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RESEARCH ARTICLE

PFAS soil concentrations surrounding a hazardous waste incinerator in East Liverpool, Ohio, an environmental justice community

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Abstract

Per- and polyfluoroalkyl substances (PFAS) are a class of synthetic compounds widely used in industrial and consumer products. While PFAS provide product durability, these chemicals are ubiquitous, persistent, bioaccumulative, and toxic. These characteristics make the ultimate disposal of PFAS a challenge. One current disposal method is incineration; however, little research has been conducted on the safety and effectiveness of PFAS incineration. The characteristics of communities with hazardous waste incinerators that have received PFAS shipments indicate that more individuals with lower incomes and individuals with less education than the US average are at higher risk of exposure, which presents important environmental justice and health equity concerns of PFAS incineration. Situated in eastern Ohio, East Liverpool is an Appalachian community that is home to a large hazardous-waste incinerator, operated by Heritage WTI, that began accepting PFAS in 2019. Residents are concerned that the disposal lacks the research necessary to assure safety for the residents. Due to both community interest and data gaps regarding PFAS incineration, our research team conducted a pilot study to examine the distribution and concentration of PFAS in soil samples surrounding the incinerator. All 35 soil samples had measurable amounts of PFAS including perfluorobutanesulfonic acid (PFBS), perfluorooctanesulfonic acid (PFOS), perfluorooctanoic acid (PFOA), and hexafluoropropylene oxide dimer acid (HFPO-DA)/GenX. PFOS was measured in the majority of soil samples (97%) with a range of 50–8,300 ng/kg. PFOA was measured in 94% of soil samples with a range of 51 ng/kg to 1300 ng/kg. HFPO-DA/GenX was measurable in 12 soil samples with concentrations of ranging from 150 ng/kg to 1500 ng/kg. Further research on PFAS disposal will advance knowledge and action related to regulatory requirements and exposure prevention, ultimately improving individual and community protections and health equity.

Keywords PFAS · PFAS incineration · Environmental justice · AFFF

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Introduction

Often referred to as "forever chemicals," per- and polyfluoroalkyl substances (PFAS) are a class of synthetic compounds that have recently become recognized as a global health threat (Environmental Protection Agency 2021f). Since the 1940s, PFAS have been widely used in industrial and consumer products. Due to water, oil, and heat-resistant characteristics, potential PFAS exposure stems from a wide range of products such as non-stick cookware, stain-resistant fabrics, waterproof materials, food packaging, and aqueous film forming foam (AFFF) or firefighting foam. There are thousands of PFAS compounds in use such as perfluorooctanoic acid (PFOA), perfluorooctanesulfonic acid (PFOS), and hexafluoropropylene oxide-dimer acid (HFPO-DA or the tradename, GenX). While PFAS provides product durability,

these man-made chemicals are persistent, bioaccumulative, and toxic (Goodrow et al. 2020).

PFAS molecules are composed of carbon–fluorine bonds, which are very short and strong, making PFAS highly resistant to degradation (Lindstrom et al. 2011). Due to a long history of use and persistence, PFAS is found in waterways, soil, groundwater, dust, animals, and humans. Based on current scientific research, humans are exposed largely through the ingestion of PFAS-containing food and water. PFAS drinking water contamination is particularly prevalent in communities surrounding military bases where AFFF was used (Anderko & Pennea 2020). A study from the Centers for Disease Control and Prevention (CDC) found that 97 percent of the United States (US) population had detectable levels of PFAS in their blood (Lewis et al. 2015); however, safe exposure levels are widely debated. Bioaccumulation has been linked with a vast array of health effects such as those involving fertility (Ding et al. 2020; Tarapore & Ouyang 2021), fetal growth (Xiao et al. 2020), metabolic outcomes (Shih et al. 2021), lipids, and thyroid disease (Jain & Ducatman 2019; Melzer et al. 2010).

Increasing regulatory attention has led to several PFAS, namely, PFOA and PFOS, being phased out of production in the US. However, the proper disposal of these legacy substances is hotly debated due to the volatility, persistence, and ubiquitous nature of PFAS. In 2018, the Department of Defense (DoD) awarded contracts to nine facilities to dispose of AFFF through incineration in states including Arkansas, Illinois, New York, Nebraska, Ohio, and Texas (Crunden 2020). To our knowledge, very little peer-reviewed research has been conducted on the efficacy of PFAS incineration. The United States Environmental Protection Agency (EPA) note that few experiments have been conducted that represent field-scale incineration and its effectiveness to destroy PFAS compounds; additionally, the formation of byproducts is not well understood (Environmental Protection Agency 2020). In addition to these questions, the DoD has acknowledged that limited air emission data exists (Sullivan 2019). Both the US EPA and DoD are currently investigating optimal PFAS disposal methods (Environmental Protection Agency 2021f).

