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Methodology for studying biotransformation of polyfluoroalkyl precursors in the environment



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ABSTRACT

Biotransformation of polyfluoroalkyl precursors contributes in part to the perfluoroalkyl carboxylates and sulfonates detected in the global environment and biota. Robust sample preparation and sensitive analytical techniques for maximum analyte recovery are essential to identify and to quantify biotransformation products often present at low levels in environmental matrices and experimental systems. This critical review covers current sample-preparation and analytical methods, including extraction, concentration, clean-up and derivatization, mass spectrometry coupled to gas or liquid chromatography, and radioisotope labeling and tracking techniques. We also critically review methodologies for molecular structural elucidation and *in-silico* prediction of potential transformation products. We describe current knowledge gaps and challenges in studying novel alternative polyfluoroalkyl substances. We discuss future trends on utilizing advanced analytical techniques.

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Abbreviations: APPI, Atmospheric pressure photoionization; ARC, Accurate radioisotopic counting; DNPH, 2,4-Dinitrophenylhydrazine; DSPE, Dispersive solid-phase extraction; ECD, Electron-capture detector; ECF, Electrochemical fluorination; EI, Electron impact; ESI, Electrospray ionization; FT, Fluorotelomer; GC-MS, Gas chromatography mass spectrometry; HRMS, High-resolution mass spectrometry; IDL, Instrument detection limit; IPE, Ion-pair extraction; LC-MS/MS, Liquid chromatography-tandem mass spectrometry; LSC, Liquid-scintillation counting; MRM, Multiple-reaction monitoring; MTBE, Methyl *tert*-butyl ether; NCI, Negative chemical ionization; PCI, Positive chemical ionization; PFASs, Per- and poly-fluoroalkyl substances; PFCA, Perfluoroalkyl carboxylate; PFP, Pentafluorophenyl; PFSA, Perfluoroalkyl sulfonate; QqQ, Triplequadupole mass spectrometry; QSAR, Quantitative structure-activity relationship; Q-TOF, Quadrupole-time of flight; TBAS, Tetrabutyl ammonium hydrogen sulfate; WMSE, Water-miscible solvent extraction; WWTP, Wastewater-treatment plant.

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1. Introduction

Perfluoroalkyl and polyfluoroalkyl substances (PFASs) are anthropogenic chemicals that have been used in the manufacture of additives and polymers for the past 60 years [1]. Due to their chemical inertness and surfactant properties, PFASs are used in household and industry applications, including surfactants, lubricants, paints, pesticides and coatings [2,3]. The broad use of PFASs has resulted in the wide distribution of perfluoroalkyl carboxylates (PFCAs) and perfluoroalkyl sulfonates (PFSAs) in environmental matrices and biological species, including humans [4–6]. The behavior of PFCAs and PFSAs, such as persistency, long-range transport propensity and potential toxicity, has attracted considerable attention to their possible adverse effects in the environment and biota [7,8].

The origins of PFASs entering into the environment are complex. Wang et al. [3] calculated the mass flux of PFCAs in the global transport processes and suggested that historical direct emissions from manufacture and consumer usages were the major contributors of PFCAs detected in the environment. However, the indirect contributions via the biodegradation and biotransformation of polyfluoroalkyl precursors and atmospheric oxidation have also been confirmed by model prediction [9], laboratory experiments [10,11] and environmental monitoring [12]. Laboratory systems utilizing microbialconsortium and animal models to study polyfluoroalkyl-precursor biotransformation provided insight to understand the extent of contributions of such precursors to PFCAs and PFSAs detected in the environment and biota.

Table 1 presents PFCA and PFSA precursors studied so far from telomerization, manufacturing and electrochemical fluorination (ECF) processes [1]. The potential precursors from telomerization include fluorotelomer alcohols (FTOHs), iodides (FTIs), olefins (FTOs), sulfonates (FTSAs), stearate monoesters (FTSs), citrate triester (TBC), polyfluoroalkyl phosphates (PAPs), polyethoxylated 2-perfluoroaklyl ethanols (FTEOs), and FTOH-based acrylate and urethane-based polymers. The potential precursors from ECF include mixtures of linear and branched isomers of perfluorooctane sulfonamide (FOSA), sulfonamido ethanol (FOSE), FOSE-based phosphate diester (SAmPAP diester) and sulfonamide-based acrylate polymers.

The design of biotransformation studies is associated with the occurrence and the partitioning of the above precursors in different environmental compartments. Both fluorotelomer-based (FT) precursors (e.g., FTOHs and FTIs) and perfluoroalkane sulfonamido derivatives, including N-ethyl perfluorooctane sulfonamide (N-EtFOSA) and N-ethyl perfluorooctane sulfonamidoethanol (N-EtFOSE), were found in ambient air particles [13–15]. Fluorotelomer alcohols, monosubstituted and disubstituted PAPs, and perfluorooctane sulfonamidoacetic acid (FOSAA) analogues have frequently been detected in wastewater-treatment plant (WWTP) effluent, activated sludge and marine sediments [15-17]. Elevated PFAS concentrations found in effluents compared with those in influents may further indicate contributions of polyfluorinated-precursor biodegradation in the WWTPs [18]. Covalent binding of certain intermediate transformation products (e.g., fluorotelomer unsaturated aldehydes or carboxylic acids) to nucleophilic amino acids and proteins, and formation of conjugated Phase II metabolites are also possible biological fates of polyfluoroalkyl precursors in mammals and fish [19-21].

Biotransformation processes of polyfluoroalkyl precursors in microbial and animal models generally initiate from the hydrocarbon part of the molecular structures, due to the high carbon-fluorine bond energy (450 KJ/mol) [22]. For example, biotransformation of fluorotelomer-based substances often involves cleavage of functional groups (e.g., ester, ether, urethane) to form FTOHs, which are then further converted to FT aldehyde (FTAL), FT unsaturated carboxylic acids (FTUCAs), FT ketone and FT secondary alcohol (sFTOH), and x:3 fluorotelomer acids ($F(CF_2)_nCH_2CH_2COOH$, n = 3-7) [23,24].

Sediment/soil-bound residues formed from precursors and related transformation products with highly absorptive properties (e.g., FTOHs and x:3 acids) are not quantifiable without optimized sample-extraction methods and proper analytical procedures [25,26]. Furthermore, sophisticated analytical instrumentation, such as high-resolution mass spectrometry (HRMS), is often needed to identify low levels of potential novel transformation products.

The aim of this review is to provide information from peerreviewed literature on comprehensive sample preparation and effective analytical methods for quantitative recovery and identification of transient intermediates and terminal polyfluorinated acids. We also discuss knowledge gaps and future trends in the analysis of novel alternative polyfluoroalkyl substances.

2. Sample-preparation strategy

2.1. Test system

A well-established test system should take into account the physical and chemical properties of the target polyfluoroalkyl precursors, and biotransformation studies should simulate close to what happens in different environmental matrices. Biotransformation of PFASs involves the defluorination process, which is usually a rate-limiting reaction, often leading to incomplete mineralization of polyfluoroalkyl precursors. Thus, measurements of the endpoints, such as biochemical oxygen demand and CO₂ production, in standardized ready and inherent biodegradability tests are not suitable for studying the biotransformation of polyfluoroalkyl precursors [24]. Instead, rigorous sample preparation and instrumental analysis methodologies in simulation tests were used to recover, to identify and to quantify specific polyfluoroalkyl precursors and transformation products to achieve understanding of biodegradation kinetics and pathways.

Generally, an aerobic test system consists of semi-static closed bottles, containing both headspace and liquid/solid phases. Aeration is achieved by pumping ambient air into the headspace when the oxygen content is below 10%. One or two C₁₈ SPE cartridges were inserted into the headspace as the conduit and to capture volatile parent and potential volatile transformation products [25,27]. To mimic continuous exchange of PFASs in surface soil or active sludge with surrounding air, flow-through systems using purge-and-trap methods were used to study 6:2 FTOH and 6:2 polyfluoroalkylphosphate biotransformation [26,28]. Wang et al. [29] found that the molar yield of perfluorooctanoic acid (PFOA) in the flowthrough system was only half of that in semi-static closed bottles. The lower yield was due to the partitioning of ¹⁴C-labeled 8:2 FTOH $[F(CF_2)_7{}^{14}CF_2CH_2CH_2OH]$ and 7:2 sFTOH $[F(CF_2)_7{}^{14}CH(OH)CH_3]$, a direct PFOA precursor, from soil to the headspace in the flow-through system, significantly reducing their availability for degradation to PFOA.

To avoid residual contamination and to reduce potential surface adsorption of the precursor and transformation products, test vessels and caps should be made of non-fluorinated materials. Polyfluoroalkyl substances in the narrow-necked glass bottles sealed with butyl-rubber stoppers and C_{18} cartridges are extractable and can be quantitatively recovered using a conventional solvent-extraction method (see sub-section 2.2) to reduce adsorption losses on the laboratory ware.

Various kinds of environmental matrices and animal models were chosen as the investigating matrices, depending on the presence and the behavior of polyfluoroalkyl precursors in the real environment. Soil is the primary deposit medium of volatile precursors through atmospheric deposition, while sewage sludge and river sediment are important sinks of PFASs in aqueous systems from household and industry emissions [15–17]. To obtain knowledge on the specific microorganisms responsible for the polyfluoroalkyl precursor biotransformation processes, microbial consortium or pure bacterial cultures from soil and sewage sludge were isolated and

Table 1

Acronyms, chemical names, and molecular structures of polyfluoroalkyl precursors, potential major or stable biotransformation products, and polyfluoroalkyl alternatives with novel functional groups

