Introduction

Despite being used in products since the 1950s, perfluoroalkyl and polyfluoroalkyl substances (PFAS) have only recently become widely recognized as a public health concern.[1] PFAS exposure is linked to immune system dysregulation, liver and kidney disease, insulin dysregulation, and cancer.[2] Exposure can occur occupationally, environmentally, or through consumer products and is widespread, as the National Health and Nutrition Examination Survey reports that 97% of Americans have PFAS in their blood.[3] Avenues of exposure are a growing area of study, particularly among pregnant people and children.[1] Pregnant people and children are disproportionately impacted by toxin exposure due to their decreased immunological resilience and sensitive developmental milestones,[4,5] thereby making toxin exposure pathways known among these populations critical. This paper evaluates existing evidence for PFAS exposure among pregnant people and children under the age of 10 years old of all races and incomes in the United States (US) from 2008 to the present in the context of the bio socio-ecological model.

Levels

Level 1: Individual factors

Factor 1 – PFAS exposure and gestational hypertension

PFAS increases the likelihood of gestational hypertension among pregnant people, which may lead to pregnancy complications such as intrauterine growth restriction and stillbirth in fetuses, thereby decreasing the likelihood of survival to childhood.[6] From 1999 to 2002, 1,558 pregnant people in the US were evaluated for blood PFAS levels and hypertensive disorders in pregnancy.[6] This evaluation throughout pregnancy revealed that PFAS presence in blood samples was associated with 1.14 times the odds of gestational hypertension compared to those without evidence of PFAS exposure (95% confidence interval: 1.03, 1.25)[6] due to PFAS-induced dysregulation of blood platelets and the placenta.[7,8] Gestational hypertension may result in poor health outcomes for both the pregnant person and the baby. Among pregnant people, gestational hypertension may cause decreased blood flow in major organs such as the brain and uterus, increasing the likelihood of hypoxia.[9] In fetuses, gestational hypertension may result in the separation of the placenta from the uterus too early in pregnancy, inadequate growth of the fetus, and stillbirth.[9] These health effects reduce the likelihood that the fetus will survive to childhood. As evidenced by these health outcomes, PFAS exposure is an important public health concern among pregnant people and children under the age of 10.

Factor 2 – PFAS exposure and immunological dysregulation

Both unborn and recently born babies with PFAS exposure experience immunological dysregulation, which has negative health implications associated with vaccine efficacy and immunosuppression.[10] PFAS exposure disproportionately impacts children because youth immune systems are immature.[10] With children's immune systems being immature, PFAS can more easily dysregulate T and B lymphocytes, resulting in a lower antibody response to vaccines and dysregulation of CD4:CD8 cell count ratios and NK-cell functioning, resulting in immunosuppression.[10] Lower antibody response to vaccines and immunosuppression increases the likelihood of children being harmed by childhood communicable diseases that are otherwise vaccine preventable, such as measles, pertussis, and influenza. To ensure that vaccine-preventable illnesses do not significantly impact the morbidity of children in the US, PFAS exposure must be reduced both while in utero and during the first 10 years of life.

Level 2: Peer/family/interpersonal relationships

Factor 1 – PFAS exposure and breast milk

A common route of PFAS exposure among newborns is through their parent's breast milk since PFAS bind to serum proteins in breast milk, which can result in PFAS-associated poor health outcomes in newborns that carry into childhood.[11] In a recent study that measured PFAS concentrations in breast milk among 50 people in the US, 16 different PFAS compounds–both long and short chain–were detected in between 4-100% of samples.[11] In particular, PFDA–a long chain PFAS compound–was found in 94% of tested samples,[11] which is especially alarming because long-chain PFAS have high affinity to blood proteins[12] and efficiency of lactational transfer is highest among these long chained PFAS compounds.[11] As a consequence to this prevalence of PFAS among breast feeding parents, the estimated daily intake of PFAS among infants less than 1 month old was 18 ng/kg bw/day,[11] which is much higher than the estimated daily intake for adults who do not drink breast milk (0.58 ng/kg bw/day).[11] This high daily intake of PFAS from breast milk results in PFAS-related health detriments among infants that can have impacts into childhood, amplifying the consequences of PFAS accumulation in the environment.