With both the effectiveness and safety of PFAS incineration in question, communities with incinerators receiving these compounds are at risk. Demographic characteristics of communities with hazardous waste incinerators that regularly receive PFAS shipments (Environmental Protection Agency 2021d) indicate that potential exposures resulting from incineration may affect individuals residing in communities with lower incomes and less education than the US average (Table 1). In addition to existing health disparities arising from these socioeconomic social determinants of health (P. Braveman et al. 2011), these communities face additional vulnerability related to the unknown hazards associated with PFAS incineration. Specifically, Appalachian communities often are environmentally exploited, which increases the potential for contaminant exposures contributing to health disparities (Haynes et al. 2010; Kozlowski & Perkins 2016). Situated in eastern Ohio (OH), East Liverpool is an Appalachian community that is home to a large hazardous-waste incinerator, which began accepting PFAS in 2019. Local residents are concerned that insufficient scientific evidence about PFAS disposal exists to assure community safety (Environmental Protection Agency 2021b; Ujhelyi 2020). In order to address the community's concern and research data gaps regarding PFAS incineration, our research team conducted a pilot study to examine the distribution and concentration of PFAS in soil and surface water surrounding the hazardous waste incinerator in East Liverpool, OH.

Methods

Soil sampling

A certified industrial hygienist (CIH) and a field technician traveled to East Liverpool, OH, to conduct environmental surface soil sampling for analysis of 28 PFAS at locations surrounding the Heritage WTI waste incinerator facility. A professional geologist offered guidance in the preparation and execution of the sampling. The first round of soil sampling occurred on January 30, 2021. A second round of soil sampling occurred on December 29, 2021. Surface soil sample locations were identified in partnership with input from local residents, academic, and the technician. Surface soil samples were obtained at locations adjacent to and further from the Heritage Thermal Services waste incinerator facility located in East Liverpool, OH. Soil sampling locations were chosen in the field by the field technicians based on accessible and vacant public lands with the majority of samples collected within a two-mile radius of the facility. In addition, Google Maps was utilized in the field to identify potential sampling locations. To avoid potential PFAS cross-contamination associated with sampling in relation to the site, areas further from the site were sampled prior to locations closer to the site. The upwind direction was based on the predominant southwest to northeast wind that historically traverses the facility. Actual wind direction observed during the day of the sampling was not considered during the environmental sampling activities.

In total, 35 surface soil samples were collected in the lands surrounding the facility, 15 were collected in January 2021, and 20 were collected in December 2021. The 15 soil samples collected in January 2021 were comprised five samples obtained in East Liverpool, OH, eight samples obtained in Chester, West Virginia, one sample obtained in Ohioville,

Table 1 Demographics of communities with hazardous waste incinerators regularly receiving PFAS for incineration in 2019–2021

