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Commentary

Improving governance of "forever chemicals" in the US and beyond

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Per- and polyfluoroalkyl substances (PFAS) are a novel entity that threaten public health due to their environmental persistence and global contamination. Interdisciplinary collaboration can address this crisis, incorporating governance, scientific, corporate, and community action. We present US perspectives on multi-scalar, multi-stakeholder solutions to protect human and environmental health.

Food, drinking water, soil, and even rainwater worldwide is contaminated with so-called "forever chemicals" at levels that may cause health problems.[1] These contaminants, per- and polyfluoroalkyl substances (PFAS), are a class of over 12,000 chemicals[2] that are used in countless industrial applications; are found consumer products ranging from nonstick cookware to waterproof fabrics to cosmetics; and are linked to a variety of health problems.[3] Action is required to prevent additional PFAS releases and target existing sources of contamination. Such efforts must incorporate not only insights from environmental health science and public health but analyses from social science and policy studies, as well as the values and needs of impacted communities. We are a group of interdisciplinary environmental health and social scientists who study the multifaceted aspects of PFAS contamination including community activism and governance approaches,[4] and we present our perspective of current challenges and future directions of PFAS management, focusing on the United States (US).

Forever chemicals everywhere

PFAS can be broadly defined as organic molecules with one or more fully fluorinated carbon atom(s). Their extremely strong carbon-fluorine bond makes them environmentally persistent and resistant to destruction. These characteristics make PFAS industrially desirable for applications such as aqueous fluorinated firefighting foams (AFFF). However, many PFAS are bioaccumulative, toxic, and mobile in water. PFAS pollution point sources include current and former military locations, fire training facilities, airports, wastewater treatment plants, landfills, and numerous types of industrial sites.[5] Figure 1 illustrates the interrelationships between PFAS releases, environmental contamination, and human exposures. PFAS move through the water cycle, leading to "ubiquity in atmospheric deposition."[1] Their contamination spans the globe and has been categorized as a "novel entity planetary boundary threat," highlighted by a recent analysis noting that PFAS in rainwater samples worldwide exceed health-based water guideline levels developed by the Danish Environmental Protection Agency, the European Union's Inland Surface Water program, and the US Environmental Protection Agency (EPA).[1]

Alongside food, occupational exposures, and other under-studied routes, drinking water is a major source of human exposure to PFAS. For example, PFAS can enter wastewater treatment plants (WTPs) like other contaminants (i.e., through residential and industrial waste), but because they are not degraded by typical treatment methods, PFAS often survive wastewater treatment and are thus reintroduced into the waterways from which drinking water is sourced. Since the solid waste from WTPs, i.e., sludge, can contain PFAS, the use of such sludge in agriculture will result in PFAS pollution in soil and food. For example, farms in the US state of Maine have been forced out of business because their land was contaminated by decades-old sludge applications. Additional PFAS sources include landfill leachate and air emissions from waste incineration facilities. Contamination is widespread: while our research group has documented approximately 1,800 known PFAS contamination sites in the US, our "presumptive PFAS contamination" approach has mapped over 57,000 suspected contamination sites, with tens of thousands of additional sites unidentified due to incomplete geolocation data.[6]

As a result of widespread exposure, nearly all people have PFAS in their bodies. For example, a nationally representative biomonitoring study detected PFAS in over 98% of US participants.[7] This is concerning because growing scientific consensus emphasizes how toxic certain PFAS are to human health. They have been associated with decreased antibody response, decreased fetal and infant growth, and increased risk of kidney cancer, and evidence suggests a relationship between PFAS exposure and the risk of breast cancer, testicular cancer, and thyroid disease.[3] These health effects

