

Regulating PFAS as a Chemical Class under the California Safer Consumer Products Program

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BACKGROUND: Perfluoroalkyl and polyfluoroalkyl substances (PFAS) are a group of manmade chemicals containing at least one fully fluorinated carbon atom. The widespread use, large number, and diverse chemical structures of PFAS pose challenges to any sufficiently protective regulation, emissions reduction, and remediation at contaminated sites. Regulating only a subset of PFAS has led to their replacement with other members of the class with similar hazards, that is, regrettable substitutions. Regulations that focus solely on perfluoroalkyl acids (PFAAs) are ineffective, given that nearly all other PFAS can generate PFAAs in the environment.

OBJECTIVES: In this commentary, we present the rationale adopted by the State of California's Department of Toxic Substances Control (DTSC) for regulating PFAS as a class in certain consumer products.

DISCUSSION: We at the California DTSC propose regulating certain consumer products if they contain any member of the class of PFAS because: *a*) all PFAS, or their degradation, reaction, or metabolism products, display at least one common hazard trait according to the California Code of Regulations, namely environmental persistence; and *b*) certain key PFAS that are the degradation, reaction or metabolism products, or impurities of nearly all other PFAS display additional hazard traits, including toxicity; are widespread in the environment, humans, and biota; and will continue to cause adverse impacts for as long as any PFAS continue to be used. Regulating PFAS as a class is thus logical, necessary, and forward-thinking. This technical position may be helpful to other regulatory agencies in comprehensively addressing this large class of chemicals with common hazard traits. <https://doi.org/10.1289/EHP7431>

Introduction

The PFAS Class

The term perfluoroalkyl and polyfluoroalkyl substances (PFASs) was first introduced by Buck et al. (2011) to describe certain manmade chemicals containing at least one fully fluorinated carbon atom (i.e., a carbon atom surrounded by fluorine instead of hydrogen). Subsequently, the U.S. Environmental Protection Agency (EPA) and others have dropped the extra “s” at the end of the class name, which has now become the standard in the United States. Determining where to draw the line between PFAS and highly fluorinated non-PFAS compounds remains an ongoing challenge. Buck et al. (2011) limited the scope of PFAS to aliphatic substances that contain at least one C_nF_{2n+1} moiety. The OECD (2018) expanded the definition to include substances with the C_nF_{2n} moiety, and are currently considering further revisions to the definition.

Since the late 1940s, PFAS have been used in a wide range of industrial and consumer product applications as oil, grease, soil, and water repellents and as surfactants (OECD 2013; Cousins et al. 2019a). Applications span many sectors of the economy, including aerospace, apparel, automotive, building and construction, chemicals and pharmaceuticals, electronics and semiconductors, energy, oil and gas exploration, first responder safety, and health care (American Chemistry Council 2021).

In 2015, the Swedish Chemicals Agency (KEMI) identified over 3,000 PFAS on the global market (KEMI 2015). A more recent study identified approximately 4,700 Chemical Abstract Services (CAS) Registry Numbers associated with individual

PFAS or PFAS mixtures (OECD 2018). In 2019, the U.S. EPA assembled a master list of 6,330 PFAS that combines information from several existing lists into one (U.S. EPA 2020b). The total number of PFAS may be even larger, given that some PFAS class members lack CAS numbers and many are not intentionally manufactured but are metabolites or degradants of other PFAS.

The widespread use, large number, and diverse chemical structures of PFAS pose challenges to any sufficiently protective regulation, emissions reduction, and remediation at contaminated sites. Specific members of the PFAS class have been regulated by several authoritative bodies. For instance, perfluorooctane sulfonic acid (PFOS) and its salts, and perfluorooctane sulfonil fluoride are listed as persistent organic pollutants (POPs) in Annex B of the Stockholm Convention, whereas perfluorooctanoic acid (PFOA), its salts, and related compounds are listed in Annex A (UNEP 2020). Perfluorohexane sulfonic acid (PFHxS), its salts, and related compounds are currently under review for listing (POPRC 2020). Several PFAS are included in the European Chemicals Agency's (ECHA) Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Candidate List of Substances of Very High Concern (SVHC) (ECHA 2020). From 2006 to 2015, the U.S. EPA worked with eight major chemical manufacturers to voluntarily phase out production and use of so-called long-chain PFAS and their precursors (U.S. EPA 2020c) and set a nonenforceable lifetime health advisory level for PFOA and PFOS, individually or combined, of 70 ppt in drinking water (U.S. EPA 2020a). Several U.S. states have also set their own drinking water guideline levels for PFOA and PFOS (Cordner et al. 2019).