	El Dorado, Arkansas	Cottage Grove, Minnesota	Kimball, Nebraska	East Liverpool, Ohio	Grafton, Ohio	Port Arthur, Texas	La Porte, Texas	Grantsville, Utah	United States
Incinerator	Clean Harbors El Dorado LLC	3 M Company	Clean Harbors Environmental Services Inc	Heritage Thermal Services Inc	Ross Incineration Services	Veolia ES Technical Solutions	Cleans Harbors Deer Park, LLC	Clean Harbors Aragonite LLC	
Demographic characteristics									
Total population	17,756	38,839	3,434	9,958	5,895	56,039	35,124	12,064	331,449,281
Population under 18 years	26.0%	28.1%	21.1%	24.9%	6.7%	27.1%	22.4%	38.8%	22.3%
Race and Hispanic origin									
White alone, percent	48.6%	84.0%	93.4%	86.8%	65.4%	50.0%	83.8%	92.8%	76.3%
Black or African American alone	47.5%	5.0%	0.4%	4.1%	27.9%	38.2%	6.2%	0.5%	13.4%
American Indian and Alaska Native alone	0.5%	0.3%	2.3%	0.0%	1.3%	0.6%	0.4%	0.6%	1.3%
Asian alone	1.0%	6.9%	1.0%	0.5%	0.2%	7.3%	1.2%	1.8%	5.9%
Native Hawaiian and Other Pacific Islander, alone	0.0%	0.2%	0.1%	0.1%	0.0%	0.1%	0.0%	1.4%	0.2%
Two or more races	1.2%	2.9%	2.9%	6.2%	4.1%	1.6%	4.1%	2.4%	2.8%
Hispanic or Latino	5.7%	4.5%	9.3%	3.0%	4.5%	34.5%	34.8%	6.3%	18.5%
White alone, not Hispanic or Latino	43.5%	80.9%	85.4%	86.5%	63.3%	18.7%	55.3%	88.4%	60.1%
Education									
High school degree or higher	81.6%	95.9%	88.7%	83.9%	82.7%	73.4%	87.7%	93.0%	88.0%
Bachelor's degree or higher	23.5%	36.3%	16.1%	9.4%	9.8%	11.7%	15.9%	27.0%	32.1%
Health									
% with a disability, under the age 65; 2015–2019	11.2%	5.6%	8.3%	17.8%	10.8%	9.7%	11.2%	7.5%	8.6%
Persons without health insurance, under age 65	10.8%	2.4%	12.3%	8.9%	6.4%	32.9%	15.7%	6.4%	10.2%
Income									
Median household income	$42,595	$102,039	$53,403	$32,119	$61,042	$36,557	$75,262	$72,378	$62, 843
% below the poverty line	23.7%	2.3%	15.7%	27.9%	7.8%	27.2%	9.9%	5.3%	11.4%
Number of PFAS shipments received from 2019–2021 (Environmental Protection Agency, 2021)	172 shipments	225 shipments	51 shipments	271 shipments	30 shipments	109 shipments	50 shipments	49 shipments	

"Regularly receiving PFAS" shipments is defined as receiving more than 25 shipments (Environmental Protection Agency, 2021). All data were obtained and reported exactly as it was from the US Census Bureau 2020 (Bureau, 2021). The authors did not redefine the terms, rather the same terms are used as the original source data

Pennsylvania, and one sample obtained in Georgetown, Pennsylvania. On the day of sampling in January 2021, the temperature ranged from 8 to 30 degrees Fahrenheit, the relative humidity was 56–80%, and the observed wind speed/direction was 3 to 10 miles per hour Southeast. The 20 soil samples collected in December 2021 included eight samples obtained in East Liverpool, Ohio, five samples obtained in Chester, West Virginia, three samples from Ohioville, Pennsylvania, one sample was collected in Glasgow, Pennsylvania, and two samples were obtained in Georgetown, Pennsylvania. Additionally, one equipment blank was collected in the field. On the day of sampling in December 2021, the temperature ranged from 40 to 50 degrees Fahrenheit, the relative humidity was 80–90%, and the observed wind speed/direction was 0 to 10 miles per hour Southwest.

The onsite field technician obtained environmental soil samples in accordance with current US EPA methods/protocols for sampling PFAS in surface soil. Samples were shipped to the analytical laboratory (ALS Environmental, Holland, MI) on ice (convenience store ice bagged in 1-gallon Ziploc® bags) in coolers provided by the analytical laboratory. The soil samples were analyzed by a liquid chromatography mass spectrometry mass spectrometry (LC tandem MS, LC–MS/MS) compliant with Table B-15 of U.S. DoD's Q Quality Systems Manual (QSM) 5.3.

We used QGIS version 3.16 to create a map of the study region using cartographic boundary files and other spatial data from the U.S. Census (Bureau 2021). On Fig. 1, we plotted the locations of the soil sampling sites and used pie charts to visualize the relative concentrations of all quantifiable PFAS chemicals in the soil at each site.

Water sampling

On January 30, 2021 and February 03, 2021, nineteen surface water samples were collected in the Ohio River, as well as creeks and streams surrounding the facility. The nineteen samples comprised nine samples obtained in East Liverpool, Ohio, eight samples obtained in Chester, West Virginia, one sample obtained in Ohioville, Pennsylvania, and one sample obtained in Georgetown, Pennsylvania. One field blank was collected on January 30, 2021.

Surface water samples were obtained utilizing three 200 ml (ml) high-density polyethylene (HDPE) containers provided by the analytical laboratory. The HDPE containers did not have a preservative. The field technician obtained surface water samples from the shoreline of the Ohio River, creeks, and streams, occasionally wading into the waterway to obtain moving water. Efforts were made to sample at the middle of the water column, as well as sampling downstream locations prior to sampling upstream. The field technician opened each individual 200 ml sampling container underwater and capped the sample underwater after the container filled. The three containers were then labeled, bagged, and placed in the sampling cooler over ice in preparation for shipment to the analytical laboratory. Field blanks for surface water samples were obtained in the field by pouring PFAS-free DI water provided by the analytical laboratory into three 200 ml HDPE blank containers. The blanks were capped and processed as described above. The surface water samples were analyzed by a liquid chromatography mass spectrometry mass spectrometry (LCMSMS) compliant with Table B-15 of U.S. DoD's Q Quality Systems Manual (QSM) 5.3.

