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全氟和多氟化合物替代品的研究进展

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摘要: 全氟和多氟化合物(per-and polyfluoroalkyl substances, PFASs)是一类新型持久性有机污染物(POPs),广泛应用于工业和人类日常生活用品中。此类化合物具有高能量的 C-F 共价键,因此具有优良的理化特性和生物稳定性。由于存在持久性、生物累积性、长距离迁移以及毒性等问题,长链 PFASs(C>7)已经成为全世界关注的焦点之一,寻找能够替代 PFASs 的新型化合物具有重要意义。本文介绍了几种可能替代 PFASs 的新型氟化替代品,PFASs 替代品在各类环境介质中的分布、持久性、人体暴露及毒性等几个方面进行了综述,特别对目前存在的问题及今后的研究方向进行了讨论和展望,以期为 PFASs 替代品的环境污染及风险评估提供参考。

关键词: 全氟和多氟化合物;PFASs 替代品;环境行为;人体暴露;毒性
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The Current Research Status of Several Kinds of Fluorinated Alternatives

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Abstract: Per-and polyfluoroalkyl substances (PFASs) are an emerging kind of persistent organic pollutant currently widely used in industrial and daily life supplies. With high-energy C-F bonds, PFASs have excellent physical, chemical properties and biological stability and have drawn the attention of researchers all over the world due to their high persistence, bioaccumulation potential, toxicity and ubiquitous distribution in the environment, biota and humans. It is of vital importance to look for fluorinated alternatives to long-chain PFASs. This paper summarizes hot issues about PFASs alternatives, such as environmental distribution and behavior, persistence, human exposure and toxicity. The emphasis is laid on existing problems and future research perspectives so as to provide evidence for the investigation of existing problems and future research directions.

Keywords: per-and polyfluoroalkyl substances; PFASs alternatives; environmental behavior; human exposure; toxicity

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全氟和多氟化合物(per-and polyfluoroalkyl substances, PFASs)是一类高度氟化的脂肪族物质,即除官能团中的氢原子外,碳骨架上的氢原子全部或部分被氟原子替代的人工合成有机化合物[1]。由于PFASs的理化特性极其特殊,包括较强稳定性、疏水、疏油性等,被广泛地应用于地毯、皮革、纺织、包装、灭火泡沫、洗发香波、地板打磨、电镀等工业和民用领域。目前环境中存在的PFASs主要有全氟烷基羧酸(PFCAs)、全氟烷基磺酸(PFSAs)、全氟烷基磺酰胺(FOSAs)、氟化调聚醇(FTOHs)、全氟磷酸(膦酸)及其酯等,其中全氟辛烷羧酸(perfluorooctanoic acid, PFOA)和全氟辛烷磺酸(perfluorooctane sulfonic acid, PFOS)是目前最受关注和应用最广泛的2种典型全氟有机化合物。由于结构中含有高能量的C-F化学键(C-F: 485.3 kJ · mol^{-1}),该类化合物普遍具有很高的稳定性,难以水解、光解和被微生物降解,因此许多PFASs具有环境持久性及高生物累积性[2]。大量研究表明PFASs已在各种环境介质和生物体中广泛检出,包括表层水[3-5]、污泥[6-7]、沉积物[8]、灰尘[9-10]、海洋生物[11-12]等,甚至人体中也检出多种PFASs[13-15]。流行病学研究发现PFASs的人体暴露与一些生化和生理指标的改变存在一定的正相关,包括肾癌和睾丸癌[16]、溃疡性结肠炎[17]、孕期高血压[18]、高胆固醇[19-20]、甲状腺机能减退[21-22]、免疫系统疾病[23-24]、胎儿生长迟缓[25-27]、妊娠期糖尿病[28]等。此外,毒理学研究也发现PFASs具有肝毒性[29]、神经毒性[30]、生殖发育毒性[29,31]、免疫毒性[29]、致癌性[32]、干扰脂肪代谢[33]以及内分泌干扰效应[34-35]等多种毒性。