The approach of regulating only individual PFAS or a limited subset of PFAS has led to the replacement of those PFAS with other members of the class that have less well-characterized hazard profiles. These alternatives may even be worse, in some respects, than the PFAS being replaced, thus constituting a “regrettable substitution” (Scheringer et al. 2014; Blum et al. 2015; Brendel et al. 2018). For instance, since the voluntary phaseout of the longer-chain PFAS in some regions, manufacturers have shifted to PFAS with six or fewer carbons, such as perfluorohexanoic acid (PFHxA) and other shorter-chain PFAS chemistries (OECD 2013; Brendel et al. 2018), which are less studied but have also been documented to display multiple hazard traits (Danish Environmental Protection Agency 2015; Gomis et al. 2018; Brendel et al. 2018; Rice et al. 2020).

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Because all PFAS show high persistence (P) or degrade to other class members that are highly persistent, several recent papers argue that regulators should take a “P-sufficient” approach and regulate all PFAS as a class (Cousins et al. 2019b, 2020a). However, the authors point out that there is no legal precedent in any jurisdiction for this approach (Cousins et al. 2020a). In this commentary, we present the first example of a regulatory agency using the P-sufficient approach as the rationale for regulating PFAS as a chemical class, under the Safer Consumer Products (SCP) framework adopted by the State of California’s Department of Toxic Substances Control (DTSC).

The Safer Consumer Products Regulations

California’s 2008 SCP law directed the DTSC to “establish a process by which chemicals of concern in products, and their potential alternatives, are evaluated to determine how best to limit exposure or to reduce the level of hazard posed by a Chemical of Concern” (Feuer 2008). The DTSC adopted this process in Article 3 of the SCP regulations (DTSC 2013). The SCP regulatory framework authorizes the DTSC to designate specific consumer products (excluding pesticides, food, and pharmaceuticals) that contain one or more specific Candidate Chemicals as “Priority Products.” Any chemical that appears on one or more of 23 established authoritative lists referenced in the DTSC’s framework regulations is a Candidate Chemical under this regulatory framework.

Once the DTSC designates a Priority Product, responsible entities (typically the product manufacturers) must either conduct an Alternatives Analysis, remove the Chemical(s) of Concern, or withdraw the product from the California market. In the Alternatives Analysis, each manufacturer identifies one or more potential alternatives to the Chemical of Concern and compares their life cycle impacts to determine whether the alternative is safer. If the DTSC determines that the Alternatives Analysis is deficient in terms of the options it considers, the quality of its research, or its characterization of the tradeoffs between the Priority Product and the alternative or alternatives under consideration, the DTSC can issue a notice of deficiency requesting additional information. If a potentially safer alternative proposed by a manufacturer lacks adequate data, the DTSC can issue a preregulatory response requiring the manufacturer to generate new data to address the data gaps. The DTSC issues a Regulatory Response based on the findings of the Alternatives Analysis. The goal of the Regulatory Response is to minimize the adverse impacts identified for the Priority Product using one or more of the following approaches: restrictions or prohibitions on the sale of the product, product labeling on safe handling procedures to prevent exposure, engineering or administrative controls to reduce exposure, end-of-life product management to reduce environmental releases, and investment in green chemistry and engineering to develop safer alternatives (DTSC 2013).

Identifying Priority Products does not require a formal risk assessment nor setting minimum threshold values. It only requires a finding that exposure to a Chemical of Concern in the product has the potential to “contribute to or cause significant or widespread adverse impacts” to human health or the environment (DTSC 2013). Thus, we believe the SCP regulations enable the DTSC to take a precautionary approach to protecting California’s most vulnerable human populations, as well as its threatened and endangered species, sensitive habitats, and impaired environments.

PFAS initially rose to the attention of the DTSC staff due to their endocrine disruption potential (White et al. 2011; C8 Science Panel 2012b) and well-established, unequivocal environmental and biological persistence (OECD 2013). The DTSC’s Candidate Chemicals list contains the entire class of PFAS as defined on one of the 23 constituent authoritative lists, namely, the Biomonitoring

California Priority Chemicals list. In 2015, Biomonitoring California designated all PFAS, as defined by Buck et al. (2011), as Priority Chemicals (Biomonitoring California 2015, 2019). This PFAS class definition includes all fluorinated aliphatic substances that contain the moiety C_nF_{2n+1} . Between 2016 and 2019, we refined our approach to regulating PFAS as a class in consumer products by researching the publicly available literature, engaging with our stakeholders, and submitting our findings to an external scientific peer review process mandated by California law. The resulting technical position described here may be helpful to other regulatory agencies in comprehensively addressing potential PFAS impacts.

