extraction of amphiphilic substances from solid matrices.

The clean-up of the extracts is an important step in sample preparation when cationic surfactants are evaluated. An on-line clean-up step using polymeric reverse-phase cartridges [33] or a liquid-liquid extraction (LLE) followed by anion exchange purification of the extracts obtained by UAE using acidic methanol [34] have been reported to purify the extracts.

2.3.2. Determination

Analyses of this surfactant class were carried out by LC using C_8 or C_{18} reverse-phase columns. LC-MS, LC-MS/MS or liquid chromatography-time of flight-mass spectrometry (LC-ToF-MS) were used in these analyses, due to the complexity of compounds and samples, and the lack of a chromophoric group in most of cationic surfactants. Merino *et al*. [31] and Ferrer and Furlong [33] used LC-MS for the analysis of QACs in sludge and benzalkonium chlorides (BACs) in sediments, respectively. The high concentrations of BACs homologues detected in sediment [33], from 22 to 206 ng g^{-1}, reflect their high affinity for solids and they preferentially concentrate in sediment rather than in

water. Martínez-Carballo *et al*. [32] used LC-MS/MS for the analysis of 12 QACs in sediment and sludge samples with high sensitivity, as illustrated by the low LOQs obtained, which ranged from 0.6 to 3 ng g^{-1} in sediments and from 1 to 5 ng g^{-1} in sludge samples. The method developed by Li and Brownawell [34] for the analysis of QACs in sediments by LC-ToF-MS showed that the concentrations of QACs found in sewage-impacted estuarine sediments, up to 74000 ng g^{-1}, were higher than the concentration of other organic contaminants measured in the same or nearby samples. In this way, these authors accomplished the determination of these compounds in shallow sediments [58] and the evaluation of the occurrence of alkyltrimethylammonium compounds (ATMACs) in urban estuarine sediments [59]. In this study, behentrimonium was identified for the first time as a new emerging contaminant. Behentrimonium is a mixture dominated by a homologue having 22 carbon atoms in the alkyl chain of the alkyltrimethylammonium compound (ATMAC 22), which showed an exponential increase along the years due to its greater use as substitute of other ATMACs in some personal care products.

3. Flame retardants

Flame retardants (FRs) are chemicals added to polymers used in paints, textiles, plastics or electronics materials to inhibit or resist the spread of fire. Different classes of chemicals are used as flame retardants: inorganic compounds (borates and antimony oxides), organic phosphate esters (with or without halogens) and brominated and chlorinated organic compounds.

Environmental studies, conducted primarily in Europe, Japan and North America, indicate that these chemicals are ubiquitous in the environment and, therefore, their determination has become an increasing concern to scientists over the past decade. In this section, the current state of analytical methods for the determination of the most widely used organic FRs is reviewed.

3.1. Organophosphate flame retardants (OPFRs)

The most commonly used OPFRs are: tris(2-chloroethyl) phosphate (TCEP), tris(2-chloropropyl) phosphate (TCPP), tris(1,3-dichloro-2-propyl) phosphate (TDCP), tris(2-butoxyethyl) phosphate (TBEP), triethyl phosphate (TEP), tris (butyl) phosphate (TBP), triphenyl phosphate (TPP), tritolyl phosphate (TCP) and tris(2-ethylhexyl) phosphate (TEHP). TCEP and TCPP are carcinogenic while TPP and TBP have neurotoxic effects. In addition, the low water solubility and relative high log Kow values of these compounds may lead to their accumulation in soil, sediment and sludge matrices. However, very few studies have been published on the occurrence of OPFRs in these solid matrices (Table 2) in comparison with other matrices such as water, air and dust.

3.1.1. Sample preparation

PLE, using ethyl acetate or acetonitrile:water as extraction solvent is the technique most often employed in the scarce published papers for the analysis of OPFRs in solid environmental samples [64,66,67]. Other techniques such as MAE [63,65], UAE [62] and Soxhlet [60,61] have been also used for the extraction of these compounds, being acetone, ethyl acetate:acetonitrile, acetone:acetonitrile or ethyl acetate the solvents often employed.

Clean-up of the extracts obtained with these procedures is generally needed before the analytical determination. In this way, SPE using Oasis, silica or Oasis with alumina is often performed. Nevertheless, some authors [60,64,67] used size exclusion chromatography or gel permeation chromatography (GPC) to remove macromolecules prior to or after SPE with silica. Recently, a combination of hot Soxhlet and solid-phase microextraction (SPME) using extraction with toluene has been reported by Mihajlovic *et al*. [61].

3.1.2. Determination

OPFRs can be analysed using either GC or LC (Table 2). Detection in GC methods can be carried out through a nitrogen–phosphorous detector (NPD) or by GC–MS. Nevertheless, non appropriate selectivity of NPD detection and excessive fragmentation of OPFRs in electron impact (EI) MS, which complicates their confirmation and quantification due to the interference from matrix components at low masses, are some of the drawbacks of these techniques. The use of GC with inductively coupled plasma mass spectrometry (ICP-MS) has also been reported [65]. On the other hand, LC-MS/MS has been scarcely employed to determine these compounds in solid environmental matrices [62]. In general, higher LODs were obtained for sludge samples than for sediment and soil samples (Table 2).

The highest concentrations of OPFRs were found in sludge samples, being TCPP the dominant compound, although also a high level of this compound (1300 ng g^{-1}) was found in sediment from Austria [62].

3.2. Brominated flame retardants (BFRs)

BFRs can be divided into the following groups: polybrominated diphenyl ethers (PBDEs), polybrominated biphenyls (PBBs), tetrabromobisphenol

Table 2. Analysis of OPFRs in environmental solid samples.

Matrix (g)	Number of analytes	Sample preparation	Determination	Recovery (%)	LOD (ng g^{-1})	Levels found (ng g^{-1})	Ref.
Sludge (10)	1	Soxhlet: EtAc Clean-up: silica gel + GPC	GC-MS	110	100[a]	1300-2200	[60]
Soil (10)	6	Hot Soxhlet: 150 mL toluene and SPME: PDMS/DVB, 1min, 40ºC	GC-MS	31-90	0.002-0.3	1.23-4.9	[61]
Sediment (5)	9	UAE: 30 mL EtAc:ACN (30:70,v/v) (2x) Clean-up: washed 2 mL ACN (2x)	LC-ESI-MS/MS	74-104	0.48-11[a]	2.4-1300	[62]
Sediment (2)	5	MAE: 40 mL acetone, 120ºC. Clean-up OASIS HLB + Al_2O_3, EtAc	GC-MS	62-106	0.05-0.15	1-12.6	[63]
Sludge (4-6)	6	PLE: EtAc, 90ºC Clean-up: Silica, SEC	GC-MS	52-96	3-30		[64]
Sediment (0.5)	10	MAE: 5 mL acetone + 5 mL ACN, 150ºC Clean-up: Silica	GC-ICP-MS	78-105	2-4[a]	≤ 10	[65]
Sediment (2)	7	PLE-clean-up: silicon dioxide + water:ACN (75:25, v/v) 90ºC Cleanup: OASIS HLB	GC-MS	77-111	0.5-5[a]	6.4-45.9	[66]
Sludge (5)	7	PLE: EtAc, 90ºC Clean-up: GPC + silica gel	GC-NPD GC-MS	93-117	0.2-5.1	3-1900	[67]

[a]*LOQ*

A (TBBPA) and hexabromocyclododecane (HBCD), and novel brominated flamed retardants (NBFRs).

Several review articles have been published by Eljarrat and Barceló [68], Covaci *et al*. [69-73] and Kierkegaard *et al*. [74] on the determination and levels of BFRs in biotic and abiotic samples, which were taken as a starting point for the overview of the analytical methods used in the determination of BFRs in solid environmental samples.

3.2.1. PBDEs and PBBs

The three main PBDEs commercial products are penta-BDE, octa-BDE and deca-BDE. These commercial products consist of a mixture of several congeners with different levels of bromination on the phenyl rings. These compounds are persistent, bioaccumulative and toxic to organisms, and this is why commercial mixtures of penta-BDE and octa-BDE were banned in Europe and North America [75]. In addition, PBBs were banned in 1976 [76] and usage restriction of deca-BDE mixture was also initiated in European countries in 2008 [77]. Then, it is expected that the use of all them will decline in the next years. Nevertheless, as there is a stock of these PBDEs, and in minor amount of PBBs, from products in service and in waste, it is still necessary to monitor the environment for the presence of these BFRs. PBDEs have been the FRs most studied in environmental matrices whereas few works are lately available for PBBs. The procedures used for the determination of PBDEs and PBBs are similar for both types of FRs, which are often determined in the same analysis.

3.2.1.1. Sample preparation

Soxhlet and PLE have been the most used techniques to extract PBDEs and PBBs from environmental solid matrices, though other techniques such as UAE, MAE and SPME are also used (Table 3). A mixture of hexane:acetone or dichloromethane:hexane, in proportion 1:1 or 3:1 v/v, are the solvents most often used in Soxhlet, whereas dichloromethane or a mixture of hexane:dichloromethane are the main solvents used in PLE.

The extraction by UAE of brominated compounds has shown good results [89,98,104] and UAE has been often used in combination with other techniques such as SBSE [92], SPME [87], hollow fibre- liquid phase microextraction (HF-LPME) [93] and matrix solid phase dispersion (MSPD) [106]. Nevertheless, sonication was reported to produce low recoveries of deca-BDE in a comparative study between extraction methods, using standard reference materials of sediment [112]. In this way, Wang *et al*. [113] obtained low recoveries of PBDEs using MAE in comparison to PLE or Soxhlet, suggesting an inappropriate optimisation of the MAE method. Less common extraction methods have been reported, like CPE, proposed by Fontana *et al*. [78] with the aim of avoiding the use of organic solvents and a modified QuEChERS reported by Andrade *et al*. [108].

Removal of sulphur and organic matter are generally necessary to improve the determination of analytes. Treatments with Cu powder, silica modified with Al_2O_3 or GPC are the procedures often used to remove sulphur [83,94,106,109]. Treatment with sulphuric acid of the

Table 3. Analysis of PBDEs and PBBs in environmental solid samples.

Matrix (g)	Analytes (number)	Sample preparation	Determination (Derivatisation)	Recovery (%)	LOD (ng g^{-1})	Levels found (ng g^{-1})	Ref.
Soil (0.5)	Tetra–hexaBDEs (4)	CPE: 10 mL water + Triton X-114 + NaCl + citrate buffer (pH 5.6), 80ºC + iso-octane and UAE	GC-MS	20	1-3.7		[78]
Sediment (1)	Mono–decaBDEs (40)	PLE–clean-up: Cu + alumina + hexane:DCM (1:1, v/v), 100ºC	GC-NCI-MS	22-82	0.001-0.046	0.86-42 ∑PBDEs	[79]
Sediment (1)	Mono–decaBDEs (40), HBCD	PLE–clean-up: Cu + alumina + hexane:DCM (1:1, v/v), 100ºC	GC-NCI-MS	53-84	0.006-0.050	2-42 ∑PBDEs) ≤ 514 HBCD	[80]
Sediment, sludge (6)	Tetra–decaBDEs (6)	Soxhlet: hexane:acetone (3:1, v/v), 70ºC Clean-up: GPC + shaking in H_2SO_4+ silica gel	GC-ECNI-MS		0.1-1	0.1-4600	[81]
Soil (15)	Tetra–hexaBDEs (20)	Soxhlet: toluene Clean-up: concentration and shaking in H_2SO_4 + hexane + silica gel (multilayer) (x2) + GPC + basic alumina	GC-NCI-MS	82-120		0.065-12 ∑PBDEs	[82]
Soil, sediment (4)	Mono–heptaBDEs (19)	Soxhlet: Cu + Na_2SO_4 + hexane:acetone (1:1, v/v) Clean-up: acidic silica gel + neutral alumina columns	GC-IT-MS/MS	61-118	0.013-0.25	0.3-824	[83]
Sediment (20)	Mono–octaBDEs (22)	PLE: DCM, 100ºC Clean-up: alumina/ copper	GC-MS	50-120	0.1-1.5	≤ 212 ∑PBDEs	[84]
Sediment (4-5)	Tri–hexaBDEs (9), Di–pentaBBs (5)	MAE: 48 mL hexane:acetone (1:1, v/v), 152ºC Clean-up: GPC	GC-IT-MS	81-96 PBDEs 74-81 PBBs	0.004-0.020	0.2-0.3 BDE-47	[85]
Soil (50)	Tri–hexaBDEs (6)	Soxhlet: hexane:acetone (2:3, v/v) Clean-up: H_2SO_4 + Florisil	GC-MS		0.0005	0.073-3.9 ∑PBDEs	[86]
Sludge (2)	Tetra–hexaBDEs (6), BB-49, BB-15	UAE-clean-up: Florisil + 8 mL hexane and HS-SPME (5 mL water, 100ºC) PDMS fibre (60 min) desorption in injector (3 min, 280ºC)	GC-MS/MS	92-138	0.01-1.2	≤ 5.8	[87]
Soil, sediment (0.5)	Tetra–hexaBDEs (8)	HS-SPME: 2 mL water,100ºC, PDMS fibre (30-60 min), desorption (3 min, 280ºC)	GC-IT-MS/MS	82-105	0.005-0.625	≤ 12	[88]
Soil (10)	Tri–heptaBDEs (6)	UAE: 5 mL EtAc (x2) Clean-up: Florisil	GC-MS	81-104	0.002-0.030	1.3-5.6	[89]
Soil (1)	Mono–heptaBDEs (9)	Soxhlet: Cu + Na_2SO_4 + hexane:acetone (1:1, v/v) Clean-up: acidic silica + neutral alumina	GC-IT-MS/MS	40-65	0.008-0.1	0.6-599	[90]
Sludge (0.25-0.5)	Tetra–decaBDEs (8)	MAE: Na_2SO_4 + 30 mL hexane:acetone (3:1, v/v), 130ºC Clean-up: H_2SO_4 + silica gel	GC-NCI-MS	80-110	1-7	≤ 800	[91]

Continued **Table 3.** Analysis of PBDEs and PBBs in environmental solid samples.

Matrix (g)	Analytes (number)	Sample preparation	Determination (Derivatisation)	Recovery (%)	LOD (ng g^{-1})	Levels found (ng g^{-1})	Ref.
Sediment (5)	Tetra–nonaBDEs (9)	UAE: 15 mL MeOH and SBSE (dilution in water, PDMS stir bar, 240 min), desorption in acetonitrile, 15 min	GC-MS/MS	66-117	0.3-203[b]	≤ 0.7	[92]
Soil (0.5)	Tri–pentaBDEs (4)	UAE: 3 mL MeOH, dilution in water and HF-LPME	GC-ICP-MS	87-111	0.015-0.0405[b]	18.7-172.2	[93]
Sediment (1)	Tri–decaBDEs (13)	PLE-clean-up: Cu + alumina + hexane:DCM (1:1, v/v), 100ºC	GC-NCI-MS	53-84	0.006-0.050	11-14395 ∑PBDEs	[94]
Soil, sediment (40-50)	Tri–decaBDEs (10) BB-153	Soxhlet: 400 mL DCM:hexane (3:1, v/v) Clean-up: Cu + silica gel (multilayer)	GC-ECD GC-MS	68-108	0.001-0.04	0.02-55 ∑PBDEs 0.0001-4.68 BB-153	[95]
Soil (1)	Mono–hexaBDEs (37)	Soxhlet: 200 mL DCM:hexane (1:1, v/v) Clean-up: silica gel (multilayer)	GC-NCI-MS	75-115	0.001-0.1	0.9-5469	[96]
Sediment (6)	Octa–decaBDEs (20), HBCD	Soxhlet: acetone:hexane (1:1, v/v) Clean-up: GPC + silica gel (multilayer) + alumina	GC-MS			0.009-7.2	[97]
Soil (3-5)	Mono–decaBDEs (39)	UAE: 40 mL hexane:DCM (1:1 v/v) (x3) Clean-up: silica gel (multilayer) (x2)	GC-NCI-MS		0.001-0.1	0.016-211	[98]
Soil (1)	Tri–decaBDEs (23)	Soxhlet: 100 mL hexane:DCM (1:1, v/v) + Cu Clean-up: H_2SO_4 + alumina	GC-MS	54-100	0.03-1.2	21-1185 ∑PBDEs	[99]
Sludge (5)	Tri–decaBDEs (13), HBCD	Soxhlet: 150 mL hexane:acetone (3:1, v/v) Clean-up: Cu + HNO_3 + Na_2SO_4 + GPC + silica gel	GC-ECD	101 PBDEs 84 HBCD	0.01-1.3 PBDEs 6.4 HBCD	0.2-617	[100]
Sludge	DecaBDEs, DBDE	PLE-clean-up: Na_2SO_4 + silica gel + hexane, 100ºC Clean-up: KOH in EtOH, 45ºC, LLP in hexane + aminopropyl gel	GC-MS	71-95	1.4-9.3	650-1100	[101]
Soil (20)	Tri–decaBDEs (10), PBEB, BTBPE, HBCD	Soxhlet: hexane:acetone (1:1, v/v) Clean-up: Silica gel	GC-MS	89-135 PBDEs	0.0003-0.340	≤ 7660	[102]
Soil (20)	Tri–decaBDEs (10)	Soxhlet: Na_2SO_4 + 100 mL DCM:hexane (3:1, v/v) Clean-up: silica gel (multilayer) + H_2SO_4 + silica gel-impregnated carbon	GC-MS GC-ECD decaBDE	88-93	0.005-0.35[a]	20-160000 ∑PBDEs 977-6390 decaBDE	[103]
Soil (3-5)	Di–decaBDEs (42)	UAE: 40 mL DCM:hexane (1:1, v/v) (x3) Clean-up silica gel (multilayer) (x2)	GC-NCI-MS		0.001-0.1	0.064-1670 ∑PBDEs	[104]

Continued **Table 3.** Analysis of PBDEs and PBBs in environmental solid samples.

Matrix (g)	Analytes (number)	Sample preparation	Determination (Derivatisation)	Recovery (%)	LOD (ng g^{-1})	Levels found (ng g^{-1})	Ref.
Sediment (4)	Di–decaBDEs (20)	PLE: DCM: acetone (3:1, v/v), 100ºC Clean-up: LLP in DCM +silica gel + Cu	GC-MS GC-ECD decaBDE	80-95		≤ 11900	[105]
Sludge (2)	Tri–decaBDEs (20)	MSPD: alumina + Cu and UAE: 6 mL DCM (x2) Clean-up: C_{18}	GC-MS	78-112	0.05-0.5	20.9-736.9 ∑PBDEs	[106]
Sediment (0.25-0.5)	Tetra–hexaBDEs (6)	SPME-HD:5 mL water + 0.5 mL diluted H_2SO_4 (1:3, v/v) + $KMnO_4$, 100ºC, PA fibre (40 min) Desorption at 300ºC (2 min)	GC-MS/MS	76-111	<0.15[a]		[107]
Soil (10)	Tri–decaBDEs (8)	Modified QuEChERS: Na_2SO_4 + DCM Clean-up: alumina	GC-NCI-MS	61-92	0.4-6	5-53	[108]
Soil (20)	Mono–decaBDEs (15)	PLE-clean-up: Cu + DCM, 120ºC Clean-up: GPC + aluminium oxide + silica gel	GC-NCI-MS	74-126	0.003-0.052	0.087-0.625 ∑PBDEs	[109]
Soil (1)	Tri–heptaBDEs (7)	PLE: DCM, 100ºC Clean-up: Silica	GC-MS	69-129	0.011-0.054	≤ 0.55	[110]
Sediment (5-10)	Mono–decaBDEs (11), MeO-and OH-PBDEs (35)	PLE: hexane:DCM (1:1 v/v), 100ºC Clean-up: GPC + Florisil	GC-HRMS (pyridine + acetic anhydride)	35-105	0.0006-0.003	≤ 1.24	[111]

[a]*LOQ;* [b]*ng mL*$^{-1}$

extract dissolved in hexane is a usual procedure to remove organic matter, because PBB and PBDEs are stable in acidic conditions [86,91,99]. A clean-up to avoid interferences with other compounds during the determination is generally performed using silica gel, alumina or Florisil, though some authors also used GPC [81,85,97,100,109,111].