Factor 2 – PFAS exposure and household products

Another route of PFAS exposure is through consumer and household products which, if used by parents, results in PFAS exposure among infants and children. PFAS is used in numerous household products such as non-stick cooking ware, carpets that are resistant to stains, and waterproof products.[13] Having these products in US households causes exposure to PFAS among pregnant people, infants, and children living in the household. For infants and children, there is an inability to choose exposure to these products due to family use. As a consequence, these products result in elevated PFAS blood concentration levels among pregnant people, infants, and children, resulting in PFAS-related poor health effects among these groups.[13]

Level 3: Immediate living, working, education, and recreational conditions

Factor 1 – PFAS exposure and dust in childcare settings

PFAS accumulates in dust, which acts as a common route of exposure among children particularly in daycare settings, making children at-risk for PFAS-related health conditions.[14] Dust from sleeping mats among childcare centers in Washington and Indiana were tested for PFAS as an indicator of PFAS-presence in childcare settings given the universal presence of sleeping mats in this setting.[14] From these samples, twenty-eight different PFAS with concentrations from 8.1 ng/g to 3,700 ng/g were found.[14] When converted into estimated daily intake of PFAS, children in these settings are expected to have an estimated PFAS-exposure through dust inhalation of 0.29 ng/kg bw/day, which is about three-quarters the total amount of PFAS-exposure among children.[14] Given the large proportion of PFAS daily intake that dust in these settings is attributed to and how children spend a significant portion of their days in these settings, dust in childcare settings is an important factor to consider in mitigating PFAS-exposure among children and the disproportionate health effect that PFAS may have on this age group.

Factor 2 – PFAS exposure and industrial facilities

PFAS-emitting industrial facilities cause PFAS exposure to nearby residents through a contaminated drinking water supply, which when consumed by pregnant people and children, results in poor health outcomes among these populations.[15] For example, the Fayette Works fluorochemical-producing facility in North Carolina polluted PFAS into the Cape Fear River from 1980 to 2017.[15] The Cape Fear River is the primary drinking water source for residents of Wilmington, North Carolina.[15] When Wilmington residents were tested for PFAS exposure, more than 97% of sampled individuals had PFAS blood level concentrations higher than the national average.[15] In particular, median PFAS blood concentration levels among residents was 4.3 ng/mL, which is higher than the 95th percentile among the entire US population (4.16 ng/mL).[15] Given that Wilmington residents include pregnant people and children, contamination of drinking water by industrial facilities is an important route of PFAS exposure among these populations.

Level 4: Technology

Factor 1 – PFAS exposure and firefighting foam

PFAS exposure among pregnant people and children occurs through exposure to firefighting foam,[13] which is the foam used in fire extinguishers and some fire truck hoses. Because PFAS is an ingredient of firefighting foam, its use in training exercises or putting out fires can result in PFAS-contamination of groundwater.[13] When PFAS enters groundwater from firefighting foam, the public drinking water supply can become contaminated.[16] For example, firefighting foam used at the Barnes Air National Guard Base in Westfield, Massachusetts resulted in PFAS contamination of municipal drinking water.[16] Community members of Hampden County who drank this water had PFAS blood levels that were four times greater than the national average.[16] Because pregnant people and children are among the community members who drink this water, firefighting foam-derived PFAS exposure is an important factor of PFAS-related health effects among this group.

Factor 2 – PFAS exposure and reverse osmosis

Reverse osmosis is an effective method of removing PFAS in water, thereby reducing PFAS exposure to pregnant people and children.[17] Among two water reuse plants in California that used reverse osmosis to decontaminate water, post-treated water had PFAS levels below method reporting limits.[17] Importantly, reverse osmosis was determined to be the most effective method overall and for short-chain PFAS, which are otherwise most difficult to remove from water.[17] Given the effectiveness of reverse osmosis in identifying and remove PFAS from water, employment of this method in the US reduces PFAS exposure among pregnant people and children, thereby resulting in reduced health effects among these groups.[17]

Level 5: Law, policy, institutions, and systems

Factor 1 – PFAS exposure and EPA regulation of drinking water

Given profuse PFAS presence in America, it is difficult to enact PFAS regulation among all the different sources of exposure, but the newly proposed Safe Drinking Water Act reduces PFAS exposure among pregnant people and children via drinking water.[18] This Safe Drinking Water Act proposed in 2021, includes a National Primary Drinking Water Regulation and Maximum Contaminant Level Goals which together address six different types of PFAS: perfluorooctanoic acid (PFOA), perfluorooctane sulfonic acid (PFOS), perfluorohexane sulfonic acid PFHxS), hexafluoropropylene oxide dimer acid (HFPO-DA) and its ammonium salt (GenX), perfluorononanoic acid (PFNA), and perfluorobutane sulfonic acid (PFBS).[18] Through these regulations, the concentration of PFOA and PFOS will be limited to 0 in water that is delivered to a public water system.[18] For the PFHxS, HFPO-DA, GenX, PFNA, and PFBS substances, a Hazard Index is proposed to provide guidance on acceptable concentrations in drinking water.[18] Furthermore, in addition to specific recommendations for all six of these PFAS compounds, the Environmental Protection Agency also proposes the monitoring of these PFAS in drinking water to ensure that these regulations are enforced.[18] Because pregnant people and children drink the water that this act is regulating, the Safe Drinking Water Act reduces PFAS exposure among these populations.[18]