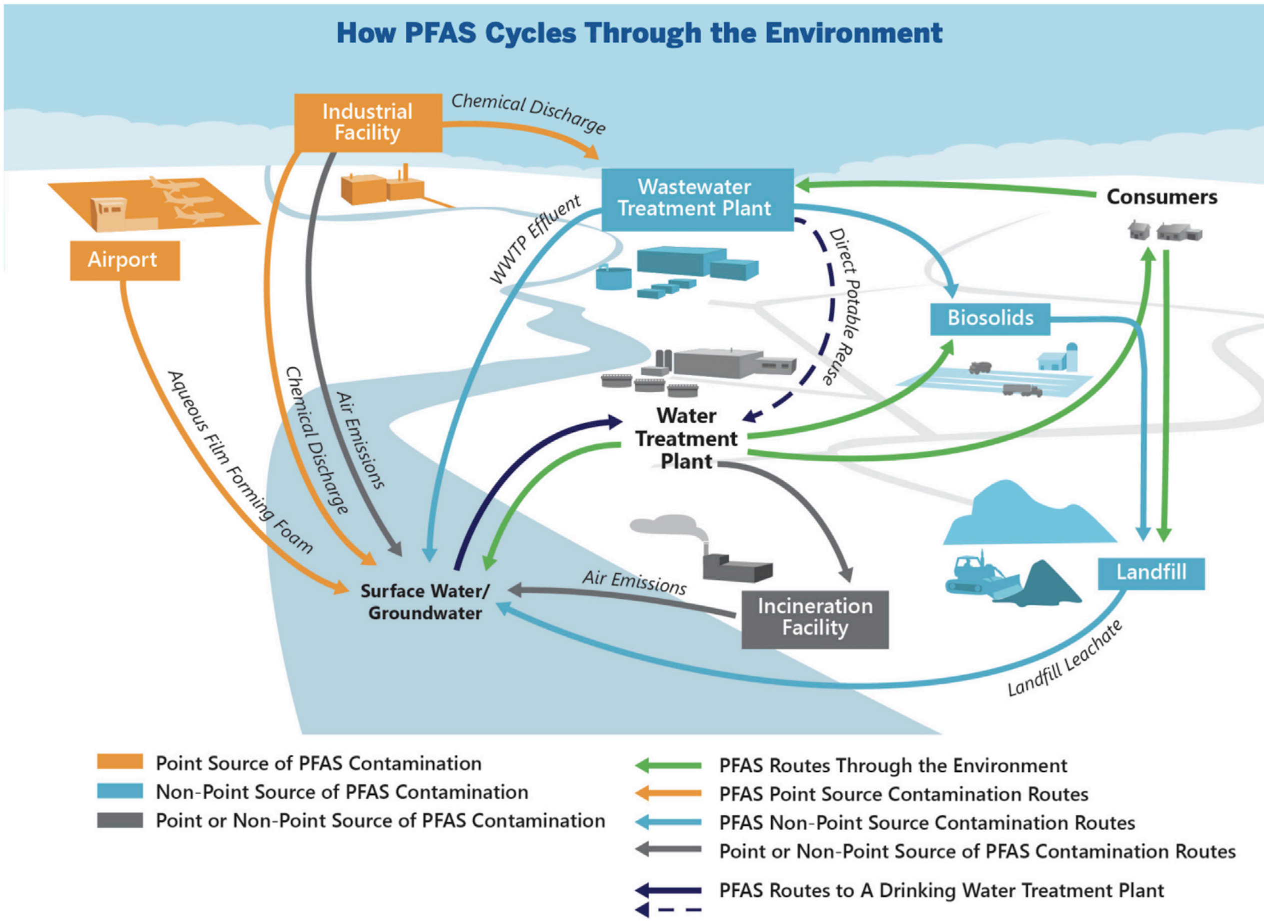

Figure 1. PFAS transport through the environment
The multifaceted pathways of PFAS transport and distribution from direct sources such as industrial emissions and secondary sources such as water treatment plant outflow and incineration facilities, connecting them to drinking water contamination. PFAS are environmentally persistent and resistant to degradation due to their strong carbon-fluorine bonds. Once emitted to the environment, they are distributed through the water cycle, contaminating drinking water through surface and groundwater and through waste management and water treatment facilities. Used with permission from the American Association for the Advancement of Science's Center for Scientific Evidence in Public Issues.

have been reported in highly exposed US communities with PFAS-contaminated drinking water supplies, such as the Mid-Ohio Valley region contaminated by a DuPont Teflon manufacturing facility.[3] This is particularly concerning for other highly exposed groups, such as fire-fighters and other workers exposed to PFAS.[8] The social costs of PFAS extend beyond these health implications and include business and agricultural impacts, remediation and disposal expenses, capacity and research expenses for governments, as well as stress and quality of life concerns for impacted residents.[9] For example, a recent analysis estimated annual health-related costs for the US from just two PFAS (perfluorooctanoic acid [PFOA] and perfluorooctane sulfonate [PFOS]) at \$5.52–\$62.6 billion.[10]