It must be mentioned that high brominated BDEs, such as BDE-209, are degraded at high temperature, are photosensitive and may bind strongly to surfaces, including laboratory materials; then, special attention is required in the extraction procedure from solid environmental samples.

3.2.1.2. Determination

GC-MS operating in negative chemical ionisation (NCI) or in EI mode are the analytical methods mostly used in the determination of PBDEs and PBBs (Table 3). Low resolution mass spectrometry (LRMS) works in these two modes, while high resolution mass spectrometry (HRMS) is used almost exclusively in EI mode. HRMS is the most selective technique for PBDEs, because its high resolution avoids the interference of coelutants, but it is more expensive that LRMS.

GC equipped with electron capture detector (ECD) has been also employed [95,100], though it is less selective because the identification is based on the retention time and the risk of interference by other halogenated co-eluted compounds is high. GC-ICP-MS was employed by Swarthout *et al*. [114] to determine 28 PBDEs in sediment samples, demonstrating a better sensitivity and lower LODs as compared to GC-NCI-MS (0.2 to 0.3 pg versus 1.5 to 24.3 pg).

In addition, a careful choice of injector, column, gas pressure, ion source and analyser temperature is necessary. In the case of high brominated PBDEs, as BDE-209, which is very sensible to thermal degradation, the residence time at high temperatures in the column and injector should be minimised [72,106].

With the restrictive legislation on BFRs, it is expected that a decline of their levels in environmental samples would arise with time. Nevertheless, high levels of DBE-209 have been recently found (Tables 3 and 5), being important to better identify and quantify contamination sources in relation with the BDE-209 levels found in the environment.

3.2.2. HBCD and TBBPA

HBCD is primarily applied for thermal insulation in the production of expanded and extruded polystyrene in buildings and upholstery textiles. The technical HBCD contains a mixture of three chiral diastereoisomers, α,

β and γ, in proportions of approximately 6, 8 and 80%, respectively, together with other lower brominated compounds. Differences in structural forms of diasteroisomers give differences in physico-chemical properties and also in their environmental behaviour [115,116].

There is scarce literature about TBBPA in environment solid samples, probably due to the low concentration values found in these matrices, although the production of TBBPA ranks first in Europe among BFRs, followed by HBCD. TBBPA is primarily used as reactive FR in printed circuit boards, but is also used as additive FR in several types of polymers.

HBCD and TBBPA are highly lipophilic, being TBBPA more polar than HBCD. HBCD has been reported to cause neurobehavioural alteration, whereas TBBPA has thyroid hormonal and estrogenic activities. HBCD and TBBPA are often determined together in solid environmental samples, and the methods used are summarised in Table 4.

In adition, tetrachlorobisphenol A (TCBPA) is also used as a FR, but in a lesser extent than HBCD and TBBPA, and is usually determined with TBBPA [118,121,122]

3.2.2.1. Sample preparation

Soxhlet and UAE are the techniques most widely applied for the extraction of TBBPA and/or HBCDs in soil, sediment and sludge samples. Shaking, PLE, MAE and MSPD have been successfully applied to sediment and, in some cases, to sludge samples [117,118,123,125,126,131]. Solvents used are of medium polarity or non polar-highly polar mixtures (Table 4). Mixtures of acetone:hexane are often used in Soxhlet extraction [124,128,130,134], whereas only dichloromethane or mixtures of dichloromethane with methanol, hexane or acetonitrile have been often employed in UAE and PLE procedures [123,125,127,131,132]. Dichloromethane is used to permit the solvation of target analytes, whereas methanol or acetonitrile allows the rupture of the analyte-matrix union. Clean-up has been generally performed by SPE, using C_{18}, Florisil, acidic alumina or silica [118,119,121-126,128-132,134].

3.2.2.2. Determination

As HBCD congeners are thermally labile, the high injector and oven temperatures required for GC analysis cause interconversion among isomers and even analyte degradation, then GC can not be used for the individual determination of HBCD isomers, being LC the best option for isomers determination. Nevertheless, GC analysis can be carried out for the total determination of HBCD, avoiding large residence times in column, protecting analytes from metal surfaces in the split injector and keeping injector temperature as low as possible [129,135].

For GC analysis of TBBPA derivatisation is necessary [119,122], whereas LC analyses do not require derivatisation and similar LODs are obtained. Then, the use of LC is more appropriate to quantify either HBCDs or TBBPA (Table 4).

ESI and atmospheric pressure chemical ionisation (APCI) sources are used with triple quadrupole instruments, APCI having 2-5 times higher signal to noise ratio (S/N) than ESI for HBCDs, whereas it is one half for TBBPA [133]. On the other hand, the sensitivity for α-HBCD is higher in a quadropole MS than in an ion trap (IT)-MS, and the contrary occurs when γ-HBCD is analysed. To increase sensitivity, additives to the mobile phase are often used. In general, the use of ammonium acetate enhances the response of HBCD and TBBPA [121]. CE has been also applied in the determination of TBBPA [118]. Ross and Wong [136] suggested that the use of anion attachment atmospheric pressure photoionisation (AA-APPI), for the analysis of HBCD enantiomers in sediment samples, offers minimal matrix effect, more sensitivity and lower LODs than a APPI source in the analysis by LC-MS.

γ-HBCD is the isomer most widely found in solid environmental samples, whereas β-HBCD is not found or found at very low levels [123,125,127,128,130,132,133]. Soil is the matrix with lower reported levels either for HBCDs or TBBPA, whereas high levels can be found in sludge and sediments [117,123,132]. In general, low levels of HBCD have been found in soil and sediment samples (<10 ng g^{-1}), but when samples are near a downstream of urban or industrial areas levels of HBCD can be higher than those of PBDEs [80,100,102].

3.2.3. Novel brominated flame retardants (NBFRs)

A number of NBFRs have been introduced as replacement of banned BFRs. In this section, the major NBFRs determined in solid environmental sample are described (Table 5). Decabromodiphenyl ethane (DBDPE or deBDethane), the compound most studied in these samples, is used as an alternative to deca-BDE, due to its similar physicochemical properties, though it is slightly more hydrophobic and less sensitive to thermal degradation than deca-BDE. Moreover, 1,2-bis(2,4,6-tribromophenoxy)ethane (BTBPE) was introduced as an alternative to the banned octa-BDE. On the other hand, TBBPA derivatives are other NBFRs very hydrophobic, which are preferably adsorbed to solid particles in the environment. Among them, tetrabromobisphenol

Table 4. Analysis of HBCD and TBBPA in environmental solid samples.

Matrix (g)	Analytes (number)	Sample preparation	Determination (Derivatisation)	Recovery (%)	LOD (ng g^{-1})	Levels found (ng g^{-1})	Ref.
Sediment, sludge (0.1-1.8)	TBBPA	Shaking: 10 mL DCM:MeOH (1:9, v/v) + UAE + shaking Clean-up: ENVI-18 cartridge (for sediment) + LLP in HCl + DCM (for sludge)	LC-ESI-MS/MS	91-94	6-18[b]	300	[117]
Sediment, sludge (0.2)	TBBPA, TCBPA and related phenolics	MSPD: HCl + Na_2SO_4 + Florisil, transferred to a Florisil column	CE-DAD	76-106	91-236[a]		[118]
Sediment (2)	TBBPA, PBDEs	UAE: Na_2SO_4 + 20 mL hexane/ acetone (1:1, v/v) Clean-up: Cu + Florisil + H_2SO_4 + silica gel (multilayer)/ alumina (for PBDEs) Cu + Florisil + silica (for TBBPA)	GC-NCI-MS (BSTFA/TMCS 99:1, v/v)	76-100	0.005-0.14	0.065-0.14 TBBPA 2.1-10.6 PBDEs	[119]
Soil (0.3)	TBBPA, tri–hexaBDEs (6)	UAE: 2 mL acetone and SBSE: NaOH in water (10%) + NaCl-PDMS-β-CD stir bar desorption in EtOH, 20min	LC-UV	56-118	2.9-4.2[c]	100-1600	[120]
Sediment, sludge (10)	TBBPA,TCBPA	Soxhlet: Na_2SO_4 + 50 mL MTBE Clean-up: LLP in hexane-NaOH, acidification + C_{18} + Silica gel	LC-ESI-MS	102-105	0.03-0.05[a]	0.14-0.54 TCBPA 2.09-28.30 TBBPA	[121]
Soil (5)	TBBPA, TCBPA	UAE: 5 mL EtAc (x2) UAE-Clean-up: acidified Florisil + 5 mL EtAc (x2) (in industrial soil)	GC-MS (BSTFA/TMCS)	88-108	0.03-0.09	≤ 32.2	[122]
Sediment (10)	HBCD	PLE: DCM, 100ºC Clean-up: silica column	LC-ESI-MS/MS			0.025-2.3	[123]
Soil	HBCD	Soxhlet: Cu, acetone:hexane (1:1, v/v) Clean-up: Silica/alumina + acidified silica	LC-TurbolonSpray-MS/MS	71-87		1.7-5.6	[124]
Sediment (0.5)	HBCD	PLE-clean-up: Al_2O_3 + hexane:DCM (1:1, v/v), 100ºC	LC-IT-MS	60	0.12-5.61	≤ 2389	[125]
Sediment (5)	HBCD	MAE: 40 mL acetone:hexane (1:3, v/v), 90ºC Clean-up: TBA-sulphite + propanol, washing with H_2SO_4 + hexane and Na_2SO_4/ acidified silica	LC-ESI-ITMS	68-91	0.005-0.01		[126]
Sludge (1)	HBCD	UAE: 5 mL DCM:ACN (1:1, v/v) (x2), 30ºC Clean-up: dSPE with PSA	LC-ESI-MS/MS	82-107	0.2-0.3	≤ 14.4	[127]
Soil	HBCD	Soxhlet: Cu, 200 mL acetone:hexane (1:1 v/v) Clean-up: silica gel (multilayer)/alumina columns	LC-MS/MS	79-88		≤ 215	[128]
Soil, sediment, sludge (10-20)	HBCD	Soxhlet: acetone Clean-up: acidic aluminium oxide	GC-ECD	52-105	0.1	0.1-1300	[129]
Soil (15)	HBCD	Soxhlet: Cu, 200 mL acetone:hexane (1:1 v/v) Clean-up: silica/ alumina column	LC-ESI-MS/MS	84-91	0.0012-0.0095	≤ 0.064	[130]
Sediment (1)	HBCD	PLE:Na_2SO_4 + DCM, 150ºC Clean-up: acidic silica + Na_2SO_4 + silica gel	LC-APCI-MS/MS	81-93		1-3964	[131]
Sludge, sediment (0.5)	HBCD, TBBPA	UAE: 10 mL DCM:MeOH (1:9, v/v), 30ºC Clean-up: C_{18}	LC-ESI-ITMS	39-110	1.4-12	0-1849	[132]

Continued **Table 4.** Analysis of HBCD and TBBPA in environmental solid samples.

Matrix (g)	Analytes (number)	Sample preparation	Determination (Derivatisation)	Recovery (%)	LOD (ng g^{-1})	Levels found (ng g^{-1})	Ref.
Sediment (1)	HBCD, TBBPA	UAE: 5 mL acetone	LC-APCI-MS/MS	101-108	0.02-0.002[b]	0.2-5.5 TBBPA 2-860 HBCDs	[133]
Sediment, sludge	HBCD,TBBPA	Soxhlet: acetone:hexane (1:1 or 1:3, v/v) Clean-up: H_2SO_4 + GPC + silica gel	LC-ESI-MS	47-104	0.5-1.2	0.1-9750	[134]

[a]*LOQ;* [b]*ng mL*$^{-1}$

A-bis(2,3-dibromopropylether) (TBBPA-dbpe) [141,146] can be cited although this NBFR is not covalently bound to polymers as TBBPA.

In addition to these compounds, other NBFRs have been considered lately, such as pentabromoethylbenzene (PBEB) [102,145] hexabromobenzene (hexaBBz) [145], tris (2,3-dibromopropyl)isocyanurate (TBC) [131,142], pentabromochorocyclohexane (PBCCH) [147], tetrabromo-o-chlorotoluene (TBoCT) [147], 2,3,5,6-tetrabromo-p-xylene (pTBX) [147], tetrabromophthalic anhydride (TBPhA) [147], 2,3,4,5,6-pentabromotoluene (PBT) [147]and tris(2,3-dibromopropyl)phosphate (TDBPP) [147].

3.2.3.1. Sample preparation

The sample treatment procedures for NBFRs have been based primarily on protocols established for PBDEs [73], but these methods have been seldom validated for NBFRs and only a few analytical procedures have been optimised and validated exclusively for NBFRs in environmental matrices.

Kierkegaard *et al*. [137] were the first in reporting the presence of DBDPE in sludge and sediment samples, although this compound was introduced in the early 1990s. They used a shaking method with toluene:acetone as extraction solvent, with a subsequent solvent change to trimethylpentane. In addition, a treatment with tetrabutyl ammonium-sulfite was carried out to remove sulphur, followed by a treatment with sulphuric acid and a further clean-up on activated silica gel. Shaking was also employed by Ilyas *et al*. [138] to extract DBDPE, but using acetone:hexane as extraction solvent. Other sample preparation methods used to extract DBDPE from solid environmental samples were Soxhlet, using acetone:hexane mixtures [139-141] and PLE with hexane, dichloromethane, hexane:dichloromethane or hexane:acetone (Table 5).

Köppen *et al*. [146] compared Soxhlet, UAE, PLE and fluidised bed extraction methods for TBBPA-dbpe analysis in sediment and sludge samples. They reported that PLE and fluidised bed extraction were superior to Soxhlet and sonication, affording the best recoveries (90-98%) with the lowest relative standard deviations. No clean-up was necessary and only a filtration of the diluted extract was carried out. Shi *et al*. [141] also analysed TBBPA-dbpe in sediment and sludge, obtaining recoveries from 88 to 105% when Soxhlet extraction with hexane:acetone, followed of a clean-up in silica/alumina column, was used.

In general, PLE was the preferred method of extraction for NBFRs in environmental samples, using dichloromethane, hexane, mixtures of them or hexane:acetone mixtures. Sulphur was removed by using activated copper, a combination of GPC with acid copper or tetrabutylammonium, though this latter compound, as indicated for deca-BDE, causes debromination of DBPE in solvent standards but in real samples this debromination is less pronounced by the protective effect of the matrix [74]. Sulphuric acid directly or via impregnation in silica was used to remove organic matter and diluted KOH in ethanol to remove fat (Table 4). Nevertheless, López *et al*. [147] assessed the effect of the acidic treatment in the degradation of some NBFRs and reported that TBPhA, TDBPP and BTBPE were degraded, whereas DBDPE, PBCCH, pTBX, TBoCT and PBT resisted the acidic treatment, therefore, GPC was used instead to remove lipids and organic matter.

A clean-up with silica, silica/alumina, GPC, Oasis HLB, aminopropyl gel with acid silica or a multilayer silica gel were other procedures used to eliminate interferences before the chromatographic determination of NBFRs (Table 5).

3.2.3.2. Determination

NBFRs are mainly determined by GC-MS with electron capture negative ionisation (ECNI) as ionisation mode, due to its higher sensitivity and selectivity to bromide than EI. Nevertheless, LC-MS/MS or LC-DAD are the techniques generally used to quantify TBC and TBPA-dbpe.

DBDPE was analysed by high resolution gas chromatography (HRGC) and quantified by LRMS with ECNI in sludge and sediment samples for the first time

Table 5. Analysis of NBFRs in environmental solid samples.

Matrix (g)	Analytes (number)	Sample preparation	Determination (Derivatisation)	Recovery (%)	LOD (ng g^{-1})	Levels found (ng g^{-1})	Ref.
Sediment (1)	TBC	PLE: Na_2SO_4 + DCM, 150ºC Clean-up: acidic silica added to extract + Na_2SO_4 and neutral silica gel columns	LC-APCI-MS/MS	81-93		136-5885	[131]
Sludge (15), sediment (5)	DBDPE	Shaking: toluene:acetone (1:1, v/v), trimethylpentane + EtOH. Clean-up: TBA-sulfite + H_2SO_4 + acidified silica gel	GC-MS			100-23	[137]
Soil (5-7)	BTBPE, DBDPE, PBDEs, HBCD	Shaking: acetone:hexane (1:1, v/v), and UAE Clean-up: silica gel (multilayer) + H_2SO_4 + GPC+ silica gel	GC-MS LC-ESI-MS/MS HBCDs	26-119		0.069-22	[138]
Sludge (1-5)	DBDPE, BDE-209	Soxhlet: acetone:toluene (1:4, v/v) Clean-up: acid digestion + Cu + silica gel (multilayer)	HRGC/LRMS			6-31.6 DBDPE 444-1800 BDE-209	[139]
Sediment	DBDPE, PBDEs, TBBPA	Soxhlet: Cu + acetone:hexane (1:1, v/v), Clean-up: LLE with KOH and HCl + silica gel (multilayer).	GC-ECNI-MS GC-MS (diazomethane)	74-116	0.01-0.8[a] PBDEs 0.004[a] TBBPA 5.6[a] DBDPE	0.7-5700 PBDEs 3.8-230 TBBPA 23-430 DBDPE	[140]
Soil, sediment, sludge (10-30)	DBDPE, BTBPE, TBBPA-dbpe	Soxhlet: 200 mL hexane:acetone (1:1, v/v) + Cu Clean-up: silica gel (multilayer)/alumina	GC-ECNI-MS	67-119	0.008-2.5	0.03-21.9 BTBPE 17.3-8946 TBBPA-dbpe 17.6-1995 DBDPE	[141]
Soil, sediment (0.5-1)	TBC	PLE: Na_2SO_4 + DCM, 150ºC Clean-up: acidic silica + Na_2SO_4 + neutral silica gel	LC-ESI-MS/MS	58-70	1.5-2.5	19.6-6030	[142]
Sludge (0.4-1.8)	DBDPE, BDE-209	PLE-clean-up : Na_2SO_4 + acidified silica + hexane, 100ºC Clean-up: LLE with KOH + aminopropyl gel with acid silica	GC-ECNI-LRMS	72 DBDPE	0.58-1.6	≤ 216 DBDPE	[143]
Sediment (7.4-13.4)	DBDPE, Deca-BDE	PLE: DCM, 100ºC Clean-up: H_2SO_4 + KOH in EtOH + re-extraction in hexane aminopropyl gel with acid silica	GC-ECNI-LRMS	106	0.009-0.1	0.2-11 DBDPE 0.55-88 Deca-BDE	[144]
Sediment (1)	PBEB, hexaBBz, DBDPE	PLE-clean-up: Cu +aluminium oxide + hexane:DCM (1:1, v/v), 100ºC.	GC-NICI-MS	58-102	0.009-0.086	≤ 24	[145]
Sediment, sludge (5)	TBBPA-dbpe	Fluidised bed: PTFE membrane filter in 40 mL MeOH (sediment) or acetone (sludge) PLE: 40 mL MeOH or acetone, 100ºC	LC-DAD	90-98	10-22		[146]

Continued **Table 5.** Analysis of NBFRs in environmental solid samples.