Discussion

Why Regulating Individual PFAS is Ineffective

Other authors have also recently made the case for managing PFAS as a chemical class (Cousins et al. 2020a; Kwiatkowski et al. 2020). To understand why this makes sense, it is important to consider that virtually all the thousands of PFAS, as defined by Buck et al. (2011), can be roughly subdivided into four interrelated categories: perfluoroalkyl acids (PFAAs), PFAA precursors, perfluoropolyethers (PFPEs), and fluoropolymers (Buck et al. 2011; Wang et al. 2017). PFAAs are the most studied PFAS subgroup. They are recalcitrant to degradation and extremely persistent in the environment (Bentel et al. 2019). Examples of PFAAs include perfluoroalkyl carboxylic acids (PFCAs) such as PFOA, perfluoroalkyl sulfonic acids (PFSAs) such as PFOS, perfluoroalkyl sulfinic acids (PFSiAs), perfluoroalkyl phosphonic acids (PFPAs), perfluoroalkyl phosphinic acids (PFPIAs), perfluoroether carboxylic acids (PFECAs) such as GenX, and perfluoroether sulfonic acids (PFESAs) such as 4,8-dioxa-3H-perfluorononanoate (ADONA). PFAAs and their precursors are further subdivided according to their chain length, which is viewed as a proxy for their bioaccumulation potential. By convention, the longer-chain PFSAs are those with six or more perfluorinated carbons; longer-chain PFCAs, PFPAs, and PFPIAs are those with seven or more perfluorinated carbons (Buck et al. 2011). The definition of longer- vs. shorter-chain PFAS is less clear for perfluoroethers.

The majority (~85%) of PFAS are PFAA precursors, that is, they can degrade or metabolize into PFAAs in the environment or in living organisms (D’eon and Mabury 2007; Butt et al. 2014; OECD 2018). Some of the intermediate metabolites of PFAA precursors may be more toxic than the final PFAA degradation products (Rand and Mabury 2012a, 2012b, 2013, 2014, 2017; Rice et al. 2020). In particular, most PFAS currently used in consumer products are side-chain fluorinated polymers, in which the fluorinated side-chains are attached to a polymeric backbone and can cleave off, leading to PFCA terminal degradation products (Washington et al. 2015, 2019). U.S. EPA scientists have estimated environmental half-lives for these polymers of between 9 and 60 y (Washington et al. 2019). Thus, the side-chain fluorinated polymers found in discarded consumer products in landfills and other waste stocks may continue releasing PFAAs and intermediate degradation products to the environment for decades, or even centuries (Lang et al. 2017; Li et al. 2017; Washington et al. 2019).

PFPEs are fluorinated polymers with ether linkages (Wang et al. 2020). They are less likely to degrade to PFAAs, except perhaps during combustion (Huber et al. 2009; Wang et al. 2020). Fluoropolymers are characterized by large molecular sizes and do not degrade to PFAAs under typical environmental conditions, although they have been observed to release PFCAs, including PFOA, when heated to temperatures between 180°C and 800°C (Schlummer et al. 2015; Feng et al. 2015). PFAAs are used in the manufacture of fluoropolymers and can occur as

impurities in the final product. In fact, fluoropolymer manufacturing is the biggest contributor to historical PFCA emissions, accounting for an estimated 55–83% of all emissions between 1951 and 2002 (Wang et al. 2014a).

Although PFAAs constitute only approximately 1% of PFAS, we find that the hazard traits of PFAAs are relevant to the entire class because they are the terminal degradation, metabolism, or combustion products, manufacturing aids, feedstocks, or impurities of nearly all other PFAS class members (OECD 2018; Kwiatkowski et al. 2020). It is, therefore, our opinion that environmental releases of and exposures to PFAAs cannot be regulated without regulating the manufacture, use, and end-of-life fate of the other PFAS.

Criteria for Regulating PFAS under the California Code of Regulations

The California Green Chemistry Hazard Traits Regulations define a series of hazard traits, which are subdivided into toxicological, environmental, exposure potential, and physical hazard traits (OEHHA 2012b), discussed in more detail below. These hazard traits are not weighted. Reliable evidence for any one of these hazard traits can suffice to indicate that a chemical's potential adverse impacts warrant regulatory action.