Challenges and current governance in PFAS management

PFAS′ persistence presents an immense challenge to remediation and destruction, whether the waste comes from water treatment plant filters, contaminated soil, or collected AFFF. PFAS can be sequestered with specific treatment technologies such as granular activated carbon filtration and reverse osmosis, but these require ongoing maintenance and pose a risk of contaminant re-release. Similarly, industrial waste or unused AFFF can be collected, but the actual destruction of PFAS molecules remains an outstanding challenge. PFAS destruction is incredibly energy-intensive due to the strong C–F bonds, and there is currently no suitable destruction technique available at an appropriate scale. Incineration is currently the most widely used PFAS destruction method, but it requires extremely high temperatures reached through the combustion of fossil fuels (>1,400°C for some PFAS) and can release PFAS-containing combustion products into the environment.[11] Promising emerging destruction technologies, such as supercritical water oxidation or low-temperature mineralization, are energy-intensive, can release PFAS-containing intermediaries, are not yet scalable, or do not address the full PFAS class. Waste disposal is a well-recognized global environmental justice issue, since incinerators, landfills, and other waste management facilities are disproportionately located in or near low-income areas and vulnerable communities. Thus, landfilling or incinerating PFAS waste would likely create additional exposures for already overburdened communities.

PFAS are emerging as a major focus of international governance efforts, but no governing body has addressed PFAS comprehensively enough to protect human health and the environment. Three PFAS have been added to the Stockholm Convention on Persistent Organic Pollutants (POPs), an international agreement aiming to regulate and eliminate POPs. Despite its international scope, implementation is not ensured even for the 152 ratifying countries. The European Union (EU) has pursued a relatively more precautionary approach to PFAS management through their Registration, Evaluation, Authorization, and Restriction of Chemicals program, which requires companies to register chemicals and provide information on safety and use. The EU is currently developing a proposal for class-based PFAS restrictions of firefighting foams, and the Netherlands, Germany, Norway, Denmark, and Sweden are expected to submit class-based regulation for consideration in 2023.[12] Other global efforts to regulate PFAS, unfortunately, have been minimal.

While the US is a major producer of PFAS and was the location for some early PFAS regulatory work,[13] it lags behind the EU in coordinated PFAS legislation. The size of the PFAS chemical class and their use in many industrial sectors, combined with limitations in US chemicals policy, pose significant challenges to developing comprehensive regulation. Congress has taken legislative action on PFAS through National Defense Authorization Acts since 2018, which have funded several exposure and health studies on and near contaminated military bases, required a still-in-progress phaseout of PFAS in AFFF, and directed the EPA to add 172 PFAS to the Toxics Release Inventory. The US EPA has recently announced several health-protective actions, including formalizing plans to designate two PFAS as hazardous substances under the Superfund program and updating its non-enforceable lifetime drinking water health advisory levels for two PFAS to below one part per trillion. While the US EPA has committed to developing binding restrictions in coming years, there are currently no federal PFAS drinking water standards or testing requirements.

In the absence of enforceable federal regulation, many US states have developed their own PFAS policies, with 19 states adopting enforceable or guidance-level drinking water standards. Other current US state actions include consumer product restrictions, regulation of firefighting foam composition and use, and non-binding governance activities like monitoring programs, research, and interagency task forces.

However, even in instances where individual states are introducing ambitious policies, implementation can be complicated. The burdens of PFAS remediation unfortunately tend to fall on communities, who can face millions of dollars in testing and remediation expenses, and costs to residents and businesses are substantial but hard to quantify.[9] PFAS are present in over 200 use categories and sometimes are unintended contaminants.[14] Actions taken in any single industrial or manufacturing sector are thus complicated and slow, involving ripple effects across diverse supply chains. For example, California's legislative ban on PFAS in textiles exempts several product categories and delays action on some outdoor apparel. Even when manufacturers want to move away from PFAS, safer replacements may be expensive and difficult to identify, and global supply chains, which lack transparency due to limited government oversight and the complexity of those supply chains, preclude identification of all potential PFAS sources. Moreover, chemical manufacturers maintain their PFAS products are safe despite emerging research highlighting health and exposure concerns.[13,15]

With thousands of PFAS in commerce, regulating each compound individually is resource- and time-intensive, allows for continued release of other PFAS chemicals, and places the burden of exposure on the global public and our ecosystems. Case-by-case PFAS regulation perpetuates a system of "regrettable substitutions" in which regulated compounds are replaced with unregulated and under-studied alternatives. Such is the case for the PFAS GenX, which was introduced as a PFOA alternative: recent evidence indicates that GenX and other replacement compounds have similar toxicological profiles, and in many cases, higher environmental mobility, than the "legacy" compounds PFOA and PFOS.