Matrix (g)	Analytes (number)	Sample preparation	Determination (Derivatisation)	Recovery (%)	LOD (ng g^{-1})	Levels found (ng g^{-1})	Ref.
Sediment (20)	DBDPE, BTBPE, PBCCH (4), TBoCT, pTBX, TBPhA, PBT, TDBPP	PLE: hexane:acetone (3:1, v/v), 70ºC Clean-up: GPC+ Oasis HLB+ silica gel	GC-ECNI-MS	81-101	0.002-0.1	≤ 9.8	[147]

[a]LOQ

[137]. Afterwards, Konstantinov *et al*. [139] reported in 2006, the characterisation of labelled DBDPE and its use as surrogate standard to positively identify and quantify DBDPE. Like BDE-209, BDPE is very sensitive to high temperatures or to the adsorption on some parts of the injection port in a GC system, being these effects more important when the sample extract is not cleaned enough; therefore, López *et al*. [147] recommended an extra clean-up with deactivated silica after SPE on Oasis HLB.

TBC was determined in sediment samples by LC-MS/MS and both APCI and ESI sources provided almost the same sensitivity in negative ion mode, according to the results reported by Feng *et al*. [131] and Ruan *et al*. [142].

DBDPE is the NBFR found at higher concentrations in environmental solid samples, with levels similar to deca-BDE, being this contamination originated primarily via atmospheric transport [144,148,149].

3.3. Dechloranes

Nowadays, the most relevant chlorinated FRs are dechloranes, synthesised through a Diels-Alder addition of one or two molecules of hexachlorocyclopentadiene to an unsaturated compound. Among them, Dechlorane Plus (DP, a mix of *anti* and *syn* isomers in a ratio 1:3, mainly) is the most used, although others like Dechlorane 602 (Dec-602), Dechlorane 603 (Dec-603) and Dechlorane 604 (Dec-604) are also used. Major applications of dechloranes are the use as additives in industrial polymers employed for coating electrical wires and cables, for connectors used in computers, and for roofing material. All of them are substitutes of the banned Mirex.

Due to the highly halogenated nature and high Kow values of these compounds, they are resistant to degradation and have a high potential to accumulate in the environment. Despite the long production history of these compounds, they received little attention until recently, when Hoh *et al*. [150] found DP in sediment, and in 2010 Dec-602, -603 and -604 were reported by Shen *et al*. [151] in sediment.

3.3.1. Sample preparation

Soxhlet and PLE have been the extraction techniques mainly employed in the analysis of dechloranes using dichloromethane, toluene, or mixtures of hexane:acetone and hexane:dichloromethane as extraction solvents (Table 6). In addition, an extract treatment with acid or GPC have been generally employed to remove lipids from the solid sample, nevertheless precaution has to be taken with the acid treatment because DP monoadducts can be degraded. These compounds are also susceptible to light, then, protection of samples from UV-light during analysis must be taken into account.

Moreover, silica, alumina or a combination of adsorbents, like silica, alumina, and Amoco PX21 carbon/silica (Table 6) have been used in the clean-up procedures.

3.3.2. Determination

GC operating in the ECNI mode has been the most common technique used for the detection and quantification of dechloranes. Some authors used EI conditions, but this ionisation mode is not very appropriate because of the low intensity of the molecular ion obtained, due to retro Diels-Alder fragmentation, forming a most intense ion that is common to the mass spectra of numerous organohalogen compounds. Dechlorination of DP in the injection port liners can occur and this should be monitored using the corresponding dechlorinated ion in ECNI [154]. It is difficult to monitor these ions in EI because of their low intensity.

LC-MS/MS using APPI as ionisation source has been reported for this group of compounds, requiring only 5 min for their chromatographic separation and obtaining good LOQs [159].

DP has been detected a high levels in sediment samples from Lake Ontario near manufacture plants [153,154]. The average syn isomer abundance is lower in environmental samples than in DP commercial formulations, indicating a stereoselective enrichment of *anti*-DP in the environment [154] and suggesting a higher persistence of the anti isomer [153]. Low levels of DP have been found in soil, even in industrial areas,

Table 6. Analysis of DP and related compounds in environmental solid samples.

Matrix (g)	Analytes	Sample preparation	Determination	Recovery (%)	LOD (ng g^{-1})	Levels found (ng g^{-1})	Ref.
Sediment (15)	DP, BDE-209	Soxhlet: Na_2SO_4 + Cu, 300 mL hexane:acetone (1:3, v/v) Clean-up: H_2SO_4 + alumina	GC-ECNI-MS	98		≤ 122	[150]
Sediment (5-10)	Dec-602, -603, -604, DP	Soxhlet: toluene Clean-up: silica gel (multilayer), alumina, Amoco PX21 carbon/silica	GC-HRMS	71-102	0.0005-0.001	≤ 310	[151,152]
Sediment (15)	DP, BTBPE, PBDEs, PBBs	Soxhlet: Na_2SO_4 + Cu + 360 mL hexane:acetone (1:1, v/v) Clean-up: H_2SO_4 + alumina	GC-ECNI-MS	87-102		310 DP 6.7 BTBPE 14 BDE209	[153]
Sediment (5)	DP	PLE: acetone:hexane (1:1, v/v) Clean-up: silica gel	GC-MS	78-97	0.025-0.030	0.061-586	[154]
Sediment (20)	DP	Soxhlet: Cu + DCM Clean-up: silica gel (multilayer)/alumina	GC-NCI-MS	96	0.0004-0.0008	0.0004-0.126	[155]
Soil	DP	Soxhlet: Cu + hexane:acetone (1:1, v/v) Clean-up: silica gel (multilayer)/alumina	GC-NCI-MS	94		≤ 2246	[156]
Soil (10)	DP	PLE: DCM, 100ºC Clean-up: H_2SO_4 + alumina + Na_2SO_4 + Cu	GC-ECNI-MS	99-111	0.0032-0.0028	0.19-910	[157]
Sludge (0.5)	DP, PBDEs	PLE-clean-up: Cu + Na_2SO_4 + hexane:DCM (1:1, v/v), 100ºC Clean-up: H_2SO_4, silica gel (multilayer)	GC-MS	75-87	0.015-0.025	0.90-995	[158]
Sediment (5-10)	Dec-602, Dec-603, Dec-604, DP, Mirex	Soxhlet: toluene Clean-up: silica gel (multilayer), alumina, Amoco PX21 carbon/silica	LC-APPI-MS/MS		0.1-2.3[a]		[159]
Sediment (10)	DP, Dec-602,-603,-604	Soxhlet: Na_2SO_4 + 100 mL hexane:acetone (1:1, v/v) Clean-up: H_2SO_4+ silica gel	GC-ECNI-MS	72-76		≤ 3.6	[160]

[a]LOQ

but DP concentration found in e-waste recycling areas in China was 3327 ng g^{-1} [156].

Dec-603 has been detected in technical pesticides such as aldrin and dieldrin, being the levels found in sediment consistent with the usage of these pesticides in the past. Similarly, DP was detected in chlordane and chlordene technical products, and was found in higher amounts in sediments near urban areas where probably these insecticides were used [152].

4. Pharmaceuticals

Human and veterinary pharmaceuticals are chemical compounds widely used to treat or prevent diseases. There are over 4000 molecules and over 10,000 products, which are mainly soluble in water [161]. Pharmaceutical drugs can be divided in two main categories: steroidal and non-steroidal pharmaceutical substances. Estrogens, progestrogens, estrogen antagonists, androgens and phytoestrogens are the main steroidal pharmaceutical drugs. In the case of non-steroidal pharmaceutics, the predominant therapeutic classes are: antibiotics, analgesic/anti-inflammatory, lipo-regulators, beta-blockers, anti-epileptics and anti-depressants, among others. Most pharmaceutical drugs are designed to be hydrosoluble and biodegradable, however, many compounds have high log Kow and, therefore, present a high affinity to sludge or soil. The presence of pharmaceuticals in soil may be explained by the spreading of sludge or manure to fertilise agricultural soils. The interest in the occurrence of pharmaceuticals in the terrestrial environment has considerably increased taking into account the scientific literature now available [162-166]. The analysis of pharmaceuticals in soil, sludge and sediment reviewed here has been divided in three categories: antibiotics, non-steroidal pharmaceutical drugs and estrogens.

4.1. Antibiotics

Antibiotics are natural or synthetic drugs with antimicrobial activity. The main antibiotics for both human and veterinary use are: β-lactams, quinolones (QNs), fluoroquinolones (FQs), macrolides (MLs), tetracyclines (TCs), sulphonamides (SAs), amphenicols, glycopeptides, and polyether ionophores. Among these, TCs, SAs, QNs and MLs, due to their higher stability, are the antibiotics usually determined in solid environmental samples. In the case of sediments, one source of contamination by antibiotics is their application in aquiculture farms to treat diseases of farmed fish.

4.1.1. Sample preparation

The extraction of antibiotics from sludge, soil or sediment requires the application of powerful extraction conditions to isolate the analytes, as some of these compounds are firmly bound to the matrix. Thus, UAE, PLE and MAE are the extraction techniques most commonly applied for the extraction of antibiotics from solid environmental samples as shown in Table 7. Nevertheless, mechanical shaking has been also used with sediment samples to extract various polyether ionophores [170] and antibiotics belonging to different classes [169]. The extraction solvents employed are usually mixtures of buffer solutions and organic solvents such as acetonitrile, methanol or acetone. TCs tend to form chelate complexes with metals ions and β-diketones and are strongly sorbed to soil. In order to improve the isolation of this kind of antibiotics from soil samples, ethylenediaminetetraacetic acid (EDTA) and McIlvaine buffer solutions are employed as chelating agents. McIlvaine buffer is a mixture of citric acid and Na_2HPO_4 that has been successfully used in the determination of antibiotics in food. FQs are zwitterionic compounds that present a high chemical stability and are insensible to hydrolysis but photodegradable. FQs are strongly sorbed to soil, in particular to clay minerals via cation bridging. The extraction of these compounds improves when it is carried out at acidic pHs [177,182]. At low pHs, both FQs and sludge surface are protonated and, therefore, electrostatically repulsed favouring the extraction [182]. Furthermore, at very high or low pHs FQs present a higher water solubility that enhances the extraction efficiency. On the other hand, MLs present basic characteristics and ionophore polyethers are neutral compounds, therefore to improve the extraction efficiency higher pHs are required [169,170]. Microwave assisted micellar extraction (MAME), which uses micellar systems instead of organic solvents as extractants, is another technique applied for the extraction of seven SAs in soil, using Triton X-114 as surfactant [185]. The increase of surfactant concentration leads to the formation of micelles capable of solubilising some compounds that when heated above the cloud-point temperature in the microwave system, two separate phases are formed, an aqueous phase and a small surfactant-rich phase which provides a high enrichment factor.

Once the extracts are obtained, the clean-up can be carried out by SPE using C_{18} [177,178] or predominantly Oasis HLB cartridges that due to its hydrophilic-lypophilic balance allow the purification of compounds with a wide range of polarity. Methanol is the main solvent used in the elution of these cartridges. It has been reported that TCs tend to bind to silanolic groups, so in order to avoid losses in C_{18} cartridges, a methanolic oxalic acid solution was used in the elution [177]. Some authors use two different cartridges in tandem, strong anion exchange (SAX) and Oasis HLB [168,179,183] or C_{18} [176]. The SAX cartridge is used to remove natural organic matter whereas the C_{18} or HLB cartridge retains the analytes. The extract is usually acidified to ensure that analytes are positively charged or in their neutral form and, therefore, not retained in the SAX cartridge. New polymeric phases, such as polystyrene-divynilbenzene, have been also applied for the clean-up of biosolid extracts [171]. Turiel *et al*. [173] synthesised a MIP using ciprofloxacin as template for the clean-up of FQs in soil extracts in which antibiotic-Mg (II) complexes were formed. Golet *et al*. [182] used a mixed-phase cation (MPC) exchange disk cartridge for the clean-up of two FQs, ciprofloxacin and norfloxacin, extracted from sludge or sludge treated soil samples. The MPC cartridge consists of nonpolar octyl and benzenesulphonate phases, combining hydrophobic and strong cation exchange properties, respectively, which increases the method specificity [186]. Although SPE is the main technique used, a clean-up by LLE with n-hexane [177] or sodium hydroxide [184] was applied for the determination of QNs in soil and sediment.

4.1.2. Determination

The analysis of antibiotics is performed by LC because they present a high polarity and are thermally labile. LC-MS/MS is the analytical tool most used due to its high selectivity and sensitivity that allows distinguishing individual compounds. Most of the methods presented in Table 7 carried out the determination using MS/MS as detection system. FL has been also used mainly for QNs because most of them show certain native fluorescence [168,176,184]. Blackwell *et al*. [179] used FL instead of UV for the determination of sulfachloropyridazine, a sulphonamide antibiotic, after derivatisation with fluorescamine, because they observed a small coeluting peak in some soil samples that could hinder the detection of this compound, especially at low concentration levels. Antibiotics have also been determined using

Table 7. Analysis of antibiotics in environmental solid samples.

Matrix (g)	Analytes (number)	Sample preparation	Determination (Derivatisation)	Recovery (%)	LOD (ng g^{-1})	Levels (ng g^{-1})	Ref.
Soil (1)	Tetracyclines (3), tylosin	Shaking: 1.2 mL citrate buffer (1 M, pH 4.7) + 6 mL EtAc	LC-ESI-MS/MS	33-127	1-2	3.7-141	[167]
Soil (1)	Enrofloxacin, ciprofloxacin	Shaking and UAE: 15 mL phosphate buffer (pH 3): ACN (1:1, v/v) Clean-up: SAX + Oasis HLB in tandem	LC-FL	61-100		13-204	[168]
Sediment	Antibiotics (19)	Shaking: 20 mL McIlvaine buffer or NH_4OH buffer + 200 μL Na_2-EDTA 5% Clean-up: Oasis HLB	LC-ESI-MS/MS	33-128	0.3-3.6[a]	1.2-30.8	[169]
Sediment (1)	Monesin, narasin, salomycin	Shaking: 20 mL NH_4OH buffer (1 M, pH 10) Clean-up: Oasis HLB	LC-ESI-MS/MS	51-105	1[a]	16.3-31.5	[170]
Biosolids (0.5)	Antibiotics (6), carbamazepine	UAE: MeOH:0.1M HAc:5% Na_2-EDTA (2:1:1, v/v/v) Clean-up: Strata-X	LC-ESI-MS/MS	31-83	0.1-15		[171]
Soil (1)	Quinolones (10)	UAE: 8 mL $MgNO_3$ aqueous solution(50%, w/v) + 4% ammonia	LC-UV	82-104	40-80		[172]
Soil (1)	Fluoroquinolones (5)	UAE: 8 mL $MgNO_3$ aqueous solution(50%, w/v) + 4% ammonia Clean-up: MISPE Ciproflaxin	LC-UV	75-85	40-70		[173]
Soil (2)	Antibiotics (15)	UAE: 10 mL citric acid buffer (0.2 M, pH 4.4) + 10 mL ACN (x3) Clean-up: Oasis HLB	LC-ESI-MS/MS	64-245	0.08-4.20	1.1-212	[174]
Sediment (50)	Antibiotics (7)	UAE: 90 mL MeOH + 45 mL acetone+ 45 mL EtAc Clean-up: Lichrolute C_{18}	LC-ESI-MS/MS	38-121	3-20[a]		[175]
Soil (1-2)	Antibiotics (13)	SAs + TCs UAE: 10 mL EDTA-McIlvaine buffer: MeOH (1:1, v/v) Clean-up: C_{18} + SAX in tandem QNs UAE: 5 mL 50% $MgNO_3$ aqueous solution containing 4% aqueous ammonia Clean-up: C_{18} + SAX in tandem	SAs + TCs LC-UV QNs LC-FL	61-94	0.8-23	5.1-1347.6	[176]
Soil (1-3)	Antibiotics (11)	TCs + SAs UAE: 30 mL MeOH:EDTA-McIlvaine buffer pH 6 (9:1, v/v) (x3) Clean-up: C_{18} FQs UAE: 30 mL ACN acidified with formic acid 2% + 0.5 g organic substratum (x3) Clean-up: LLE (n-hexane)	TCs + SAs LC-ESI-MS/MS FQs LC-ESI-MS	61-105	100[a]		[177]
Soil (5)	Tobramycin	UAE: 20 mL acetone:water (7:3, v/v) Clean-up: C_{18}	LC-UV (CNBF)	78-91	20		[178]
Soil (4)	Oxytetracycline, sulfachloropyridazine, tylosin	UAE: 5 mL MeOH:0.1M EDTA: McIlvaine buffer pH 7 (50:25:25, v/v/v) Clean-up: SAX + HLB in tandem	LC-UV LC-FLD	27-105	18-40		[179]
Sediment (2)	Antibiotics (14)	UAE: 10 mL citric buffer (0.2 M, pH 4):ACN (1:1, v/v) (x3) Clean-up: Oasis HLB	LC-ESI-MS/MS	48-160	0.08-4.2	0.93-1560	[180]

Continued **Table 7.** Analysis of antibiotics in environmental solid samples.

Matrix (g)	Analytes (number)	Sample preparation	Determination (Derivatisation)	Recovery (%)	LOD (ng g^{-1})	Levels (ng g^{-1})	Ref.
Sludge (0.2)	Antibiotics (10)	PLE: water:MeOH (1:1, v/v), 100°C Clean-up: Oasis HLB	LC-ESI-MS/MS	78-142	3-41	12-197	[181]
Sludge (0.2), soil (0.5)	Ciprofloxacin, norfloxacin	PLE: H_3PO_4 (50 mM, pH 2):ACN (1:1,v/v), 100°C Clean-up: MCP	LC-FL	75-94	180-450[a]	1400-2400	[182]
Soil (10)	Antibiotics (6)	PLE: MeOH:citric acid (0.2 M, pH 4.7) (1:1, v/v), RT Clean-up: SAX + HLB in tandem	LC-MS/MS	50-100	0.6-5.6		[183]
Soil, sediment (0.5)	Flumequine, oxolinic acid	MAE: 10 mL H_3PO_4 buffer (1M, pH 2) + 10 mL DCM Clean-up: LLE: NaOH (1 M)	LC-FL	79-94			[184]
Soil (2)	Sulfonamides (7)	MAME: 20 mL Triton X-114 (5%, v/v)	LC-UV	81-93	3.2-5.7		[185]

[a]LOQ

UV detection although it is not selective or specific. In the case of tobramycin, in order to enhance the chromatographic response, it was derivatised with 4-chloro-3,5-dinitrobenzotrifluoride before its LC-UV analysis [178]. The presence of matrix components has a significant effect on the chromatographic response of these analytes with signal suppression or enhancement, particularly when ESI is used as ionisation source. These effects can be more remarked when MS/MS is applied since the clean-up of extracts is not so thorough because the technique is very selective [171].

4.2. Non-steroidal pharmaceutical drugs

The determination of pharmaceuticals is commonly performed together with personal care products since both are consumed on a daily basis by the general public and released into the municipal sewage system. The trend is to analyse as many compounds as possible at once, that is, to develop multiresidue methods. As mentioned above, there are several types of non-steroidal drugs based on their therapeutic classes, among which anti-inflammatory/analgesics, lipid regulators, antiepileptics, beta-blockers and antidepressants are the pharmaceuticals most studied in the terrestrial environment. Table 8 gives an overview of the analytical methods developed for the determination of these types of drugs in soil, sediments, and sludge.