Phythacoskly incrustor reported in Iterature X2 FTOIs Huorotelomer ioldies FIC5_LOLLOII X2 FTOs Huorotelomer ofens FIC5_LOLLOII X2 FTOs Huorotelomer sulfonares FIC5_LOLLOI X2 FTOs Huorotelomer sulfonares FIC5_LOLLOI X2 FTOs Huorotelomer sulfonares FIC5_LOLLOI X2 TROS Huorotelomer stearate monoseter FIC5_LOLLOI X2 TROS Huorotelomer stearate monoseter FIC5_LOLLOI X2 TROS Huorotelomer chaoylate FIC5_LOLLOI X2 TROS Huorotelomer stavate monoseter FIC5_LOLLOI X2 TROS Huorotelomer sulfonarmides FIC5_LOLLOI NHOSS Huorotelomer sulfonarmides FIC5_LOLLOI NHOSS Herlinooctane sulfonarmides thanols FIC5_LOLLOI SamMP dister Huorotelomer sulfonarmides FIC5_LOLLOI X2 FTUCA Ruorotelomer sulfonarmides FIC5_LOLLOI X2 FTUCA Ruorotelomer sulfonarmides FIC5_LOLLOI X2 FTUCA Huorotelomer sulfonarmides FIC5_LOLLOI X2 FTUCA SamMP dister FIC5_LOLLOI	Acronym	Chemical name	Molecular structure					
X.2 FTO/hs Fluorotelomer alcohols FCF3,/CH2,CH3 X.2 FTOS Fluorotelomer olefins FCF3,/CH2,CH3 X.2 FTOS Fluorotelomer stanate monoseters FCF3,/CH2,CH3 X.2 FTSA Fluorotelomer stanate monoseters FCF3,/CH2,CH3,OG2,CH3 X.2 FTSA Fluorotelomer stanate monoseters FCF3,/CH2,CH3,OG2,CH3 X.2 FTSA Fluorotelomer stanate monoseters FCF3,/CH2,CH3,OG2,CH3 X.2 mono-PAPs Polyfluoroally phosphoric imooceter FCF3,/CH2,CH3,OG4 X.2 mono-PAPs Polyfluoroally phosphoric anoseter FCF3,/CH2,CH3,OG4 X.2 FTAA Fluorotelomer actoylates FCF3,/CH2,CH3,OG4 X.2 FTAA Pluorotelomer actoylates FCF3,/CH2,CH3,OG4 X.2 FTAA Perfluoroally phosphoric alcosetar FCF3,/CH2,CH3,OG4 X.2 FTAA Perfluoroally calonate alcohogic acids FCF3,/CH2,CH3,OG4 X.2 FTAA X.2 FTAA Samoure theore alcohogic acids FCF3,/CH2,CH3 X.2 FTCA X.2 FTAA Y.2 FUNCH FCF3,/CH2,CH3 X.2 FTCA X.2 FTAA Y.2 FUNCH FCF3,/CH2,CH3 X.2 FTCA X.2 FTAA Y.2 FUNCH FCF3,/CH2,CH3 X.2 FTCA Y.2 FUNCH FCF3,/CH2,CH3 FCF3,/CH2,CH3 X.2 FTCA Y.2 FUNCH Y.2 FUNCH Y.2 FUNCH FCF3,/CH2,C	Polyfluoroalkyl precursors reported in literature							
X2 FTIs Plooretelomer idefins F(C5),CH+CH X2 FTOs Plooretelomer seturate monoesters F(C5),CH+CH5,OGH X2 FTSs Plooretelomer seturate monoesters F(C5),CH+CH5,OGH X2 TTSs Plooretelomer seturate monoesters F(C5),CH+CH5,OGH X2 mone-Pha Polythomaakly plosphore: directer F(C5),CH+CH5,OGH X2 mone-Pha Polythomaakly plosphore: directer F(C5),CH+CH5,OGH X2 mone-Pha Polythomaakly plosphore: directer F(C5),CH+CH5,OGH X2 TAcs Flooretelomer acrybter F(C5),CH+CH5,OGH X4 FTAcs Flooretelomer acrybter F(C5),SCH,OCH5,OCH5,OH N+FOS5 Perfluocatae sufformatideethanols F(C5),SCH,OCH5,OH Migor or stable bitramformator profilemer staturated carboxylic acids F(C5),SCH,OCH4,OH X2 FTAL Plooretelomer atorbayde F(C5),SCH,OCH4,OH X2 FTAL Plooretelomer staturated carboxylic acids F(C5),CCH4,OCH4,OH X2 FTAL Plooretelomer ketone F(C5),CCH4,OCH4,OH X2 FTAL Plooretelomer ketone adehyde F(C5),CCH4,OCH4,OH X2 FTAL Plooretelomer ketone adehyde F(C5),CCH4,OCH4,OH X2 FTAL Plooretelomer ketone adehyde F(C5),CCH4,OCH4,OH X2 FTOH Polythomaakly adoble carboxylic acids F(C5),CCH4,OCH4,OH X2 FTOH	X:2 FTOHs	Fluorotelomer alcohols	F(CF ₂) _x CH ₂ CH ₂ OH					
X2 FTOS Fluorotelomer suforates F(G), CHC, CH, SO, H X2 FTSS Fluorotelomer suforates F(G), CHC, CH, SO, H X2 TEGS Fluorotelomer suforates F(G), CHC, CH, SO, H X2 TEGS Fluorotelomer suforates F(G), CHC, CH, SO, CHC, CO, CHJ, CHC, SO, CHC, CHC, CO, CHL, CHC, CO, CHL, CHC, CHC, CHC, CHC, CHC, CHC, CHC	X:2 FTIs	Fluorotelomer iodides	F(CF ₂) _x CH ₂ CH ₂ I					
X2 FTSAFlooratelomer subarate monosetersFLTSAFLTSAX2 FTSAFlooratelomer straate monosetersFLTSA, CHS, CHS, CHS, CHS, CHS, HSX2 mono-PMAPolyfluorakky phosphoric monoseterFLTSA, CHS, CHS, CHS, CHS, CHS, CHS, CHS, CHS	X:2 FTOs	Fluorotelomer olefins	$F(CF_2)_xCH=CH_2$					
X.2 TPSsFluorotelomer stearate monosetersFLG2, LHCL4, DOCC, HLBX.2 TBCSFluorotelomer citate triesterFLG2, LHCL4, DOCC, HLBX.2 der-NPsPolyfluoralkyl phosphoric monoseterFLG2, LHCL4, DOCC, HLBX.2 der-NPsPolyfluoralkyl phosphoric diesterFLG2, LHCL4, DOCC, HLBFFEOFluorotelomer ethysiteFLG2, LHCL4, DOCC, HLBX.2 FLASHuorotelomer acrylatesFLG2, LHCL4, DOCC, HLBN-FOSAN-Alsyl perfluoroctane sulfoamidesFLG2, LSO, NHC, HLBN-FOSAN-Alsyl perfluoroctane sulfoamidesFLG2, LSO, NHC, HLBSharib distanceFluorotelomer acrylatesFLG2, LSO, NHC, HLBSharib distanceFluorotelomer acrylatesFLG2, LSO, NHC, HLBX.2 FLAX.2 FLAS.2 FLAFLOX.2 FLAFLOFLOFLOX.3 FTAFluorotelomer alkehydeFLG2, LSO, CHC, HDX.3 FTAFluorotelomer staturate carboxylic acidsFLG2, LSO, CHC, HDX.3 FTAS.3 Fluorotelomer staturate carboxylic acidsFLG2, LSO, CHC, HDX.3 FTAPolyfluorinated scondary alcoholFLG2, LCG2, CHC, HDX.3 FTAPolyfluorinated scondary alcoholFLG2, LCG2, CHC, HDX.3 FTAPolyfluorinated scondary alcoholFLG2, LCG2, CHC, HDX.3 FTA </td <td>X:2 FTSAs</td> <td>Fluorotelomer sulfonates</td> <td>F(CF₂)_xCH₂CH₂SO₃H</td>	X:2 FTSAs	Fluorotelomer sulfonates	F(CF ₂) _x CH ₂ CH ₂ SO ₃ H					
X2 TDCsFluorotelomer citrate triester(FC),Ch(CLH)Q(FL)(CD)(FL)(CO)(FL)(FL),CP)X2 dnon-PAPsPolyfluoroaliky phosphoric diester[FC),Ch(CL)Q(FL)(CL)(D)/hX2 d1-PAPsPolyfluoroaliky phosphoric diester[FC),Ch(CL)(D)/hX2 FTAsFluorotelomer etholyate[FC),Ch(CL)(D)/hX2 FTAsFluorotelomer etholyates[FC),Ch(CL)(D)/hX2 FTAsPerfluoroctane sulfonanidoethanol-bas[FC),SOQ/FC,SL(GL)(D)/HN-FOSAN-AKISP effluoroctane sulfonanidoethanol-bas[FC),SOQ/FC,SL(GL)(D)/HN-FOSAPerfluoroctane sulfonanidoethanol-based phosphate[FC),SOQ/FC,SL(GL)/HMajor atsubic biotemaformation productX2 FTAAX2 Fluorotelomer adethyde[FC),SCQ/FC,SL(GO)/HX2 FTAAX2 Fluorotelomer adethyde[FC),SCQ/FC,HC)/H[FC),SCQ/FC,HC)/HX2 FTAAX2 Fluorotelomer adethyde[FC),SCQ/FC,HC)/HX2 FTAAY2 Fluorotelomer adethyde[FC),SCQ/FC,HC)/HX2 FTCAY2 Fluorotelomer adethyde[FC),SCQ/FC,HC)/HX3 FTOAPluorotelomer adethyde[FC),SCQ/FC,HC)/HX3 FTOAY3 Fluorotelomer saturated carboxylic acids[FC),SCQ/FC,HC)/HX3 FTOAY3 Fluorotelomer asturated carboxylic acids[FC),SCQ/FC,HC)/HX3 FTOAY3 Fluorotelomer asturated carboxylic acids[FC),SCQ/FC,HC)/HX3 FTOAPerfluoroctane sulfonanidae carboxylic acids[FC),SCQ/FC,HC)/HX3 FTOAPerfluoroctane sulfonanidae carboxylic acids[FC),SCQ/FC,HC)/HX3 FTOAPerfluoroctane sulfonanidae carboxylic acids[FC),SCQ/FC,HC)/HX3 FTOAPerfl	X:2 FTSs	Fluorotelomer stearate monoesters	$F(CF_2)_x CH_2 CH_2 OOCC_{17}H_{35}$					
X.2 mon-PMPsPolyfluoralley (absophoric monester[PCF2),CH2(F4)6)P(=O)(OH);Y.2 di HAPSPolyfluorozolley (absophoric diester[PCF2,CF4,CH2(F4)6)P(=O)(OH);PFDSFluorotelomer actylate[PCF2,CF2,CH2(F4)6)P(=O)(OH);X.2 FTAsN-Malvj perfluorocance sulfonamides[PCF2,SC9,MHC_aH2m_1)N+FDSSPerfluorocance sulfonamideshanols[PCF2,SC9,MHC_aH2m_1)Aday or stable biotranaformation product[PCF2,SC9,MHC_aH2m_1)X.2 FTAkPerfluorocance sulfonamidoethanols[PCF2,SC9,HC2,HC2,HC2,HC2,HC2,HC2,HC2,HC2,HC2,HC2	X:2 TBCs	Fluorotelomer citrate triester	F(CF ₂) _x CH ₂ CH ₂ OOCC(OH)[CH ₂ COO CH ₂ CH ₂ (CF ₂) _x F] ₂					
X.2 in PAPsPolyflaoroalley inosphorie diesser(PCFs,)C,CH,CH;0,0/H)PTEOFluorotelomer ethorylate(PCFs,)C,CH,CH;0,0/H)X.2 FTAcsFluorotelomer advylates(PCFs,)CAP,CH;CH;0,0/H)N=POSAN=Akly perfluoroctane sulfonamides(PCFs,)CAP,CH;CH;0,0/H)N=POSAN=Akly perfluoroctane sulfonamides(PCFs,)CAP,CH;CH;0,0/H)N=POSAPerfluoroctane sulfonamidethanol-based phosphate(PCFs,)CAP,CH;0K2 FTALFluorotelomer addethyde(PCFs,)CH;CH0X.2 FTAS.2 FTACAS.2 Fluorotelomer addethyde(PCFs,)CH;CH0X.2 FTAFluorotelomer saturated carboxylic acids(PCFs,)CH;CH0X.2 FTCAS.2 Fluorotelomer saturated carboxylic acids(PCFs,)C(G)CH;H0X.2 FTAFluorotelomer saturated carboxylic acids(PCFs,)C(G)CH;H0X.2 FTAPluorotelomer staturated carboxylic acids(PCFs,)C(G)CH;H0X.3 rdidS.3 Fluoro 5.3 FT saturated carboxylic acids(PCFs,)C(G)CH;H0X.3 rdidY.3 Fluoro 5.3 FT saturated carboxylic acids(PCFs,)C(G)CH;H1X.2 FTOH-SulfPerfluoroctanic acid(PCFs,)C(G)CHY.2 UTOH-SulfFTOH sulfate conjugate(PCFs,)C(G)CHY.2 UTOH-SulfFTOH sulfate conjugate(PCSs,)C(G)CH;CHOX.2 FTOH-SulfCOH(PCSs,)C(G)CH;CHOX.2 UTOH-SulfPerfluoroctane sulfonamidethanol(PCSs,)S(G)CH;CHOX.2 UTOH-SulfS.1 fluoroctane sulfonamidethanol(PCSs,)S(G)CH;CHOY.2 UTOH-SulfPerfluoroctane sulfonamidethanol(PCSs,)S(G)CH;CHOY.2 UTOH-SulfS.1 fluoroctane sulfon	X:2 mono-PAPs	Polyfluoroalkyl phosphoric monoester	$[F(CF_2)_xCH_2CH_2O]P(=O)(OH)_2$					
FTE0Fluorotelomer ethoxylateFCF2_CF2_A(CH2,CUC)CHX2 FTASFluorotelomer arylasFCF2_SOSN(CH2,CH2,CUC)CHN+ROSEPerfluorotane sulfonamidoethanolsFCF2_SOSN(CH2,CH2,CUC)CHSAm/PA diesterPerfluorotane sulfonamidoethanolsFCF2_SOSN(CH3,CH2,CH2,CH3,CH2,CH3,CH2Major or stable biotransformation productsFCF2_SOSN(CH3,CH2,CH3,CH3,CH2,CH3,CH3,CH2,CH3,CH3,CH2,CH3,CH3,CH2,CH3,CH3,CH4,CH3,CH3,CH3,CH3,CH3,CH3,CH3,CH3,CH3,CH3	X:2 di-PAPs	Polyfluoroalkyl phosphoric diester	$[F(CF_2)_xCH_2CH_2O]_2P(=O)(OH)$					
X-2 FrAcsFluorotelomer arylatesF(Tz),CLH2,CLQC(0/CL+CH2,N-FOSAN-KlgV perfluoroctane sulfonamideethanolsF(Tz),SO,NK(C,Hz),CH2,CLH2,O1N-FOSEPerfluoroctane sulfonamideethanol-based phosphateF(Tz),SO,NK(C,Hz),CH2,CLH2,O1,P(P=O)(OH)Major or stable biotransformation productsF(Tz),CLH2,CLH2,OLH2,CLH2,O1,P(P=O)(OH)X-2 FTAAX-2 Fluorotelomer saturated carboxylic acidsF(Tz),CLH2,CH0X-2 FTAAFluorotelomer saturated carboxylic acidsF(Tz),CLH2,CH0X-2 FTAAFluorotelomer saturated carboxylic acidsF(Tz),CLG2,COOHX-2 FTAAFluorotelomer texturated carboxylic acidsF(Tz),CLG2,COOHX-2 FTAAFluorotelomer texturated carboxylic acidsF(Tz),CLG2,COOHX-2 FTOHFluorotelomer texturated carboxylic acidsF(Tz),CCOOHX-2 FTOHS-3 lection adject adject acidsF(Tz),CCOOHX-2 FTOHS-3 lection adject adject acidsF(Tz),CCOOHX-2 FTOH-SulfFOH sulfate conjugateF(Tz),CCOOHX-2 FTOH-SulfFOH sulfate conjugateF(Tz),CCOOHX-2 FTOH-SulfFOH sulfate conjugateF(Tz),CCOOHX-2 FTOH-SulfFOH sulfate conjugateF(Tz),SCONCH4,DH2X-2 FTOH-SulfS-1 suturated FTOH glutathione conjugate <td>FTEO</td> <td>Fluorotelomer ethoxylate</td> <td>$F(CF_2CF_2)_x(CH_2CH_2O)_vH$</td>	FTEO	Fluorotelomer ethoxylate	$F(CF_2CF_2)_x(CH_2CH_2O)_vH$					
N-HOSAsN-Alkyl perfluoroctane sulfonamidoethanolsF(Tc)_SONN(Lq,H2,m)(H2,H2,M)N-HOSESPerfluoroctane sulfonamidoethanol-based phosphateF(Tc)_SONN(Lq,H2,m)(H2,H2,M)Major or stable biotransformation productsF(Tc)_LCH2,CH3X2 FTALFluorotelomer staturated carboxylic acidsF(Tc)_LCH2,ODX2 FTALX2 Biorotelomer staturated carboxylic acidsF(Tc)_LCH2,ODX2 FTALSamorelomer ketoneF(Tc)_LCH2,ODX3 FTUCAFluorotelomer ketoneF(Tc)_LCH2,ODX3 FTUCAFluorotelomer ketone aldehydeF(Tc)_LCH2,ODX3 station aldehydeS-3 Fluorotelomer staturated carboxylic acidsF(Tc)_LCH2,ODX3 stationS-3 Fluorotelomer staturated carboxylic acidsF(Tc)_LCH2,ODX3 stationS-3 Fluorotelomer staturated carboxylic acidsF(Tc)_LCH2,ODX3 stationS-1 Fluorotelomer staturated carboxylic acidsF(Tc)_LCH4,ODX3 stationPerfluoroalkyl carboxylic acidsF(Tc)_LCH4,ODX2 FTOH-ClucFTOH statifer conjugateF(Tc)_LCH4,ODX2 FTOH-ClucFTOH glucatifier conjugateF(Tc)_LCH4,ODX2 FTOH-ClucFTOH glucatifier conjugateF(Tc)_LCH4,ODX2 FTOH-ClucF1OH glucatifier conjugateF(Tc)_LCH4,OD <td>X:2 FTAcs</td> <td>Fluorotelomer acrylates</td> <td>$F(CF_2)_xCH_2CH_2OC(0)CH=CH_2$</td>	X:2 FTAcs	Fluorotelomer acrylates	$F(CF_2)_xCH_2CH_2OC(0)CH=CH_2$					