由于PFASs具有持久性、累积性、长距离迁移以及高毒性等特性,严重地威胁了生态环境和人体健康,2001年国际社会共同签署了《关于持久性有机污染物(Persistent Organic Pollutants,简称POPs)的斯德哥尔摩公约》,开启了保护环境和人类健康免受有毒污染物危害的全球行动。3M公司于2002年停止生产PFOS及其相关产品。2009年5月9日联合国环境规划署正式将PFOS及全氟辛基磺酰氟(PASF)等列为新的持久性有机污染物,同意减少并最终禁止使用该类物质。最近,欧洲化学品管理局(ECHA)公布提案,建议将PFOA、全氟辛酸铵(APFO)以及C11~C14 PFCAs等化学品列为高度关注物质[36]。

长链PFASs的安全问题已经引发全球研发者和使用者的高度关注。淘汰部分长链PFASs,虽然减少了含氟聚合物生产过程中某些长链PFASs的使用量及排放量,但仍然无法从根本上解决长链PFASs的环境问题。为了适应全球化的发展,保护自身环境,研发无潜在生物蓄积性、低毒性的高性能化合物已迫在眉睫,寻找和研发新的PFASs替代品成为近年来科研工作者研究的热点之一。本文在2篇已有综述的基础上[37-38],概述了几种可能替代PFASs的新型化合物及其持久性、人体暴露及毒性等,对目前存在的问题及今后的研究方向进行了讨论和展望,以期为PFASs替代品的环境污染及风险评估提供参考。

1 长链PFASs替代品分类(The classification of long chain PFASs alternatives)

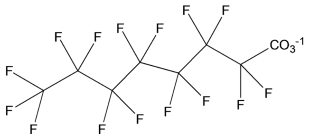
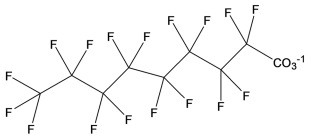
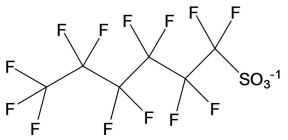
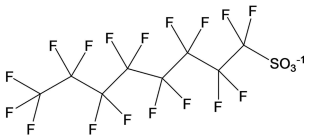
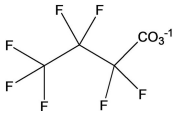
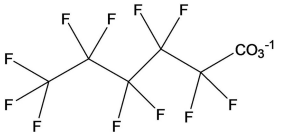
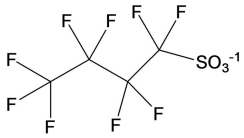
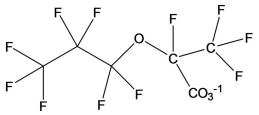
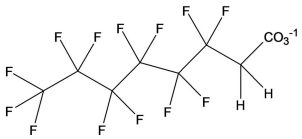
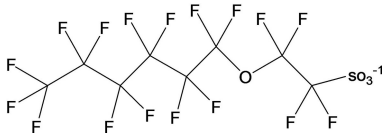
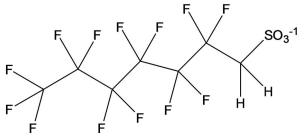
美国环境保护署(USEPA)提出禁用PFOA以后,其国内外就开展了PFASs替代品研究并取得了实质进展。迄今为止,3M、大金、杜邦、旭硝子、阿科玛和苏威在内的国际氟化工生产商已经向USEPA上报了50余种PFASs替代品以待评估。如3M公司研发的PFOS替代品全氟丁基磺酸(PFBS)无明显生物积累性,短时间内可随人体新陈代谢排出体外。由杜邦等公司利用调聚反应生产的全氟烷基C6基产品,由于没有C8基成分,没有PFOS及其衍生物,也不产生PFOA。这些调聚物基含氟表面活性剂很可能降解为 $C_6F_{13}CH_2CH_2SO_3H$(6:2 FTSA)或 $C_6F_{13}CH_2CH_2COOH$(6:2 FTCA),而不是PFOS或PFOA,其毒性较C8小。国内外针对PFASs替代品的研发一般分为2类:(1)使用C4、C6结构的短链全氟烷基羧酸或磺酸盐,如PFBA、PFHxA、PFBS。(2)含功能官能团的全氟聚醚(PFPEs),尤其是全氟聚醚羧酸和磺酸(PFESAs和PFECAs),如6:2 FTCA、GenX、F-53B、6:2 FTSA。各化合物的结构和名称如表1所示。