4.2.1. Sample preparation

The extraction of pharmaceuticals other than antibiotics from soil, sediment or sludge has been, in general, carried out with the assistance of radiation. Among the extraction techniques available, UAE is one of the most used due to its advantages, such as cost, ease of use, and availability (Table 8). Different solvents or mixtures have been selected for the UAE of pharmaceuticals, but in general, due to the polarity of these compounds, solvents such as methanol, acetone or acetonitrile have been used. Successive UAE with methanol and acetone were carried out for the extraction of pharmaceuticals from sludge and sediments [191,192]. As it was indicated above, EDTA used as chelating agent improves the recovery of antibiotics from soil, however when it was used in the extraction of antifungal azoles from sludge no improvement was observed [189]. A possible explanation is that azole compounds, due to their lipophilic character, tend to be adsorbed onto sludge through hydrophobic interactions rather than by ion exchange or surface complexation, therefore chelate formation with EDTA does not improve the recovery. The extraction is usually carried out at acidic pH due to the acidic characteristics of many of the pharmaceuticals, as for example anti-inflammatory drugs like ibuprofen, ketoprofen, naproxen and diclofenac, which are a group of compounds that are searched for in different environmental matrices. The acidification with formic acid of methanol [189] or ethyl acetate [174] allowed the extraction of four antifungal azoles from sludge and 19 pharmaceuticals from soil, respectively. United States Environmental Protection Agency (US-EPA) published in 2007 a method for the determination of pharmaceuticals and personal care products in environmental samples based on UAE [213]. Solid and semisolid samples are divided in two different fractions, acid and basic, and sonicated three times with acetonitrile:phosphate buffer (acid fraction) or with acetonitrile:ammonium hydroxide (basic fraction). Afterwards, the extracts are concentrated to remove acetonitrile and diluted with water prior to the purification of the extract.

PLE is another extraction method that has increasingly been used for the determination of non-steroidal pharmaceutical drugs in solid environmental

Table 8. Analysis of non-steroidal pharmaceutical drugs in environmental solid samples.

Matrix (g)	Analytes (number)	Sample preparation	Determination (Derivatisation)	Recovery (%)	LOD (ng g^{-1})	Levels (ng g^{-1})	Ref.
Sediment (5)	Pharmaceuticals (5)	Shaking: 40 mL acetone:McIlvaine buffer pH 4 + UAE (x2) Clean-up: Evolute ABN + OASIS HLB	LC-ESI-MS/MS UPLC-ESI-QToF	60-75	0.4-8[a]		[187]
Sludge, soil (1)	Ibuprofen, ciprofloxacin	Shaking: ACN UAE: 50 mL Na_2-EDTA phosphate buffer pH 3:ACN (1:1, v/v) Clean-up: Oasis HLB	LC-UV GC-MS (MSTFA)	28-97	0.27-25.56	0.68-4100	[188]
Soil (5)	Pharmaceuticals (19)	UAE: 10 mL EtAc:formic acid (50:1, v/v) (x3) Clean-up: Silica gel	LC-ESI-MS/MS	43-245	0.02-4.20	1.4-10.7	[174]
Sludge (0.1), sediment (1)	Clotrimazole, econazole, ketoconazole, miconazole	UAE: 4 mL MeOH containing formic acid 0.1% (v/v) (x3) Clean-up: Oasis HLB	UPLC-ESI-MS/MS	43-104	3-9[a]	1-1442	[189]
Sludge (1)	Clotrimazole, econazole, ketoconazole, fluconazole	UAE: 5 mL MeOH (x2) Clean-up: C_{18}	LC-ESI-MS/MS	72-116	0.5-5.0	378-5133	[190]
Sediment (50)	Acidic pharmaceuticals (8) + metabolites(2), ivermectin	UAE: 45 mL acetone:HAc (20:1, v/v) + 45 mL EtAc (x3) Clean-up: MCX (acidic) Lichrolute EN (ivermectin)	LC-APCI-MS/MS	40-152	0.4-8[a]		[175]
Sludge (1), sediment (2)	Pharmaceuticals (16)	UAE: 7 mL MeOH + 2 mL acetone Clean-up: Oasis HLB	LC-UV LC-FL	41-108	1.39-360	4.85-5096	[191]
Sludge (0.5)	Pharmaceuticals (19), iodinated contrast media (8)	UAE: 6 mL MeOH + 2 mL acetone (x2) Clean-up: OASIS MCX (acidic) C_{18} (neutral) C_{18}-ENV+ in tandem (iodinated contrast)	LC-APCI-MS/MS (acidic) LC-ESI-MS/ MS (neutral and iodinated)	80-201	20-50[a]		[192]
Soil (5)	Anti-inflammatory drugs (4), clofibric acid	UAE: 9 mL acetone + 9 mL EtAc Clean-up: C_{18}	GC-MS (MTBSTFA)	52-117	0.2-0.4	0.55-9.08	[193]
Sludge (0.04)	Anti-inflammatory drugs (4)	UAE: 2.5 mL MeOH + 1.5 mL water Clean-up: C_{18}	GC-MS (pyridine:BSTFA (1:5))	98-107	18-25	54	[194]
Soil, sediment (10)	Carbamazepine	UAE: 15 mL iPOH:water (8:2, v/v) (x2) Clean-up: Oasis HLB - Florisil in tandem	GC-MS	67-96	110		[195]
Biosolids (0.5)	Pharmaceuticals (15)	PLE: ACN:water (7:3, v/v), 100°C Clean-up: Oasis HLB	LC-ESI-MS/MS	49-94	0.6 -146	2.6-743.6	[196]
Soil (10)	Pharmaceuticals (6) and metabolites (2)	PLE: acetone:hexane:HAc (50:50:2, v/v/v), 100°C Clean-up: Oasis HLB	GC-MS (MTBSTFA)	62-118	0.5-2	0.25-6.48	[197]
Biosolids (1)	Pharmaceuticals (8)	PLE: acetone:water (1:7, v/v), 90°C (acidic) acetone:water (3:7, v/v), 80°C (neutral) MeOH/water/HAc (49:49:2, v/v/v), 50°C (atenolol) Clean-up: OASIS HLB or OASIS MCX (atenolol)	LC-ESI-MS/MS or LC-APCI-MS/MS				[198]
Sediment (10-15)	Atorvastatin, carbamazepine	PLE: MeOH, 100°C	LC-ESI-MS/MS	70 -89	4.7 -7.99		[199]
Soil, sediment (20)	Pharmaceuticals (32)	PLE: 0.1 M ammonium:MeOH (1:1, v/v), 80°C Clean-up: MAX-HLB in tandem	LC-ESI-MS/MS	66-114	0.1-1.5	0.6-24.3	[200]
Sludge (1)	Pharmaceuticals (31)	PLE: water:MeOH (2:1,v/v), 100°C Clean-up: Oasis HLB	LC-ESI-MS/MS	3-130	0.15-258.5	0.6-547.9	[201]

Continued **Table 8.** Analysis of non-steroidal pharmaceutical drugs in environmental solid samples.

Matrix (g)	Analytes (number)	Sample preparation	Determination (Derivatisation)	Recovery (%)	LOD (ng g^{-1})	Levels (ng g^{-1})	Ref.
Sludge, sediment (1)	Pharmaceuticals (43)	PLE: water:MeOH (2:1,v/v), 100ºC Clean-up: Oasis HLB	LC-QqLIT-MS	33-206	0.01-8.84	0.1-120	[202]
Sediment (1)	Psychoactive drugs (8)	PLE: water:MeOH (1:1, v/v), 100ºC Clean-up: Oasis HLB	LC-ESI-MS/MS	>97	2-5[a]		[203]
Soil (20)	Pharmaceuticals (19)	PLE: ACN:water (7:3,v/v), 130ºC	LC-ESI-MS	63-113	0.76-5.46	0.02-15	[204]
Sediment (20)	Antidepressant pharmaceuticals (8) and degradates (2)	PLE: ACN:water (7:3,v/v), 130ºC	LC-ESI-MS/MS	32-66	0.25-2.50[a]	0.39-26.07	[205]
Sludge (0.5)	Anti-inflammatory drugs (4)	PLE : water (0.01 M NaOH), 120ºC Clean-up: HF-LPME	LC-ESI-MS	100-109	0.4-3.7	7.7-588	[206]
Soil, sediment (3)	Pharmaceuticals (17)	PLE: water, 90ºC Clean-up: SAX + HLB in tandem	LC-ESI-MS/MS	34-105	0.1-6.8		[207]
Soil (3)	Anti-inflammatory drugs (3), diphenhydramine hydrochloride	MAE: 10 mL DCM:MeOH (2:1, v/v) (x3), 115ºC Clean-up: Silica microcolumns	GC-MS (pyridine:BSTFA (2:1))	< 40			[208]
Sludge (0.5)	Anti-inflammatory drugs (4)	MAE: 50 mL water, 100ºC Clean-up: DME: neutral alumina + aluminium sulphate SPE: OASIS HLB	GC-MS (HMDS+ TFA)	80-105	15-22[a]	10-140	[209]
Sediment (5)	Anti-inflammatory drugs (4)	MAE: 50 mL water, 100ºC Clean-up DME: neutral alumina + aluminium sulphate SPE: OASIS HLB	GC-MS (HMDS+ TFA)	95-103	2-6[a]	2-38	[210]
Sediments (2)	Pharmaceuticals (8)	MAME: 8 mL water + polyoxyethylene 10 lauryl ether (2.75%, v/v) Clean-up: Oasis HLB	LC-UV	6-114	4-167		[211]
Sludge (0.5-1.5)	Anti-inflammatory drugs (4)	HF-LPME	LC-MS		10[b]	29-138	[212]

[a]*LOQ*; [b]*ng mL*$^{-1}$

samples. This technique provides a fast extraction of the analytes with a low consumption of solvents. In general, the extraction is carried out with methanol [199], water [206,207], or mixtures of water with an organic solvent, such as acetonitrile [196,204,205], acetone [198] or methanol [201-203]. Temperature is one of the parameters that have more effect on the extraction efficiency besides the extraction solvent. The extraction is commonly carried out at temperatures ranging from 80ºC to 100ºC because, at higher temperatures thermal degradation can occur and more interferences can be coextracted. Nevertheless, Edwards *et al*. [198] studied the determination in biosolids of 9 pharmaceutical drugs belonging to different therapeutic classes together with two antibacterial personal care products performing five different PLE methods and the working temperatures ranged from 25ºC for sulphamethoxazole to 90ºC for the acidic drugs. In another study, where water was used as extraction solvent, temperatures from 80ºC to 120ºC were evaluated and the best results were achieved at 120ºC for four anti-inflammatory drugs [206]. The effect of pH was also evaluated, using a solution of phosphoric acid at pH 2 and a 0.01M NaOH solution. The analytes were completely extracted using a 0.01M NaOH solution because, at this pH, these acidic drugs are deprotonated and are more soluble in aqueous solutions.

Although UAE and PLE are the most commonly employed extraction techniques for the determination of pharmaceuticals in environmental solid samples, MAE has been also used. Nowadays, the trend is to develop analytical methods environmentally friendlier, the so called green chemistry. In this way, MAE using water as extractant was recently applied for the determination of four acidic anti-inflammatory drugs (ibuprofen, naproxen, ketoprofen, and diclofenac) in sludge [209] and sediments [210]. The use of water as solvent, reported also for PLE analyses, reduced the extraction of interfering compounds and, hence, lower matrix effects were observed. MAME is an alternative to MAE, in which a surfactant is added to water. Cueva-Mestanza *et al*. [211] applied MAME to the analysis of a selected group of eight pharmaceutical compounds in sediment

using a nonionic surfactant, polyoxyethylene 10 lauryl ether. Several parameters were optimised in the MAME procedure (such as microwave conditions and surfactant volume and concentration) using a factorial design. HF-LPME, a miniaturised procedure that is generally carried out with liquid matrices, was applied for the simultaneous extraction and clean-up of four anti-inflammatory drugs from sludge [212] that was based on a previous work that monitored the same pharmaceuticals in sewage treatment plant effluents [214]. A three phase HF-LPME was performed, thus, analytes were extracted from an aqueous solution of sludge through an organic solvent, dihexylether to the acceptor phase (0.1 M ammonium carbonate) at pH 9. The pH of the acceptor phase is above the pk_a, so the analytes are deprotonated avoiding their diffusion through the membrane and, as a result, the enrichment of the acceptor phase is produced. This acceptor phase was directly analysed by LC without the need of a subsequent clean-up step.

It is usually necessary the purification of the obtained extracts, especially after applying energy to isolate bound analytes from solid environmental matrices. As in the case of antibiotics, SPE is the main clean-up procedure employed, using predominantly HLB cartridges, as it can be observed in Table 8 [188,189,191,195-197,202]. Other sorbents as C_{18} [175,192,193] or silica [174,208] have also been used but not as frequently as HLB. In the determination of pharmaceuticals in dewatered municipal biosolids applied to an agricultural field, Oasis HLB was used for all the analytes except for the betablocker atenolol, where an Oasis MCX cartridge was employed [198]. This sorbent combines the benefits of the HLB sorbent with cation exchange, due to the presence of strong sulphonic groups, and it was also used in the determination of acidic pharmaceuticals in sediments [175] and in activated and digested sludge [192]. Although the clean-up is, in general, carried out using one cartridge, some authors have performed two successive clean-up steps using SPE cartridges with different functionality. In this way, Minten *et al*. [187] first used an Evolute ABN column and an Oasis HLB afterwards. The first column was used to remove matrix constituents that could compete for the adsorption sites of the Oasis cartridge and, as a result, higher extraction yields were obtained. Other authors stacked two cartridges and performed a clean-up in tandem. The cartridge in top usually contains a strong anion exchange sorbent [200,207] to absorb anionic fulvic and humic acids reducing the presence of matrix interferences. The extract was adjusted to pH 7 before clean-up so the analytes were in their neutral or cationic form and not retained in the anion exchange cartridge.

A new purification procedure applying a modified dispersive solid phase extraction followed by a conventional SPE technique was carried out for the analysis of acidic pharmaceuticals in river sediment [210] and sludge [209]. The extract obtained by MAE was shaken for 10 min with neutral alumina (sorbent) and aluminium sulphate (electrolyte). Afterwards, the mixture was filtered or centrifuged before loading an Oasis HLB cartridge that was consequently washed with distilled water to remove the electrolytes before eluting with an organic solvent. HF-LPME, as clean-up procedure, was applied to sludge extracts obtained by PLE [200] using the same acceptor and organic phases as those reported by Sagrista *et al*. [212].

4.2.2. Determination

LC is the technique chosen for the analysis of the target pharmaceuticals, due to their high polarity, solubility in water and thermolability. UV and FL detection have been used in lesser extent since the implementation of LC-MS and LC-MS/MS, which has gained in popularity due to its versatility, selectivity and specificity. ESI is the ionisation source most commonly used in LC-MS/MS, working in positive mode when neutral and basic compounds are analysed and in negative mode for acidic drugs (Table 8). APCI in the negative mode has been also applied in the determination of acidic pharmaceuticals [175,192]. Although LC-MS/MS is a very selective tool and, thus, an exhaustive clean-up would not be necessary, the presence of matrix components has important effects in the quantitative determination of target compounds. To overcome these effects, the best option is to use isotopically labelled analytes as internal standards [215] and when there are no labelled standards available, the standard addition methods should be applied.

Although pharmaceuticals are usually determined by LC, due to the polarity of these compounds, GC has been also applied but a derivatisation step previous to the analysis is required to improve their thermal stability. Silylation is the reaction usually carried out to obtain trimethylsilyl derivatives. Among the different reagents, BSTFA [208] and N-(terbutyldimethylsilyl)-N-methyl trifluoroacetamide (MTBSTFA) [193,197] are usually employed. Hexamethyldisilazane catalysed by trifluoracetic acid and combined with pyridine containing hydroxylamine hydrochloride provided a cost-effective and quantitative silylation of the active proton functional groups of four anti-inflammatory drugs [209,210]. When carbamazepine was derivatised, a partial degradation was observed as two peaks, the parent compound and iminostilbene were detected [197]. The degradation

product was observed when standards were injected, whereas in soil extracts the degradation product did not appear because the matrix components acted protecting the analyte from its degradation in the injection port.

4.3. Estrogens

Estrogens are a group of steroid hormones that act as endocrine disruptors [216]. Estrogenic compounds, of natural and synthetic origin, are excreted in conjugated forms, but are subsequently transformed into their corresponding free steroids, which are the main compounds causing environmental concern. Natural hormones such as 17β-estradiol and estrone are derived from excreta of humans and livestock, and 16α-hydroxyestrone from the hepatic metabolism of the natural estrone. Estrogens have moderate to high hydrophobicity and, as a consequence, sorption to bed sediment and sludge could be a cumulative process.

4.3.1. Sample preparation

Different conventional extraction methods, summarised in Table 9, such as shaking [217,218] and UAE [193,219-221] have been reported for the analysis of estrogens in solid matrices. In these conventional methods, the extraction step is mostly performed with acetone mixed with hexane or ethyl acetate. It is important to underline that extraction of estrogens from sediment and sludge is performed with polar solvents that coextract many interferences, then a purification step is required. In most cases, this purification is carried out with SPE C_{18} cartridges and elution with acetonitrile or ethyl acetate. Termes *et al*. [221] reported the purification of sludge and sediment extracts, based on GPC and silica gel clean-up, for removal of matrix components with high molecular masses.

Few studies have used PLE to extract estrogens from solid samples. Nieto *et al*. [222] developed a method for the simultaneous extraction of natural and synthetic estrogens and their conjugates in sludge. The PLE conditions were the following: extracting solvents methanol:acetone (1:1, v/v) and water (pH 7):methanol (1:1, v/v); extraction temperature 75ºC; a preheating period of 5 min and 4 cycles. Fernandez *et al*. [223] analysed different sludge samples from Barcelona, Spain. The sludge was extracted using PLE with Florisil and methanol:dichloromethane (3:7, v/v) at 75ºC. A post-extraction clean-up of the extracts was carried out with 5% deactivated Florisil and elution with dichloromethane:acetone (7:3,v/v). Few works have been reported on the MAE of estrogens from solid matrices. Liu *et al*. [224] developed a MAE technique for the simultaneous detection of 17β-estradiol, estrone, 17α-ethynylestradiol and 16α-hydroxyestrone, among other compounds, from river sediment samples. The effect of various parameters on the extraction efficiency of MAE was investigated. The most efficient extraction was achieved using methanol as solvent, an extraction temperature of 110ºC and 15 min of holding time. The clean-up of extracts was carried out with a non-deactivated silica gel column and elution using ethyl acetate:hexane (4:6,v/v). The extraction efficiency of MAE was similar to that obtained with UAE. However, the advantages of MAE included a low solvent consumption (25 mL) and a short extraction time (15 min). Hibberd *et al*. [49] developed an analytical method for the determination of estrogens from sediments samples by MAE using methanol as extracting solvent. The clean-up step was carried out with water and the aqueous solution was then extracted with an SPE Oasis HLB cartridge. Morales-Muñoz *et al*. [225] studied the application of focused microwave-assisted Soxhlet extraction (FMASE) to the determination of compounds with different polarity, estrogens among them, in marine sediments. A sequential extraction with dichloromethane and water was performed. This method was compared with conventional Soxhlet extraction using water as extractant for 12 h, which was less efficient than the proposed FMASE method. The efficiency obtained with dichloromethane was similar for both methods, although differences in time of extraction were important (25 min *vs* 12 h). Labadie and Hill [226] developed a method for the determination of estrone, 17β-stradiol and the synthetic estrogen17α-ethynylestradiol in river sediments by MAE-SPE Strata cartridge clean-up and Matejicek *et al*. [227] developed a sensitive method for the simultaneous determination of estrogens and their sulphate, glucuronide and acetate conjugates in river sediments using MAE followed by a clean-up step through ion-exchange SPE on Oasis WAX. Comparing Soxhlet extraction with MAE, the latter has been found to be more suitable with shorter extraction times.

4.3.2. Determination

Although estrogens are polar compounds and then LC would be the preferred technique, their determination by GC is frequently accomplished. In most cases, derivatisation of estrogens is needed to improve peak shape and provide adequate sensibility. Derivatisation was usually done via acetylation with heptafluorobutyric acid (HFBA) [218] or silylation with BSTFA or MTBSTFA [193,224]. Acetylation with HFBA is a good derivatisation technique for steroid hormones, which yields highly informative fragment ions that allow definitive identification and quantification of analytes. MTBSTFA is also a good derivatisation reagent because of the great thermal and hydrolytic stability of the tertbutyldimethyl

Table 9. Analysis of estrogens in environmental solid samples.