Steps toward addressing the PFAS crisis

Global solutions to the PFAS crisis must prioritize primary prevention efforts that stop PFAS emissions at the source, ensure that PFAS are replaced with safer alternatives, and require that remediation of existing contamination is thorough and just. This requires work across scientific, governance, corporate, and community spheres (Figure 2).

Scientific advances supporting the reduction of PFAS use must be designed parallel to strong legislation to prevent ongoing and new PFAS production, emission, and regrettable substitution. Following the "essential use" framework described by Cousins and colleagues,[16] PFAS use should be eliminated whenever possible, based not on industry-championed notions of usefulness or convenience but on the necessity of chemical functions to health and safety. Accordingly, the vast majority of PFAS uses would be considered *non-essential* or *substitutable* because the use is not societally necessary or because safer substitutions are currently available.[16] In this model, essentiality is not a static designation, rather it is a temporary categorization used only until suitable alternatives are found. Identifying an essential use requires meaningful regulation of PFAS and active research to identify safer alternatives to avoid the pattern of regrettable substitution described above.

Aligned with green chemistry principles, alternatives to currently used PFAS should be "designed for degradation," with transformation and degradation products that are innocuous and environmentally transient.[17] Current PFAS were not designed with such concerns in mind, so remediation depends on effective, scalable destruction technologies. As discussed above, emerging technologies for PFAS destruction highlight the need for technical imagination and resource dedication to remediation, a key area for scientific investment. However, such technologies are not quick or universal "silver bullets" to the overwhelming problem of global PFAS contamination.

We join international scholars in calling for class-based PFAS regulation to protect public health and the environment.[18] To enable more efficient and effective PFAS management, instead of chemical-by-chemical evaluation, a class-based