Exposure potential hazard traits. At the DTSC, we have found that PFAS display one or more of the following exposure potential hazard traits listed in the California Code of Regulations: environmental persistence, mobility in environmental media, bioaccumulation, lactational or transplacental transfer, and global warming potential. Environmental persistence is the most widely recognized hazard trait of the class of PFAS. The carbon–fluorine bond shared by all members of the class is one of the strongest in organic chemistry, and the strongest single bond to carbon (Kiplinger et al. 1994). This makes PFAAs, the terminal degradation products of most PFAS, extremely recalcitrant in the environment (D'eon and Mabury 2011; Buck et al. 2011; Washington et al. 2015; Krafft and Riess 2015)—so much so that they have been called the “forever chemicals” (Pelch et al. 2019). Persistence is arguably “the most important single criterion affecting chemical exposure and risk via the environment” (Mackay et al. 2014). Some have even proposed that high persistence alone should be a sufficient basis for chemical regulation because if adverse impacts are identified, contamination cannot be reversed at scale within a reasonable time frame (Cousins et al. 2019b). According to the Statement of Reasons for the California Green Chemistry Hazard Traits Regulations, “Persistence of a chemical in the environment promotes sustained exposure and contributes to accumulation in the environment. Because persistence is an inherent property of a chemical in the environment that results in increased exposure to the chemical and consequently potential for health risks, it can appropriately be identified as a hazard trait. Legacy chemicals such as dichlorodiphenyltrichloroethane (DDT) and polychlorinated biphenyls (PCBs) remain public health concerns decades after their production was banned because of their ability to persist in the environment” (OEHHA 2012a).

PFAAs and some of their precursors are known to bioaccumulate in animals or plants. Unlike other persistent organic pollutants, PFAAs are proteinophilic and tend to accumulate not in fat but in protein-rich tissues such as blood (Jones et al. 2003; Chen and Guo 2009; Hebert and MacManus-Spencer 2010; Greaves et al. 2012; Hurley et al. 2018), liver (Greaves et al. 2012; Pérez et al. 2013; Gebbink et al. 2016), brain (Greaves et al. 2012; Pérez et al. 2013), kidney and lung (Pérez et al. 2013), and muscle (Greaves et al. 2012). Human serum elimination half-lives of longer-chain PFAAs range from years (Bartell et al. 2010; Olsen et al. 2007a; Seals et al. 2011) to decades (Shi et al. 2016). For

shorter-chain PFAAs, human serum elimination half-lives are on the order of days (Chang et al. 2008; Nilsson et al. 2010; Olsen et al. 2007a). However, recent studies have indicated that some of the intermediate short-chain PFAS metabolites, such as 5:3 fluorotelomer carboxylic acid (FTCA), may biopersist and bioaccumulate (Kabadi et al. 2018, 2020). Shorter-chain PFAAs also tend to accumulate in plants (Blaine et al. 2013, 2014; Gobelius et al. 2017; Lechner and Knapp 2011; Scher et al. 2018; Stahl et al. 2009; Yoo et al. 2011), allowing them to enter terrestrial and aquatic food chains.

PFAAs and several of their nonpolymeric precursors have high mobility in environmental media and can be transported long distances in the atmosphere or hydrosphere (Wang et al. 2014b; Xie et al. 2015; Dreyer et al. 2015). Shorter-chain PFAS are known to be more mobile and difficult to remove from water (Brendel et al. 2018; Ateia et al. 2019), readily contaminating groundwater (McLachlan et al. 2019) and escaping from waste stocks such as landfills and dumps (L Li et al. 2017; F Li et al. 2020). Because they tend to be more volatile, they are more likely to be released from consumer products.

Several PFAS are known to undergo transplacental (Midasch et al. 2007; Zhang et al. 2013; Yang et al. 2016; F Chen et al. 2017; Zhao et al. 2017; Mamsen et al. 2019; Eryasa et al. 2019; Cai et al. 2020) and lactational (Kärman et al. 2007; Llorca et al. 2010; Mogensen et al. 2015; Mondal et al. 2014; Tao et al. 2008b; Kim et al. 2014; Fromme et al. 2010; Kang et al. 2016; Nyberg et al. 2018; Lee et al. 2018) transfer in humans. Up to 30.3% of the PFAS found to undergo transplacental transfer using nontarget screening were novel PFAS whose impacts on the developing fetus are yet unknown (Y Li et al. 2020).