Matrix (g)	Analytes	Sample preparation	Determination (Derivatisation)	Recovery (%)	LOD (ng g^{-1})	Levels (ng g^{-1})	Ref.
Sludge (0.5), sediment (5)	E1, E2, E3, EE2	Shaking: 10 mL acetone:hexane (1:1, v/v) +10 mL DEE:hexane (10:1, v/v) Clean-up: GPC-SX-3, C_{18}	LC-ESI-MS GC-MS (BSTFA/TMS)	>70 >90			[217]
Solid waste (5)	E1, E2, E3,MDP, P	Shaking: 5 mL 1M NaOH + 30 mL DEE	GC-MS (HFBA)			76-2100	[218]
Sediment (3)	E1, E2, E3, EE2,DES,DIE	UAE: 50 mL hexane:acetone (1:1, v/v) Clean-up: GPC Oasis HLB	LP-GC-MS GC-GC-HSToF-MS	75-133	1.5-5		[219]
Sediment (5)	E1, E2, E3, EE2, DES, P, N, L	UAE: 55 mL MeOH:acetone (1:1, v/v) Clean-up: C_{18}	LC-DAD-MS LC-ESI-MS	66-102 64-100	1-2 0.04-1	11.9-22.8	[220]
Soil (5)	E1	UAE:10 mL EtAc:acetone (1:1, v/v) Clean-up: C_{18}	GC-MS (MTBSTFA)	63-110	1.2	9	[193]
Sludge (0.5) Sediment (5)	E1, E2, E3, EE2	UAE: 7 mL MeOH + 6 mL acetone Clean-up: GPC SX-3- Silica gel	GC-MS/MS (MSTFA)	80-120	2-4	17-49	[221]
Sludge (1)	Synthetic and natural	PLE-clean-up: aluminium oxide + 25 mL MeOH:acetone (1:1, v/v) + water(pH 7):MeOH (1:1, v/v), 75ºC	LC-ESI-MS/MS	>81	26	7-406	[222]
Sludge (0.2)	Synthetic and natural	PLE-clean-up: Florisil+MeOH:DCM (3:7, v/v), 75ºC Clean-up: 5% deactivated Florisil	LC-ESI-MS/MS	>80			[223]
Sediment (5)	E1, E2, EE2, HE1	MAE: 25 mL MeOH, 110ºC Clean-up: Silica gel	GC-MS (BSTFA)	>61	0.2-0.4	2-12	[224]
Sediment (3)	E1, E2, EE2, HE1	MAE: 45 mL MeOH, Clean-up: water, Oasis HLB	GC-MS/MS (BSTFA)	86-102	0.05-0.14	≤ 11.2	[48]
Sediment (1)	E1, E2, DES	FMASE: 35 mL DCM-water	GC-MS/MS	85-91	0.0004-0.004	2.5-4	[225]
Sediment (1)	E1, E2, EE2,	MAE: 25 mL MeOH, 90ºC Clean-up: Strata-X-AW, silica gel	LC-ESI-MS/MS LC-ToF-MS/MS	82-98	0.015-0.04	0.04-3.3	[226]
Sediment (1)	E1, E2, E3 and their conjugates	MAE: 10 mL aqueous MeOH (25:75, v/v) Clean-up: Oasis-WAX	LC-ESI-MS/MS	83-107	>1	1	[227]

silyl derivatives. Table 9 summarises the agents that can be used to derivatise extracts prior to GC-MS or GC-MS/MS analysis.

GC-MS/MS is a determination technique with LODs in the low pg g^{-1} range. However, because of the high polarity of some members of this group and poor derivatisation efficiency that hinders GC analysis, LC-MS methods have been developed. Labadie *et al*. [226] compared the performances of LC-ToF-MS and LC-MS/MS for the determination of estrogens in sediments. LC-MS/MS was approximately 13 times more sensitive than LC-ToF-MS with LODs ranging from 15 to 40 pg g^{-1}. Hajkova *et al*. [219] published a GC-MS method for the analysis of 5 estrogens in river sediments without derivatisation. Considering a high probability of signal suppression, they tested different GC and MS systems: GC-MS, low pressure GC-MS, GC-ToF-MS and GCxGC-ToF-MS. The combination of highly sophisticated instrumentation methods achieved LODs between 0.4 and 12 ng g^{-1} for GC-ToF-MS. Time of flight (ToF) instruments offer a resolving power superior to quadrupole and IT detectors by minimising matrix interferences and increasing S/N. Nevertheless, LC-MS/MS provides good sensitivity and selectivity and seems to be the preferred analytical technique for the determination of estrogens. Deuterated and labelled standards are commercially available for most estrogens to be used as recovery and internal standards.

5. Personal care products

Personal care products (PCPs) constitute a group of emerging contaminants, which have received considerable attention in recent years. PCPs are regarded as being potentially hazardous compounds as many of them are ubiquitous and persistent and due to their continuous introduction might cause unwanted effects in the environment. The main PCPs considered in this review are: UV filters, preservatives, disinfectants and musk fragrances.

5.1. UV filters

UV filters are common ingredients in sunscreens and skin creams, as well as in agricultural and pharmaceutical products and in plastics. The use of these products is increasing, with approximately 10,000 tonnes/year employed in the EU in 2008. UV filters may enter the environment in two ways, either indirectly *via* WWTPs or directly from swimming and bathing in lakes and rivers. Regarding organic UV filters, there are 27 compounds approved in the EU, including benzophenones, p-aminobenzoic acid and derivatives, salicylates, cinnamates, camphor derivatives, benzotriazole, benzimidazole derivatives, and other compounds.

5.1.1. Sample preparation

Benzophenone type-UV filters have been analysed in soil samples by shaking with methanol [228,229] or with ethyl acetate:methanol (90:10, v/v) assisted with sonication, with a simultaneous clean-up step [230]. Sludge is an extremely complex matrix that requires an adequate sample preparation. The first method for sludge was proposed by Plagellat *et al*. [231]. For the isolation of the target UV filters, fresh sludge (60 g) was mixed with NaCl and then three consecutive extractions by mechanical shaking with mixtures of pentane:ethyl acetate (1:1, v/v), pentane:diethyl ether (1:1, v/v) and diethyl ether:chloromethane (4:1, v/v) were done. The combined extracts were concentrated to dryness and cleaned up by column purification with activated silica. This technique is time consuming and with a solvent consumption above 200 mL per sample. The use of automated modern technologies, such as PLE, for the analysis of UV filters in solid matrices has been proven as an efficient way to overcome those drawbacks. Rodil *et al*. [232] applied PLE for extracting UV filters from sediments. Extraction was performed with ethyl acetate:hexane (80:20, v/v), followed by the derivatisation of analytes. An interesting alternative was presented by Rodil *et al*. [233] for sludge and sediment samples using pressurised membrane-assisted liquid extraction. A non-porous low-density membrane bag was used and filled with 0.5 g of sample and 1 mL of extraction solvent. Subsequently, the membrane bags were extracted under pressure at elevated temperature and, due to the membrane, extraction and some clean-up were combined in a single step.

In a recent investigation by Negreira *et al*. [234], PLE was applied with success to extract eight UV filter compounds, belonging to different chemical classes in freeze-dried sludge samples. Hexane:dichloromethane (80:20, v/v) was used as the extraction solvent at 75ºC. GCB and primary secondary amine (PSA) bonded silica sorbents were used on line for removing interferences. Another PLE method was developed for the determination in sludge of UV filters and some degradation products and derivatives with different polarities [235]. The conditions were as follows: 1 g of sludge was mixed in the extraction cells with aluminium oxide and two static cycles using methanol as extraction solvent followed by two static cycles using methanol:water (1:1, v/v) were done at 100ºC. Methods used for the analysis of UV filters in environmental solid samples are summarised in Table 10.

5.1.2. Determination

Because of the high polarity of UV filters, derivatisation of these analytes is necessary to increase their GC response. Many factors as reaction time, derivatising reagent and temperature affect the derivatisation. N-methyl-N-(trimethylsilyl)trifluoroethyl acetamide (MSTFA) [228] and BSTFA with 1% TMCS [230,232] have been used to transform UV filters into their trimethylsilylethers (Table 10).

A complete derivatisation of the hydroxyl group of benzophenones is achieved after silylation and they can be analysed by GC-MS in selected ion monitoring (SIM) mode with remarkable sensitivity. Common GC stationary phases, such as 5% phenylpolysiloxane, can be used for the separation of these compounds [228,230].

LC-DAD and LC-MS have also been employed, especially for polar and high molecular weight UV filters or mixtures of several classes of UV filters. Recently, the application of ultra performance liquid chromatography tandem mass spectrometry (UPLC-MS/MS) for the analysis of UV filters and their derivatives in sludge was reported [235]. This technique offers improved performance for quantitative analysis with reduced analysis time and solvent consumption. LC-MS/MS presents an improvement over GC-MS since the derivatisation step is avoided. Reverse phases like C_8 and C_{18} are most commonly used in the separation of UV filters.

Internal recovery standards were not used in the majority of the papers reviewed, due to the lack of isotopically labelled UV filters. Therefore, quantification with matrix-matched standards was used instead. In the last years, deuterated or labelled BPA has been used as surrogate standard for quantification, due to its similar physicochemical properties to UV filters [229,230]. Good recoveries (60-125%) were obtained with the different methods employed, which showed good LODs as well (Table 10). UV filters have been found in environmental solid samples in the low ng g^{-1}.

Table 10. Analysis of UV filters and parabens in environmental solid samples.

Matrix (g)	Analytes (number)	Sample preparation	Determination (Derivatisation)	Recovery (%)	LOD (ng g^{-1})	Levels (ng g^{-1})	Ref.
Soil (10)	BPs (7)	Shaking: 20 mL MeOH + 20 mL EtAc	GC-MS (MSTFA)	60-125	0.1	0.5-18.3	[228]
Sludge (0.05-0.1), sediment (0.5-1)	UV filters (5)	Shaking: 5 mL MeOH (x2) Clean-up: Oasis HLB	LC-ESI-MS/MS	82-106	0.06-0.33	104-6370	[229]
Soil, sediment (2)	BPs (5) Salicilates (2)	UAE-clean-up: 16 mL EtAc:MeOH (90:10, v/v), C_{18}	GC-MS-EI-SIM (BSTFA)	89-105	0.07-0.28	0.6-20	[230]
Sludge (60)	UV filters (4)	Shaking: 20 mL Pentane:acetone (1:1, v/v) 20 mL Pentane:DEE(1:1, v/v) 20 mL DEE:DCM (1:1, v/v) Clean-up: Silica gel	GC-MS HPLC-DAD HPLC-MS/MS	75-101	3-57	110-5510	[231]
Sediment (4)	UV filters (8)	PLE-clean-up:Silica gel + EtAc:hexane (80:20, v/v), 160 °C	GC-MS (BSTFA)	73-128	1-5	14-93	[232]
Sludge (0.5)	UV filters (11)	PLE-clean-up:Silica gel-EtAc:hexane (1:3, v/v), 70ºC	LC-MS/MS	95-124	0.3-25	1.4-2479	[233]
Sludge (0.5)	UV filters (8)	PLE-clean-up: GCB + hexane:DCM (80:20, v/v), 75ºC Clean-up: PSA	GC-MS	73-112	17-61[a]	600	[234]
Sludge (1)	UV filters and derivatives (8)	PLE-clean-up: aluminium oxide + MeOH (x1), MeOH:water (1:1, v/v) (x2), 100ºC	LC-ESI-MS/MS	70-102	19	40-9170	[235]
Sludge (50)	UV filters (4)	Shaking: 20 mL hexane (x3) Clean-up: GPC-BIO-Beads SX-3	GC-MS HPLC-DAD	75-103	4-6		[236]
Soil, sediment (10)	Parabens (6)	SAESC: 4 mL ACN (x3)	LC-MS/MS	83-110	0.04-0.14	≤ 6.35	[238]
Soil, sediment (10)	Parabens (7)	SAESC: 4 mL ACN (x3) Clean-up: MISPE	HPLC-UV LC-MS/MS	80-90	1	11.5	[239]
Sludge (1)	Parabens (4)	PLE-clean-up: aluminium oxide + MeOH:water (1:1, v/v), 100ºC	LC-MS/MS	72-108	205-6.3	5-202	[240]

[a]*LOQ*

5.2. Preservatives: Parabens

Parabens are a group of alkyl esters of the p-hydroxybenzoic acid widely used as preservatives in pharmaceuticals and PCPs. These simple esters are very effective anti-microbial agents, showing an increase of anti-microbial activity with the length of the alkyl side chain from, methyl to butyl. Although their toxicity is relatively low, parabens possess endocrine disruption activity and, in the EU, their use in cosmetics is limited to a maximum concentration of 0.4% (w/w) for each compound and a total maximum concentration of 0.8% (w/w), expressed as p-hydroxybenzoic acid (EU cosmetic directive 76/768/EC) [237]. There are currently seven different types of parabens in use: methyl, ethyl, propyl, butyl, benzyl, isopropyl and isobutyl.

5.2.1. Sample preparation

There have been few methods published for parabens in environmental solid matrices. Parabens have been extracted from solid samples (soil and sediment) using sonication-assisted extraction in small columns (SAESC) with acetonitrile as extraction solvent [238]. Later, these authors used molecularly imprinted solid-phase extraction (MISPE) for the determination of parabens in those matrices [239]. Samples were extracted by SAESC with ethyl acetate followed by MISPE as clean-up step, eluting the analytes with acetonitrile:methanol containing 2.5% acetic acid. PLE with two extraction cycles of methanol, followed by two cycles of water:methanol (1:1, v/v) was also used to extract these compounds from sludge [240].

5.2.2. Determination

Parabens have been analysed by LC with detectors such as DAD and UV, although the best option is LC-MS due to the low concentrations of these compounds in environmental samples. Recently, the first application of UPLC for residue analysis of parabens in sludge was reported [222]. The major benefit of this technique is the increased column efficiency that resulted in shorter analytical times and improved sensitivity and selectivity compared to conventional LC analyses. Recoveries were, in all cases, greater than 72%. The columns commonly used were C_8 and the lowest LODs were achieved with LC-MS/MS, followed by LC-MS. Concentration of methyl and propyl parabens in the range of 5 to 202 ng g^{-1} were found in sludge from Spain [222].

Although LC methods dominate the analysis of parabens, a GC method was reported for the determination of parabens in soil samples [241]. Due to their polar nature, these compounds were derivatised before GC analysis to improve sensitivity and peak resolution by silylation with BSTFA containing 1% TMCS. The analytical methods developed for determination of parabens in solid matrices are summarised in Table 10.

5.3. Desinfectants / antimicrobials: triclosan, triclocarban

Triclosan (TCS) and triclocarban (TCC) are broad-spectrum bactericides used in consumer products that are disposed of down residential drains. A significant proportion of these compounds will be retained in sewage sludge produced in the WWTPs. These contaminants may enter the environment by spreading sludge on agricultural lands or through treated water effluents. They have been used for more than 40 years and their use as antimicrobial and antibacterial products is increasing worldwide. This widespread use, about 0.6-10 million kg $year^{-1}$ [242], is a cause for concern because of recent reports of incomplete TCS and TCC removal during wastewater treatment and their detection in surface waters together with a metabolite, methyl triclosan (methyl-TCS) and some chlorinated derivatives.

5.3.1. Sample preparation

TCS and TCC have been extracted from agricultural soils shaking with methanol [243] or ethyl acetate [244] (Table 11). PLE with methanol [245] or acetone [246] was chosen for the extraction of TCS and TCC together with other contaminants, from soil after biosolids application, and analytes were isolated from coextracted compounds by a clean-up with an ABN SPE cartridge, which contains a polymer-based sorbent for the extraction of a broad range of acidic, neutral and basic compounds. Lozano *et al*. [247] reported the analysis of TCS in soil and biosolids using PLE with water:isopropanol (80:20, v/v) as extraction solvent and a clean-up of the extracts by SPE with Oasis cartridges, eluting with dichloromethane:diethyl ether (80:20, v/v). UAE with acetone:ethyl acetate (1:1, v/v) [248] and MSPD with C_{18} and acetonitrile [249] have been also proposed as extraction techniques for the analysis of TCS and methyl-TCS in soil and sludge. Methyl-TCS and TCS were analysed in river sediments by Kronimus *et al*. [250] using acetone:hexane as extraction solvent and SPE with silica gel as clean-up step. Freeze-dried sludge samples were Soxhlet extracted with ethyl acetate for the analysis of TCS and extracts were purified using silica cartridges eluting with ethyl acetate [253]. TCS was among ten compounds extracted from freeze-dried sediment samples by sequential Soxhlet extraction with dichloromethane (12 h) and water (12 h) or water (12 h) and dichloromethane (12 h) [254]. When FMASE was applied, the extraction was considerably reduced using the same extraction solvents (25 min for dichloromethane and 50 min for water extractions). A sequential extraction was carried out using dichloromethane for non polar analytes and water for semipolar and polar compounds. Chenxi *et al*. [171] reported the determination of various antibiotics and TCS in digested sludge by UAE followed by a clean-up step using Strata X cartridges. UAE was also used for the extraction of TCS from an Australian sludge with ethyl acetate [255] and the extracts were purified with C_{18} cartridges. The extraction time was reduced when MAE and PLE were used. TCS was analysed in river sediments and sludge by MAE with acetone:methanol (1:1, v/v) as extractant solvent, and the analyte was isolated from coextracted compounds on Oasis SPE cartridges and eluted with ethyl acetate [251]. Aguera *et al*. [252] developed an analytical method for the extraction of TCS and biphenylol in marine sediments by PLE with dichloromethane. The clean-up of the extracts was carried out with silica gel and the analyte eluted with acetone. PLE has been also proposed as extraction methodology for the determination of TCS and TCC in sludge, followed by clean-up with Oasis HLB cartridges [256-258].

5.3.2. Determination

TCS and TCC are compounds unable to be determined directly by GC, so they should be derivatised to more volatile analytes. The use of diazomethane to derivatise this class of compounds has been reported, but due to its toxicity it is not suitable for routine analysis [258].

Table 11. Analysis of preservatives in environmental solid samples.

Matrix (g)	Analytes	Sample preparation	Determination (Derivatisation)	Recovery (%)	LOD (ng g^{-1})	Levels (ng g^{-1})	Ref.
Soil (5), biosolid (1)	TCS, TCC TCS, TCC	PLE: 70% MeOH, 100°C PLE: 70% MeOH 80°C Clean-up: pH 4 cartridge ABN	LC-ESI-MS/MS	80-142 82-132	0.1-5.1 0.5-27	760-22588	[245]
Soil (5), biosolid (0.2)	TCS, TCC TCS, TCC	PLE: acetone, 100°C	LC-ESI-MS/MS	>95	0.05-0.58 0.11-3.08	0.16-65.2	[246]
Soil (10), biosolid (0.2-0.3)	TCS TCS	PLE: water:iPOH (80:20, v/v), 100°C Clean-up: Oasis HLB cartridge	LC- ESI-MS/MS	87 86	2[a]	4.1-4.5 15600	[247]
Soil (10)	TCS	UAE:15 mL acetone:EtAc (1:1, v/v) Clean-up: C_{18}	GC-MS (MTBSTFA)	96	0.2		[248]
Soil (2), sludge (1)	TCS, methyl-TCS	MSPD: C_{18}+10 mL ACN	GC-MS (MTBSTFA)	96-101	0.05-0.12	0.8-4.7 4-2987	[249]
Sediment	methyl-TCS	Dipersion-extraction: acetone-hexane Clean-up: Silica gel	GC-MS	73-112			[250]
Sludge (0.5)	TCS	UAE: MeOH-0.1 M HAc-5% Na_2-EDTA Clean-up: Strata X	LC-MS/MS	68	17	320	[171]
Sediment (1), sludge (0.5)	TCS	MAE: 30 mL acetone:MeOH (1:1, v/v), 130°C Clean-up: Oasis HLB cartridge	GC-MS/MS (MTBSTFA)	82-99	0.2[a]	4.4-35 418-5408	[251]
Sludge (10)	TCS	Soxhlet : EtAc Clean-up: Silica gel	GC-MS	94	4[a]	1200	[253]
Sludge (0.5)	TCS	UAE: 12 mL EtAc Clean-up: C_{18} cartridge	GC-MS (MSTFA)	73-74	5[a]	23200	[255]
Sludge (0.1-0.2)	TCS, TCC	PLE: DCM, 60°C Clean-up: Oasis HLB cartridge	LC-MS/MS	98	1.5-0.2	620-11550	[256]
Sludge (0.1-0.2)	TCS	PLE: acetone, 70°C Clean-up: Oasis HLB cartridge	LC-ESI-MS	60-104	1000	20000-55000	[257]
Sludge (1), sediment (1)	TCS, methyl-TCS	PLE: DCM, 100°C Clean-up: Silica gel 5% water cartridge	GC-MS/MS (diazomethane)	100	5	2580	[258]

[a]*LOQ*

Alternatively, silylating reagents like MSTFA [255] and MTBSTA [248,249] have been used. Because methyl-TCS is a metabolite of TCS, this method can overestimate the TCS concentration, although TCS concentrations can be determined by difference if the methyl-TCS concentration is determined prior to methylation.