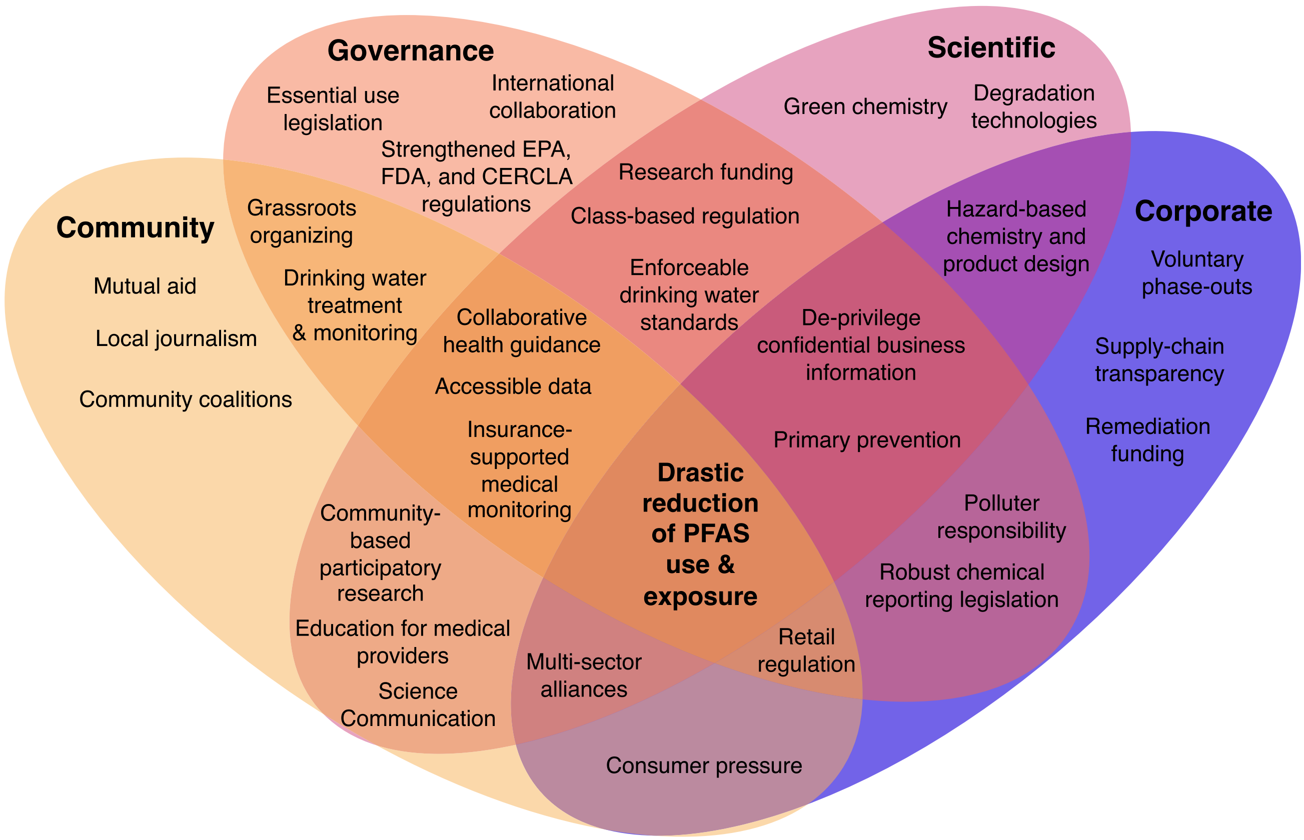

Figure 2. An intersecting system of PFAS management

Comprehensive reduction of PFAS production, use, and exposure requires interdisciplinary collaboration incorporating scientific, governmental, corporate, and community action. Here we highlight some ongoing and necessary PFAS actions in and among these spheres.

approach is needed that treats all PFAS as a single class based on their high persistence, bioaccumulation potential, and known and potential hazards.[11] Class-based approaches have been successfully employed against other environmental contaminants including polychlorinated biphenyls, halogenated flame retardants, and chlorofluorocarbons. The EU has imposed drinking water limits of 0.5 parts per billion for total PFAS in drinking water. In the US, states including Maine and California have defined PFAS as a class in legislative efforts.

Meaningful governance initiatives are also needed to address PFAS disposal challenges. For example, several European countries have stopped using fluorinated AFFF, and the European Chemicals Agency has proposed a full ban on AFFF manufacture, use, and export. Fluorinated AFFF is still required at military bases and airports in the US and in other parts of the world, and the US military has missed Congressional-ordered deadlines related to revising these requirements. Current and former military sites around the globe are hotspots of PFAS contamination,[6] and governments could require contaminated bases to provide testing and remediation to neighboring civilian areas.

As with nearly all environmental exposure and health issues, transdisciplinary research approaches and meaningful community involvement are central to identifying the problem and steering solutions. The 2022 National Academies of Science, Engineering, and Medicine PFAS Medical Guidance Committee[3] shows the importance of including voices and needs of affected community residents. Government agencies in many countries have a history of funding community-driven research, education, and environmental justice projects, and more support for those PFAS efforts is needed. Community PFAS activism has been one of the most prominent forms of toxics activism in recent years, identifying problems and solutions that were either unknown or under-appreciated by official agencies, and leading to successes at local, state, and national levels in terms of public information, research, regulation, and remediation. Likewise, firefighter activism has pressed on the problems of PFAS in both AFFF and protective gear, issues previously overlooked by regulators. Funds need to be made available through environmental and health agencies at all geographic scales to provide resources for community groups to conduct PFAS water testing and biomonitoring and to engage with municipalities on monitoring, public education, medical guidance activities, and remediation. Local- and state-level multi-agency task forces could provide new and creative forms of assistance to community activists and groups. Moreover, Indigenous communities have much proximity to known and suspected PFAS contamination sites, though our research shows they are disproportionately excluded from US PFAS testing initiatives.

Additional support, including Tribal-specific funding sources, would also provide Indigenous communities with PFAS-related resources.

While the challenges posed by PFAS are significant, progress is both possible and necessary. The growth of activism, regulation, and corporate action has been surprisingly strong. Dramatically reducing PFAS production, use, and exposure requires innovative governance interventions, proactive and conscientious business actions, and scientific advances that defy disciplinary boundaries, all guided by the voices, experiences, and needs of impacted communities. It is only through this transdisciplinary, multi-sectoral, justice-oriented approach that we will achieve the needed drastic reduction of PFAS use and exposure to protect public health and the environment.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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