2 PFASs替代品的环境含量以及应用(The content, and application of PFASs alternative in environment)

一些研究表明作为C8全氟化合物替代物的C4全氟化合物在环境中的浓度不断升高。Zhou等[39]在武汉汤逊湖氟化学工厂附近的水样检测到高浓度的PFBA和PFBS等短链全氟化合物,其浓度分别为3 660 ng · L^{-1}、4 770 ng · L^{-1}。6:2 FTSA作为PFOS的一种替代物,近年来被越来越多地使用在装

表 1　全氟和多氟化合物(PFASs)及其替代品

Table 1　Per- and polyfluoroalkyl substances (PFASs) and PFASs alternatives

简称 Abbreviation	化学名 Chemical name	分子式 Molecular formula	结构式 Structural formula
PFOA	Perfluorooctanoic acid	$C_7F_{15}COOH$	
PFNA	Perfluorononanoic acid	$C_8F_{17}COOH$	
PFHxS	Perfluorohexane sulfonic acid	$C_6F_{13}SO_3H$	
PFOS	Perfluorooctane sulfonic acid	$C_8F_{17}SO_3H$	
PFBA	Perfluorobutanoic acid	C_3F_7COOH	
PFHxA	Perfluorohexanoic acid	$C_5F_{11}COOH$	
PFBS	Perfluorobutane sulfonic acid	$C_4F_9SO_3H$	
GenX	2,3,3,3-Tetrafluoro-2-(1,1,2,2,3,3,3-heptafluoropropoxy)propanoic acid	$C_3F_7OCF(CF_3)COOH$	
6:2 FTCA	6:2 Fluorotelomer carboxylic acid	$C_6F_{13}CH_2COOH$	
F-53B	6:2 Chlorinated polyfluoroalkyl ether sulfonic acid	$ClC_6F_{12}OC_2F_4SO_3H$	
6:2 FTSA	6:2 Fluorotelomer sulfonic acid	$C_6F_{13}CH_2SO_3H$	

饰性电镀行业和泡沫灭火器的生产过程中,如杜邦公司以 6:2 FTSA 合成了 Forafac® 1176。此外,6:2 FTSA 还是 Capstone® FS-17 的主要成分[40]。最近在水体[41-44]、污泥[42,45-46]、消防基地[47]、城市垃圾填埋场渗滤液[48]等中都发现了 6:2 FTSA。在我国,PFOS 的替代物 F-53B 作为雾抑制剂广泛地应用于镀铬工业。Wang 等[49]在温州一个镀铬工业的废水处理厂的进水、出水中检测到了高浓度的 F-53B。由于污水处理厂不能够有效去除该类物质,在污水处理厂排放的地表水中也可以检测到高浓度的 F-53B。最近一些研究发现在污泥中也检测到 F-53B。据统计,F-53B 年产量高达 10 多吨,其销售保持逐年稳步增长的态势。由于全球禁止使用 PFOS,F-53B 在未来可能会有更大的市场份额[50-51]。在欧洲,PFOA 替代物 GenX 作为加工助剂广泛应用于氟聚树脂制造业,年产量高达 10~100 吨[50]。此外,在中国含氟乳化剂用 6:2 FTCA 替代了 PFOA。目前在水体、污泥等介质中均已检测到 PFASs 替代物的存在(表 2)。