TCS, methyl-TCS and TCC have been analysed by LC-MS, LC-MS/MS and GC-MS with or without derivatisation. SIM is the monitoring mode used for the qualitative and quantitative analysis of the target analytes in single-quadrupole MS. Lower LODs are achieved with derivatisation using GC-MS, and LC-MS provides lower sensitivity than LC-MS/MS. Labelled $^{13}C_{12}$ TCS and $^{13}C_{12}$ methyl-TCS are currently available for use as recovery standards. In order to obtain recoveries over the overall analytical method, surrogate standards, spiked before extraction to compensate for losses during sample preparation, were used [249]. Low levels of these compounds have been detected in soil and sediment samples, whereas higher concentrations were found in sludge samples.

5.4. Synthetic musk fragrances

Synthetic musk fragrances are compounds added to provide scent in a variety of PCPs, including deodorants, shampoos and detergents. Based on their chemical structure, synthetic musks are usually divided into three groups: nitro, polycyclic and macrocyclic musks. Nitro musk fragrances were the first to be produced but their use has decreased in recent years due to the concern about their toxicity; they include musk xylene (MX), musk ketone (MK), musk ambrette (MA), musk moskene (MM) and musk tibetene (MT). In the environment, nitro substituents can be reduced to form amino metabolites of these compounds [259].

In contrast to nitro musks, polycyclic musks are widely used in many household products and toxalide (AHTN) and galaxolide (HHCB) represent about 95% of the market. AHTN and HHCB production has been estimated at about 1 million pounds per year [260].

5.4.1. Sample preparation

Polycyclic musks have been extracted from solid matrices by Soxhlet, which is a less attractive technique due to the long time and solvent consumed, and by modern techniques like MAE or PLE (Table 12). Zeng *et al*. [261] reported a Soxhlet extraction of sludge with dichloromethane and a purification of the resulting extract using an alumina and silica gel column with elution with hexane and dichloromethane. MAE and PLE have become well established techniques and show advantages for the extraction of musk fragrances from solid matrices, due to their high extraction efficiency in a short time, using a low solvent consumption and with the possibility of automation. The sample was mixed with an inert material (sand, aluminium oxide or diatomaceous earth) to increase surface area exposure. The presence of polycyclic and nitro musk in sludge, using MAE and a silica gel column for the cleaning of the extracts, was reported [262]. Smyth *et al*. [266] reported two extraction methods, based on supercritical fluid extraction (SFE) and MAE, for the analysis of polycyclic and nitro musks in sludge samples. They found no significant differences between both extraction methods. Nevertheless, the air-drying of the sample required for SFE may potentially result in the degradation or volatilisation of some polycyclic and nitro musks. A MAE method was developed for the simultaneous detection of diverse musks in soil and sediments that included the derivatisation of polar analytes after a silica gel open column clean-up [208]. Regarding the application of MAE, Wu *et al*. [263] developed a solvent-free one step in situ MAE headspace solid-phase microextraction (MA-HS-SPME) method for the determination of polycyclic musks in sludge and sediments. Nitro and polycyclic musks were extracted from biosolid samples by PLE with hexane:ethyl acetate (1:1, v/v) [265]. Extracts were purified by GPC using Bio-Beads S-X eluting with hexane:ethyl acetate (1:1, v/v) and further cleaned up by a silica gel column. In another work, fragrances were extracted from sludge amended soils and sludge by PLE with dichloromethane [264]. The extraction cells were packed with activated silica and diatomaceous earth and the resulting extract was purified in a silica column with dichloromethane as elution solvent. Among these techniques, MAE and PLE are the most widely used (Table 12).

5.4.2. Determination

The presence of synthetic musk fragances in environmental matrices is well known. The determination of these contaminants has been usually carried out by GC-MS due to their volatility. In so far, well established GC-MS methods are nowadays available for routine monitoring (Table 12). Synthetic musk fragrances are commonly analysed by GC-EI-MS, but GC-NCI-MS is more sensitive for nitro musks. As isotopically labelled standards are not commercially available, a variety of internal standards have been used instead for the analysis of musk fragrances, including deuterated PAHs and various labelled and unlabelled PCBs. GC-MS methods show good selectivity and sensitivity, and recoveries >80% and LODs at low ng g^{-1} levels have been obtained with the developed methods (Table 12).

5.5. Multimethods

Current trends for PCPs clearly indicate the importance of multiresidue methods for chemically different classes of PCPs together with other emerging contaminants, such as pharmaceuticals. LC-MS/MS after a SPE preconcentration on Oasis HLB for sludge samples have been employed for the determination of 11 UV filters, preservatives and antimicrobials in sludge [267]. Wick *et al*. [268] developed an analytical method for the simultaneous determination of different classes of compounds such as, biocides, UV filters and benzothiazoles by PLE and LC-MS/MS. These authors applied APCI as an alternative ionisation source to ESI. Zhang *et al*. [229] analysed benzotriazole and benzophenone UV filters in sediment and sludge by shaking with methanol followed by clean-up with Oasis SPE cartridges and determination by LC-MS/MS. Xu *et al*. [193] developed an analytical method for the simultaneous determination of six different pharmaceuticals and PCPs, one estrogen and three EDCs in soil. The soil was extracted by sonication with acetone:ethyl acetate followed by SPE as a clean-up procedure. The purified extracts were derivatised with MTBSTFA and then analysed by GC-MS. Nieto *et al*. [240] developed a PLE method for the extraction of several PCPs, including six UV filters, four preservatives and two antimicrobials, from sludge. Analytes were extracted with methanol followed by methanol:water mixtures and on-line purification with alumina. With a sample intake of 1 g and 25 mL as the volume of final extract, recoveries over 79% were obtained by LC-MS/MS. In addition, a sensitive method was developed and validated for the determination of diverse groups of pharmaceutics, steroid hormones and PCPs in sludge. Samples were extracted by UAE followed by SPE clean-up. Analytes were determined by UPLC-MS/MS in multiple reaction monitoring mode and recoveries from 63 to 119% and LOQs in the range of 0.1-3 ng g^{-1} dry weight were obtained. Ternes *et al*. [192] compared PLE with UAE for extracting pharmaceuticals and polycyclic musk fragrances from sludge, using methanol and methanol and acetone, respectively.

Table 12. Analysis of musk fragrances in environmental solid samples.

Matrix (g)	Analytes	Sample preparation	Determination (Derivatisation)	Recovery (%)	LOD (ng g^{-1})	Levels (ng g^{-1})	Ref.
Sludge (1)	Polycyclic musk	Soxhlet: DCM Clean-up: Silica gel-3% alumina	GC-FID GC-MS	58-108	0.05-0.1	5.4-2870	[261]
Sludge (1-2.5)	Polycyclic, nitro musk	MAE: 30 mL acetone:hexane (1:1, v/v), 110ºC Clean-up: Silica gel	GC-EI-MS Polycyclic GC-NCI-MS nitro	80-105	4-41	4-500	[262]
Sludge (50)	Polycyclic musk	Shaking: 20mL hexane (x3) Clean-up: GPC Bio-Beads	GC-MS	84-103	1-6		[236]
Soil, sediment (3)	Nitro musk	MAE: 30mL DCM-MeOH (2:1, v/v), 160ºC Clean-up: Silica gel	GC-MS (BSTFA)	90		10000	[208]
Sludge, sediment (5)	Polycyclic musk	MAE-HS-SPME: 20mL water, PDMS/DVB fibre	GC-MS	85-96	0.04-0.1	0.3-10.9	[263]
Soil, sludge (2)	Polycyclic musk	PLE-clean-up: DCM, silica gel + hydromatrix, 60ºC	GC-MS	>80	1		[264]
Biosolid (4-6)	Polycyclic, nitro musk	PLE: hexane:EtAc (1:1, v/v), 80ºC Clean-up: GPC Bio-Beads + silica gel	GC-MS	>80	0.2-1.9[a]	96-470	[265]
Sludge (2)	Polycyclic, nitro musk	MAE: 30 mL acetone:hexane (1:1, v/v), 110ºC Clean-up: Silica gel	GC-EI-MS Polycyclic GC-NCI-MS nitro	>80	4-41	123-22000	[266]

[a]*LOQ*

Sample extracts resulting from both methods were dissolved in water, loaded into C_{18} cartridges and analytes were eluted with methanol and determined by LC-MS/MS or GC/MS. The extracts were further purified using 1.5% deactivated silica column and elution with hexane:acetone. Both extraction methods were compared and the extraction efficiency obtained was in good agreement, considering the statistical errors. Rice and Mitra [208] developed a time and cost-effective MAE based method for the simultaneous analysis of eight pharmaceuticals and PCPs in soil and sediments. The method consisted of optimising the following variables; derivatisation of the polar target analytes, silica gel open column clean-up, and GC-MS analysis. The final method was applied to both standard-amended soil samples and natural sediment samples and good recoveries were obtained. The extraction of synthetic musk fragrances and UV filters from sludge has been accomplished by shaking three times with hexane followed by purification with GPC [236].

6. Conclusions

Sample preparation is particularly important in trace analysis, as it can account for a significant amount of the variability of a particular method. Extraction methods such as Soxhlet are often not selective enough to meet the analytical requirements needed for the determination of emerging contaminants in environmental solid matrices. Alternative sample preparation methods have been developed to be more selective, faster and miniaturised, requiring less extraction solvent and sample amount. In addition, the automation of these techniques allows on line extraction, which enables to increase the number of samples to be processed and to reduce human errors by minimising operator intervention. The combination of several sample preparation techniques is often needed to increase the performance, sensitivity, accuracy and precision of the analytical method.

Modern methods for measuring trace amounts of emerging contaminants are mainly based on the application of GC and LC, particularly coupled to MS. Time of flight mass spectrometry (ToF-MS) alone or in combination with quadrupole instruments (QToF-MS), are expected to be applied increasingly for screening and identification of unknown analytes and metabolites. In addition, more attention will have to be paid in the future to metabolites of these contaminants released to the environment as well as to derivatives generated in the environment by degradation reactions. The application of advanced GC and LC coupled to MS/MS has allowed the determination of a broad range of compounds. LODs achieved by GC-MS/MS have been slightly better than those obtained with the LC-MS/MS but this technique has advantages in terms of versatility and less complicated sample preparation avoiding derivatisation of analytes. With this aim,

the development of analytical methods more environmentally friendly and requiring less sophisticated and expensive instruments than those used nowadays will continue to be an important challenge for the determination of emerging contaminants in environmental samples.

Abbreviations

AA-APPI: anion attachment atmospheric pressure photoionisation;
ACN: acetonitrile;
AEOs: alcohol polyethoxylates;
AES: alkyl ethoxy sulphates;
AEs: alkyl ethoxylates;
AHTN: toxalide;
ANEO: alkylamine ethoxylates;
APCI: atmospheric pressure chemical ionisation;
APECs: alkylphenoxy carboxylates;
APEOs: alkylphenol ethoxylates;
APG: alkylpolyglycosides;
APPI:atmospheric pressure photoionisation;
APs: alkylphenols;
AS: alkyl sulphates;
ATBEP: tris(2-butoxyethyl)phosphate;
ATMACs: alkyltrimethylammonium compounds;
BACs: benzalkonium chlorides;
BF3: boron trifluoride;
BFRs: brominated flame retardants;
BPs: benzophenone-type;
BPA: bisphenol A;
BSTFA: N,O-bis(trimethylsilyl)trifluoro ethyl acetamide;
BTBPE: 1,2-bis(2,4,6-tribromophenoxy)ethane;
CDEAs: coconut diethanol amides;
CE: capillary electrophoresis;
CHex: cyclohexane;
CNBF: 4-chloro-3,5-dinitrobenzotrifluoride;
CPE: cloud point extraction;
DAD: diode array detector;
DATS: dialkyltetralinsulphonates;
DBDPE: decabromodiphenyl ethane;
DCM: dichloromethane;
DeBDE: decabromodiphenyl ether;
Dec-: dechlorane;
DEE: diethylether;
DES: diethylstilbestrol;
DIE: dienestrol;
DME: dispersive matrix extraction;
DP: Dechlorane Plus;
dSPE: dispersive solid phase extraction;
E1: Estrone;
E2: 17ß-estradiol;
E3: Estriol;
ECD: electron capture detector;

ECNI: electron capture negative ionisation;
EDCs: endocrine disrupting compounds;
EDTA: ethylenediaminetetraacetic acid;
EE2: 17α-ethinylestradiol;
EI: electron impact;
ESI: electrospray ionization;
EtAc: ethyl acetate;
EtOH: ethanol;
EU: European Union;
FAA: fatty acid alkanolamides;
FL: fluorescence detector;
FMASE: focused microwave assisted Soxhlet extraction;
FQs: fluoroquinolones;
FRs: flame retardants;
GC: gas chromatography;
GCB: graphitised carbon black;
GC-MS/MS: gas chromatography tandem mass spectrometry;
GPC: gel permeation chromatography;
HAc: acetic acid;
HBCD: hexabromocyclododecane;
HE1: 16α-hydroxyestrone;
hexaBBz: hexabromobenzene;
HFBA: heptafluorobutyric acid;
HF-LPME: hollow fibre liquid-phase microextraction;
HHCB: galaxolide;
HRGC: high resolution gas chromatography;
HRMS: high resolution mass spectrometry;
HS-SPME: headspace solid-phase microextraction;
HSToF-MS: high speed time of flight mass spectrometry;
ICP: inductively coupled plasma;
iPOH: isopropanol;
IT: ion trap;
IPC: ion pair chromatography;
L: levonorgestrel;
LAS: linear alkylphenol sulphonates;
LC: liquid chromatography;
LC-MS/MS: liquid chromatography tandem mass spectrometry;
LC-MS^n: liquid chromatography multiple-stage mass spectrometry;
LLE: liquid-liquid extraction;
LOD: limit of detection;
LOQ: limit of quantification;
LP: low pressure;
LRMS: low resolution mass spectrometry;
LVI: large volume injection;
MA: musk ambrette;
MAE: microwave assisted extraction;
MA-HS-SPME: microwave assisted headspace solid-phase microextraction;
MAME: microwave assisted micellar extraction;
MDP: medroxyprogesterone;
MeOH: methanol;
MIPs: molecularly imprinted polymers;
MISPE: molecularly imprinted solid-phase extraction;
MK: musk ketone;

MLs: macrolides;
MM: musk moskene;
MPC: mixed-phase cation;
MS: mass spectrometry;
MSPD: Matrix solid phase dispersion;
MSTFA: N-methyl-N-(trimethylsilyl)trifluoroethyl acetamide;
MT: musk tibetene;
MTBE: tert-butyl methyl ether;
MTBSTFA: N-(terbutyldimethylsilyl)-N-methyl trifluoroacetamide;
MX: musk xylene;
N: norethindrone,
NBFRs: novel brominated flame retardants;
NCI: negative chemical ionisation;
NMG: n-methylglucamides;
NP: nonylphenol;
NP1EC: nonylphenoxy acetic acid;
NP1EO: nonylphenol monoethoxylate;
NP2EC: nonylmonoethoxy acetic acid;
NP2EO: nonylphenol diethoxylate;
NPD: nitrogen-phosphorus detector;
NPECs: nonylphenol ethoxy carboxylates;
NPEOs: nonylphenol polyethoxylates;
OP: octylphenol;
OPFRs: organophosphate flame retardants;
P: progesterone;
PAH: polycyclic aromatic hydrocarbons;
PBBs: polybrominated biphenyls;
PBCCH: pentabromochorocyclohexane;
PBDEs: polybrominated diphenyl ethers;
PBEB: pentabromoethylbenzene;
PBT: 2,3,4,5,6-pentabromotoluene;
PCBs: polychlorinated byphenols;
PCPs: personal care products;
PDMS-β-CD: polydimethylsiloxane-β-cyclodextrin;
PDMS/DVB: polydimethylsiloxane/divinylbenzene;
Pent: pentane;
PLE: pressurized liquid extraction;
PPCP: pharmaceutical and personal care products;
PSA: primary secondary amine;
pTBX: 2,3,5,6-tetrabromo-p-xylene;
PTFE: Polytetrafluoroethylene;
PTV: programmable temperature vaporizer;
QACs: quaternary ammonium compounds;
QNs: quinolones;
QToF: quadrupole time-of-flight;
S/N: signal to noise ratio;
SAESC: sonication-assisted extraction in small columns;
SAS: secondary alkane sulphonates;
SAs: sulphonamides;
SAX: strong anion exchange;
SBSE: stir bar sorptive extraction;
SIM: selected ion monitoring;
SPCs: sulphophenyl carboxylate compounds;

SPE: solid phase extraction;
SPME: solid-phase microextraction;
SWE: subcritical water extraction;
TBA: tetrabutylammonium;
TBBPA: tetrabromobisphenol A;
TBBPA-dbpe: tetrabromobisphenol A-bis(2,3-dibromopropylether);
TBC: tris(2,3-dibromopropyl)isocyanurate;
TBoCT: tetrabromo-o-chlorotoluene;
TBP: tris (butyl) phosphate;
TBPhA: tetrabromophthalic anhydride;
TCBPA: tetrachlorobisphenol A;
TCC: triclocarban;
TCEP: tris(2-chloroethyl) phosphate;
TCP: tritolyl phosphate;
TCPP: tris(2-chloropropyl) phosphate;
TCs: tetracyclines;
TCS: triclosan;
TDBPP: tris(2,3-dibromopropyl) phosphate;
TDCP: tris(1,3-dichloro-2-propyl) phosphate;
TEA: triethylamine;
TEHP: tris(2-ethylhexyl) phosphate;
TEP: triethyl phosphate;
TMCS: trimethylchlorosilane;
TMS: trimethylsilyl;
ToF: time of flight;
TPP: triphenyl phosphate;
UAE: ultrasound assisted extraction;
UPLC-MS/MS: ultra performance liquid chromatography tandem mass spectrometry;
US-EPA: United States Environmental Protection Agency;
UV: ultraviolet-visible detection;
WWTPs: wastewater treatment plants.