N-POSEsPerfluocetane sulfonamideethanolsPCE3pSOR(CaPban);CH2;CH2;OHMajor or stable biotransformation productsX2: PTAHuorotelomer saturated carboxylic acidsPCE3pSOR(CaPban);CH2;CH2;OHX2: PTAK12: Buorotelomer saturated carboxylic acidsPCE3pSOR(CaPban);CH2;CH00HX2: PTCAK12: Buorotelomer saturated carboxylic acidsPCE3pSOR(CaPban);CH2;CH00HX2: PTCAFluorotelomer unstrutted carboxylic acidsPCE3pSOR(CH2)X2: PTCAFluorotelomer saturated carboxylic acidsPCE3pSOR(CH2)X2: PTCASi Biorotelomer saturated carboxylic acidsPCE3pSOR(CH2)X3: StridtX3: Fluorotelomer saturated carboxylic acidsPCE3pSOR(CH2)X3: acidX3: Fluorotelomer saturated carboxylic acidsPCE3pSOR(CH2)PFOAPerfluorolatoric acidPCE3pSOR(CH2)PFOAPerfluorolatoric acidPCE3pSOR(CH2)PFOAPerfluorolatoric acidPCE3pSOR(CH2)X2: PTOH-SufPTOH glucuronic conjugatePCE3pSOR(CH2)X2: PTOH-SufPTOH glucuronic conjugatePCE3pSOR(CH2)CH2)X2: PTOH-SufPTOH glucuronic sulfonamidoethanolPCE3pSOR(CH2)CH2)X2: PTOH-SufPCE1pSOR(CH2)CH2)PCE3pSOR(CH2)CH2)X2: PTOH-SufPCE1pSOR(CH2)CH2)PCE1pSOR(CH2)CH2)X2: PTOH-SufPCE1pSOR(CH2)CH2)PCE1pSOR(CH2)CH2)X2: PTOH-SufPCE1pSOR(CH2)CH2)PCE1pSOR(CH2)CH2)X2: PTOH-SufPCE1pSOR(CH2)CH2)PCE1pSOR(CH2)CH2)X2: PTOH-SufPCE1pSOR(CH2)CH2)PCE1pSOR(CH2)CH2)X2: PTOH-SufPCE1pSOR(CH2)CH2)<	N-FOSAs	N-Alkyl perfluorooctane sulfonamides	$F(CF_2)_8SO_2NH(C_mH_{2m+1})$					
SAm2P diesterPerfluoctane sulfonamidoethanol-based phosphate[F(CF2)_bSO,N(C,H2,(CH2,OL)_2)(=0)(OH)Major or stable biotrandformation proteomer studentyF(CF2)_bC,FCOOHX2 FTALFUnoreleomer stude carboxylic acidsF(CF2)_bC,FCOOHX2 FTVCAFluorotelomer stude carboxylic acidsF(CF2)_bC,FCOOHX2 FTVCAFluorotelomer insaturated carboxylic acidsF(CF2)_bC,FCOOHX2 FTVCAFluorotelomer ketone aldelydeF(CF2)_bC,OCH4,CH0X3 stotne aldelyde5.3 Fluorotelomer studed carboxylic acidsF(CF2)_bC,OCH4,CH0X3 stotne aldelydeS.3 Fluorotelomer stude carboxylic acidsF(CF2)_bCH0,CHC1,H1X3 acidX3 Fluorotelomer stude carboxylic acidsF(CF2)_bCH0,CHC1,H1X3 acidS.3 Fluorotelomer stude carboxylic acidsF(CF2)_bCH0,CH0X3 acidS.3 Fluorotelomer stude carboxylic acidsF(CF2)_bCH0,CH0,CH1X3 acidS.1 fluorotelomer aldelydeF(CF2)_bCH0,CH0,CH1X2 FT0H-GlucFT0H glucurnide conjugateF(CF2)_bCH0,CH2,CH0,CH1,CH1X2 FT0H-GlucInsaturated FT0H glutarhine conjugateF(CF2)_bCH0,CH2,CH1,CH1,OH1X2 FT0H-GlucB.1 fluorotelomer selfonamidoethanolF(CF2)_bCD0,N(CH4,CH2,CH1,OH1X2 FT0H-GlucB.1 fluorotelomer selfonamidoethanolF(CF2)_bCD0,N(CH4,CH2,CH1,OH1X3 FT0H0B.1 fluorotelomer selfonamidoethanolF(CF2)_bCD0,N(CH4,CH2,CH1,OH1X4 FT0APerfluoroctare sulfonamidoethanolF(CF2)_bCD0,N(CH4,CH2,CH1,OH1N-EFOSANetbyl perfluoroctare sulfonamidoethanolF(CF2)_bCD0,N(CH4,CH2,CH1,OH1N-EFOSANetbyl perfluoroctare sulfo	N-FOSEs	Perfluooctane sulfonamidoethanols	$F(CF_2)_8SO_2N(C_mH_{2m+1})CH_2CH_2OH$					
Major or stable biotransformation productsX:2 FTA.Furoretoimer saturated carboxylic acidsF(CF2),CH2CH0X:2 FTCARuoretoimer saturated carboxylic acidsF(CF2),CH2CH00HX:2 FTUCAFluoretoimer usturated carboxylic acidsF(CF2),CCPCH00HX:2 FTUCAFluoretoimer usturated carboxylic acidsF(CF2),CCPCH00HX:2 FTUCAFluoretoimer usturated carboxylic acidsF(CF2),CCPCH200HX:3 acidS:7 Fluoretoimer tetorae aldehydeF(CF2),CCPCH200HX:3 acidS:7 Fluoretoimer startaret carboxylic acidsF(CF2),CCPCH200H3 Fluoro 5:3 acid3-Fluoroscanic acidF(CF2),CCPCHPFCAsPerfluoroalityl carboxylic acidsF(CF2),CCPCHPFCAsPerfluoroalityl carboxylic acidsF(CF2),CCPCHX:2 FTOH-SufFTOH gluctanide conjugateF(CF2),CCPCHX:2 FTOH-SufFTOH gluctanide conjugateF(CF2),CCPCH2X:2 FTOH-SufFTOH gluctanide conjugateF(CF2),CCH2-CH3X:2 FTOH-SufFTOH gluctanide conjugateF(CF2),SCPCH2X:2 FTOH-SufS:1 fluoroteimer silfonamidoethanolF(CF2),SCPCH2X:2 FTOH-SufN=thyl perfluorooctane silfonamidoethanolF(CF2),SCPCH2X:2 FTOH-SufN=thyl-perfluorooctane silfonamido actic acidF(CF2),SCPCH2X:2 FTOH-SufPerfluorooctane silfonamido actic acidF(CF2),SCPCH2X:2 FTOHPerfluorooctane silfonamido actic acidF(CF2),SCPCH2X:2 FTOH-SufPerfluorooctane silfonamido actic acidF(CF2),SCPCH2N=EFOSAPerfluorooctane silfonamido actic acidF(CF2),SCPCH2<	SAmPAP diester	Perfluooctane sulfonamidoethanol-based phosphate	$[F(CF_2)_8SO_2N(C_2H_5)CH_2CH_2O]_2P(=O)(OH)$					
X.2 FTALFluorotelomer addehydeFICF2,CH;CHOX.2 FTCAX.2 ProcesFluorotelomer strutarde carboxylic acidsFICF2),CH;COOHX.2 FT KeoneFluorotelomer strutarde carboxylic acidsFICF2),CH;COOHS.3 Ectone aldehyde5:3 Fluorotelomer strutarde carboxylic acidsFICF2),CG(CH;CHOS.3 acidX.3 Fluorotelomer strutarde carboxylic acidsFICF2),CG(CH;CHOX.3 acidX.3 Fluorotelomer strutarde carboxylic acidsFICF2),CG(CH;CHO3-Fluoro 5:3 acid3-Fluoros 7:3 acidFIF strutarde carboxylic acidsFICF2),CG(CH;CHO3-Fluoro 5:3 acid9-Fluoroalkyl carboxylic acidsFICF2),CG(CH;CHO-CHU2-FIOH-SulfFOH sulfate conjugateFICF2),CG(CH;CHO-CHUX.2 FTOH-SulfFTOH sulfate conjugateFICF2),CG(CH;CHO-CHUX.2 FTOH-SulfFTOH sulfate conjugateFICF2),CG(CH;CHO-CHUX.2 FTOH-SulfS:1 FT olefn8:1 fluorotelomer olefinFICF2),SON(CH;CH;CHO-OHUN-EtrOSEN-ethyl perfluorooctane sulfonamidoethanolFICF2),SON(CH;CH;CHON-EtrOSAN-ethyl-perfluorooctane sulfonamidoethanolFICF2),SON(CH;CH;CHON-EtrOSAN-ethyl-perfluorooctane sulfonamidoethanolFICF2),SON(CH;CH;CHON-EtrOSAPerfluorooctane sulfonamido alcholFICF2),SON(CH;CHOFDSAPerfluorooctane sulfonamido alcholFICF2),SON(CH;CHOFDSAPerfluorooctane sulfonamido alcholFICF2),SON(CH;CHOFDSAPerfluorooctane sulfonamido alcholFICF2),SON(CH;CHO)FDSAPerfluorooctane sulfonamido alcholFICF2),SON(CH;CH;CHC)FDSA <t< td=""><td>Major or stable biotransformation product</td><td>S</td><td></td></t<>	Major or stable biotransformation product	S						
X.2 FTCAX.2 FTCAFLorotelomer saturated carboxylic acidsF(CFa)_C/CF_CHCOHX.2 FTCAFluorotelomer ketoneF(CFa)_C/CF_CHCOHX.2 FTCAFluorotelomer ketoneF(CFa)_C/CF_CHCOHS.3 Iketone aldehydeS 3 Fluorotelomer ketoneF(CFa)_C/CF_CHCOHS.3 ketone aldehydeS 3 Fluorotelomer ketoneF(CFa)_C/CF_CHCOHS.3 ketone aldehydeS 3 Fluorotelomer saturated carboxylic acidsF(CFa)_C/CHCHOHX.3 acidX.3 Fluorotelomer saturated carboxylic acidsF(CFa)_C/CHCHOHPFCAPerfluorootalyl carboxylic acidsF(CFa)_C/COHPFCAPerfluorootanoi caidF(CFa)_C/COHX.2 FTOH-CLucFTOH glucuronide conjugateF(CFa)_C/CHCHOHOSOrX.2 FTOH-CSUnsaturated FTOH glutathione conjugateF(CFa)_C/CHCHOHOSOrX.2 FTOH-CSUnsaturated FTOH glutathione conjugateF(CFa)_C/CHCHOHOSOrX.2 FTOH-CSUnsaturated FTOH glutathione conjugateF(CFa)_C/CHCHOHOX.2 FTOH-CSS1 fluorotelomer olefinF(CFa)_SCN/CHa)_CHCHOHN-EHOSFN-ethyl perfluorooctane sulfonamidoethanolF(CFa)_SCN/CHa)_CHCHOHN-EHOSAN-ethyl perfluorooctane sulfonamidoethanolF(CFa)_SCN/CHa)_CHCHOHN-EHOSAN-ethyl perfluorooctane sulfonamido acetic acidF(CFa)_SCN/CHA]_CHCHOHN-EHOSAPerfluorooctane sulfonamido acetic acidF(CFa)_SCN/HCHA]FOSAPerfluorooctane sulfonamido acetic acidF(CFa)_SCN/HCHA]FOSAPerfluorooctane sulfonamido acetic acidF(CFa)_SCN/HCHA]FOSAPerfluorooctane sulfonamido acetic acidF(CFa)_SCN/HCHA	X:2 FTAL	Fluorotelomer aldehyde	F(CF ₂) _x CH ₂ CHO					
X.2 FT KenneFluorotelomer unsaturated carboxylic acidsF(CF2)_LC)(C)(H)X.2 FT KenneFilorotelomer ketone aldehydeF(CF2)_LC)(C)(H)S.3 ketone aldehydeS.3 Fluorotelomer ketone aldehydeF(CF2)_LC)(H)(H)(H)X.3 setTOIPolyduorinated scondary alcoholF(CF2)_LC)(H)(H)(H)X.3 stoidX.3 Fluorotelomer staturated carboxylic acidsF(CF2)_LC)(H)(H)(CO)(H)3 -Ruoro S.3 acid3 -Fluoro S.3 FT saturated carboxylic acidsF(CF2)_LC)(H)(C)(C)(H)PFCAsPerfluoroalkyl carboxylic acidsF(CF2)_LC)(H)(C)(C)(H)PFCAPerfluoroalkyl carboxylic acidsF(CF2)_LC)(H)(-C)(L)X.2 FTOH-SulfFTOH sulfat conjugateF(CF2)_LC)(H)(-C)(L)X.2 FTOH-SulfFTOH sulfat conjugateF(CF2)_LC)(H)(-C)(L)X.2 FTOH-SulfG.2 unsaturated FTI oldideF(CF2)_LC)(H)(-H)(H)S.2 UFTOH-SulfS.1 luorotelomer olefinF(CF2)_LC)(H)(-H)(H)N-EfTOSEN-ethyl perfluoroactane sulfonamidoethanolF(CF2)_LSON(H)(H)(H)(H)N-EfTOSAN-ethyl-perfluoroactane sulfonamidoethanolF(CF2)_LSON(H)(H)(H)(H)N-EfTOSAN-ethyl-perfluoroactane sulfonamido alcoholF(CF2)_LSON(H)(H)(H)(H)N-EfTOSAPerfluoroactane sulfonamido alcoholF(CF2)_LSON(H)(H)(H)(H)N-EfTOSAPerfluoroactane sulfonamido alcoholF(CF2)_LSON(H)(H)(H)(H)N-EfTOSAPerfluoroactane sulfonamido alcoholF(CF2)_LSON(H)(H)(H)(H)(H)N-EfTOSAPerfluoroactane sulfonamido alcoholF(CF2)_LSON(H)(H)(H)(H)(H)N-EfTOSAPerfluoroactane sulfonamido alcoholF(CF2)_LSON(H)(H)(H)(H)(H)(H)(H) <td>X:2 FTCA</td> <td>X:2 Fluorotelomer saturated carboxylic acids</td> <td>F(CF₂)_xCH₂COOH</td>	X:2 FTCA	X:2 Fluorotelomer saturated carboxylic acids	F(CF ₂) _x CH ₂ COOH					
X.2 FI KetoneFluorotelomer ketone aldehydeF(CF)_kC(O)CH_5(-HOS.3 ketone aldehydeSi Stetone aldehydeF(CF)_kCH(OH)CH_5X.3 acidX.3 Fluorotelomer saturated carboxylic acidsF(CF)_kCH(Ch)COOHX.3 acid3Fluoro 5.3 T F saturated carboxylic acidsF(CF)_kCHCh4COOHPFCAPerfluoroalkyl carboxylic acidsF(CF)_kCH2COOHPFCAPerfluoroalkyl carboxylic acidsF(CF)_kCH2CH3CH3CH3CH3CH3CH3CH3CH3CH3CH3CH3CH3CH3C	X:2 FTUCA	Fluorotelomer unsaturated carboxylic acids	F(CF ₂) _{x-1} CF=CHCOOH					
5:3 Evonc aldehyde5:3 Fluorotelomer ketone aldehydeF(CF);C(O)(CH;CHOX:3 arcidX:3 Fluorots/a condary lacoholF(CF);C(HO)(CH);CH);CHO3-Ruoro 5:3 acid3-Fluoros/S:3 FT saturated carboxylic acidsF(CF);C(CH)(CH);CH);CHO3-Ruoro 5:3 acid3-Fluoros/S:3 FT saturated carboxylic acidsF(CF);C(CH);CH);COOH3-Ruoro 5:3 acid3-Fluoros/S:3 FT saturated carboxylic acidsF(CF);C(CH);CH);COOHPFCAsPerfluoroalky(1 carboxylic acidsF(CF);C(CH);CH);COOHPFOAPerfluoroalky(1 carboxylic acidsF(CF);C(CH);CH);OOHX:2 FTOH-SulfFTOH sulfate conjugateF(CF);C(CH);CH);OOHX:2 FTOH-SulfFTOH sulfate conjugateF(CF);C(CH);CH);OOHX:2 FTOH-SulfFTOH sulfate conjugateF(CF);C(CS) = CHCH;OHS:1 FT olefin8:1 ftrolefinF(CF);C(CS) = CHCH;OHS:2 FTOHSilf Inorotelomer olefinF(CF);C(CS) = CHCH;OHN=EFOSAN=ethyl perfluorooctane sulfonamidoethanolF(CF);S(SO);CH;CH;QCH)N=EFOSAN=ethyl-perfluorooctane sulfonamidoethanolF(CF);S(SO);CH;CH;QCH)N=EFOSA aldehydeN=ethyl-perfluorooctane sulfonamido alcoholF(CF);S(SO);NHCH;CH;QOHN=EFOSA alcoholPerfluorooctane sulfonamido acetic acidF(CF);S(SO);NHCH;CH;QOHN=EFOSAPerfluorooctane sulfonamido acetic acidF(CF);S(SO);NHCH;CH;QOHN=EFOSAPerfluorooctane sulfonamido acetic acidF(CF);S(SO);NHCH;CH;QOHN=EFOSAPerfluorooctane sulfonamido acetic acidF(CF);S(SO);NHCH;CH;QOHN=EFOSAPerfluorooctane sulfonamido acetic acidF(CF);S(SO);NHCH;CH;QOH	X:2 FT Ketone	Fluorotelomer ketone	$F(CF_2)_xC(O)CH_3$					
X.2 strOitPolyfluorinated secondary alcoholF(CF2),CH(D)(CH3X.3 acidX.3 Fluorotores sturated carboxylic acidsF(CF2),CH2,CH2,OOHPFCAPerfluoroalkyl carboxylic acidsF(CF2),CCH2,CH2,OOHPFCAPerfluoroalkyl carboxylic acidsF(CF2),CCH2,CH2,OOHPFOAPerfluoroacid acidF(CF2),CCH2,CH2,OOHX.2 FTOH-GlucFTOH glucroonide conjugateF(CF2),CH2,CH2,OOG)X.2 FTOH-SulfFTOH sulface conjugateF(CF2),CH2,CH2,OOG)X.2 FTOH-SulfFTOH glucroonide conjugateF(CF2),CH2,CH2,OOG)X.2 FTOH-SulfUnsaturated FTO idideF(CF2),CF2 CH2N=EFOSEN=ethyl perfluorooctane sulfonamidoethanolF(CF2),SO2,N(CH4),CH2,OHN=EFOSEAll fluorotelomer olefanF(CF2),SO2,N(CH4),CH2,OHN=EFOSEN=ethyl perfluorooctane sulfonamidoethanolF(CF2),SO2,N(CH4),CH2,OHN=EFOSAN=ethyl-perfluorooctane sulfonamidoethanolF(CF2),SO2,N(CH4),CH2,OHN=EFOSAN=ethyl-perfluorooctane sulfonamidoethanolF(CF2),SO2,N(CH4),CH2,OHN=EFOSAN=ethyl-perfluorooctane sulfonamido acetic acidF(CF2),SO2,N(CH4),CH2,OHN=EFOSAPerfluorooctane sulfonamido alcoholF(CF2),SO2,N(CH4),CH2,OHN=EFOSAPerfluorooctane sulfonamido acetic acidF(CF2),SO2,N(CH4),CH2,OHPFOSPerfluorooctane sulfonamido acetic acidF(CF2),SO2,N(CH4),CH2,OHPFOSPerfluorooctane sulfonamidoF(CF2),SO2,NH2,H2,CH2,OOHPFOSPerfluorooctane sulfonaridoF(CF2),SO2,NH2,H2,CH2,OOHPFOSPerfluorooctane sulfonamido acetic acidF(CF2),SO2,NH2,H	5:3 ketone aldehyde	5:3 Fluorotelomer ketone aldehyde	F(CF ₂) ₅ C(O)CH ₂ CHO					