Toxicological and environmental hazard traits. PFAAs, which are relevant to the entire class as manufacturing aids, degradants, or impurities, collectively also display several toxicological and environmental hazard traits. Potential adverse human health effects and risk factors from longer-chain PFAA exposure include increased serum cholesterol (Skuladottir et al. 2015; Winquist and Steenland 2014), thyroid disease (Winquist and Steenland 2014), immune dysregulation (Grandjean and Clapp 2014; Grandjean et al. 2017a, 2017b), pregnancy-induced hypertension (C8 Science Panel 2011), and kidney and testicular cancers (C8 Science Panel 2012a). Other studies have found positive correlations between long-chain PFAA exposure and low birth weight in humans (Malits et al. 2018), as well as suppressed immune system response, dyslipidemia, impaired kidney function, and delayed first occurrence of menstruation (Rappazzo et al. 2017).

Due to their shorter observed biological half-lives, shorter-chain PFAS have been assumed to be less toxic compared with the longer-chain PFAS (DeWitt 2015; Stahl et al. 2011; Wolf et al. 2008). However, more and more studies are questioning this assumption. A toxicokinetic study found that the potency of shorter-chain PFAAs to induce increased liver weight is similar to that of the longer-chain PFOA, and even greater for the PFCA GenX (Gomis et al. 2018). Limited animal data on GenX and related perfluorinated ethers indicate potential associations with cancer, body weight gain, changes to the immune system and cholesterol levels, increased kidney and liver weights, and liver cell changes (Caverly Rae et al. 2015; Beekman et al. 2016). Several toxicokinetic studies and receptor binding assays report biological activity from exposure to the shorter-chain PFBA and PFBS (Wolf et al. 2008; Danish Environmental Protection Agency 2015). Studies on zebrafish and rodents have linked PFBA with reproductive and developmental toxicity (Das et al. 2008; Hagenshaars et al. 2011) and ocular toxicity (Butenhoff et al. 2012), PFBS with developmental toxicity (Hagenshaars et al.

2011) and hematotoxicity (Lieder et al. 2009), and PFHxA with respiratory toxicity (Loveless et al. 2009). Neurodevelopmental toxicity has also been demonstrated *in vitro* for PFBS (Slotkin et al. 2008).

Less is known about the toxicity of most PFAA precursors. Some studies suggest that fluorotelomer-based PFAA precursors, including their intermediate degradation products, are more toxic than the final PFAA metabolites (Phillips et al. 2007; Rand et al. 2014; Rice et al. 2020). Hazard traits reported for these precursors include endocrine toxicity (Ishibashi et al. 2008; Rosenmai et al. 2016; Weiss et al. 2009; Ladics et al. 2008; Winkens et al. 2017; Rice et al. 2020), developmental toxicity (Shi et al. 2017b; Rice et al. 2020), and hepatotoxicity and nephrotoxicity (Ladics et al. 2008; Rice et al. 2020).

Available data also link PFAAs and some of their precursors with several of the environmental hazard traits identified in California's Green Chemistry Hazard Traits Regulations: phytotoxicity (Latafa et al. 2009), wildlife developmental impairment (Hagenaars et al. 2011; Ulhaq et al. 2013; Shi et al. 2017a), wildlife reproductive impairment (Liu et al. 2009), and wildlife survival impairment (O'Connor et al. 2014; Klaunig et al. 2015; Eggers Pedersen et al. 2015; Shi et al. 2017a).

Widespread human and ecological exposures. In addition to the hazard traits discussed above, the SCP regulations consider the potential for exposures to the Candidate Chemical in a product and the aggregate effects of exposures to the Candidate Chemical from multiple exposure sources and media (DTSC 2013).