Factor 2 – PFAS and lack of EPA regulation of non-drinking water

Unfortunately, the US Safe Drinking Water Act's regulation of PFAS only applies to drinking water sources, resulting in a lack of regulatory oversight for non-drinking water sources such that pregnant people and children remain exposed to PFAS.[18] Because this regulation only applies to drinking water sources, there is a lack of PFAS oversight in other sources of water, such as groundwater and wastewater.[19] As a consequence, pregnant people and children continue to be exposed to PFAS through non-drinking water sources, resulting in continued poor health effects among these groups.

Level 8: Planetary health

Factor 1 – PFAS exposure and garden produce

Given PFAS emission from polluters in America, there is elevated PFAS concentrations in groundwater, resulting in PFAS exposure among pregnant people and children via garden produce.[20] Because PFAS is found in groundwater and this groundwater is used to water gardens among households, PFAS then contaminates garden produce.[20] Especially given that 31% of households have gardens in the US,[21] pregnant people and children eat this PFAS-contaminated produce, resulting in PFAS exposure.[20] For instance, in 2010, the Minnesota Department of Health discovered that perfluorobutanoic acid, a type of PFAS, was found at ten times higher concentration in garden produce than in groundwater, highlighting the amplifying effect that PFAS-contaminated groundwater has on human exposure.[20] This effect is highest among young children because their ratio of home-grown foods to body weight is highest, resulting in a PFAS exposure dose among this age group of 2.74e-5 mg/kg/day,[20] providing evidence of PFAS exposure among children, though this exposure occurs in pregnant people to since all groups of people eat produce.

Factor 2 – PFAS exposure and fish

Because PFAS is emitted into bodies of water in the US by polluters, PFAS exposure among pregnant people and children occurs from consumption of fish that lived in these polluted bodies of water.[22] From 2013 to 2015, the US's EPA monitoring program, National Rivers and Streams Assessment, and Great

Lakes Human Health Fish Filet Tissue Study analyzed fish filet samples from American freshwater bodies of water.[22] It was discovered that PFAS levels in freshwater fish was 278 times higher than US Food and Drug Administration tested fish.[22] When people consume these freshwater fish, PFAS blood concentration levels are elevated, as a fish that has been determined to have median PFOS levels results in a PFAS blood concentration increase by 0.92 ng/mL if consumed only once.[22] If this fish was consumed weekly, the PFAS blood concentration increase was calculated to be 47.96 ng/mL.[22] Because pregnant people and children eat freshwater fish, this is a route of exposure among these groups, contributing to PFAS-related health issues.

Intervention

1. What did this course teach you about choice and circumstance as it relates to health and distribution of poor health? (3-5 sentences) This course has given me a better understanding of how a person's ability to choose is limited by the circumstances they experience. In other words, a person's behavior or decisions cannot be fully explained by their decisions made alone, and as future public health practitioners, we must address the context in which people make decisions when considering a person or population's decision. For example, when evaluating how to reduce tobacco-related health morbidities, it is important to recognize that people may not necessarily have the uninfluenced agency to choose whether or not to participate in tobacco use. Simplifying this health issue down to whether or not people choose to use tobacco fails to recognize the impact that culture (e.g. using tobacco in cultural or religious ceremonies), interpersonal influences (e.g. living in a community where tobacco use is normalized), or social stability (e.g. tobacco use as a coping mechanism for chronic stress) may have. Therefore, to adequately address tobacco use and related morbidities, these other influences on behavior *must* be evaluated as well because these influences better explain the agency one has in whether or not to engage in tobacco use.

2. How do you think your growing awareness of the drivers of health might impact you in your professional life? Be as specific as possible. (2-4 sentences) My growing awareness of the drivers of health will impact my professional life by giving me an interdisciplinary focus on the intersections of health. Through this course, we have learned that numerous factors influence health, from a person's neighborhood to the products they use, and the behaviors their peers engage in. Given that I hope to design and implement public health interventions in the future, I foresee myself using multi-level interventions that adequately address these interdisciplinary influences. For example, if I were to design an intervention for mental health, in addition to determining the degree of access to mental health resources, I would also consider the community's cultural norms, environmental conditions, and the types of technology used by community members.