X:3 relutorelomer saturated carboxylic acidsF(CF2),CH2,CH2,CDCOH3-Fluoro 5:3 acid3-Fluoro 5:3 relutrated carboxylic acidsF(CF2),CCOHPFCAsPerfluoroalkyl carboxylic acidsF(CF2),CCOHPFCAsPerfluoroalkyl carboxylic acidsF(CF2),CCOHPFCAsPerfluoroalkyl carboxylic acidsF(CF2),CCOHPFCAsPerfluoroalkyl carboxylic acidsF(CF2),CCOHPFCAsPerfluoroalkyl carboxylic acidsF(CF2),CCH2,CH2,CH2,OCOLX:2 FTOH-SulfFTOH sulfate conjugateF(CF2),CCSC) = C(CH2,OGNS:2 FTOH-SulfSaturated FT iodideF(CF2),CCF = CH2S:1 FT olefinS:1 Hoorotelomer olefinF(CF2),CCF = CH2N-EtOSEN-ethyl perfluorooctane sulfonamidoethanol aldehydeF(CF2),SO2,N(CH2,H2,H2,CH2)N-EtOSAN-ethyl-perfluorooctane sulfonamido acidaF(CF2),SO2,N(CH2,H2,H2,CH2)N-EtFOSAN-ethyl-perfluorooctane sulfonamido acidaF(CF2),SO2,N(CH2,H2,H2,CH2)N-EtFOSAPerfluorooctane sulfonamido acidaF(CF2),SO2,N(CH2,H2,CH2)N-EtFOSAPerfluorooctane sulfonamido acidaF(CF2),SO2,N(CH2,H2,CH2)N-EtFOSAPerfluorooctane sulfonamido acida CaidaF(CF2),SO2,N(CH2,H2,H2,CH2)N-EtFOSAPerfluorooctane sulfonamido acida CaidaF(CF2),SO2,N(CH2,H2,H2,CH2)PFOSPerfluorooctane sulfonamido acidaF(CF2),SO2,N(CH2,H2,H2,CD0)PFOSPerfluorooctane sulfonamido acidaF(CF2),SO3,N(CH2,H2,H2,CD0)PFOSPerfluorooctane sulfonamido acidaF(CF2),SO3,N(CH2,H2,H2,CD0)PFOSPerfluoroactane sulfonamido acidaF(CF2),SO3,N(CH2,H2	X:2 sFTOH	Polyfluorinated secondary alcohol	F(CF ₂) _x CH(OH)CH ₃					
3-Fluoro 5:3 acid3-Fluoro 5:3 FT saturated carboxylic acidsF(CF2)sCFHCH2cOOHPFCAsPerfluoroatleyl carboxylic acidsF(CF2)sCOOHPFOAPerfluoroatleyl carboxylic acidsF(CF2)sCH2CH2CH2CH2CH2CH2CH2CH2CH2CH2CH2CH2CH2C	X:3 acid	X:3 Fluorotelomer saturated carboxylic acids	F(CF ₂) _x CH ₂ CH ₂ COOH					
PFCAsPerfluoroalkyl carboxylic acidsF(CF2)cC0HPFOAPerfluoroalcan cia caidF(CF2)cC0HPFOAPTOH glucuronide conjugateF(CF2)cC0HX:2 FTOH-SulfFTOH glucuronide conjugateF(CF2)cCH2,CH2,CH2,OCJ0CX:2 FTOH-SulfFTOH sulfate conjugateF(CF2)cCH2,CH2,CH2,OCJ0C6: 2 FTUI6: 2 unsaturated PT iodideF(CF2)cCH2,CH2,CH2,OCJ0C6: 2 FTUI6: 2 unsaturated PT iodideF(CF2)sCH2,CH2,CH2,OCJ0C8: 1 FT olefin8: 1 fluorotelomer olefinF(CF2)sCD4,CH3,CH2,CH2,OHN-EtFOSEN-ethyl perfluorooctane sulfonamidoethanolF(CF2)sC90,N(C;H3,CH2,CH2,OHN-EtFOSAN-ethyl-perfluorooctane sulfonamide acteic acidF(CF2)sS02,N(C;H3,CH2,CH2,OHN-EtFOSAN-ethyl-perfluorooctane sulfonamido acteic acidF(CF2)sS02,N(C;H2,CH2,OHN-EtFOSAPerfluorooctane sulfonamido acteic acidF(CF2)sS02,N(C;H2,CH2,OHN-EtFOSAPerfluorooctane sulfonamido acteic acidF(CF2)sS02,N(C;H2,CH2,OHN-EtFOSAPerfluorooctane sulfonamido acteic acidF(CF2)sS02,N(C;H2,CH2,OHPOSAPerfluorooctane sulfonamido acteic acidF(CF2)sS02,NHCH2,CH2,OHPFOSPerfluorooctane sulfonamido acteic acidF(CF2)sS02,NHCH2,CH2,OHPFOSAPerfluorooctane sulfonamido acteic acidF(CF2)sS02,NHCH2,CH2,OHPFOSAPerfluoroalkyl sulfonic acidsF(CF2)sS02,NHCH2,CH2,OHPFOSAPerfluoroalkyl sulfonic acidsF(CF2)sS02,NHCH2,CH2,OHPFOSAPerfluoroalkyl sulfonic acidsF(CF2)sS02,NHCH2,CH2,OHPFSASPerfluoroalkyl sulfonic acidsF(CF2)sS	3-Fluoro 5:3 acid	3-Fluoro 5:3 FT saturated carboxylic acid	F(CF ₂) ₅ CFHCH ₂ COOH					
PFOAPerfluorooctanoic acidF(CFa),COOHX:2 FTOH-GlucFTOH glucuronic conjugateF(CFa),CH2,CH2,O-GlucX:2 FTOH-SulfFTOH sulfate conjugateF(CFa),CH2,CH2,O-GucX:2 HTOH-GSUnsaturated FTOH glutathione conjugateF(CFa),CH2,CH2,OOGX:2 HTOH-GSUnsaturated FTIOH glutathione conjugateF(CFa),CCH2,CH4,OH38:1 FT olefin8:1 fluorotelomer olefinF(CFa),CCH2,CH4,OH3N-EtFOSEN-ethyl perfluorooctane sulfonamidoethanolF(CFa),SOS,N(CH3,CH2,OH4N-EtFOSEN-ethyl-perfluorooctane sulfonamide acetic acidF(CFa),SOS,N(CH3,CH2,OH4N-EtFOSAN-ethyl-perfluorooctane sulfonamide acetic acidF(CFa),SOS,N(CH3,CH2,OH4N-EtFOSAPerfluorooctane sulfonamido acetic acidF(CFa),SOS,N(H2,H2,H2,OHN-EtFOSAPerfluorooctane sulfonamido acetic acidF(CFa),SOS,N(H2,H2,OH4PERSAPerfluorooctane sulfonamido acetic acidF(CFa),SOS,NHCH2,CH2,OHPFOSAPerfluorooctane sulfonamido acetic acidF(CFa),SOS,NHCH2,CH2,OHPFOSAPerfluorooctane sulfonamido acetic acidF(CFa),SOS,NHCH2,CH2,OHPFOSPerfluorooctane sulfonamido acetic acidF(CFa),SOS,NHCH2,CH2,OHPFOSPerfluorooctane sulfonamido acetic acidF(CFa),SOS,NHCH2,CH2,OHPFOSPerfluorooctane sulfonamido acetic acidF(CFa),SOS,NHCH2,DY,OHPFOSPerfluoroalkyl sulfonic acidF(CFa),SOS,NHCH2,DY,OHPFOSPerfluoroalky sulfonamido sulfonatesF(CFa),SOS,NHCH2,DY,OHAPFOSPerfluoroalky agueous film-forming foams:X:2 FTASX:2 FTASFluorotelo	PFCAs	Perfluoroalkyl carboxylic acids	F(CF ₂) _x COOH					
X:2 FTOH-GlucFTOH glucuronide conjugateF(CF ₂),CH ₂ CH ₂ O-GlucX:2 FTOH-SulfFTOH sulfate conjugateF(CF ₂),CH ₂ CH ₂ OSO ₃ ⁻ X:2 HTOH-CSUnsaturated FT ohd glutathione conjugateF(CF ₂),CH ₂ CH ₂ OSO ₁ = CH ₂ OH6:2 FTUI6:2 unsaturated FT iodideF(CF ₂),CH=CH ₂ O6:1 FTo olefin8:1 fluorotelomer olefinF(CF ₂),SO ₂ N(C)+S()-H ₂ CH ₂ OHN-EtFOSEN-ethyl perfluorooctane sulfonamidoethanolF(CF ₂),SO ₂ N(C)+S()-H ₂ COOHN-EtFOSAN-ethyl-perfluorooctane sulfonamidoethanol aldehydeF(CF ₂),SO ₂ N(C)+S()-H ₂ COOHN-EtFOSAN-ethyl-perfluorooctane sulfonamido acetic acidF(CF ₂),SO ₂ N(C)+S()-H ₂ COOHN-EtFOSAN-ethyl-perfluorooctane sulfonamido acetic acidF(CF ₂),SO ₂ N(H ₂ H ₂ CH ₂ OHN-EtFOSAPerfluorooctane sulfonamido acetic acidF(CF ₂),SO ₂ NH(H ₂ CH ₂ OHFOSAPerfluorooctane sulfonamido acetic acidF(CF ₂),SO ₂ NH(H ₂ CH ₂ OHFOSAPerfluorooctane sulfonamido acetic acidF(CF ₂),SO ₂ NHPFOSPerfluorooctane sulfonamido acetiF(CF ₂),SO ₂ NHPFOSPerfluorooctane sulfonamido acetiF(CF ₂),SO ₂ NHPFOSPerfluorooctane sulfonamido acetiF(CF ₂),SO ₂ NHX:2 PtTAoSFluorotelomer thiohydroxy ammoniumF(CF ₂),CC ₂ Ch ₂ CH ₂ Ch ₂ CONHCC(CH ₃),CH ₂ COX:2 PtTANFluorotelomer thiohydroxy ammoniumF(CF ₂),CCH ₂ Ch	PFOA	Perfluorooctanoic acid	F(CF ₂) ₇ COOH					
X.2 ETOH-SulfFTOH sulface conjugateFTCP:,CtP:,CtP:,CtP:,CtP:,CtP:,CtP:,CtP:,C	X:2 FTOH-Gluc	FTOH glucuronide conjugate	F(CF ₂) _x CH ₂ CH ₂ O-Gluc					
X.2 µFOH-GS Unsaturated FT0l glutathione conjugate F(CF2), r(CS2) = CHCH2OH 6:2 FTUI 6:2 unsaturated FT iodide F(CF2), CF1 = CH2 8:1 FT olefin 8:1 fluorotelomer olefin F(CF2), SC2, P(CF2 = CH2 N-EtFOSE N-ethyl perfluorooctane sulfonamidoethanol F(CF2), SS02, N(C3H3, CH2, CH2OH N-EtFOSE N-ethyl-perfluorooctane sulfonamidoethanol aldehyde F(CF2), SS02, N(C3H3, CH2, CH2OH N-EtFOSA N-ethyl-perfluorooctane sulfonamido acctic acid F(CF2), SS02, N(C3H3, CH2, CH2OH N-EtFOSA N-ethyl-perfluorooctane sulfonamido acctic acid F(CF2), SS02, N(C3H3, CH2, CH2OH N-EtFOSA N-ethyl-perfluorooctane sulfonamido acctic acid F(CF2), SS02, NHC4, CH2OH NEFOSA Perfluorooctane sulfonamido acctic acid F(CF2), SS02, NHC4, CH0OH FOSA Perfluorooctane sulfonamido acctic acid F(CF2), SS02, NHC4, CO0H FOSA Perfluorooctane sulfonamido acctic acid F(CF2), SS02, NHC4, CO0H PFOS Perfluorooctane sulfonamido acctic acid F(CF2), S02, NHC4, CO0H PFOS Perfluorooctane sulfonamido acctic acid F(CF2), S02, NHC4, CO0H PFOS Perfluorooctane sulfonamido asufonates F(CF2), S02, NHC4, S02, S03H <	X:2 FTOH-Sulf	FTOH sulfate conjugate	$F(CF_2)_x CH_2 CH_2 OSO_3^-$					
6:2 FTUI6:2 unsaturated FT iodideFCF2, SCH=CH218:1 FT olefin8:1 fluorotelomer olefinF(CF2,)SCF=CH2N-EtFOSEN-ethyl perfluorooctane sulfonamidoethanolF(CF2,)SSO,N(C;H3,CH2,CH2OHN-EtFOSEN-ethyl-perfluorooctane sulfonamidoethanol aldehydeF(CF2,)SSO,N(C;H3,CH2,CH2OHN-EtFOSAN-ethyl-perfluorooctane sulfonamidoethanol aldehydeF(CF2,)SSO,N(C;H3,CH2,CH0OHN-EtFOSAN-ethyl-perfluorooctane sulfonamide acetic acidF(CF2,)SSO,N(H2,H3,CH2,CH0OHN-EtFOSAN-ethyl-perfluorooctane sulfonamido aldehydeF(CF2,)SSO,N(H2,CH3,CH2,CH0OHEtFOSAPerfluorooctane sulfonamido aldehydeF(CF2,)SSO,N(H2,CH0OHFOSAPerfluorooctane sulfonamido aldehydeF(CF2,)SSO,NH2,CH0OHFOSAPerfluorooctane sulfonamido acetic acidF(CF2,)SSO,NH2,CH0OHFOSAPerfluorooctane sulfonamido acetic acidF(CF2,)SSO,NH2PFOSPerfluorooctane sulfonamideF(CF2,)SSO,NH2PFOSPerfluorooctane sulfonamideF(CF2,)SSO,NH2PFOSPerfluorooctane sulfonamido acetic acidF(CF2,)SO,SO,H4PFOSPerfluorootane sulfonarideF(CF2,)SO,SO,H4PFOSPerfluorootane sulfonamido sulfonatesF(CF2,)SO,CH2,CH2,CD0,SO,H4Viterionic, cationic and anionic fluoroalkyl autematives with novel functional groupsTX:2 PtTASFluorotelomer thiohydroxy ammoniumF(CF2,)CH2,CH2,CH2,CH0,CH4,S),CH2,CO0^-X:2 PtTASFluorotelomer sulfonamido sulfonatesF(CF2,)CH2,CH2,CH2,CH0,CH4,S),SCX:2 PtTASFluorotelomer sulfonamido aminesF(CF2,)CH2,CH2,CH2,CH2,SD,2,M1(CH2,)	X:2 uFTOH-GS	Unsaturated FTOH glutathione conjugate	$F(CF_2)_{x-1}C(SG) = CHCH_2OH$					
8:1 Fr olefin8:1 fluorotelomer olefinFCCF2);CFC H22N-EtFOSEN-ethyl perfluorooctane sulfonamidoethanolFCCF2);SO2N(C;H3;CH2;CH2OHN-EtFOSE aldehydeN-ethyl perfluorooctane sulfonamido acetic acidFCCF2);SO2N(C;H3;CH2COOHN-EtFOSAN-ethyl-perfluorooctane sulfonamido acetic acidFCCF2);SO2N(C;H3;CH2COOHN-EtFOSA alcoholPerfluorooctane sulfonamido alcoholFCCF2);SO2NHCH3;CH2COOHEtFOSA alcoholPerfluorooctane sulfonamido alcoholFCCF2);SO2NHCH3;CH2OOHFOSAPerfluorooctane sulfonamido acetic acidFCCF2);SO2NHCH3;CDQHFOSAPerfluorooctane sulfonamido acetic acidFCCF2);SO2NHCH3;CDQHFOSAPerfluorooctane sulfonamido acetic acidFCCF2);SO2NHCH3;CDQHFOSAPerfluorooctane sulfonamido acetic acidFCCF2);SO2NHCH3;CDQHPOSIPerfluorooctane sulfonamido acetic acidFCCF2);SO2NHCH3;CDQHPFOSPerfluorooctane sulfonamido acetic acidFCCF2);SO3HCH3;CDQHPFOSPerfluorooctane sulfonarido acetic acidFCCF2);SO3HCH3;CDQHPFOSPerfluorooctane sulfonic acidsFCCF2);SO3HPFOSPerfluorooctane sulfonarido acetic acidFCCF2);SO3HPFOSPerfluorooctane sulfonarido forming foars:TCCF2);SO3HX:2 FTASFluorotelomer thiohydroxy ammoniumFCCF2);CH2(H2SO2H;CH2);CH2);CH2;CH2;CD2,CH4;CH3);CH3);CH2;CD0^CX:2 FTASFluorotelomer thiohydroxy ammoniumFCCF2);CH2(H2);SO3H(CH2);SN(H2);CH2);COC^CX:2 FTASFluorotelomer sulfonamido betainesFCCF2);CH2(H2);SO2H(CH2);SN(H2);CH2);COC^CX:2 FTASFluorotelomer sulfonam	6:2 FTUI	6:2 unsaturated FT iodide	$F(CF_2)_6CH = CH_2I$					
N-EtFOSEN-ethyl perfluorooctane sulfonamidoethanolF(CF2)sS02N(C2H3)CH2CH2CH4CH2AN-EtFOSAN-ethyl-perfluorooctane sulfonamidoe acetic acidF(CF2)sS02N(C2H3)CH2CH3CH4CH2AN-EtFOSAN-ethyl-perfluorooctane sulfonamido aldehydeF(CF2)sS02N(C2H3)CH2CH3CH4CH2AN-EtFOSAN-ethyl-perfluorooctane sulfonamido alceholF(CF2)sS02N(C4H3)CH2COHEtFOSA alcoholPerfluorooctane sulfonamido aldehydeF(CF2)sS02NHCH2CH2OHFOSAPerfluorooctane sulfonamido acetic acidF(CF2)sS02NHCH2CH0OHFOSAPerfluorooctane sulfonamido acetic acidF(CF2)sS02NHCH2CH0OHPFOSPerfluorooctane sulfonic acidsF(CF2)sS02NHCH2CH0OHPFOSPerfluorooctane sulfonic acidsF(CF2)sS02NH2POSPerfluorooctane sulfonic acidsF(CF2)sS03HPolyfluoroalkyl alternatives with novel <i>fuuctorone sulfonamido aslifonates</i> F(CF2)sS03HX:2 PtFAoSPerfluoroacky sulfonic acidsF(CF2)sS03HX:2 PtFAoSFluorotelomer thioamido sulfonatesF(CF2)sC92H2CH2CCNCHCC(H3)2 CH2S03-X:2 PtFAoSFluorotelomer thioamido sulfonatesF(CF2)sCH2CH2CH2CCNCHCC(H3)2 CH2S03-X:2 PtFAoSFluorotelomer sulfonamido adeinesF(CF2)sCH2CH2CH2CNCHCC(H3)2 CH2S03-X:2 PtFAoSFluorotelomer sulfonamido adeinesF(CF2)sCH2CH2CN2CH2CH2CH2CONCCX:2 PtFAAFluorotelomer sulfonamido adminesF(CF2)sCH2CH2CN2CH2CH2CONCCX:2 PtFAAFluorotelomer betainesF(CF2)sCH2CH2CNCHCH3)2 CH2COCX:2 PtFAASi Fluorotelomer betainesF(CF2)sCN2N(H4)2)NH(CH3)2CH2COCX:2 PtFAAPerfluoroalkyl sulfonamido amines<	8:1 FT olefin	8:1 fluorotelomer olefin	$F(CF_2)_7CF = CH_2$					