3 生物及人体暴露水平(The exposure of PFASs alternatives in the human and organisms)

自 2002 年 3M 公司终止全氟辛烷磺酰氟(POSF)的生产和 PFOS 正式进入 POPs 名单以来,PFASs 在环境中的浓度虽然有所下降,但是 PFASs 替代物在生物体不断检出。一项研究表明,在东格陵兰岛海洋哺乳动物环海豹、北极熊、虎鲸中发现了高浓度 F-53B[53]。Shi 等[54]在小清河和汤逊湖中鲫鱼血清、肾、性腺、肝脏以及心脏中检出了 F-53B。同时 Shi 等[55]研究发现食鱼偏好者、镀铬工人以及普通人群尿液和血清也存在 F-53B。另一项对 6:2 FTSA 的检测发现,6:2 FTSA 也存在于生物以及人体中(表 3)。

暴露途径研究是准确认识污染物健康效应的一个重要前提。Shi 等[55]研究认为灰尘/空气、饮用水和食物可能是 PFASs 替代物人体暴露的重要途径。偏好食鱼的人群血清中 F-53B 浓度中值是普通人的 20 倍,说明淡水鱼可能是人体暴露的重要途径。镀铬工人血清中浓度也远远超过普通人,可能通过灰尘/空气、皮肤接触等暴露途径。最近一项研究也发现,通过罗纳河的沉积物暴露,钩虾体内发现了 6:2 FTSA,因此食物和呼吸可能是钩虾暴露的途径[42]。

高度重视 PFASs 替代物的人体累积和清除是科学研究的一个热点。与普通人群不同的是,一些特殊人群可能面临比普通人群更高或者不同特征的 PFASs 替代品暴露,这种情况值得高度关注。一项

表 2 PFASs 替代品在环境中的检出量

Table 2 The detection of PFASs alternatives in the environment

PFASs 替代品 PFASs alternatives	CAS 号 CAS number	水 Water	污泥 Sewage sludge	爆米花包装袋 Microwave popcorn bags
F-53B	73606-19-6	F-53B 在温州废水处理厂入水口和出水口浓度分别为 65~112 μg·L^{-1},43~78 μg·L^{-1}[49] F-53B was found in the influent and effluent of electroplating plant wastewater in WenZhou, with the concntration of 65-112 μg·L^{-1} and 43-78 μg·L^{-1} [49]	F-53B 在废水处理厂几何平均值 2.15 ng·g^{-1}[46] F-53B with a geometric mean (GM) value of 2.15 ng·g^{-1} dry weight[46]	
GenX	62037-80-3	德国朔伊尔河中 GenX 浓度为 73.1 ng·L^{-1} [50] GenX with a concentration of 73.1 ng·L^{-1} in the Scheur River [50]		
6:2 FTSA	59587-38-1	废水处理厂最高浓度为 370 ng·L^{-1}[41] 6:2 FTSA were observed in wastewater at a high level of 370 ng·L^{-1}[41]	废水处理厂干重几何平均值为 0.13 ng·g^{-1}[46] 6:2 FTSA with a geometric mean (GM) value of 0.13 ng·g^{-1} dry weight[46]	
6:2 FTCA	53826-12-3			爆米花包装袋含量为 161.6 ng·g^{-1}[52] 6:2 FTCA with a level of 161.6 ng·g^{-1} in microwave popcorn bags [52]

对食鱼偏好者、镀铬工人、以及普通人体血液和尿液中血清中的 F-53B 和 PFOS 浓度清除半衰期的研究表明,人体对 F-53B 的血液清除较慢,半衰期较长,其半衰期的中值分别为 15.3 和 6.7 年,F-53B 的半衰期显著长于 PFOS[55]。