PFAAs and some of their precursors are widespread in the environment, including in air (Kim and Kannan 2007; Muir et al. 2019; Wang et al. 2019), dust (Haug et al. 2011; Eriksson and Kärrman 2015; Yao et al. 2018; Shin et al. 2020), wastewater treatment plant effluent (Hamid and Li 2016; Wang et al. 2016; Houtz et al. 2016; H Chen et al. 2017), biosolids (Letcher et al. 2020; Kim Lazcano et al. 2020), soil (Rankin et al. 2016; Dalahmeh et al. 2018; Muir et al. 2019; Washington et al. 2019), snow (Kim and Kannan 2007; Kirchgeorg et al. 2016), inland and ocean waters (Prevedouros et al. 2006; Zhao et al. 2012; Wang et al. 2016; Muir et al. 2019), drinking water (Gellrich et al. 2013; Wang et al. 2016; Boone et al. 2019), and human foods (Pérez et al. 2014; Gebbink et al. 2015; Domingo and Nadal 2017; Christensen et al. 2017; EFSA CONTAM Panel et al. 2018). As a result, human (Cariou et al. 2015; Calafat et al. 2007; Chang et al. 2014; Fraser et al. 2013; Kang et al. 2016; Monroy et al. 2008; OECD 2013; Olsen et al. 2007b; Tao et al. 2008a, 2008b) and ecological (Giesy and Kannan 2001; Liu et al. 2011; OECD 2013) exposures to PFAS mixtures are widely documented. Shorter-chain PFAAs are often not detectable in human serum and plasma but can be found at concentrations comparable to or higher than those of longer-chain PFAS in human whole blood (Poothong et al. 2017), hair (Alves et al. 2015; Ruan et al. 2019; Martín et al. 2019), urine (Hartmann et al. 2017; Kim et al. 2014; Pérez et al. 2012), and certain organs, including the kidney, lung, liver, and brain (Pérez et al. 2013). Given that PFAS are highly persistent and capable of long-range transport, we expect that environmental contamination and exposures will continue for as long as PFAS are manufactured or used anywhere in the world.

Thus, human and ecological receptors are exposed to mixtures of PFAS whose environmental fate and hazard traits are interlinked. Despite recent analytical advancements, most of the PFAS observed in the environment, wildlife, and human tissues remain unidentified (Xiao 2017). Only a small fraction (sometimes <5%) of the organofluorine present in these media have been targeted for analysis. Until analytical methods are

developed and validated for more members of the class, the full extent of PFAS contamination, despite extensive research, will remain poorly understood.

Regulatory Implications

Based on the currently available science, we have concluded that it is both ineffective and impractical to regulate this complex class of chemicals with a piecemeal approach and have, therefore, initiated regulatory action to list certain consumer products containing any PFAS as Priority Products under the SCP regulations. The available information demonstrates that all PFAS or their degradation, reaction, or metabolism products have at least one hazard trait of concern to the State of California: environmental persistence. As others have argued, high persistence alone can be a sufficient criterion for regulatory action (Cousins et al. 2019b, 2020b). In the case of PFAS, we believe that all members of the class have a potential for significant and widespread adverse impacts due to their extremely high environmental persistence, coupled with growing evidence for human and ecological health hazards for the impurities, metabolites, and degradation products of the subset commonly used in consumer products. The concerns identified in this commentary reflect our best understanding of the current PFAS in production and use. However, significant data gaps remain, and we cannot exclude the possibility that new PFAS may be developed in the future following green chemistry principles.

Because individual PFAS never occur in isolation, we believe they cannot be effectively regulated in isolation. The potential for widespread exposures will remain for as long as PFAS continue to be used and concerns over their fate and transport remain inadequately addressed. However, although virtually all PFAS studied show at least suggestive evidence of toxicity, the observed effects are variable. This means that PFAS cannot be regulated as a class based on a common mode of action or toxicity. At the DTSC, we were able to take a class approach to regulating PFAS because *a*) persistence is codified as a hazard trait in the California code of regulations; *b*) the entire class is on the DTSC's list of Candidate Chemicals, after being designated as priority chemicals for biomonitoring in California; and *c*) the SCP regulatory framework is based on an inherently precautionary approach, to protect the most vulnerable human and ecological (sub)populations.

Thus, the California Green Chemistry Hazard Traits and SCP regulations (OEHHA 2012b; DTSC 2013) offer a more comprehensive, precautionary approach to assessing potential adverse impacts of PFAS and can serve as a model for other regulatory agencies aiming to address potential PFAS impacts comprehensively. Taking a class approach to regulating PFAS in consumer products could also encourage innovation in developing safer alternatives and reducing the risk of regrettable substitutions. Indeed, under California's regulatory framework, our identification of the entire PFAS class as a Chemical of Concern will compel manufacturers to identify, and rigorously evaluate, the relative safety of non-PFAS alternatives throughout a product's life cycle.

This precautionary regulatory approach may be applicable to other chemical classes in consumer products where class members share life cycle fates or hazard traits, limited toxicological and exposure data are publicly available, and regrettable substitutions are likely. For example, we are also proposing to regulate nonylphenol ethoxylates in laundry detergents as a class (DTSC 2018). We also recommend consideration of this approach for regulating nontraditional complex classes of compounds that are of concern but lack a common mode of action or toxicity, such as microplastics.

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