N-EtrOSE aldehydeN-ethyl perfluorooctane sulfonamidoethanol aldehydeF(CF2)sS02N(C2H3)CH2CH0N-EtrOSAAN-ethyl-perfluorooctane sulfonamida ecitic acidF(CF2)sS02N(C2H3)CH2COHN-EtrOSAN-ethyl-perfluorooctane sulfonamido alcoholF(CF2)sS02NHC2H3EtFOSA alcoholPerfluorooctane sulfonamido alcoholF(CF2)sS02NHC42CH0EtFOSA aldehydePerfluorooctane sulfonamido alcehydeF(CF2)sS02NHCH2CH0FOSAPerfluorooctane sulfonamido acetic acidF(CF2)sS02NHCH2CH0FOSAPerfluorooctane sulfonamido acetic acidF(CF2)sS02NHCH2CH0POSIPerfluorooctane sulfonic acidsF(CF2)sS02NHCH2CH0PFOSPerfluorooctane sulfonic acidsF(CF2)sS02NHCH2CH0PFOSPerfluorooctane sulfonic acidsF(CF2)sS02NHCH2CH0PrOSPerfluoroalkyl sulfonic acidsF(CF2)sS02NHCH2CH0PrOSPerfluoroalkyl sulfonic acidsF(CF2)sS02NHCH2CD0NHCC(CH3)2 CH2CD3Zi FtAoSIeurotelomer thiopadoxy ammoniumF(CF2)sCF2/CH2CH2CD2CNHCC(CH3)2 CH2CD3X:2 FtSASFluorotelomer thiopadoxy ammoniumF(CF2)sCF2/CH2CH2CD0NHCC(CH3)2 CH2CD3X:2 FtSASFluorotelomer sulfonamido batinesF(CF2)sCF2/CH2CH2CD0NHCC(CH3)2 CH2CD3X:2 FtSASFluorotelomer thiopadoxy ammoniumF(CF2)sCF2/CH2CH2CD0NHCC(CH3)2 CH2CD3X:2 FtSASFluorotelomer sulfonamido aminesF(CF2)sCF2/CH2CH2CD0NHCC(CH3)2 CH2CD3X:2 FtSASFluorotelomer sulfonamido aminesF(CF2)sCP2/CH2CH2CD0C)X:2 FtSASAMPerfluoroblys sulfonamido aminesF(CF2)sCP2/CH2CD3/CH42/SD2/H(CH3)2N(CH3)2CH2CD3PFASAMAPerfluoroblys	N-EtFOSE	N-ethyl perfluorooctane sulfonamidoethanol	F(CF ₂) ₈ SO ₂ N(C ₂ H ₅)CH ₂ CH ₂ OH					
N-EtFOSAAN-ethyl-perfluorooctane sulfonamide acetic acidF(CF2)sD0_N(Cf2H3)CH2_COOHN-EtFOSAN-ethyl-perfluorooctane sulfonamide acetic acidF(CF2)sD0_NHCH2_CH3EtFOSA alcoholPerfluorooctane sulfonamido alcoholF(CF2)sD0_NHCH2_CH0EtFOSA aldehydePerfluorooctane sulfonamido alcehydeF(CF2)sD0_NHCH2_CH0FOSAPerfluorooctane sulfonamido acetic acidF(CF2)sD0_NHCH2_CH0FOSAPerfluorooctane sulfonamido acetic acidF(CF2)sD0_NHCH2_CH0FOSAPerfluorooctane sulfonamido acetic acidF(CF2)sD0_NHC2PFOSPerfluorootane sulfonic acidF(CF2)sD0_NH2PFOSPerfluorootane sulfonic acidsF(CF2)sD0_HPofluoroalkyl alternatives with novel functional groupsFZwitterionic, cationic and anionic fluoroalkyl aqueous film-forming foams:FX:2 FTTAOSFluorotelomer thioamido bulfonatesF(CF2),CH2_CH2_SO1_CH2_CN2_CH2_CONHCC(CH3)2 CH2_SO3X:2 FTTAN*Fluorotelomer sulfonamido betainesF(CF2),CH2_CH2_SO2_NH(CH2)3N(CH3)2 CH2_SO3X:2 FTTAN*Fluorotelomer sulfonamido betainesF(CF2),CH2_CH2_SO2_NH(CH2)3N(CH3)2 CH2_SO3X:2 FTTAN*Fluorotelomer sulfonamido betainesF(CF2),CH2_CH2_SO2_NH(CH2)3N(CH3)2 CH2_COO*X:2 FTSABFluorotelomer sulfonamido aminesF(CF2),SO2,NH(CH2)3N(CH3)2CH2_COO*X:3 FtBX:3 Fluorotelomer betainesF(CF2),SO2,NH(CH2)3N(CH3)2,CH2_COO*PFASAmAPerfluoroalkyl sulfonamido aminesF(CF2),SO2,NH(CH2)3N(CH3)2,CH2_COO*PFASAmAPerfluoroalkyl sulfonamido aminesF(CF2),SO2,NH(CH2)3N(CH3)2,CH2_COO*PFASAmAPerflu	N-EtFOSE aldehyde	N-ethyl perfluorooctane sulfonamidoethanol aldehyde	F(CF ₂) ₈ SO ₂ N(C ₂ H ₅)CH ₂ CHO					
N-EtFOSAN-ethyl-perfluorooctane sulfonamideF(CF2)sSO2NHC2H5EtFOSA alcoholPerfluorooctane sulfonamido alcoholF(CF2)sSO2NHCH2CH2OHEtFOSA aldehydePerfluorooctane sulfonamido acetic acidF(CF2)sSO2NHCH2CH0FOSAPerfluorooctane sulfonamido acetic acidF(CF2)sSO2NHCH2COOHFOSAPerfluorooctane sulfonamideF(CF2)sSO2NHCH2COOHPOSIPerfluorooctane sulfonic acidF(CF2)sSO2NH2PFOSPerfluorootane sulfonic acidF(CF2)sSO3HPFOSPerfluorootane sulfonic acidF(CF2)sSO3HPFOSPerfluorootane sulfonic acidF(CF2)sSO3HPofluoroalkyl alternatives with novel furctional groupsF(CF2)sSO3HZvitterionic, cationic aluanici fluoriztiva queeus film-forming foamsF(CF2)sSO3HX:2 PtTAOSFluorotelomer thioamido sulfonatesF(CF2)sCH2CH2SCH2CH2ONHCC(CH3)2 CH2SO3-X:2 PtTASFluorotelomer sulfonamido betainesF(CF2)sCH2CH2SO2NH(CH2)3N(CH3)2H2COO-X:2 PtSaBFluorotelomer sulfonamido aminesF(CF2)sCH2(CH2SO2NH(CH2)3N(CH3)2H2COO-X:1 2 FLBX:1 2 Fluorotelomer betainesF(CF2)sCN2NH(CH2)3NH(CH3)2H2COO-X:3 PtBX:3 Fluorotelomer betainesF(CF2)sCN2NH(CH2)3NH(CH3)2+PrASaAmAPerfluoroalkyl sulfonamido aminesF(CF2)sCN2NH(CH2)3NH(CH3)2+PrASAmAPerfluoroalkyl sulfonamido aminesF(CF2)sCN2NH(CH2)3NH(CH3)2+PrASAMACAS No. 958445-44-8CF3OCF2CF2OCFHC7COO-GenX (DuPont)CAS No. 62037-80-3CF3CF2CF2OCFHC72OCO-Asahi's productCAS No. 908020-52-0CF3CF2CF2OCFCF2OC-Solv	N-EtFOSAA	N-ethyl-perfluorooctane sulfonamide acetic acid	F(CF ₂) ₈ SO ₂ N(C ₂ H ₅)CH ₂ COOH					
EtFOSA alcoholPerfluorooctane sulfonamido alcoholF(CF2)_sSO2_NHCH2CH2OHEtFOSA aldehydePerfluorooctane sulfonamido alcetia caidF(CF2)_sSO2_NHCH2COOHFOSAPerfluorooctane sulfonamido acetia caidF(CF2)_sSO2_NHCH2COOHFOSAPerfluorooctane sulfonic acidF(CF2)_sSO2_NH2PFOSIPerfluorooctane sulfonic acidF(CF2)_sSO2_NH2PFOSPerfluorooctane sulfonic acidF(CF2)_sSO3_HPFOSPerfluorooctane sulfonic acidF(CF2)_sSO3_HPFOSPerfluorooctane sulfonic acidF(CF2)_sSO3_HPFOSPerfluorooctane sulfonic acidF(CF2)_sSO3_HPFOSPerfluorooctane sulfonic acidF(CF2)_sSO3_HPFOSPerfluorooctane sulfonic acidF(CF2)_sSO3_HPFOSPerfluorooctane sulfonic acidF(CF2)_sCD3_HProsPerfluorooctane sulfonic acidF(CF2)_sCD3_HProsPerfluorooctane sulfonic acidF(CF2)_sCD4_2CH2_SCH2_CH2_SCH2_CH2_SO3_HProsFuorotelomer thiopdroxy ammoniumF(CF2)_sCH2_CH2_SCH2_CH2_SCH2_CH2_SO3_HX:2 PtTAN*Fluorotelomer thiopdroxy ammoniumF(CF2)_sCH2_CH2_SCA2_CH2_SO2_H(CH2)_SCH2_CCO2_CX:2 PtSaAmFluorotelomer sulfonamido aminesF(CF2)_sCH2_CH2_SO2_H(CH2)_SO2_H(CH2)_SUHCH3)_2*X:3 PtBX:3 Fluorotelomer betainesF(CF2)_SO2_NH(CH2)_SUH(CH3)_2*PtASaAmPerfluoroalky sulfonamido aminesF(CF2)_SO2_NH(CH2)_SO2_H(CH2)_SO2_H(CH3)_2*PtASaAmAPerfluoroalky sulfonamido aminesF(CF2)_SO2_NH(CH2)_SO2_H(CH2)_SO2_H(CH2)_SO2_H(CH3)_2*PtASaAmACAS No.558445-44-8CF3_CCF2_CF2_COCHCF2_CO	N-EtFOSA	N-ethyl-perfluorooctane sulfonamide	$F(CF_2)_8SO_2NHC_2H_5$					
EtFOSA aldehyde Perfluorooctane sulfonamido aldehyde F(CF2)sS02NHCH2CHO FOSA Perfluorooctane sulfonamido acetic acid F(CF2)sS02NHCH2COOH FOSA Perfluorooctane sulfonamido acetic acid F(CF2)sS02NH2 PFOS Perfluorooctane sulfonic acid F(CF2)sS03H PFOS Perfluorooctane sulfonic acid F(CF2)sS03H Polyfluoroalkyl alternatives with novel functorotane sulfonic acid F(CF2)sS03H Polyfluoroalkyl alternatives with novel functorotane sulfonic acid F(CF2)sS03H Vitterionic, cationic and anionic fluorotally aqueous film-forming foams:	EtFOSA alcohol	Perfluorooctane sulfonamido alcohol	F(CF ₂) ₈ SO ₂ NHCH ₂ CH ₂ OH					
FOSAAPerfluoroctane sulfonamido acetic acidF(CF2)gSO2NHCH2COOHFOSAPerfluoroctane sulfonamideF(CF2)gSO2NH2PFOSPerfluoroctane sulfinic acidF(CF2)gSO3HPFOSPerfluoroctane sulfonic acidsF(CF2)gSO3HPFOSPerfluoroctane sulfonic acidsF(CF2)gSO3HPotfluoroalkyl sulfonic acidsF(CF2)gSO3HPFOSPerfluoroatne sulfonic acidsF(CF2)gSO3HPotfluoroalkyl atternatives with novel functional groupsF(CF2)gSO3HZwitterionic, cationic and anionic fluoroalkyl aqueous film-forming foams:F(CF2)gCH2CH2CSCH2CH2CONHCC(CH3)2 CH2SO3^-X:2 FtTAoSFluorotelomer thioamido sulfonatesF(CF2)gCH2CH2SCH2CH(OH)CH2N(CH3)3'X:2 FtSaAFluorotelomer sulfonamido aminesF(CF2)gCH2CH2SO2NHC(CH3)2(CH2)COCO-X:2 FtSaAFluorotelomer sulfonamido aminesF(CF2)gCH2(H2)SO2H(CH2)3N(CH3)2CH2COO-X:3 FtBX:1:2 FtBX:1:2 Ftuorotelomer betainesF(CF2)gCH2(CH2)SO2H(CH2)3N(CH3)2CH2COO-X:3 FtBX:3 Fluorotelomer betainesF(CF2)gSO2H(CH2)SN(CH2)3N(CH3)2CH2COO-FASaAmAPerfluoroalkyl sulfonamido aminesF(CF2)gSO2NH(CH2)3NH(CH3)2'Functionalized perfluoroplyethers:FFADONA (3M)CAS No.958445-44-8CF30CF2CF2CF2CF20CP(CF3)COC-GenX (DuPont)CAS No.958445-44-8CF30CF2CF2CF2CF2COC-GenX (DuPont)CAS No.958205-52-0CF3CF2CF2CF2CF2CF2COC-Solvay's productCAS No.329238-24-6CF3CF2CF2CFCF30Dm2CFCF30Dm2CFCF30Dm2CF2CF2COC-	EtFOSA aldehyde	Perfluorooctane sulfonamido aldehyde	F(CF ₂) ₈ SO ₂ NHCH ₂ CHO					
FOSAPerfluoroctane sulfonamideF(CF2)sS02H22PFOSIPerfluoroctane sulfnic acidsF(CF2)sS02HPFSAsPerfluoroalkyl sulfonic acidsF(CF2)sS03HPFOSPerfluoroalta sulfnic acidsF(CF2)sS03HPolyfluoroalkyl alternatives with novel furrorate sulfonic acidsF(CF2)sS03HPolyfluoroalkyl alternatives with novel furrorate sulfonic acidsF(CF2)sS03HZwitterionic, cationic and anionic fluoroulkyl aqueous film-forming foams:TX:2 PtTAoSFluorotelomer thioamido sulfonatesF(CF2)sCH2CH2CH2CH2CQONHCC(CH3)2 CH2SO3-X:2 PtTASFluorotelomer thiohydroxy amnoniumF(CF2)sCH2CH2CH2CQO2CH2CH2OH)(CH2)sCH2CH2CO2X:2 PtTSaBFluorotelomer sulfonamido betainesF(CF2)sCH2CH2CSO2NH(CH2)sN(CH3)2CH2COO-X:2 PtSaAmFluorotelomer betainesF(CF2)sCH2CH2CSO2NH(CH2)sNH(CH3)2CH2COO-X:1:2 FtBX:1:2 Fluorotelomer betainesF(CF2)sCP2(CH2CH2SO2NH(CH2)sNH(CH3)2CH2COO-X:1:2 FtBX:3 Fluorotelomer betainesF(CF2)sCSO2NH(CH2)sNH(CH3)2CH2COO-Y:3 FtBX:3 Fluorotelomer betainesF(CF2)sCSO2NH(CH2)sNH(CH3)2CH2COO-Y:A StAmAPerfluoroalkyl sulfonamido aminos carboxylatesF(CF2)sSO2NH(CH2)sNH(CH3)2CH2COO-PFASAMAPerfluoroalkyl sulfonamido amino carboxylatesF(CF2)sC92CF2CPCCH2CDO-Protonalized perfluoroplyethers:FFADONA (3M)CAS No.58445-44-8C50CF2CF2CPCFC3)COO-GenX (DuPont)CAS No.62037-80-3CF3CF2CF2CPCFCS)OO-Asahi's productCAS No.62037-80-3CF3CF2CPCFCF2COO-Solvay's productCAS No.329238-24-6CF	FOSAA	Perfluorooctane sulfonamido acetic acid	F(CF ₂) ₈ SO ₂ NHCH ₂ COOH					
PFOSIPerfluorooctane sulfinic acidF(CF2) ₈ SO2HPFSAsPerfluorootane sulfonic acidsF(CF2) ₈ SO3HPFOSPerfluorootane sulfonic acidF(CF2) ₈ SO3HPolyfluoroalkyl alternatives with novel fur-tional groupsF(CF2) ₈ SO3HZvitterionic, cationic and anionic fluoroet fluoroet fluoroet sulfonic solf of aniotF(CF2) ₈ CH2CH2SCH2CH2CCH2COHCC(CH3) ₂ CH2SO3 ⁻¹ X:2 FtTAoSFluorotelomer thioamido sulfonatesF(CF2) ₈ CH2CH2SCH2CH2COHCC(CH3) ₂ CH2SO3 ⁻¹ X:2 FtSABFluorotelomer sulfonamido betainesF(CF2) ₈ CH2CH2SCH2CH2COHCC(CH3) ₂ CH2COC ⁻¹ X:2 FtSABFluorotelomer sulfonamido betainesF(CF2) ₈ CH2CH2SCH2CH2ONHCC(CH3) ₂ CH2COC ⁻¹ X:2 FtSABFluorotelomer sulfonamido betainesF(CF2) ₈ CH2CH2CSCH2CH2ONHCC(CH3) ₂ CH2COC ⁻¹ X:2 FtSABFluorotelomer sulfonamido betainesF(CF2) ₈ CH2(CH2) ₂ CH2CH2CSQ2NH(CH2) ₃ NH(CH3) ₂ CH2COC ⁻¹ X:1 2 FtSBX:1 2 Fluorotelomer sulfonamido aminesF(CF2) ₈ CH2(H2) ₂ ON(CH2) ₂ ON(CH3) ₂ CH2COC ⁻¹ X:3 FluOrotelomer betainesF(CF2) ₈ CP3/CH2(H2) ₂ ON(CH3) ₂ CH4COO ⁻¹ FYEFASAAMPerfluoroalkyl sulfonamido aminesF(CF2) ₈ CSQ2NH(CH2) ₃ NH(CH3) ₂ ⁺¹ PFASaAmAPerfluoroalkyl sulfonamido amine carboxylatesF(CF3) ₂ CSQ2NF(CF2) ₂ CPCCOC ⁻¹ Furctionalized perfluoropolyethers:FADONA (3M)CAS No. 958445-44-8CF3CF2CF2CCFCF3COC ⁻¹ GenX (DuPont)CAS No. 62037-80-3CF3CF2CP2CF(CF3)COC ⁻¹ Asahi's productCAS No. 908020-52-0CF3CF2CP2CF(CF3)O0m_1(CFC3)O] ₁ CF2COC ⁻¹ Solvay's productCAS No. 329238-24-6CF3CF2CF2	FOSA	Perfluorooctane sulfonamide	$F(CF_2)_8SO_2NH_2$					