4　PFASs 替代品的潜在影响(The potential impact of PFASs alternatives)

最近一些研究表明短链全氟替代物生物富集因子较低,基本没有生物富集趋势[42,60]。但仍有研究学者提出部分 PFASs 替代物具有持久性、生物累积性以及毒性等问题。最近研究发现有些替代物的降解产物仍然具有毒性。如全氟丁基磺酰氟(PBSF)和 6:2 全氟调聚物最终降解为短链 PFASs 和其他物质,如高毒性的碳酰氟(COF_2)[61]。因此,PFASs 替代物对环境和生态影响仍然值得关注。关于 PFASs 替代物的特性见表 4。

表 3　PFASs 替代品在生物及人体组织中的检出量

Table 3　The detection of PFASs alternatives in the human and organisms

	生物 Organism	人 Human
F-53B	格陵兰岛海洋哺乳动物环北极熊、海豹、虎鲸 F-53B 浓度分别为 0.27 ng・g^{-1}、0.045 ng・g^{-1}、0.023 ng・g^{-1}[53] The F-53B concentrations were 0.27, 0.045 and 0.023 ng・g^{-1} in polar bears, ringed seals and killer whales of Greenland, respectively [53]	食鱼爱好者、镀铬工人、中低水平食鱼者血清中浓度分别为 93.7 ng・mL^{-1}、51.5 ng・mL^{-1}、4.78 ng・mL^{-1}[55] The median serum levels of F-53B observed in high fish consumers, metal plating workers, and people who had a low to medium intake of fish were 93.7, 51.5 and 4.78 ng・mL^{-1} respectively [55]
6:2 FTSA	鸡蛋中浓度 1.67~3.11 pg・g^{-1}[56];在鹗卵浓度 6.3~52 ng・g^{-1}[57] The concentrations in chicken eggs and osprey eggs were 1.67-3.11 pg・g^{-1} [56] and 6.3-52 ng・g^{-1} [57]	人体脐带血中浓度 24.78 pg・mL^{-1}[58]; 另一项研究发现母体及脐带血中浓度平均值分别为 13.39 pg・mL^{-1}、20.99 pg・mL^{-1}[59] The concentrationin human cord blood was 24.78 pg・mL^{-1} [58]. Another research found that the concentration in paired maternal and cord serum were 13.39 pg・mL^{-1}, 20.99 pg・mL^{-1} [59]

表 4　短链 PFASs 和全氟聚醚(PFPEs)的理化性质

Table 4　The physical and chemical properties of short chain PFASs and perfluoropolyether (PFPEs)

	短链 PFASs 替代品 Short chain PFASs and alternatives	全氟聚醚 PFPEs
持久性 Persistence (P)	与长链类似物相比,持久性类似 As persistent as the long-chain homologues	很难水解、羟基(OH)介导的反应、光解、生物降解 Resistant to hydrolysis, hydroxyl (OH)-radical-mediated reactions, photolysis, and biodegradation
生物累积性 Bioaccumulative (B)	与长链类似物相比,累积性小 Less bioaccumulative than the long-chain homologues	与长链 PFASs 结构类似,累积性可能相似 Might be as bioaccumulative as the predecessors, because of similarity of physicochemical properties
长距离迁移 Long-range transport potential (LRTP)	与长链类似物相比,更易迁移 More mobile than the long-chain homologues	与长链 PFAAs 结构类似,迁移性可能相似 Likely to be as mobile as the predecessors, due to similar physicochemical properties
毒性 Toxicity (T)	大多数毒性小,但存在物种差异 Less toxic than the long-chain homologues, but there are variation in species sensitivity	3 个 PFPEs 已经检测到可以引起肝毒,另外 1 个 PFPEs 已经列入 REACH 法规 Three PFECAs have been shown to cause liver damage; one PFECA is under the REACH regulation
总结 Summary	持久性; 无积累性;长距离运输;可能有毒性。 P; Less B; LRTP; May be less T	持久性; 可能有积累性;长距离运输;毒性。 P; maybe B; LRTP; T