3. Based on what you know now, describe **how you would intervene** to address this issue **to achieve the greatest impact?** (2-3 sentences per point)

(a) What would the intervention be? Given the profuse levels of PFAS in the US among pregnant people and children, interpersonal influences and individual factors do not play a significant role in PFAS exposure so interventions to mitigate PFAS exposure ought to focus on more "upstream" factors. Therefore, I propose a policy that prioritizes the enforcement of PFAS testing in manufacturing and industrial settings such that these facilities are held accountable for widespread PFAS exposure among pregnant and child populations. This policy would include harsh penalties that may require the shutting down of facilities with persistent PFAS presence and the designation of PFAS auditors in these companies to ensure that large companies are held equally as accountable as smaller companies.

(b) Describe the levels of the BSE the interventions would take place and the rationale. This intervention would largely fall under the "institutions, systems law and policy" level of the BSE because this upstream factor can create nationwide change by applying requirements to general sets of institutions. In other words, if manufacturing plants of a certain type are major contributors to PFAS exposure among pregnant people and children, federal law could impose requirements across all manufacturers of this type in the US. This intervention would also require the "technology" level of the BSE because it is likely that the regulation of PFAS necessitated via this proposed policy would require a specialized technology that can precisely detect PFAS.

(c) What would success look like? The success of this policy would be envisioned as a future where there are fewer accidental major exposures of PFAS among entire communities of pregnant people and children, and when these major exposures occur, there is accountability held on those who are responsible for the exposure by imposing restitution of an environment free of significant PFAS concentrations. In other words, polluters responsible for PFAS-emission must be required to aid with community clean-up by providing financial and environmental reparations to community members. Through this policy, success will also be measured by the newfound attention that major manufacturers have on PFAS safety via the hiring of consultants to ensure PFAS-safe processes and the provision of a new federally employed group responsible for auditing organizations for safe PFAS practices.

(d) How long do you think it would take to see an impact? Given that this policy aims to impose harsher restrictions on corporations that are responsible for PFAS emissions and deploy a federal team that serves to champion safe PFAS practices in these industrial settings, I would imagine that the five years following policy implementation would result in a decrease in incidences of major PFAS exposures among communities with pregnant people and children. However, to see a decrease in overall PFAS concentrations would require multiple decades given the environmental persistence of these chemicals.

4. Describe **how feasible** this proposal is in your setting. (1-2 sentences for each response)

(a) Cost: Given their large profit margins, large industrial facilities would be able to cover the costs of the implementation of PFAS-safe practices. However, smaller industrial facilities would likely be unable to pay for the expenses required to implement PFAS-safe practices and would require grants or loans from the federal government to subsidize the cost of this implementation.

(b) Likelihood of impact in five years: In five years following the implementation of the policy and the grace period for companies to change their methods before policy enforcement, it would be reasonable to anticipate a decrease in the number of major community exposure events among pregnant people and children by large corporations. However, given the environmental persistence of PFAS, this policy will likely not influence the overall concentration of PFAS in the environment in five years.

(c) Political will: Industry is a hugely influential sector in politics because industry results in employment opportunities and large financial accumulations. Those in power may not support this intervention because it would require the prioritization of environmental health over a lucrative sector, and prioritizing environmental health does not have an immediate profit margin, despite environmental improvements reducing health-related expenditure long term.

(d) Public support: Public support will likely vary depending on the values people have. Those who do not favor federal oversight on business, possible reduction of employment opportunities through shutting down of some industrial facilities, and reduction in immediate economic returns may not support this intervention. Those who favor federal oversight on business and environmental and climate-related causes, for example, would support this intervention.

(e) Capacity to implement: Presently, there is still a lot of research to be done to understand what processes result in PFAS exposure and there is still a need to develop widely financially accessible methods to detect PFAS. Therefore, technology limits this policy's feasibility. A policy like this may not be feasible until there is a stronger understanding of the sources of PFAS exposure and cheaper and more precise technology is developed to detect PFAS, but these impairments to feasibility should not discredit the strong need to make technological advances such that a policy like this is feasible soon.

5. What was your biggest take home from this course about multilevel influences on health? (2-5 sentences) In previous courses, we have often talked about the need to address "upstream" factors when considering health issues. In the context of the BSE, these "upstream" factors are usually referring to the higher levels (i.e., climate change, culture, political instability). Through this course, I have built a stronger appreciation for the need to address both "upstream" and "downstream" factors to have a more holistic view of health. Therefore, my biggest takeaway is that although addressing "upstream" factors is

important, these factors should not be the only factors alone when designing public health interventions. Instead, a multi-level approach is the most comprehensive in evaluating not only who is disproportionately impacted by certain health issues, but also why they exist and in what forms they exist.

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