PFSAs Perfluoroalkyl sulfonic acids F(CF2)xS03H PFOS Perfluorooctane sulfonic acids F(CF2)xS03H Polyfluoroalkyl alternatives with novel furritores F(CF2)xS03H Zwitterionic, cationic and anionic fluoroalkyl aqueous film-forming foams: F(CF2)xCH2CH2CH2CCH2CCH42CCH43CCH2CONHCC(CH3)2 CH2S03 X:2 FtTAoS Fluorotelomer thioamido sulfonates F(CF2)xCH2CH2CH2CH2CH(DH)CH2)X(H3)2CH2COO ⁻ X:2 FtTAOS Fluorotelomer sulfonamido betaines F(CF2)xCH2CH2CH2CH2CH(DH)CH2)X(CH3)2CH2COO ⁻ X:2 FtSAB Fluorotelomer sulfonamido betaines F(CF2)xCH2CH2CH2SO2NH(CH2)3N(CH3)2CH2COO ⁻ X:2 FtSAB Fluorotelomer betaines F(CF2)xCH2CH2CH2SO2NH(CH2)3N(CH3)2CH2COO ⁻ X:2 FtSB X:1:2 Ftuorotelomer betaines F(CF2)xCH2CH2DN(CH3)2CH2COO ⁻ X:3 FtB X:3 Fluorotelomer betaines F(CF2)xCH2(CH2)3N(CH3)2CH2COO ⁻ Y:3 FtB X:3 Fluorotelomer betaines F(CF2)xSO2NH(CH2)3NH(CH3)2 ⁺ PFASAAM Perfluoroalkyl sulfonamido amino carboxylates F(CF2)xSO2NH(CH2)3NH(CH3)2 ⁺ PFASAAMA Perfluoroalkyl sulfonamido amino carboxylates F(CF2)xSO2NCH2CP2COC ⁻ (CH2)3NH(CH3)2 ⁺ ADONA (3M) CAS No. 958445-44-8 CF3OCF2CF2COCF4CF2COCF4CF2COC ⁻	PFOSI	Perfluorooctane sulfinic acid	F(CF ₂) ₈ SO ₂ H					
PFOS Perfluorooctane sulfonic acid F(CF2)sQ3H Polyfluoroalkyl alternatives with novel furcional groups Zwitterionic, cationic and anionic fluoroalkyl aqueous film-forming foams: X:2 FtTAOS Fluorotelomer thioamido sulfonates F(CF2)sCH2CH2CH2CH2CH2CH42ONHCC(CH3)2 CH2SO3 X:2 FtTAOS Fluorotelomer thioamido sulfonates F(CF2)sCH2CH2CH2CH2CH2CH42ONHCC(CH3)2 CH2SO3 X:2 FtTAOS Fluorotelomer thiopydroxy ammonium F(CF2)sCH2CH2CH2CH2CH(OH)CH2)N(CH3)2CH2COO ⁻ X:2 FtSaB Fluorotelomer sulfonanido betaines F(CF2)sCH2CH2SO2NH(CH2)3NH(CH3)2 ⁺ X:1 FtB K1:12 Fluorotelomer betaines F(CF2)sCH2(CH2)2N(CH3)2CH2COO ⁻ X:3 FtB X:3 Fluorotelomer betaines F(CF2)sQ2NH(CH2)3NH(CH3)2 ⁺ PFASaAm Perfluoroalkyl sulfonamido amines F(CF2)sQ2NH(CH2)3NH(CH3)2 ⁺ PFASAAmA Perfluoroalkyl sulfonamido amines carboxylates F(CF2)sQ2NH(CH2)3NH(CH3)2 ⁺ Furctionalized perfluoroplytethers: PFASAAmA Perfluoroalkyl sulfonamido amines carboxylates F(GF2)sQ2NH(CH2)3NH(CH3)2 ⁺ Furctionalized perfluoroplytethers: Solo A30M) CAS No. 958445-44-8	PFSAs	Perfluoroalkyl sulfonic acids	F(CF ₂) _x SO ₃ H					
Polyfluoroalkyl alternatives with novel fur-tional groupsZwitterionic, cationic and anionic fluoroalkyl aqueous film-forming foams:X:2 FtTAoSFluorotelomer thioamido sulfonatesX:2 FtTAoSFluorotelomer thioamido sulfonatesX:2 FtTHN*Fluorotelomer thiohydroxy ammoniumX:2 FtSaBFluorotelomer sulfonamido betainesX:2 FtSaAmFluorotelomer sulfonamido betainesX:12 FtBX:12 Fluorotelomer betainesX:2 FtBX:12 Fluorotelomer betainesX:3 FtBX:3 Fluorotelomer betainesFCF2)xCH2(H2)2N(CH3)2CH2COO-X:3 FtBX:3 Fluorotelomer betainesPFASaAmPerfluoroalkyl sulfonamido amino carboxylatesFurctionalized perfluoropolyethers:ADONA (3M)CAS No. 958445-44-8GenX (DuPont)CAS No. 908020-52-00Asahi's productCAS No. 329238-24-6CAS No. 329238-24-6CIF ₆ C ₃ O(F2CF2(FCF3)O) _m [CF(CF3)O] _m [CF(CF3)O] _m [CF(CF3)O] _m CF2COO-	PFOS	Perfluorooctane sulfonic acid	F(CF ₂) ₈ SO ₃ H					
Zwitterionic, cationic and anionic fluoroalkyl aqueous film-forming foams:X:2 FtTAoSFluorotelomer thioamido sulfonatesF(CF2)xCH2CH2SCH2CH2CONHCC(CH3)2 CH2SO3^X:2 FtTAh*Fluorotelomer thiohydroxy ammoniumF(CF2)xCH2CH2SCH2CH2CH(OH)CH2N(CH3)3^+X:2 FtSaBFluorotelomer sulfonamido betainesF(CF2)xCH2CH2SO2NH(CH2)3N(CH3)2CH2COO^X:2 FtSaBFluorotelomer sulfonamido aminesF(CF2)xCH2CH2SO2NH(CH2)2N(CH3)2CH2COO^X:1 2 FtBX:1:2 Fluorotelomer betainesF(CF2)xCH2(LS2O2NH(CH2)2N(CH3)2CH2COO^X:3 FtBX:3 Fluorotelomer betainesF(CF2)xCH2(LS2O2NH(CH2)2N(CH3)2CH2COO^YFASaAmPerfluoroalkyl sulfonamido aminesF(CF2)xCH2(LS2O2NH(CH2)2N(CH3)2CH2COO^PFASaAmAPerfluoroalkyl sulfonamido aminesF(CF2)xSO2NH(CH2)3NH(CH3)2^+Functionalized perfluoroplyethers:FFADONA (3M)CAS No. 958445-44-8CF30CF2CF2CF2CF2CF2CFCHCF2COO^GenX (DuPont)CAS No. 908020-52-0CF3CF2CF2CF2CFCF(CF3)CO0^-Asahi's productCAS No. 329238-24-6CH3CSA2A2Solvay's productCAS No. 329238-24-6CH5CSA2A2	Polyfluoroalkyl alternatives with novel fun	ctional groups						
X:2 FtTAoS Fluorotelomer thioamido sulfonates F(CF2)xCH2CH2SCH2CH2CONHCC(CH3)2 CH2SO3 X:2 FtTHN* Fluorotelomer thiobydroxy ammonium F(CF2)xCH2CH2SCH2CH(OH)CH2N(CH3)3 ⁺ X:2 FtSaB Fluorotelomer sulfonamido betaines F(CF2)xCH2CH2SO2NH(CH2)3N(CH3)2CH2COO X:2 FtSaB Fluorotelomer sulfonamido amines F(CF2)xCH2CH2SO2NH(CH2)3N(CH3)2CH2COO X:2 FtSa Fluorotelomer sulfonamido amines F(CF2)xCH2(LH2)2N(CH2)2N(CH3)2CH2COO X:1 2 FtB X:1 2 Fluorotelomer betaines F(CF2)xCH2(LH2)3N(CH3)2CH2COO X:3 FtB X:3 Fluorotelomer betaines F(CF2)xCH2(LH2)3N(CH3)2CH2COO PFASaAm Perfluoroalkyl sulfonamido amines F(CF2)xSO2NH(CH2)3NH(CH3)2 ⁺⁻ PFASaAmA Perfluoroalkyl sulfonamido amine carboxylates F(CF2)xSO2N(CH2CH2COO)(CH2)3NH(CH3)2 ⁺⁻ Furctionalized perfluoroplyethers:	Zwitterionic, cationic and anionic fluoroalkyl aqueous film-forming foams:							
X:2 FtTHN* Fluorotelomer thiohydroxy ammonium F(CF2)xCH2CH2CH(0H)CH2N(CH3)3* X:2 FtSaB Fluorotelomer sulfonamido betaines F(CF2)xCH2CH2SO2NH(CH2)3N(CH3)2CH2COO^- X:2 FtSaAm Fluorotelomer sulfonamido amines F(CF2)xCH2CH2SO2NH(CH2)3N(CH3)2* X:1 2 FtB X:1 2 Fluorotelomer betaines F(CF2)xCH2(CH2)2N(CH2)3N(CH3)2CH2COO^- X:3 FtB X:1 2 Fluorotelomer betaines F(CF2)xCH2(LH2)3N(CH3)2CH2COO^- Y:3 FtB X:3 Fluorotelomer betaines F(CF2)xCH2(LH2)3N(CH3)2CH2COO^- PFASaAm Perfluoroalkyl sulfonamido amines F(CF2)xSO2NH(CH2)3NH(CH3)2* PFASaAmA Perfluoroalkyl sulfonamido amine carboxylates F(CF2)xSO2NH(CH2)3NH(CH3)2* Functionalized perfluoropolyethers: Functionalized perfluoropolyethers: Functionalized perfluoropolyethers: ADONA (3M) CAS No. 958445-44-8 CF30CF2CF2CF2CFCHCF2COO^- GenX (DuPont) CAS No. 62037-80-3 CF30CF2CF2CF2CCF(CF3)COO^- Asahi's product CAS No. 93020-52-0 CF3CF2CF2CF2CF(CF3)O0_n Solvay's product CAS No. 329238-24-6 CH6c30(F2CFC(CF3)O]m[CF(CF3)O]m[CF(CF3)O]m[CF(CF3)O]m[CF(CF3)O]m[CF(CF3)O]m[CF(CF3)O]m[CF(CF3)O]m[CF(CF3)O]m[CF(CF3)O]m[CF(CF3)O]m[CF(CF3)O]m[CF(CF3)O]m[CF(CF3)O]m[CF(CF3)O]m[CF(CF3)O]m[CF(CF3)O]m[CF(CF3)O]m[CF(CF3)O]m[CF(X:2 FtTAoS	Fluorotelomer thioamido sulfonates	F(CF ₂) _x CH ₂ CH ₂ SCH ₂ CH ₂ CONHCC(CH ₃) ₂ CH ₂ SO ₃ ⁻					
X:2 FtSaB Fluorotelomer sulfonamido betaines F(CF2)xCH2CH2SO2NH(CH2)3N(CH3)2CH2COO ⁻ X:2 FtSaAm Fluorotelomer sulfonamido amines F(CF2)xCH2CH2SO2NH(CH2)3NH(CH3)2 ⁺ X:1:2 FtB X:1:2 Fluorotelomer betaines F(CF2)xCH2(LP2)2N(CH3)2CH2COO ⁻ X:3 FtB X:3 Fluorotelomer betaines F(CF2)x(CH2)3N(CH3)2CH2COO ⁻ PFASaAm Perfluoroalkyl sulfonamido amines F(CF2)xSO2NH(CH2)3NH(CH3)2 ⁺ PFASaAmA Perfluoroalkyl sulfonamido amine carboxylates F(CF2)xSO2NH(CH2)3NH(CH3)2 ⁺ <i>Functionalized perfluoropolyethers:</i> F(CF2)xSO2NH(CH2)3NH(CH3)2 ⁺ F(CF2)xSO2NH(CH2)3NH(CH3)2 ⁺ ADONA (3M) CAS No. 958445-44-8 CF3)CF2CF2CF2CDCFHCF2COO ⁻ CF3)CF2CF2CF2CCFCF2OCF(CF3)ON ⁻ GenX (DuPont) CAS No. 62037-80-3 CF3)CF2CF2CF2CCF(CF3)COO ⁻ CF3)CF3CF2CF2CCCCCCCCCCCCCCCCCCCCCCCCCCC	X:2 FtTHN ⁺	Fluorotelomer thiohydroxy ammonium	$F(CF_2)_xCH_2CH_2SCH_2CH(OH)CH_2N(CH_3)_3^+$					
X:2 FtSaAm Fluorotelomer sulfonamido amines F(CF2)xCH2CH2SO2NH(CH2)3NH(CH3)2* X:1:2 FtB X:1:2 Fluorotelomer betaines F(CF2)xCFH(CH2)2N(CH3)2CH2COO^- X:3 FtB X:3 Fluorotelomer betaines F(CF2)x(CH2)3N(CH3)2CH2COO^- PFASaAm Perfluoroalkyl sulfonamido amines F(CF2)x(CH2)3N(CH3)2CH2COO^- PFASaAmA Perfluoroalkyl sulfonamido amines F(CF2)xSO2NH(CH2)3NH(CH3)2* PFASaAmA Perfluoroalkyl sulfonamido amines F(CF2)xSO2NH(CH2)3NH(CH3)2* PFASaAmA Perfluoroalkyl sulfonamido amine carboxylates F(CF2)xSO2NH(CH2)3NH(CH3)2* PFASAAMA CAS No.958445-44-8 CF30CF2CF2CF2COCF(CF2)0ONC(CH2)3NH(CH3)2* ADONA (3M) CAS No.62037-80-3 CF30CF2CF2CF2COCF(CF3)COO^- GenX (DuPont) CAS No.98020-52-0 CF3CF2CF2CF2CF2CF2COCF Asahi's product CAS No.329238-24-6 CIF6C30[CF2CF(CF3)O]m[CF(CF3)O]m CF2COO^-	X:2 FtSaB	Fluorotelomer sulfonamido betaines	F(CF ₂) _x CH ₂ CH ₂ SO ₂ NH(CH ₂) ₃ N(CH ₃) ₂ CH ₂ COO ⁻					
X:1:2 FtB X:1:2 Fluorotelomer betaines F(CF2)xCFH(CH2)2N(CH3)2CH2COO ⁻ X:3 FtB X:3 Fluorotelomer betaines F(CF2)x(CH2)3N(CH3)2CH2COO ⁻ PFASaAm Perfluoroalkyl sulfonamido amines F(CF2)xSO2NH(CH2)2N(CH3)2 ⁺ PFASaAmA Perfluoroalkyl sulfonamido amines F(CF2)xSO2NH(CH2)2N(CH3)2 ⁺ PFASaAmA Perfluoroalkyl sulfonamido amino carboxylates F(CF2)xSO2N(CH2CH2CDCO ⁻)(CH2)3NH(CH3)2 ⁺ Functionalized perfluoropolyethers: - - - ADONA (3M) CAS No. 958445-44-8 CF3OCF2CF2CF2OCF(CF3)COO ⁻ CF3OCF2CF2CF2OCF(CF3)COO ⁻ GenX (DuPont) CAS No. 62037-80-3 CF3CF2CF2OCF(CF3)COO ⁻ - Asahi's product CAS No. 93020-52-0 CF3CF2CF2CF2CF2CF2COC ⁻ - Solvay's product CAS No. 329238-24-6 CIF6_C3O[CF2CF2CFCF3)O]m[CF(CF3)O]n CF2COO ⁻	X:2 FtSaAm	Fluorotelomer sulfonamido amines	$F(CF_2)_xCH_2CH_2SO_2NH(CH_2)_3NH(CH_3)_2^+$					
X:3 FtB X:3 Fluorotelomer betaines F(CF2)x(CH2)3N(CH3)2CH2COO ⁻ PFASaAm Perfluoroalkyl sulfonamido amines F(CF2)xSO2NH(CH2)3NH(CH3)2 ⁺ PFASaAmA Perfluoroalkyl sulfonamido amino carboxylates F(CF2)xSO2N(CH2CH2COO ⁻)(CH2)3NH(CH3)2 ⁺ Functionalized perfluoropolyethers: F F(CF2)xSO2N(CH2CH2COO ⁻)(CH2)3NH(CH3)2 ⁺ ADONA (3M) CAS No. 958445-44-8 CF30CF2CF2CF2CF2CFCF4CF2cOO ⁻ GenX (DuPont) CAS No. 62037-80-3 CF3CF2CF2OCF(CF3)COO ⁻ Asahi's product CAS No. 93020-52-0 CF3CF2CF2CF2CF2CF2CF2COC ⁻ Solvay's product CAS No. 329238-24-6 CIF6C30[CF2CF(CF3)O]m[CF(CF3)O]m CF2COO ⁻	X:1:2 FtB	X:1:2 Fluorotelomer betaines	$F(CF_2)_x CFH(CH_2)_2 N(CH_3)_2 CH_2 COO^-$					
PFASaAm Perfluoroalkyl sulfonamido amines F(CF2)_xSO2NH(CH2)_3NH(CH3)_2^+ PFASaAmA Perfluoroalkyl sulfonamido amino carboxylates F(CF2)_xSO2N(CH2CH2COO^-)(CH2)_3NH(CH3)_2^+ Functionalized perfluoropolyethers:	X:3 FtB	X:3 Fluorotelomer betaines	$F(CF_2)_x(CH_2)_3N(CH_3)_2CH_2COO^-$					
PFASaAmA Perfluoroalkyl sulfonamido amino carboxylates F(CF2)xSO2N(CH2CH2COO ⁻)(CH2)3NH(CH3)2 ⁺ Functionalized perfluoropolyethers:	PFASaAm	Perfluoroalkyl sulfonamido amines	$F(CF_2)_xSO_2NH(CH_2)_3NH(CH_3)_2^+$					
Functionalized perfluoropolyethers: CAS No. 958445-44-8 CF ₃ OCF ₂ CF ₂ OCFHCF ₂ COO ⁻ ADONA (3M) CAS No. 958445-44-8 CF ₃ OCF ₂ CF ₂ OCFHCF ₂ COO ⁻ GenX (DuPont) CAS No. 62037-80-3 CF ₃ CF ₂ CF ₂ OCF(CF ₃)COO ⁻ Asahi's product CAS No. 908020-52-0 CF ₃ CF ₂ OCF ₂ CCF ₂ COO ⁻ Solvay's product CAS No. 329238-24-6 CIF ₆ C ₃ O[CF ₂ CF(CF ₃)O] _m [CF(CF ₃)O] _m CF ₂ COO ⁻	PFASaAmA	Perfluoroalkyl sulfonamido amino carboxylates	$F(CF_2)_xSO_2N(CH_2CH_2COO^-)(CH_2)_3NH(CH_3)_2^+$					
ADONA (3M) CAS No. 958445-44-8 CF ₃ OCF ₂ CF ₂ OCFHCF ₂ COO ⁻ GenX (DuPont) CAS No. 62037-80-3 CF ₃ CF ₂ CF ₂ OCF(CF ₃)COO ⁻ Asahi's product CAS No. 908020-52-0 CF ₃ CF ₂ OCF ₂ CCF ₂ COC ⁻ Solvay's product CAS No. 329238-24-6 CIF ₆ C ₃ O[CF ₂ CF(CF ₃)O] _m [CF(CF ₃)O] _m CF ₂ COO ⁻	Functionalized perfluoropolyethers:							
GenX (DuPont) CAS No. 62037-80-3 CF ₃ CF ₂ CF ₂ OCF(CF ₃)COO ⁻ Asahi's product CAS No. 908020-52-0 CF ₃ CF ₂ OCF ₂ COCF ₂ COO ⁻ Solvay's product CAS No. 329238-24-6 ClF ₆ C ₃ O[CF ₂ CF(CF ₃)O] _m [CF(CF ₃)O] _m CF ₂ COO ⁻	ADONA (3M)	CAS No. 958445-44-8	CF ₃ OCF ₂ CF ₂ CF ₂ OCFHCF ₂ COO ⁻					
Asahi's product CAS No. 908020-52-0 CF ₃ CF ₂ OCF ₂ CCO ⁻ Solvay's product CAS No. 329238-24-6 ClF ₆ C ₃ O[CF ₂ CF(CF ₃)O] _m [CF(CF ₃)O] _n CF ₂ COO ⁻	GenX (DuPont)	CAS No. 62037-80-3	$CF_3CF_2CF_2OCF(CF_3)COO^-$					
Solvay's product CAS No. 329238-24-6 CIF ₆ C ₃ O[CF ₂ CF(CF ₃)O] _m [CF(CF ₃)O] _n CF ₂ COO ⁻	Asahi's product	CAS No. 908020-52-0	$CF_3CF_2OCF_2CF_2OCF_2COO^-$					
	Solvay's product	CAS No. 329238-24-6	$ClF_6C_3O[CF_2CF(CF_3)O]_m[CF(CF_3)O]_n CF_2COO^-$					