4.1 持久性

短链 PFASs 与长链类似物具有相似的化学结构,因而其持久性与长链类似物相似[62-63]。而对于 PFPEs 有研究认为将氧杂原子引入到全氟烷基链中形成的全氟聚醚提供了一个攻击位点,全氟醚链可能更易降解为短链 PFASs[1]。Hori 等[64]研究发现,6 h 后,超过 40% 的 $C_2F_5OC_2F_4SO_3^-$ 和 $C_3F_7OC_2F_4SO_3^-$ 在 350 ℃有氧的亚临界水中降解(在 300 ℃下没有分解),而 $C_4F_9SO_3^-$ 在相同的条件下却不能降解。但是也有研究证明 PFPEs 在热、光、机械力、化学试剂、微生物等环境条件下并不易降解(表 5)。关于 PFPEs 的持久性还需要更多的实验验证。

4.2 生物累积性

生物累积性是衡量污染物是否属于 POPs 的一个极其重要依据,也是近年来 PFASs 研究的一个重要内容。与长链类似物相比,短链全氟化合物在生物和人体内基本没有生物累积趋势[60],但在植物的叶、茎、果实中很易积累[69-70]。最近研究发现,6:2 FTSA 对虹鳟鱼的生物富集系数< 40,同时研究发现虹鳟鱼对 6:2 FTSA 的食物吸收效率、生长半衰期以及食物放大因子分别为 0.435、23.1 和 0.295,因此虹鳟鱼对 6:2 FTSA 的积累性很低[71]。Shi 等[55]对不同人群血液及尿液中的 F-53B 的消除动力学进行了分析,F-53B 的血液清除半衰期小于 PFOS 的清除半衰期,但是由于物种的敏感度、灌喂的剂量方法以及实验技术等原因,关于 PFECAs 和 PFESAs 的生物累积性还需要更多的验证。

4.3 长距离迁移

许多 PFASs 具有 POPs 的远距离迁移特性,与长链类似物相比,具有较高水溶性、低吸附性的短链 PFASs 更易在环境中迁移[72-73]。PFECAs 和 PFESAs 不仅与 PFCAs 和 PFSAs 结构类似,而且具有持久性,因此在水中也可能具有长距离运输的潜力[74]。到目前为止,还未在偏远地区发现 PFECAs 和 PFESAs,可能由于(1)有些 PFECAs 和 PFESAs 近期才开始使用,使用量少并且排放量少;(2)PFECAs 和 PFESAs 可能以前体形式存在;(3)排放和迁移到偏远地区形成污染物之间有一定的时间间隔;(4)没有灵敏的检测方法以及检测标准。

4.4 毒性

高度重视人体健康效应研究是 PFASs 环境研究的一个前沿和重点领域。研究表明,与长链类似物相比,大多数的短链 PFASs 替代品对人体和环境中生物没有明显的毒性效应[75-76]。在对水生生物的

表 5 PFASs 替代品的降解性实验

Table 5 The degradability of PFASs alternatives

替代品 Alternatives	物理降解 Physical degradation	化学降解 Chemical degradation	微生物降解 Microbiological degradation	机械化学法 Mechanochemical destruction
F-53B	紫外照射 2 h 后分解率为 0%[49] 0% after 2 h irradiation[49]	UV/H_2O_2体系中,2 h 后分解率 < 5%[49] < 5% after 2 h in a UV/H_2O_2 system[49]	不易降解(OECD 301D)[49] Not readily (OECD 301D)[49]	与 PFOS 相比,F-53B 在 KOH 中研磨更易降解[65] Compared to PFOS, F-53B showed better treatability by milling with KOH[65]
6:2 FTSA	在紫外照射下不易降解[40] Not readily after irradiation[40]	在 UV/H_2O_2体系内,60 min 后剩余 9.6%,80 min 后,剩余 4.2%[65];在热活化过硫酸盐中很快转化[66] Remaining 9.6% after 60 min and 4.2% after 80 min in a UV/H_2O_2 system[65]; Rapid transformation in thermal activation of sulfates[66]	100 d 后,在活性污泥中仅有 7% 的 6:2 FTSA 降解[67]; 7% 6:2 FTSA was degradated after 100 d in the sludge[67]	
GenX		5 d 后,降解率 0%(OECD 111)[68] 0% after 5 days (OECD 111)[68]	28 d 后,降解率为 0%(OECD 301B)[69] 0% after 28 days (OECD 301B)[69]	