References

[1] A.F. Cirelli, C. Ojeda, M.J.L. Castro, M. Salgot, Organic Farming, Pest Control and Remediation of Soil Pollutants. Sustainable Agriculture Reviews 1, 227 (2010)
[2] G.G. Ying, Environ. Intern. 32, 417 (2006)
[3] M.I. Levinton, Surfactant production: present realities and future perspectives. Handbook of Detergents (Taylor & Francis, CRC Press Books, 2009)
[4] A.K. Mungray, P. Kumar, Int. Biodeter. Biodegr. 63, 981 (2009)
[5] P. Eichhorn, S. Lopez, D. Barceló, J. Chromatogr. A 1067, 171 (2005)
[6] V. Andreu, Y. Picó, Anal. Chem. 76, 2878 (2004)
[7] M. Villar, M. Callejon, J.C. Jimenez, E. Alonso, Anal. Chim. Acta 599, 92 (2007)
[8] M. Villar, M. Callejon, J.C. Jimenez, E. Alonso, A. Guiraum, Anal. Chim. Acta 634, 267 (2009)
[9] M. Villar, R. Fernandez-Torres, M. Callejon, R. Villar, J.C. Jimenez, Microchem. J. 90, 164 (2008)
[10] J. Riu, E. Martínez, D. Barceló, A. Ginebreda, L.L. Tirapu, Fresenius J. Anal. Chem. 371, 448 (2001)
[11] F. Bruno, R. Curini, A. Di Corcia, I. Fochi, M. Nazzari, R. Samperi, Environ. Sci. Technol. 36, 4156 (2002)
[12] R. Alzola, B. Pons, D. Bravo, A. Arranz, Environ. Technol. 30, 463 (2009)
[13] S. Cantarero, A. Zafra-Gómez, O. Ballesteros, A. Navalón, J.L. Vílchez, C. Verge, J.A. de Ferrer, Environ. Toxicol. Chem. 30, 813 (2011)
[14] R. Jeannot, H. Sabik, E. Sauvard, T. Dagnac, K. Dohrendorf, J. Chromatogr. A 974, 143 (2002)
[15] M. Petrovic, S. Lacorte, P. Viana, D. Barceló, J. Chromatogr. A 959, 15 (2002)
[16] P.A. Lara-Martin, A. Gomez-Parra, E. Gonzalez-Mazo, J. Chromatogr. A 1114, 205 (2006)
[17] P.A. Lara-Martin, A. Gomez-Parra,

E. Gonzalez-Mazo, J. Chromatogr. A 1137, 188 (2006)
[18] S. González, M. Petrovic, D. Barceló, J. Chromatogr. A 1052, 111 (2004)
[19] K.A. Krogh, B.B. Mogensen, B. Halling-Sorensen, A. Cortes, K.V. Vejrup, D. Barceló, Anal. Bioanal. Chem. 376, 1089 (2003)
[20] I. Jiménez-Díaz, O. Ballesteros, A. Zafra-Gómez, G. Grovetto, J.L. Vílchez, A. Navalón, C. Verge, J.A. de Ferrer, Chemosphere 80, 248 (2010)
[21] V. Andreu, E. Ferrer, J.L. Rubio, G. Font, Y. Picó, Sci. Total Environ. 378, 124 (2007)
[22] M. Petrovic, D. Barceló, A. Diaz, F. Ventura, J. Am. Soc. Mass. Spectrom. 14, 516 (2003)
[23] M. Fountoulakis, P. Drillia, C. Pakou, A. Kampioti, K. Stamatelatou, G. Lyberatos, J. Chromatogr. A 1089, 45 (2005)
[24] M. Cantero, S. Rubio, D. Pérez-Bendito, J. Chromatogr. A 1046, 147 (2004)
[25] J. Bernacka, L. Pawlowska, P. Chaber, S. Bórska, I. Kondzielski, E. Polubiec. Environ. Protec. Eng. 35, 65 (2009)
[26] Y.K.K. Koh, T.Y. Chiu, N. Paterakis, A. Boobis, M.D. Scrimshaw, J.N. Lester, E. Cartmell. Environ. Technol. 30, 1415 (2009)
[27] M. Fernández-Sanjuan, A. Rigol, A. Sahuquillo, S. Rodríguez-Cruz, S. Lacorte, Anal. Bioanal. Chem. 394, 1525 (2009)
[28] T. Isobe, H. Takada, Environ. Toxicol. Chem. 23, 599 (2004)
[29] L. Núñez, E. Turiel, A. Martín-Esteban, J.L. Tadeo, J. Sep. Sci. 31, 2492 (2008)
[30] L. Núñez, E. Turiel, J.L. Tadeo, J. Chromatogr. A 1146, 157 (2007)
[31] F. Merino, S. Rubio, D. Pérez-Bendito, J. Chromatogr. A 998, 143-154 (2003)
[32] E. Martínez-Carballo, C. González-Barreiro, A. Sitka, N. Kreuzinger, S. Scharf, O. Gans, Environ. Pollut. 146, 543 (2007)
[33] I. Ferrer, E.T. Furlong, Anal. Chem. 74, 1275 (2002)
[34] X. Li, B.J. Brownawell, Anal. Chem. 81, 7926 (2009)
[35] P.A. Lara-Martin, M. Petrovic, A. Gomez-Parra, D. Barceló, E. Gonzalez-Mazo, Environ. Pollut. 114, 483 (2006)
[36] European Commission. Working Document on Sludge 3rd draft (27 April 2000) (http://ec.europa.eu/environment/waste/sludge/pdf/sludge_en.pdf)
[37] Hera, Human & Environmental Risk Assessment on ingredients of European household cleaning products. LAS. Linear Alkylbenzene Sulphonate. June 2009. Version 4.0.
[38] J.J. Morelli, G. Szajer, J. Surfactants Deterg. 3, 539 (2000)
[39] European Union, Decision No 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, Off. J. L331, 15/12/2001
[40] S. Savic, M. Lukic, I. Jaksic, S. Reichl, S. Tamburic, C. Müller-Goymann, J. Colloid Interface Sci. 358, 182 (2011)
[41] P.S. Piispannen, M. Persson, P. Claesson, T. Norin, J. Surfactants Deterg. 7, 147 (2004)
[42] L. Sánchez-Prado, C. Garcia-Jares, M. Llompart, J. Chromatogr. A 1217, 2390 (2010)
[43] K.H. Langford, M.D. Scrimshaw, J.N. Lester, Environ. Technol. 25, 975 (2004)
[44] J. Llorca-Pórcel, M. Martínez-Parreño, E. Martínez-Soriano, I. Valor, J. Chromatogr. A 1216, 5955 (2009)
[45] M. Petrovic, D. Barceló, Chromatographia 56, 535 (2002)
[46] V. Croce, L. Patrolecco, S. Olesello, S. Valsecchi, Chromatographia 58, 145 (2003)
[47] M. Petrovic, S. Tavazzi, D. Barceló, J. Chromatogr. A 971, 37 (2002)
[48] J.L. Berna, G. Cassani, C.-D Hager, N. Rehman, I. López, D. Schowanek, J. Steber, K. Taeger, T. Wind, Tenside Sur. Det. 44, 312 (2007)
[49] A. Hibberd, K. Maskaoui, Z. Zhang, J.L. Zhou, Talanta 77, 1315 (2009)
[50] A. Arditsoglou, V. Doutsa, Environ. Sci. Pollut. Res. 15, 228 (2008)
[51] R. Céspedes, M. Petrovic, D. Raldúa, U. Saura, B. Piña, S. Lacorte, P. Viana, D. Barceló, Anal. Bioanal. Chem. 378, 697 (2004)
[52] R. Liu, J.L. Zhou, A. Wilding, J. Chromatogr. A 1038, 19 (2004)
[53] S. Gang, Y. Gang, C. Zhenxiao, Z. Zulin, Chinese Sci. Bull. 50, 2681 (2005)
[54] I. Aparicio, J.L. Santos, E. Alonso, Anal. Chim. Acta 584, 455 (2007)
[55] G. Gatidou, N.S. Thomaidis, A.S. Stasinakis, T.D. Lekkas, J. Chromatogr. A 1138, 32 (2007)
[56] L. Bartolomé, E. Cortazar, J.C. Raposo, A. Usobiaga, O. Zuloaga, N. Etxebarria, L.A. Fenández, J. Chromatogr. A 1068, 229 (2005)
[57] A. Errekatxo, A. Prieto, O. Zuloaga, A. Usobiaga, N. Etxebarria, L.A. Fernández, Anal. Bioanal. Chem. 392, 1471 (2008)
[58] X. Li, B.J. Brownawell, Environ. Sci. Technol. 44, 7561(2010)
[59] P.A. Lara-Martin, X. Li, R.F. Bopp, B.J. Brownawell, Environ. Sci. Technol. 44, 7569 (2010)

[60] K. Bester, J. Environ. Monit. 7, 509 (2005)
[61] I. Mihajlović, M.V. Miloradov, E. Fries, Environ. Sci. Technol. 45, 2254 (2011)
[62] E. Martínez-Carballo, C. González-Barreiro, A. Sitka, S. Sigrid, O. Gans, Sci. Total Environ. 388, 290 (2007)
[63] H-W. Chung, W-H. Ding, Anal. Bioanal. Chem. 395, 2325 (2009)
[64] X. Chen, K. Bester, Anal. Bioanal. Chem. 395, 1877 (2009)
[65] M. García-López, I. Rodríguez, R. Cela, K.K. Kroening, J.A. Caruso, Talanta 79, 824 (2009)
[66] M. García-López, I. Rodríguez, R. Cela, J. Chromatogr. A 1216, 6986 (2009)
[67] A. Marklund, B. Anderson, P. Haglund, Environ. Sci. Technol. 39, 7423 (2005)
[68] E. Eljarrat, D. Barceló, Trends Anal. Chem. 23, 10 (2004)
[69] A. Covaci, S. Voorpoels, J. de Boer, Environ. Intern. 29, 735 (2003)
[70] A. Covaci, A.C. Gerecke, R.J. Law, S. Voorspoels, M. Kohler, N.V. Heeb, H. Leslie, C.R. Allchin, J. de Boer, Environ. Sci. Technol. 40, 3679 (2006)
[71] A. Covaci, S. Voorpoels, M.A-E. Abdallah, T. Geens, S. Harrad, R.J. Law, J. Chromatogr. A 1216, 346 (2009)
[72] A. Covaci, S. Voorpoels, L. Ramos, H. Neels, R. Blust, J. Chromatogr. A 1153, 145 (2007)
[73] A. Covaci, S. Harrad, M.A-E. Abdallah, N. Ali, R.J. Law, D. Herzke, C.A. de Wit, Environ. Intern. 37, 532 (2011)
[74] A. Kierkegaard, U. Sellström, M.S. McLachlan, J. Chromatogr. A 364 (2009)
[75] Directive 2006/11/EC of the European Parliament and of the Council of 6 February 2003 amending for the 24th time Council directive 76/769/EEC relating on the marketing and the use of certain dangerous substances and preparations (pentabromodiphenyl ether and octabromodiphenyl ether), Official Journal L 042, 15/02/2003
[76] WHO-World Heath Organization. EHC-152: Polybrominated biphenyls; International Program on Chemical Safety (WHO, Geneva, Switzerland, 1994) 76
[77] European Court of Justice, Cases C-14/06 and C-295/06. Judgement of the Court. 1 April 2008. Directive 2002/95/EC and Commission Decision 2005/717/EC. htpp://curia.europa.eu accessed July 2010
[78] A.R. Fontana, M.F. Silva, L.D. Martínez, R.G. Wuilloud, J.C. Altamirano, J. Chromatogr. A 1212, 4339 (2009)
[79] A. de la Cal, E. Eljarrat, D. Barceló, J. Chromatogr. A 1021, 165 (2003)
[80] E. Eljarrat , A. de la Cal, D. Raldúa, C. Duran, D. Barceló, Environ. Sci. Technol. 38, 2603 (2004)
[81] J. de Boer, P.G. Wester, A. van der Horst, P.E.G. Leonards, Environ. Pollut. 122, 63 (2003)
[82] A. Hassanin, K. Breivik, S.N. Meijer, E. Steinnes, G.O. Thomas, K. Jones, Environ. Sci. Technol, 38, 738 (2004)
[83] D. Wang, Z. Cai, G. Jiang, M.H. Wong, W.K. Wong, Rapid Commun. Mass Spectrom. 19, 83 (2005)
[84] D.H. Oros, D. Hoover, F. Rodigari, D. Crane, J. Sericano, Environ. Sci. Technol, 39, 33 (2005)
[85] V. Yusà, O. Pardo, A. Pastor, M. de la Guardia, Anal. Chim. Acta 557, 304 (2006)
[86] S. Harrad, S. Hunter, Environ. Sci. Technol. 40, 4548 (2006)
[87] C. Salgado-Petinal, M. Llompart, C. García-Jares, M. García-Chao, R. Cela, J. Chromatogr. A 1124, 139 (2006)
[88] C. Salgado-Petinal, M. García-Chao, M. Llompart, C. García-Jares, R. Cela, Anal. Bioanal. Chem 385, 637 (2006)
[89] C. Sánchez-Brunete, E. Miguel, J.L. Tadeo, Talanta 70, 1051 (2006)
[90] Z. Cai, G. Jiang, Talanta 70, 88 (2006)
[91] M. Shin, M.L. Svoboda, P. Falleta, Anal. Bioanal. Chem. 387, 2923 (2007)
[92] P. Sedôdio, M. Salomé Cabrial, J.M.F. Nogueira, J. Chromatogr. A 1141, 259 (2007)
[93] Q, Xiao, B. Hu, J. Duan, M. He, W. Zu, J. Am. Soc. Mass Spectrom. 18, 1740 (2007)
[94] E. Eljarrat, A. Labandeira, G. Marsh, D. Raldúa, D. Barceló, Chemosphere 69, 1278 (2007)
[95] S.H. Yun, R. Addink, J.M. McCabe, A. Ostaszewski, D. Mackenzie-Taylor, A.B. Taylor, K. Kannan, Arch. Environ. Contam. Toxicol. 55, 1 (2008)
[96] Z.Z. Yang, X.R. Zhao, Q. Zhao, Z.F. Qin, X.F. Qin, X.B. Xu, Z.X. Jin, C.X. Xu, Bull. Environ. Contam. Toxicol. 80, 340 (2008)
[97] M. Kohler, M. Zennegg, C. Bogdal, A.C. Gerecke, P. Schmid, N.V. Heeb, M. Sturm, H. Vonmont, H-P.E. Kohler, W. Gifer, Environ. Sci. Technol. 42, 6378 (2008)
[98] K. Li, S. Fu, Z.Z. Yang, X.B. Xu, Bull. Environ. Contam. Toxicol. 81, 588 (2008)
[99] E. Eljarrat, G. Marsh, A. Labandeira, D. Barceló, Chemosphere 71, 1079 (2008)
[100] T. Kupper, L.F. de Alencastro, R. Gatsigazi, R. Furrer, D. Grandjean, J. Tarradellas, Chemosphere 71, 1173 (2008)
[101] N. Ricklund, A. Kierkegaard, M.S. McLachlan, C. Wahlberg, Chemosphere 74, 389 (2008)
[102] X. Wang, N. Ren, H. Qi, W. Ma, Y. Li, J. Environ.

Sci. 21, 1541 (2009)
[103] J. Ma, R. Addink, S. Yun, J. Cheng, W. Wang, K. Kannan, Environ. Sci. Technol. 43, 7350 (2009)
[104] K. Li, S. Fu, Z.Z. Yang, X.B. Xu, Bull. Environ. Contam. Toxicol. 83, 926 (2009)
[105] K. Mizukawa, H. Takada, I. Takeuchi, T. Ikemoto, K. Omori, K. Tsuchiya, Mar. Pollut. Bull. 58, 1217 (2009)
[106] C. Sánchez-Brunete, E. Miguel, J.L. Tadeo, J. Sep. Sci. 32, 109 (2009)
[107] R. Montes, I. Rodríguez, R. Cela, J. Chromatogr. A 1217, 14 (2010)
[108] N.A. Andrade, L. McConneli, A. Torrents, M. Ramirez, J. Agric. Food Chem. 58, 3077 (2010)
[109] U.R. Thorenz, B.A.M. Bandowe, J. Sobocka, W. Wilcke, Environ. Pollut. 158, 2208 (2010)
[110] Z. Zhang, M. Shanmugam, S.M. Rhind, Chromatographia 72, 535 (2010)
[111] S. Lacorte, M.G. Ikonomou, M. Fischer, J. Chromatogr. A 1217, 337 (2010)
[112] H.M. Stapleton, J.M. Keller, M.M. Schantz, J.R. Kurcklick, S.D. Leigh, S.A. Wise, Anal. Bioanal. Chem. 387, 2365 (2007)
[113] P. Wang, Q. Zhang, Y. Wang, T. Wang, X. Li, L. Ding, G. Jiang, Anal. Chim. Acta 663, 43 (2010)
[114] R.F. Swarthout, J.R. Kucklick, W.C. Davis, J. Anal. At. Spectrom. 23, 1575 (2008)
[115] C.A. de Wit, Chemosphere 46, 583 (2002)
[116] R.J. Law, M. Alaee, C.R. Alchin, J.P. Boon, M. Lebeuf, P. Lepom, G.A. Stern, Environ. Intern. 29, 757 (2003)
[117] R. Saint-Louis, E. Pelletier, Analyst 129, 724 (2004)
[118] E. Blanco, M.C. Casais, M.C. Mejuto, R. Cela, Anal. Chem, 78, 2772 (2006)
[119] P. Labadie, K. Tili, F. Alliot, C. Bourges, A. Desportes, M. Chevreuil, Anal. Bioanal. Chem. 396, 865 (2010)
[120] C. Yu, B. Hu, J. Chromatogr. A 1160, 71 (2007)
[121] S. Chu, G.D. Haffner, R.J. Letcher, J. Chromatogr. A 1097, 25 (2005)
[122] C. Sánchez-Brunete, E. Miguel, J.L. Tadeo, J. Chromatogr. A 1216, 5497 (2009)
[123] C.H. Marvin, G.T. Tomy, M. Alaee, G. MacInnis, Chemosphere 64, 268 (2006)
[124] Z. Yu, Ping, A. Peng, G. Sheng, J. Fu, J. Chromatogr. A 1190, 74 (2008)
[125] P. Guerra, E. Eljarrat, D, Barceló, J. Chromatogr. A 1203, 81 (2008)
[126] H.H. Wu, H.C. Chen, W.H. Ding, J. Chromatogr. A 1216, 7755 (2009)
[127] A.I. García-Valcárcel, J. L. Tadeo, J. Sep. Sci. 32, 3890 (2009)
[128] S. Gao, J. Wang, Z. Yu, Q. Guo, G. Sheng, J. Fu, Environ. Sci. Technol. 45, 2093 (2011)
[129] M, Remberger, J. Sternbeck, A. Palm, L. Kaj, K. Strömberg, E. Brorström-Lundén, Chemosphere 54, 9 (2004)
[130] X.Z. Meng, Y.P. Duan, C. Yang, Z.Y. Pan, Z.H. Wen, L. Chen, Chemosphere 82, 725 (2011)
[131] J. Feng, Y. Wang, T. Ruan, G. Qu, G. Jiang, Talanta 82, 1929 (2010)
[132] P. Guerra, E. Eljarrat, D. Barceló, Anal. Bioanal. Chem. 397, 2817 (2010)
[133] S. Suzuki, A. Hasegawa, Anal. Sci. 22, 469 (2006)
[134] E. Morris, C.R. Allchin, B.N. Zegers, J.J.H. Haftka, J.P. Boon, C. Belpaire, P.E.G. Leonards, S.P.J. van Leeuwen, J, de Boer, Environ. Sci. Technol. 38, 5497 (2004)
[135] T. Kupper, L.F. Alencastro, R. Gatsigazi, R. Furrer, D. Grandjean, J. Tarradellas, Chemosphere 71, 1173 (2008)
[136] M.S. Ross, C.S. Wong, J. Chromatogr. A 1217, 7855 (2010)
[137] A. Kierkegaard, J. Björklund, U. Fridén, Environ. Sci. Technol. 38, 3247 (2004)
[138] M. Ilyas, A. Sudaryanto, I.E. Setiawan, A.S. Riyadi, T. Isobe, S. Ogawa, S. Takahashi, S. Tanabe, Chemosphere 83, 783 (2011)
[139] A. Konstantinov, G. Arsenault, B. Chittim, T. Kolic, K. MacPherson, A. McAlees, R. McCrindle, D. Potter, E.J. Reiner, C. Tashiro, B. Yeo, Chemosphere 64, 245 (2006)
[140] X.L. Zhang, X.J. Luo, S.J. Chen, J.P. Wu, B.X. Mai, Environ. Pollut. 157, 1917 (2009)
[141] T. Shi, S.J. Chen, X.J. Luo, X.L. Zhang, C.M. Tang, Y. Luo, Y.J. Ma, J.P. Wu, X.Z. Peng, B.X. Mai, Chemosphere 74, 910 (2009)
[142] T. Ruan, Y. Wang, C. Wang, P. Wang, J. Fu, Y. Yin, G. Qu, T. Wang, G. Jiang, Environ. Sci. Technol. 43, 3080 (2009)
[143] N. Ricklund, A. Kierkegaard, M.S. McLachlan, C. Wahlberg, Chemosphere 73, 1799 (2008)
[144] N. Ricklund, A. Kierkegaard, M.S. McLachlan, Environ. Sci. Technol. 44, 1987 (2010)
[145] P. Guerra, E. Eljarrat, D. Barceló, J. Hydrology 383, 39 (2010)
[146] R. Köppen, R. Becker, C. Jung, C. Piechotta, I. Nehls, Anal. Bioanal. Chem. 384, 1485 (2006)
[147] P. López, S. A. Brandsma, P.E.G. Leonards, J. de Boer, Anal. Bioanal Chem. 400, 871 (2011)
[148] K. Breivik, F. Wania, D.C. Muir, M. Alaee,