used [30–32]. To elucidate the metabolism mechanism and possible adverse effects due to covalent binding of unsaturated polyfluoroalkyl intermediate metabolites to biological macromolecules, *in-vitro* bioassays were performed using hepatocytes, cytosol fractions and liver microsomes from mammalian and fish species [19,21]. *In-vivo* dietary exposure studies were also conducted to evaluate uptake, metabolism and elimination dynamics of PFASs in Sprague-Dawley rats and juvenile rainbow trout [20,33,34].

2.2. Sample-extraction method

The selection of extraction methods is mainly based on the complexity of the investigated medium in the incubation systems (Table 2 and references therein). For a test system with simple components and weak matrix interference, such as a pure bacterial culture, a straightforward water-miscible solvent extraction (WMSE) plus centrifugation and filtration procedures would be sufficient to obtain a representative sample extract for further instrumental analysis [31]. This was done by adding an equal or slightly larger volume of a solvent (e.g., acetonitrile) to the bacterial liquid culture medium to extract precursors and transformation products.

Bound residues or conjugates between fluorinated transformation products and natural organic components were frequently found in more complex environmental samples, such as living soil and sediment, requiring multiple extraction procedures to improve analyte recovery [25,26]. Dispersive solid-phase extraction (DSPE) methods, Literature information on analytical and sample-preparation methodologies for studying biotransformation of polyfluoroalkyl precursors in environmental and biological matrices

Matrix	Compounds Extraction	Extraction ^a	Clean-up/	Derivatization ^c		Quantification	Isotopic tracking ^d	Structure elucidation	Ref.
			Concentrate ^D		Instrument	Chromatographic separation			
Environmental									
Activated	[3- ¹⁴ C] 8:2	WMSE (MTBE)	Ν	TMS	GC-MS	DB-5 MS ($30m \times 0.25 mm \times 1 \mu m$), Zorbax Bx-C8 ($150 \times 21 mm 5 \mu m$)	LSC, LC-ARC	LC-Q-TOF, GC-TOF (RT, accurate	[10]
Sediment	6:2 FTOH	DSPE (ACN, NaOH, bottle & septa)	C18 (ACN)/ Envi-Carb	Ν	LC-MS/MS	Zorbax Rx-C8 (150×2.1 mm, 5 μ m)	Ν	N	[25]
Forest soil	[1,2- ¹⁴ C] 6:2 FTOH	DSPE (ACN, NaOH, bottle & septa)	C18 (ACN)/ Envi-Carb	Ν	LC-MS/MS	Fluorous PF-C8 (150 \times 4.6 mm, 5 $\mu m)$	LSC, LC-ARC, TC	Ν	[26]
Forest soil	6:2 FTI	DSPE (ACN, NaOH, bottle & septa)	C18 (ACN)/ Envi-Carb	Ν	LC-MS/MS	Zorbax Rx-C8 (150 \times 2.1 mm, 5 $\mu m)$	Ν	LC-LTQ-Orbitrap MS, GC-TOF (mass defect, accurate mass, MS ²)	[27]
Sewage sludge	Mono-PAPs (4:2, 6:2, 8:2, 10:2) Di-PAPs (6:2)	WMSE (MeOH), IPE (TBAS, MTBE)	XAD-2 (EA)	Ν	GC-MS LC-MS/MS	ZB-WAX (30m \times 0.25 mm \times 0.25 μ m), Gemini C18 (50 \times 4.6 mm, 3 μ m)	Ν	N	[28]
Forest & Agricultural	[3- ¹⁴ C] 8:2 FTOH	DSPE (ACN, NaOH, bottle & septa)	C18 (ACN)/ Envi-Carb	Ν	LC-MS/MS	Zorbax Rx-C8 (150 \times 2.1 mm, 5 μm), DB-5 MS (30m \times 0.25 mm \times 1 $\mu m)$	LC-ARC, TC	LC-Q-TOF, GC-TOF, GC-MS (suspect ion screening, MS ²)	[29]
Forest soil	6:2 FTOH	DSPE (ACN, NaOH, bottle & septa)	C18 (ACN)/ Envi-Carb	DNPH	LC-MS/MS	Zorbax Rx-C8 (150 × 2.1 mm, 5 µm), Zorbax SB-C18 (150 × 2.1 mm, 5 µm)	Ν	LC-LTQ-Orbitrap MS (non- target screening, MS ² , in- source CID)	[30]
Activated sludge	6:2 FTSA	DSPE (ACN, NaOH, bottle & septa)	C18 (ACN)/ Envi-Carb	DNPH	LC-MS/MS	Zorbax Rx-C8 (150 \times 2.1 mm, 5 $\mu m)$	Ν	N	[35]
Marine sediment	N-EtFOSE & SAmPAP Diester	DSPE (MeOH, ACN)	Envi-Carb	Ν	LC-MS/MS	xTerra C18 (30 × 4.6 mm, 5 μm)	Ν	Ν	[36]
Agricultural soil	8:2 FTS	DSPE (EA, ACN, NaOH)	C18 (ACN)/ Envi-Carb	Ν	GC-MS LC-MS/MS	DB-5 MS (30m × 0.25 mm × 0.25 μm) Synergi Max-RP (150 × 2 mm, 4 μm)	Ν	Ν	[37]
Activated sludge	5:3 acid	DSPE (ACN, NaOH, bottle & septa)	C18 (ACN)/ Envi-Carb	Ν	LC-MS/MS	Zorbax Rx-C8 (150 × 2.1 mm, 5 μm), Zorbax SB-C18 (150 × 2.1 mm, 5 μm)	Ν	LC-LTQ-Orbitrap MS (non- target screening, accurate mass, mass defect, suspect ion screening)	[38]
Anaerobic sludge	6:2 FTOH, [3- ¹⁴ C] 8:2 FTOH	DSPE (ACN, NaOH, bottle & septa)	C18 (ACN)/ Envi-Carb	DNPH	LC-MS/MS	Zorbax Rx-C8 (150 × 2.1 mm, 5 μm), Zorbax SB-C18 (150 × 2.1 mm, 5 μm)	TC	LC-LTQ-Orbitrap MS (non- target screening, accurate mass, MS ²)	[39]
Microbial Isola Mixed sludge bacterial	tes: [3- ¹⁴ C] 8:2 FTOH	WMSE (ACN, MTBE, bottle & septa)	C18 (ACN)	Ν	LC-MS/MS	Zorbax Rx-C8 (150 × 2.1 mm, 5 μm), Fluorous PF-C8 (150 × 4.6 mm, 5 μm) DR-5 MS (30m × 0.25 mm × 1 μm)	LSC, LC-ARC	LC-Q-Orbitrap MS, GC-TOF, GC- MS (RT, accurate mass,	[11]
Mixed sludge bacterial culture	6:2 FTOH	WMSE (ACN, bottle & septa)	Ν	DNPH	LC-MS/MS	Zorbax Rx-C8 (150 × 2.1 mm, 5 μm)	Ν	LC-Q-Orbitrap MS, (non-target screening, suspect ion screening, MS ²)	[30]
Pure Pseudomonas strains	FTOHs (4:2, 6:2, 8:2)	WMSE (ACN, hexane)	Ν	Ν	GC-MS, GC- ECD, LC-MS/MS	DB-5 ($30m \times 0.25 \text{ mm} \times 0.25 \mu \text{m}$), DB-1 MS ($30m \times 0.25 \text{ mm} \times 0.25 \mu \text{m}$), Zorbax Rx-C8 ($150 \times 21 \text{ mm} 5 \mu \text{m}$)	Ν	N	[31]
Pure soil bacterial isolates	8:2 FTOH	WMSE (ACN)	Ν	Ν	LC-MS/MS	Luna C8 (100 × 2 mm, 3 µm), Synergi Max-RP (100 × 4.6 mm, 5 µm) Zorbax Rx-C8 (150 × 2.1 mm, 5 µm)	Ν	Ν	[32]
Mixed culture (sediment & wastewater)	8:2 FTOH	WMSE (MeOH)	PDMS	Ν	GC-ECD, GC- MS, LC-MS/MS	DB-35 (30m × 0.25 mm × 0.25 μm), DB-WAX (30m × 0.25 mm × 0.25 μm), Zorbax Rx-C8 (250 × 4.6 mm, 5 μm)	Ν	Ν	[40]

(continued on next page)

Table 2 (continued)

Matrix	Compounds	Extraction ^a	Clean-up/	Derivatization ^c	Quantification		Isotopic	Structure	Ref.
			Concentrate ^D		Instrument	Chromatographic separation	tracking ^d	elucidation	
In-vitro assays: Isolated rat hepatocytes	FTOHs (4:2, 6:2, 8:2, 10:2)	IPE (TBAS, MTBE) WMSE (MeOH, ACN)	Ν	DNPH	LC-MS/MS	Genesis C8 (50 × 2.1 mm)	Ν	LC-QqQ (neutral loss scan, precursor ion scan, suspect ion	[19]
Isolated cytosol hepatocytes, microsome (rat, mouse, human, trout)	[3- ¹⁴ C] 8:2 FTOH	WMSE (ACN)	Ν	DNPH	LC-MS/MS	Zorbax Rx-C8 (150 × 2.1 mm, 5 μm), Zorbax SB-C18 (150 × 2.1 mm, 5 μm)	LC-ARC, LSC	LC-QqQ, GC-MS, GC-TOF (suspect ion screening, MS ²)	[20]
Human microsome & recombinant human CYP2C9, C19	N-EtFOSA	WMSE (MTBE), WMSE (MeOH)	PDMS	Ν	GC-ECD, LC- MS/MS	DB-35 MS (80m \times 0.25 mm \times 0.25 μ m), FluoroSep RP C8 (150 \times 2.1 mm, 3 μ m)	Ν	Ν	[41]
Pooled rat liver microsome	6:2 FTI, [1,2- ¹⁴ C] 6:2 FTOH	WMSE (ACN, bottle & septa)	C18 (ACN)	Ν	LC-MS/MS, GC- MS	Zorbax Rx-C8 (150 × 2.1 mm, 5 μm), DB-5 MS (30m × 0.25 mm × 1 μm)	LSC	Ν	[42]
In-vivo studies:									
Sprague- Dawley rats	[3- ¹⁴ C] 8:2 FTOH	WMSE (ACN, plasma), ASE (ACN/ water, MeOH/water, Feces)	PDMS	DNPH	GC-MS, LC-MS/ MS	DB-5 MS ($30m \times 0.25 mm \times 1 \mu m$) Synergi Max-RP ($20 \times 2 mm, 2 \mu m$) Zorbax SB-C18 ($150 \times 2.1 mm, 5 \mu m$)	LC-ARC, LSC, TC	LC-Q-TOF (suspect ion screening, MS ²)	[20]
Juvenile Rainbow Trout	PFPAs (C6, C8, C10); PFPiAs (C6-6, C6-8, C8-8)	IPE (TBAS, MTBE)	Ν	Ν	LC-MS/MS	Kinetex C18 (50 × 4.6 mm, 2.6 μm)	Ν	Ν	[33]
Sprague- Dawley rats	Mono-PAPs, Di-PAPs (4:2, 6:2, 8:2, 10:2)	Sonication (ACN, blood, urine), Sonication (ACN/water, feces)	Ν	Ν	LC-MS/MS	Gemini NX C18 (50 \times 4.6 mm, 3 $\mu m)$	Ν	Ν	[34]
Sprague- Dawley rats	8:2 Mono- PAPs, 8:2 Di- PAPs	IPE (TBAS, MTBE)	Ν	Ν	LC-MS/MS	Genesis C18 (50 \times 2.1 mm, 4 μm), Allure PFP propyl (50 \times 2.1 mm, 4 μm)	Ν	Ν	[43]
Rainbow Trout	8:2 FTAc	WMSE (EA)	Ν	Ν	GC-MS, LC-MS/ MS	RTX-WAX (30m \times 0.25 mm \times 0.25 $\mu m) ACE$ C18 (50 \times 2.1 mm, 3 $\mu m)$	Ν	LC-QqQ (suspect ion screening, MS ²)	[44]

^a WMSE, Water-miscible solvent extraction (including centrifugation and filtration); DSPE, Dispersive solid-phase extraction; IPE, Ion-pair extraction; ASE, Accelerated solvent extraction; ACN, Acetonitrile; MeOH, Methanol; MTBE, Methyl tert-butyl ether; EA, Ethyl acetate; TBAS, Tetrabutyl ammonium hydrogen sulfate;

^b N, Not applied; PDMS, Polydimethylsiloxane;

^c TMS, Trimethyl silyl; DNPH, 2:4-dinitrophenylhydrazine; ^d LSC, Liquid-scintillation countering; LC-ARC, Liquid chromatography accurate radioisotope counting; TC, Thermal combustion.

initially established for the determination of PFCAs in environmental matrices, were widely adapted in soil, sediment and activated sludge-incubation systems [26,35–37,45]. Specifically, solid samples were first soaked in an organic solvent (methanol, acetonitrile, or methyl tert-butyl ether), then constantly shaken at 150-200 rpm for from several hours up to 5 days and then centrifuged to obtain supernatant. If methyl tert-butyl ether (MTBE) was used for extraction, the soil was first saturated with deionized water before adding MTBE to avoid soil aggregation during extraction. The supernatant was then mixed with Envi-Carb graphitized carbon adsorbent to reduce matrix effects, which may enhance or suppress instrumental signals of analytes [33,46]. Liu et al. [30] developed the procedure by including an alkaline treatment (25 mM NaOH final concentration, Fig. 1) for the soil extract to release ¹⁴C-labeled transformation products from dissolved soil-component conjugates. This led to enhancement of 5:3 acid [F(CF₂)₅CH₂CH₂COOH] recovery by 6-38 times.

For biological matrices, such as animal tissue and serum samples, extraction methods based on ion-pair extraction (IPE), initially developed by Hansen et al. [47], were more applicable. Briefly, sodium carbonate buffer (pH = 10) and tetrabutyl ammonium hydrogen sulfate (TBAS) were mixed with solid samples, which were extracted by MTBE. The MTBE aliquots were then combined, brought to dryness under a stream of nitrogen, and the polyfluorinated analytes were reconstituted in methanol. The methods were successfully applied to recover FOSAs, mono-PAPs, di-PAPs, perfluoroalkyl phosphonic acids (PFPAs) and corresponding biotransformation products in both *in-vitro* and *in-vivo* exposure studies [33,43,46,47]. Washington et al. [48] also developed multi-step extraction procedures for PFCAs in soils by combining both DSPE and IPE pretreatment procedures, achieving quantitative recoveries with minimized matrix effects.

Despite the well-established DSPE and IPE methods that could be applied to other novel polyfluoroalkyl precursor biotransformation studies, optimization of the detailed sample-pretreatment procedures is still essential. For example, hydrolysis of ester bonds in 8:2 fluorotelomer citrate triester (8:2 TBC) and substantial formation of 8:2 FTOH occurred when dosed ⁶⁰Co-γ-irradiated sterile soil samples were extracted using the DSPE method [49]. The ester hydrolysis was enhanced by solvents with high dielectric constants (i.e., methanol and acetonitrile) compared with less polar solvents (e.g., MTBE and ethyl acetate). An additional 10-20% of 14Clabeled polyfluoroalkyl transformation products was recovered from soil initially dosed with 14C-labeled 8:2 FTOH when the DSPE extraction temperature was elevated to 50°C [29]. D'eon et al. [16] also found that the removal of sodium-carbonate buffer in the IPE procedures minimized 8:2 diPAP blank contamination in the analysis of mono-PAP and di-PAP concentrations in human-serum samples with adequate extraction efficiencies ($85 \pm 22\%$).