急性和慢性毒性暴露研究发现,6:2 FTSA 对水生生物几乎没有毒性。如虹鳟鱼 96 h 半数效应浓度(96 h-LC_{50})> 107 mg·L^{-1},大型蚤 48 h 的半数效应浓度(48 h-EC_{50}) > 112 mg·L^{-1}[72]。Hoke 等[77]研究发现 6:2 FTCA 对水蚤的 48 h-LC_{50}> 97.5 mg·L^{-1},海藻 72 h-EC_{50}= 47.9 mg·L^{-1},摇蚊 10 d-LC_{50}= 75.2 mg·L^{-1},浮萍 7 d-EC_{50}= 1.3 mg·L^{-1}。根据美国环保署毒品管理条例(USEPA TSCA)中水生动物毒性评估条例的规定,急性毒性的参考值为 1 mg·L^{-1}< EC/LC_{50}< 100 mg·L^{-1},因此,6:2 FTCA 对水生无脊椎动物毒性并不大。Mitchell 等[78]也研究发现 6:2 FTCA 对淡水无脊椎动物的毒性不大。如 6:2 FTCA 抑制小球藻生长的 EC_{50}= 26.2 mg·L^{-1},对月牙藻的生长抑制 EC_{50}>53 mg·L^{-1},而对端足虫 10 d 的死亡 LC_{50}= 33.1 mg·L^{-1}。Phillips 等[79]也发现 6:2 FTCA 抑制摇蚊生长的 EC_{50}= 63 mg·L^{-1}。Wang 等[38]研究发现 F-53B 对斑马鱼毒性与 PFOS 类似,其 96 h-LC_{50}分别为 15.5 mg·L^{-1}和 17 mg·L^{-1}。GenX 不仅对皮肤、眼睛造成刺激,在低剂量浓度连续暴露(≤ 10 mg·kg^{-1}·d^{-1})还可能引起肝癌[70]。关于 PFASs 替代品的毒性还需要更多的实验验证。

5　PFASs 替代品研究存在的问题与展望(The existing problems and perspectives of PFASs alternatives)

PFASs 替代品对人和环境是否安全?最近一些研究发现结构类似物的替换并不能真正解决问题,相反会出现“锁定”问题[38]。为了解决这一问题,PFASs 替代品的信息如特性、产量、用量、排放量以及毒性需要公开。然而,目前由于新型化合物研发费用高、时间长以及公司为了增加竞争力,PFASs 替代品信息并未完全公开。同时对 PFASs 替代品的环境行为及生态毒理效应方面的研究也尚未系统开展。今后应该开展如下研究:鼓励公司公开替代品的信息,加强各部门之间的交流;注重 PFASs 替代品在各环境介质以及人体内的监测,加快对 PFASs 替代品在各种环境介质降解机制的研究;完善新的替代品在环境介质和生物中的分析方法,以使分析数据具有可比性;系统地进行全氟替代品的来源、分布、迁移转化等研究;重视暴露途径、生物有效性的研究,并与风险评估相结合;开展低剂量、长期、慢性毒性和复合毒性研究,整合多种组学从分子、基因等水平研究其毒性机制,这些研究结果为研发新的无潜在生物蓄积性、无毒性的高性能化合物提供技术支撑。

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