S. Backus, G. Apacepavicius, Environ. Sci. Technol. 40, 4612 (2006).
[149] C. Bogdal, P. Schmid, M. Kohler, C.E. Müller, S. Iozza, T.D. Buchelli, M. Scheringer, K. Hungerbühler, Environ. Sci. Technol. 42, 6817 (2008)
[150] E. Hoh, L. Zhu, R.A. Hites, Environ. Sci. Technol. 40, 1184 (2006)
[151] L. Shen, E.J. Reiner, K.A. Macpherson, T.M. Kolic, E. Sverko, P.A. Helm, S.P. Bhavsar, I.D. Brindle, C.H. Marvin, Environ. Sci. Technol. 44, 760 (2010)
[152] L. Shen, E.J. Reiner, K.A. Macpherson, T.M. Kolic, P.A. Helm, L.A. Richman, C.H. Marvin, D.A. Burniston, B. Hill, I.D. Brindle, R. McCrindle, B.G. Chittim, Environ. Sci. Technol. 45, 693 (2011)
[153] X. Qiu, C.H. Marvin, R.A. Hites, Environ. Sci. Technol. 41, 6014 (2007)
[154] E. Sverko, G.T. Tomy, C.H. Marvin, D. Zaruk, E. Reiner, P. Helm, B. Hill, B.E. McCarry, Environ. Sci. Technol. 42, 361 (2008)
[155] Z. Zhao, G. Zhong, A. Möller, Z. Xie, R. Sturm, R. Ebinghaus, J. Tang, G. Zhang, Chemosphere 83, 984 (2011)
[156] Z. Yu, S. Lu, S. Gao, J. Wang, H. Li, X. Zeng, G. Sheng, J. Fu, Environ. Pollut. 158, 2920 (2010)
[157] B. Wang, F. Iino, J. Huang, Y. Lu, G. Yu, M. Morita, Chemosphere 80, 1285 (2010)
[158] A. de la Torre, E. Sverko, M. Alaee, M.A. Martínez, Chemosphere 82, 692 (2011)
[159] S.N. Zhou, E.J. Reiner, C.H. Marvin, P.A. Helm, L. Shen, I.D. Brindle, Rapid Commun. Mass Spectrom. 25, 436 (2011)
[160] H. Jia, Y. Sun, X. Liu, M. Yang, D. Wang, H. Qi, L. Shen, E. Sverko, E.J. Reiner, Y.F. Li, Environ. Sci. Technol. 45, 2613 (2011)
[161] J. Beausse, Trends Anal. Chem. 23, 735 (2004)
[162] A. Nieto, F. Borrull, E. Pocurull, R.M. Marcé, Trends Anal. Chem. 29, 752 (2010)
[163] A. Kot-Wasik, J. Dębska, J. Namieśnik, Trends Anal. Chem. 26, 557 (2007)
[164] W.W. Buchberger, J. Chromatogr. A 1218, 603 (2011)
[165] M.S. Díaz-Cruz, M.J. García-Galán, P. Guerra, A. Jelic, C. Postigo, E. Eljarrat, M. Farré, M.J. López de Alda, M. Petrovic, D. Barceló, Trends Anal. Chem. 28, 1263 (2009)
[166] C. Hao, X. Zhao, P. Yang, Trends Anal. Chem. 26, 569 (2007)
[167] G. Hamscher, Silke Sczesny, H. Höper, H. Nau, Anal. Chem. 74, 1509 (2002)
[168] M.Ö. Uslu, A. Yediler, I.A. Balcioğlu, S. Schulte-Hostede, Water Air Soil Pollut. 190, 55 (2008)
[169] S.C. Kim, K. Carlson, Anal. Bioanal. Chem. 387, 1301 (2007)
[170] S.C. Kim, K. Carlson, Water Res. 40, 2549 (2006)
[171] W. Chenxi, A.L. Sponberg, J.D. Witter, Chemosphere 73, 511 (2008)
[172] E. Turiel, A. Martín-Esteban, J.L. Tadeo, Anal. Chim. Acta 562, 30 (2006)
[173] E. Turiel, A. Martín-Esteban, J.L. Tadeo, J. Chromatogr. A 1172, 97 (2007)
[174] F. Chen, G.G. Ying, L.X. Kong, L. Wang, J.L. Zhao, L.J. Zhou, L.J. Zhang, Environ. Pollut. 159, 1490 (2011)
[175] D. Löffler, T.A. Ternes, J. Chromatogr. A 1021, 133 (2003)
[176] Y.W. Li, X.L. Wu, C.H. Mo, Y.P. Tai, X.P. Huang, L. Xiang, J. Agric. Food Chem. 59, 7268 (2011)
[177] E. Martínez-Carballo, C. González-Barreiro, S. Scharf, O. Gans, Environ. Pollut. 148, 570 (2007)
[178] S.He, Q. Chen, Y. Sun, Y. Zhu, L. Luo, J. Li, Y. Cao, J. Chromatogr. B 879, 901 (2011)
[179] P.A. Blackwell, H.C. Holten Lützhøft, H.P. Ma, B. Halling-Sørensen, A.B.A. Boxall, P. Kay, Talanta 64, 1058 (2004)
[180] J.F. Yang, G.G. Ying, J.L. Zhao, R. Tao, H.C. Su, F. Chen, Sci. Total Environ. 408, 3424 (2010)
[181] A. Göbel, A. Thomsen, C.S. McArdell, A.C. Alder, W. Giger, N. Theiss, D. Löffler, T.A .Ternes, J. Chromatogr. A 1085, 179 (2005)
[182] E.M. Golet, A. Strehler, A.C. Alder, W. Giger, Anal. Chem. 74, 5455 (2002)
[183] A.M. Jacobsen, B. Halling-Sørensen, F. Ingerslev, S.H. Hansen, J. Chromatogr. A 1038, 157 (2004)
[184] M.D. Prat, D. Ramil, R. Compañó, J.A. Hernández-Arteseros, M. Granados, Anal. Chim. Acta 567, 229 (2006)
[185] L. Chen, Q. Zhao, Y. Xu, L. Sun, Q. Zeng, H. Xu, H. Wang, X. Zhang, A. Yu, H. Zhang, L. Ding, Talanta 82, 1186 (2010)
[186] E.M. Golet, A.C. Alder, A. Hartmann, T.A Ternes, W. Giger, Anal. Chem. 73, 3632 (2001)
[187] J. Minten, M. Adolfsson-Erici, T. Alsberg, Intern. J. Environ. Anal. Chem. 91, 553 (2011)
[188] A. Karnjanapiboonwong, J.G. Suski, A.A. Shah, Q. Cai, A.N. Morse, T.A. Anderson, Water Air Soil Pollut. 216, 257 (2011)
[189] Q. Huang, Y. Yu, C. Tang, X. Peng, J. Chromatogr. A 1217, 3481 (2010)
[190] A.I. García-Valcárcel, J.L. Tadeo, J. Sep. Sci. 34,

1228 (2011)
[191] J. Martin, J.L. Santos, I. Aparicio, E. Alonso, J. Sep. Sci. 33, 1760 (2010)
[192] T.A. Ternes, M. Bonerz, N. Herrmann, D. Löffler, E. Keller, B. Bagó Lacida, A.C. Alder, J. Chromatogr. A 1067, 213 (2005)
[193] J. Xu, L. Wu, W. Chen, A.C. Chang, J. Chromatogr. A 1202, 189 (2008)
[194] V.G. Samaras, N.S. Thomaidis, A.S. Stasinakis, T.D. Lekkas, Anal. Bioanal. Chem. 399, 2549 (2011)
[195] J.P. Bossio, J. Harry, C.A. Kinney, Chemosphere 70, 858 (2008)
[196] Y. Ding, W. Zhang, C. Gu, I. Xagoraraki, H. Li, J. Chromatogr. A 1218, 10 (2011)
[197] J.C. Durán-Alvarez, E. Becerril-Bravo, V. Silva Castro, B. Jiménez, R. Gibson, Talanta 78, 1159 (2009)
[198] M. Edwards, E. Topp, C.D. Metcalfe, H. Li, N. Gottschall, P. Bolton, W. Curnoe, M. Payne, A. Beck, S. Kleywegt, D.R. Lapen, Sci. Total Environ. 407, 4220 (2009)
[199] E.B. Dussault, V.K. Balakrishnan, K.R. Solomon, P.K. Sibley, Can. J. Chem. 87, 662 (2009)
[200] E. Pérez-Carrera, M. Hansen, V.M. León, E. Björklund, K.A. Krogh, B. Halling-Sørensen, E. González-Mazo, Anal. Bioanal. Chem. 398, 1173 (2010)
[201] J. Radjenović, A. Jelić, M. Petrović, D. Barceló, Anal. Bioanal. Chem. 393,1685 (2009)
[202] A. Jelić, M. Petrović, D. Barceló, Talanta 80, 363 (2009)
[203] K. Stein, M. Ramil, G. Fink, M. Sander, T.A. Ternes, Environ. Sci. Technol. 42, 6415 (2008)
[204] C.A Kinney, E.T. Furlong, S.L. Werner, J.D. Cahill, Environ. Toxicol. Chem. 25, 317 (2006)
[205] M.M. Schultz, E.T. Furlong, D.W. Kolpin, S.L. Werner, H.L. Schoenfuss, L.B. Barber, V.S. Blazer, D.O. Norris, A.M. Vajda, Environ. Sci. Technol. 44, 1918 (2010)
[206] A. Saleh, E. Larsson, Y. Yamini, J.A. Jönsson, J. Chromatogr. A 1218, 1331 (2011)
[207] P. Vazquez-Roig, R. Segarra, C. Blasco, V. Andreu, Y. Picó, J. Chromatogr. A 1217, 2471 (2010)
[208] S.L. Rice, S. Mitra, Anal. Chim. Acta 589, 125 (2007)
[209] J. Dobor, M. Varga, J. Yao, H. Chen, G. Palkó, G. Záray, Microchem. J. 94, 36 (2010)
[210] M. Varga, J. Dobor, A. Helenkár, L. Jurecska, J. Yao, G. Záray, Microchem. J. 95, 353 (2010)
[211] R. Cueva-Mestanza, Z. Sosa-Ferrera, M.E. Torres-Padrón, J.J. Santana-Rodríguez, J. Chromatogr. B 863, 150 (2008)
[212] E. Sagristá, E. Larsson, M. Ezoddin, M. Hidalgo, V. Salvadó, J. A. Jönsson, J. Chromatogr. A 1217, 6153 (2010)
[213] US-EPA. Method 1694: Pharmaceuticals and personal care products in water, soil, sediment and biosolids by HPLC/MS/MS. Washington DC, USA (2007)
[214] N. Larsson, E. Petersson, M. Rylander, J. A. Jönsson, Anal. Method 1, 59 (2009)
[215] W.W. Buchberger, Anal. Chim. Acta 593, 129 (2007)
[216] V. Gabet, C. Miege, P. Bados, M. Coquery, Trends Anal. Chem. 26, 1113 (2007)
[217] R.L. Gomes, E. Avcioglu, M.D. Scrimshaw, J.N. Lester, Trends Anal. Chem. 23, 737 (2004)
[218] W. Zheng, S.R. Yates, S.A. Bradford, Environ. Sci. Technol. 42, 530 (2008)
[219] K. Hajková, J. Pulkraborá, J. Schurek, J. Hajková, J. Poustka, M. Napravniková, V. Kocourek, Anal. Bioanal. Chem. 387, 1351 (2007)
[220] M.J. Lopez de Alda, A. Gil, E. Paz, D. Barceló, Analyst 127, 1299 (2002)
[221] T.A. Termes, H. Ardensen, D. Gilberg, M. Bonerz, Anal. Chem. 74, 3498 (2002)
[222] A. Nieto, F. Borull, E. Pocurull, R.M. Marcé, J. Chromatogr. A 1213, 224 (2008)
[223] M.P. Fernandez, T-N. Noguerol, S. Lacorte, I. Buchanan, B. Piña, Anal. Bioanal. Chem. 393, 957(2009)
[224] R. Liu, J.L. Zhou, A. Wilding, J. Chromatogr. A 1038, 19 (2004)
[225] S. Morales-Muñoz, J.L. Luque-Garcia, M.J. Ramos, M.J. Martinez-Bueno, M.D. Luque de Castro, Chromatographia 62, 69 (2005)
[226] P. Labadie, E.M. Hill, J. Chromatogr. A 1141, 174 (2007)
[227] D. Matejicek, P. Houserova, V. Kuban, J. Chromatogr. A 1171, 80 (2007)
[228] H.K. Jeon, Y. Chung, J.C. Ryu, J. Chromatogr. A 1131, 192 (2006)
[229] Z. Zhang, N. Ren, Y-F. Li, T. Kunisue, T. D. Gao, K. Kannan, Environ. Sci.Technol.45, 3909 (2011)
[230] C. Sánchez-Brunete, E. Miguel, B. Albero, J.L. Tadeo, J. Chromatogr. A 1218, 4291 (2011)
[231] C. Plagellat, T. Kupper, R. Furrer, L.F. de Alecanstro, D. Grandjean, J. Tarradellas, Chemosphere 62, 915 (2006)
[232] R. Rodil, M. Moeder, Anal. Chim. Acta 612, 152 (2008)
[233] R. Rodil, S. Schrader, M. Moeder, J. Chromatogr. A 1216, 8851 (2009)
[234] N. Negreira, I. Rodriguez, E. Rubí, R. Cela, J. Chromatogr. A 1218, 211 (2011)

[235] P. Gago-Ferrero, M.S. Diaz-Cruz, D. Barceló, Chemosphere 84, 1158 (2011)
[236] T. Kupper, C. Plagellat, R.C. Brandii, L.F. de Alencastro, D. Grandjean, J. Tarradellas, Water Res. 40, 2603 (2006)
[237] The Council Directive 76/768/EEC (1976). http://www.leffingwell.com/cosmetics/vol_1en.pdf
[238] L. Nuñez, J.L.Tadeo, A.I. Garcia-Valcarcel, E. Turiel, J. Chromatogr. A 1214, 178 (2008)
[239] L. Nuñez, E. Turiel, A. Martín-Esteban, J.L.Tadeo, Talanta 80, 1782 (2010)
[240] A. Nieto, F. Borrull, R.M. Marcé, E. Pocurull, J. Chromatogr. A 1216, 5619 (2009)
[241] R.A. Pérez, B. Albero, E. Miguel, C. Sánchez-Brunete, Anal. Bioanal. Chem. (2011 in press)
[242] T.R. Miller, J. Heidler, S.N. Chillrud, A. Delaquil, J.C. Ritchie, J.N. Mihalic, R. Bopp, R.U. Halden, Environ. Sci. Technol. 42, 4570 (2008)
[243] A.J. Al-Rajab, L. Sabourin, A. Scott, D.R. Lapen, E. Topp, Sci. Total Environ.407, 5978 (2009)
[244] G.C. Ying, X.Y. Yu, R.S. Kookana, Environ. Pollut. 450, 300 (2007)
[245] C. Wu, A.L. Spongberg, J.D. Witter, M. Fang, A. Ames, K.P. Czajkowski, Clean-Soil, Air, Water 38, 230 (2010)
[246] J. Cha, A.M. Cupples, Water Res. 43, 2522 (2009)
[247] N. Lozano, C.P. Rice, M. Ramírez, A. Torrents, Chemosphere 78, 760 (2010)
[248] J. Xu, L. Wu, A.C. Chang, Chemosphere 77, 1299 (2009)
[249] C. Sánchez-Brunete, E. Miguel, B. Albero, J.L. Tadeo, J. Sep. Sci. 33, 2768 (2010)
[250] A. Kronimus, J. Schwarzbauer, L. Dsikowitzky, S. Heim, R. Little, Water Res. 38, 3473 (2004)
[251] S. Morales, P. Canosa, I. Rodríguez, E. Rubi, R. Cela, J. Chromatogr. A 1082, 128 (2005)
[252] A. Aguera, A.R. Fernandez-Alba, L. Piedra, M. Mézcua, M. J. Gómez, Anal. Chim. Acta 480, 193 (2003)
[253] K. Bester, Water Res. 37, 3891(2003)
[254] S. Morales-Muñoz, J.L. Luque-Garcia, M.J. Ramos, M.J. Martinez-Bueno, M.D. Luque de Castro, Chromatographia. 62, 69 (2005)
[255] G.G. Ying, R.S. Kookana, Environ. Intern. 33, 199 (2007)
[256] S. Chu, C.D. Metcalfe, J. Chromatogr. A 1164, 212 (2007)
[257] J. Heilder, R.U. Halden, Chemosphere 66, 362 (2007)
[258] H. Singer, S. Miller, C. Tixier, L. Pillonel, Environ. Sci. Technol. 36, 4998 (2002)
[259] L. Sánchez-Prado, M. Lores, M. Llompart, C. Garcia-Jares, M. Lourido, R. Cela, J. Chromatogr. A 1048,73 (2004)
[260] A.M. Perck, Anal. Bioanal. Chem. 386, 907 (2006)
[261] X. Zeng, G. Sheng, Y. Xiong, J. Fu, Chemosphere 60, 817 (2005)
[262] M.L. Svoboda, J-J. Yang, P. Failleta, H.B. Lee, Water Qual. Res. J. Can. 42, 11 (2007)
[263] S.F. Wu, W.H. Ding, J. Chromatogr. A 1217, 2776 (2010)
[264] A.M. Difrancesco, P.C. Chiu, L.J. Standley, H.E. Allen, D.T. Salvito, Environ. Sci. Technol. 38, 194 (2004)
[265] J.J. Yang, C.D. Metcalfe, Sci. Total Environ. 363, 149 (2006)
[266] S.A. Smyth, L. Lishman, M. Alaee, S. Kleywegt, L. Svoboda, J-J- Yang, H-B Lee, P. Seto, Chemosphere 67, 267 (2007)
[267] M. Pedrouzo, F. Borrull, R.M. Marcé, E. Pocurull, J. Chromatogr. A 1216, 6994 (2009)
[268] A. Wick, G. Fink, T.A. Ternes, J. Chromatogr. A 1217, 2088 (2010)
[269] Y. Yu, Q. Huang, J. Cui, K. Zhang, C. Tang, X. Peng, Anal. Bioanal. Chem. 399, 891 (2011)