2.3. Sample concentration and clean-up

The starting concentrations of polyfluoroalkyl precursors were generally in the part-per-million range (ppm, mg/kg of soil, sediment, or activated sludge) in most studies, without the need for sample concentration and allowing known transformation products to be quantified with either gas chromatography MS (GC-MS) or liquid chromatography-tandem MS (LC-MS/MS) instruments. However, identification of low levels of novel transformation products requires HRMS analysis in the full-scan mode. An elevated precursor concentration up to 10–100 mg/kg soil or sludge helped reduce false positives and obtain clean mass spectra of several novel transformation products [30]. For volatile precursors, such as FTOHs, FOSAs and FOSEs, with the tendency to move into the headspace, concentration procedures were performed over long-term incubation periods [40,41]. In semi-static systems, the headspace was usually purged through C₁₈ SPE cartridges at the beginning of sample preparation to trap volatile precursors and transformation products [25,27]. XAD adsorbents were also chosen to monitor the formation of FTOHs from the degradation processes of mono-PAPs and di-PAPs by aerobic microbes from a WWTP in flow-through systems [28]. Meanwhile, polydimethylsiloxane solid-phase microextraction materials were expediently used in enrichment and identification of novel transformation intermediates and products in headspace and to quantify the gas-fraction concentrations of analytes [27,40,41].

To reduce matrix effects caused by complex organic components in environmental and biological samples, treatment used Envi-Carb graphitized carbon powder or cartridges as an effective clean-up approach [45]. Organic interferents with a degree of aromaticity will be strongly adsorbed on the surface of graphitized carbon, while interactions between Envi-Carb and PFASs are implausible. The selectivity is not influenced by the presence of organic solvents, such as methanol, acetonitrile and MTBE, which made the purification procedure easily coupled to both DSPE and IPE methods, as mentioned in sub-section 2.2. The protocol was simple and robust for quantitative recovery of fluorotelomers- and EtFOSE-based precursors and transformation products [29,30,35–37]. Zhang et al. [46] demonstrated low matrix effects for PFCAs (C_5-C_{10}), PFSAs (C_{4.6.8}), FOSAs and FOSAAs in the range -13% to +24% in digested sewage-sludge extract using the Envi-Carb clean-up procedure.

2.4. Derivatization step

The derivatization step improves PFAS analysis through formation of stable derivatives . Fluorotelomer aldehydes (FTALs) are short-lived initial intermediates of fluorotelomer-based product transformation, and could be quickly oxidized into fluorotelomer carboxylic acids (FTCAs). 2,4-Dinitrophenylhydrazine (DNPH) was frequently used as the derivatization reagent for the identification of FTALs in *in-vitro* animal studies by mixing organic-sample extracts with DNPH solution in hydrochloric acid prior to LC-MS analysis [19–21]. The derivatization step was also applied to microbial incubation systems to identify 8:2 FTAL and 5:3 ketone aldehyde in 8:2 FTOH dosed soil and 6:2 FTOH dosed mixed bacterial culture, respectively [29,30].

Recently, Peng et al. [50] developed a novel derivatization technique using the dansyl-chloride (5-(dimethylamino)naphthalene-1-sulfonyl chloride) reaction with FTOHs, allowing sub-ppb (part per billion, μ g/kg) quantitation in LC-MS analysis. Also, Wang et al. [10] used trimethyl silyl (TMS) to increase the volatility of metabolites derived from an 8:2 FTCA biodegradation study in GC-MS analysis, and 7:3 FTCA was firstly recognized as the proposed structure of an unidentified peak.

3. Instrumental analysis

3.1. LC/GC-MS quantitative analysis

3.1.1. LC-MS

The majority of polyfluoroalkyl precursors and transformation products are in ionic form under environmentally relevant pH conditions [51]. LC separation coupled with triple-quadupole MS (QqQ) detection is the most common method to analyze anionic PFASs because of its good compatibility with aqueous samples and polar extraction solvents. Perfluorinated carbon chains of PFASs ($C \ge 6$) ensure appropriate retention behavior on reversed-phase stationary phases, such as C_8 , C_{18} and pentafluorophenyl (PFP) [10,29,30,43], whereas ion-exclusion chromatography was also used to separate perfluoroalkylsulfonic acids and perfluoroaklylsulfinic acids with short alkyl-chain lengths up to C_4 and C_6 , respectively [52].



Fig. 1. Chromatograms from accurate radioisotopic counting instruments coupled to liquid chromatography (LC-ARC) of transformation products in [1,2-¹⁴C] 6:2 FTOH-dosed live and sterile forest-soil samples (day 1 and day 84), showing alkaline (NaOH) treatment in dispersive solid-phase extraction (DSPE) on elimination of unresolved analyte-matrix conjugates for better recoveries. Peak 1: [1,2-¹⁴C] 6:2 FTUCA [F(CF₂)₅CF=¹⁴CH₂¹⁴COOH]; Peak 2: [1,2-¹⁴C] 5:3 acid [F(CF₂)₅CH₂¹⁴CH₂¹⁴COOH]; Peak 3: [¹⁴C] 5:2 sFTOH [F(CF₂)₅CH(OH)¹⁴CH₃]; and, Peak 4: [1,2-¹⁴C] 6:2 FTOH [F(CF₂)₆¹⁴CH₂OH]. The unresolved peaks in the grey area (retention time: 62–76 min) are ¹⁴C-labeled analyte-matrix conjugates. {From [26] with permission, ©Elsevier Ltd.}.

LC-MS/MS operated in the multiple-reaction monitoring (MRM) mode offered both wide linear dynamic range of at least three orders of magnitude and excellent sensitivity at sub-ppb levels. Negative electrospray ionization (ESI) was the most suitable LC-MS interface, and anionic PFASs were obtained as the deprotonated ([M-H]⁻) ions. Pre-column formation of analyte adducts by adding additives to the LC mobile phases, such as acetate-adducts ([M+59]⁻) of FTOHs, sFTOHs and FT ketones, could avoid LC-peak broadening and offer sufficient sensitivity for the neutral FT alcohols and ketones (instrument detection limits, IDLs: 0.14–0.22 ng on column) along with anionic PFCAs and PFSAs (IDLs: 4.0–42 pg on column) [27,29,30]. Moreover, LC-atmospheric pressure photoionization (APPI)-MS proved to be effective in direct ionization of FTOHs and FOSAs with excellent IDLs less than 1 pg on column [53].

3.1.2. GC-MS

GC-MS is an effective tool to quantify neutral volatile polyfluoroalkyl precursors, such as FTOHs, FTIs and FT acrylates, in different biotransformation incubation systems [44,54]. DB-WAX, DB-35 and analogous stationary phases were normally used to separate FTOHs and FOSEs [40,41,44,55], whereas DB-5 and DB-624 analytical columns were options for semi-volatile and highly-volatile PFAS precursors, respectively [10,11,37,54].

GC-MS can provide enhanced selectivity and sensitivity to target analytes as well as tolerances to sample-matrix effects. Electronimpact (EI) ionization was suitable for measuring FTOHs, FTIs, 8:2 FTS in organic solvent extracts [37,54,55]. Martin and co-workers also suggested that positive chemical ionization (PCI) was the mode of choice for FTOH routine analysis, whereas negative chemical ionization (NCI) showed sensitivity advantages for sulfonamidebased derivatives, such as N-EtFOSA, N-MeFOSE and N-EtFOSE [55]. The electron-capture detector (ECD) has also been used for GC analysis [41,52]. The element-specific microwave plasma detector was also successfully applied to study 8:2 FTOH biotransformations in rat to avoid the insufficient specificity of ECD in complex biological matrices [52].

3.2. ¹⁴C-labeling and detection techniques

Tracking the partitioning of polyfluorinated precursors and formation of novel degradation products in complex test media is quite challenging. Nevertheless, radio-isotopic labeling provides a means of overcoming this by measuring positron emission from radioactive decaying chemicals. Due to low natural abundance and lasting half-life, ¹⁴C was selected to label PFAS precursors in order to trace chemical transformations in environmental and biological trials [10,11,26,42].

Liu et al. [26] noted that mass-balance analysis of precursorbiodegradation processes based on solvent extraction and LC-MS/ MS quantification methods suffered from matrix effects and formation of bound residues and unknown degradation products in complex sample media. Nevertheless, a simple, accurate liquid scintillation counting (LSC) measurement allowed quantification of novel transformation products and biological conjugates without the need for authentic standards. Accurate radioisotopic counting instruments coupled to LC (LC-ARC) could further promote separation of total radioactive precursor/metabolite mixtures by different physical-chemical properties and also facilitate information sharing with other qualitative equipment, particularly HRMS [10,11,26,29]. Retention times of unknown signals from both LC-ARC and LCquadrupole-time of flight (Q-TOF) MS were precisely matched, and ¹⁴C-labeled 8:2 FTOH transformation products (Fig. 2) were confirmed in activated sludge with 7:3 acid [F(CF₂)₇¹⁴CH₂CH₂COOH] being identified for the first time [10]. Non-extractable soil- or sedimentbound ¹⁴C-residues can also be quantified after thermal combustion to ¹⁴CO₂, which was trapped in a liquid scintillation cocktail for

radioactivity measurements. Up to 35% of ¹⁴C-labeled FTOH precursors and transformation products were irreversibly bound to soils after two-day incubation, and could be recoverable by only high-temperature soil combustion (900°C) [29].

3.3. Mass-spectrometry elucidation of novel transformation products

High resolution power and sufficient sensitivity are both essential to elucidate the molecular structure of novel degradation products at low abundance during polyfluoroalkyl-precursor transformation, so GC-MS or LC-MS emerged as a powerful tool. Use of accurate-mass measurements and multiple-mass fragmentation are two major applicable strategies in identifying unknown metabolites [56]. In accurate-mass measurement, selected suspect-ion monitoring or retrospective screening of the full-scan spectrum are effective in confirming plausible analytes without using authentic standards. For example, typical phase II metabolites (glutathione, glucuronide and sulfate conjugates) of polyfluorinated alcohols, aldehydes and unsaturated telomer acids could easily be observed once deprotonated molecular ions of corresponding conjugates were monitored [19-21]. When searching for plausible unknown metabolites without a priori information, exact mass filtering is also one principal step in the so-called "non-target screening" strategy [57]. As the accurate mass of fluorine (m/z = 18.998) is very close to its nominal mass, mass-defect filtration (-50 to +10 mDa) of nominal masses could eliminate the majority of irrelevant information in the full-scan MS spectrum [27]. Comparison of differences in full-scan chromatograms of paired live and matrix samples could also help find signals that might represent potential transformation products that existed in live samples only [38]. A limited number of rational molecular compositions by a combination of C, H, F, O, N elements could be further obtained with a mass accuracy of less than 5 ppm [27,39,58].

MSⁿ is particularly attractive for providing molecular structure information through multiform scanning functions. The elemental composition of cleaved functional groups (e.g., consecutive loss of CO₂+2HF and HF) in given pseudo-molecular ions by collisioninduced dissociation (CID) could be accurately measured by HRMS [39]. Besides, precursor-ion scan can be used to search for transformation products structurally related to the parent compound. Once neutral structure segments are lost in MSⁿ experiments, constant neutral-loss scan could be set to search for plausible metabolites [59] {e.g., a neutral loss of 20 in the MS/MS spectra corresponds to the neutral loss of HF in most polyfluorinated metabolites [19]}. At m/z 306, m/z 272 and m/z 254, there are highly specific ions produced by dissociation of the glutathione moiety, which were used as diagnostic ions in precursor-ion scans for polyfluorinated glutathione conjugates [19]. Moreover, for single-quadrupole MS instruments with no MSⁿ functions, structural information of novel metabolites could provide confirmation by in-source fragmentation in an MS ionization source with the aid of reference standards [30].

3.4. Computer-aided prediction of biotransformation pathways

Computer-aided pathway prediction relies on quantitative structure-activity (QSAR) models, which link biodegradation potential with molecular descriptors, such as physical-chemical descriptors and connectivity indexes generated from chemicalstructure fragments [60]. *In-silico* calculation is a quick, costeffective assessment to predict chemical-degradation potential, metabolites, and pathways at the screening level.

The University of Minnesota Pathway Prediction System (UM-PPS) is an open-access web interface, which provides information on microbial enzyme-catalyzed reactions. The prediction is based



Fig. 2. (A and B) Radiochromatograms from accurate radioisotopic counting instruments coupled to liquid chromatography (LC-ARC) of transformation products in [3-¹⁴C] 8:2 FTOH-dosed live and sterile activated sludge samples (day 28). (C–F) LC quadrupole time-of-flight (LC-Q-TOF) product-ion mass spectra of deprotonated molecular ions (Compounds 1-4). Compound 1: [1-¹⁴C] PFOA [F(CF₂)7¹⁴COOH]; Compound 2: [3-¹⁴C] 8:2 FTCA [F(CF₂)7¹⁴CF₂CH₂COOH]; Compound 3: [3-¹⁴C] 8:2 FTUCA [F(CF₂)7¹⁴CF=CH₂COOH]; Compound 4: [3-¹⁴C] 7:3 acid [F(CF₂)7¹⁴CH₂CH₂COOH]; and, Compound 5: [3-¹⁴C] 8:2 FTOH [F(CF₂)7¹⁴CF₂CH₂CH₂CH₂OH]. {Modified from [10] with permission, ©American Chemistry Society}.

on reorganization of organic functional groups in a coded molecular structure input and predicts transformation according to biotransformation rules from pure culture studies in the UM-BBD database and other scientific literature [61]. Pathways are generated based on a precursor's possible transformation sequence to downstream products with the likelihood being graded as "likely", "neutral" and "unlikely" with no other priority obviation logic provided [61].

Meanwhile, CATALOGIC (formally CATABOL) is proprietary software for simulating catabolism and predicting biodegradation products under biodegradation conditions of a given chemical. Different from UM-PPS, metabolism rules in CATALOGIC are hierarchically ranked by occurrence probabilities judged by expert knowledge and documented metabolic maps [60,62]. Metabolic trees could be generated with quantitative distributions of the precursor and subsequent transformation products.

Fig. 3 gives a detailed comparison between UM-PPS and CATALOGIC software predictions on N-EtFOSE biotransformation pathways. Both models correctly predicted the intermediate, N-ethylperfluorooctane sulfonamido acetic acid and the end-product perfluorooctane sulfonic acid (PFOS), with CATALOGIC predicting more experimentally-confirmed intermediates. However, both models failed to predict novel biotransformation pathways of 6:2 FTOH and 8:2 FTOH that are experimentally confirmed [29,30] due





CATALOGIC

Fig. 3. Comparison of computer-aided predictions of N-EtFOSE biotransformation pathways by UM-PPS framework and CATALOGIC software. The green and orange colors of the solid-line boxes in the UM-PPS framework represent the likelihood of the reactions as "likely" and "neutral", and the numbers inside the solid-line boxes are codes of enzyme reactions in the UM-BBD database. The compounds inside the dashed-line boxes in both UM-PPS and CATALOGIC frameworks are stable transformation products confirmed in laboratory experiments. "*" symbol in CATALOGIC framework represents the probabilities of occurrence of corresponding transformation reactions.

to lack of broad training sets of perfluoroalkyl-transformation products built into the two QSAR models. Inclusion of the latest knowledge on biotransformation reactions and molar yields of transformation products from various polyfluoroalkyl precursors would enhance the accuracy of the *in-silico* predictions.

4. Conclusions and future perspectives

In this review, we summarized up-to-date sample preparation and instrument-analysis methodologies, which were successfully employed in elucidation of major degradation products and biotransformation pathways of biodegradable polyfluorinated chemicals, and might also contribute to future studies on environmental monitoring and ecotoxicology evaluation of emerging PFAS contaminants. Nevertheless, analytical challenges remain in investigating environmental behavior and fate of a broad range of polyfluoroalkyl precursors.

The production volume of polyfluoroalkyl substances with 4 or 6 perfluorinated carbon backbones ("short-chain" precursors) is likely to increase significantly in the next few years. There is an urgent need to expand and to modify current analytical methodologies to focus more on short-chain precursors and to cover more types of environmental matrices and biota species.

Moreover, the application of polyfluoroalkyl alternatives with novel functional groups, such as functionalized perfluoropolyethers (PFPEs) and zwitterionic, cationic and anionic fluoroalkyl aqueous film-forming foams, is also increasing [63,64]. New samplepreparation and instrumental methods are in demand to understand the contributions of these polyfluoroalkyl alternatives to PFCAs and PFSAs detected in the environment and biota.

New analytical technologies could also be adopted to manage vast sets of data besides the state-of-the-art pretreatment and instrumental methods. For example, processing tools (automated data deconvolution, chromatographic peak detection, alignment, feature filtering and scaling) in modern MS analysis could help identify important transformation products that may otherwise be missed by retrospective analysis of HRMS full-scan spectra. Current knowledge on PFAS-biotransformation processes is mainly based on investigating the occurrence and the quantity of relatively stable transformation products. More effective sample-pretreatment techniques to trap and to derivatize possible unstable intermediates may provide new insight into transformation mechanisms among key degradation intermediates and to recognize unknown transformation pathways.

Despite progress in current understanding of biodegradation pathways of polyfluoroalkyl precursors, it is still not well understood what key enzymes and cofactors are involved. Omics studies (e.g., proteomics, transcriptomics, and metabolomics) of polyfluoroalkylprecursor biotransformation with increased instrumentation sensitivity and throughput may further discern the defluorination mechanisms and other important biotransformation steps.

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