We used QGIS version 3.16 to create a map (Supplemental Fig. 1) of the study region using cartographic boundary files and other spatial data from the U.S. Census (Bureau 2021). On the map, we plotted the locations of the surface water sampling sites and used pie charts to visualize the relative concentrations of all quantifiable PFAS chemicals in the water at each site.

Results and discussion

Soil concentrations of PFOS and PFOA

All 35 soil samples had measurable amounts of PFAS (Table 2); however, due to the study design, we cannot directly link the observed PFAS levels in our study to the hazardous waste incinerator. Concentrations of PFOS and PFOA were quantifiable in the majority (97% and 94%, respectively) of the soil samples. As depicted in Fig. 1, Table 2, and Supplemental Table 1, the quantifiable PFOS concentrations were higher than PFOA. The average concentration of PFOS was 1225 ng/kg with a range of 50–8,300 ng/kg. Site C had the highest PFOS concentration (8,300 ng/kg). Interestingly, site C is located over one kilometer upwind of the incinerator. This location is located in a residential area along the Ohio River with no known source of PFAS. A recent pilot study of water and soil samples completed by faculty and students at Bennington College in Vermont described a similar trend with PFOS soil concentrations being higher than PFOA levels in sampling sites surrounding a plant incinerating AFFF (Bond and Enck 2020). The study found a maximum PFOS concentration of 1.2 ng/g in soil located adjacent (250 m) to the plant (Bond and Enck 2020). In our study, we detected even higher PFOS concentrations at 7 of our sampling locations, sites C, H, and J1. Interestingly, each of these sites is upwind of the incinerator making it unlikely to have stemmed from the incinerator. At site H, which is located closest to the incinerator, we detected a PFOS concentration approximately 7 times higher than the maximum observed in New York. A review study investigating global background concentrations of

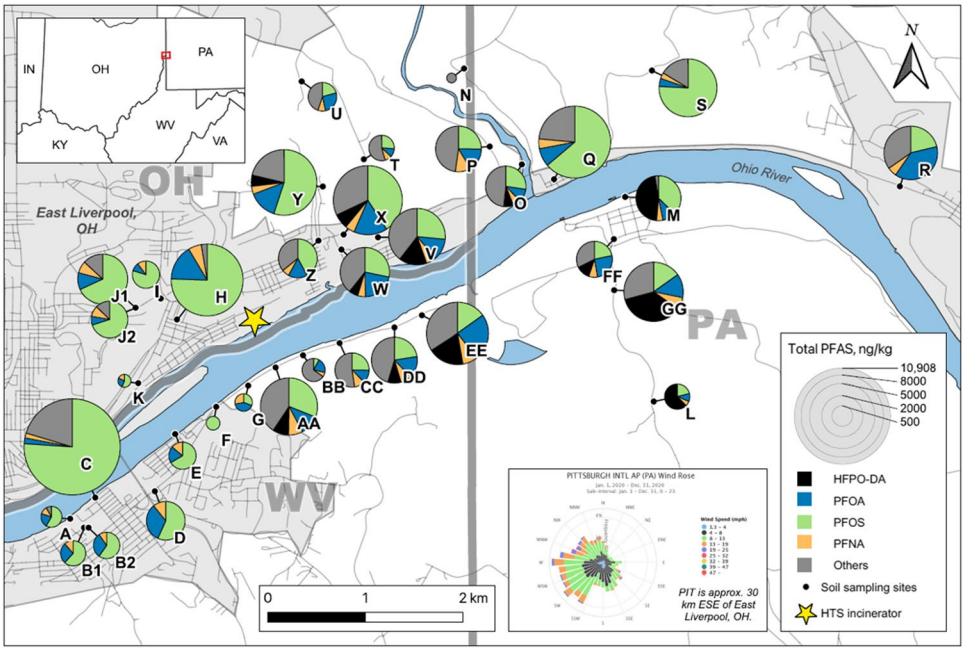

Fig. 1 Map of PFAS concentrations at soil sampling sites in East Liverpool, Ohio

PFOA and PFOS observed median maximum concentrations of 2,700 ng/kg for both PFOS and PFOA among the included studies (Brusseau et al. 2020). The PFOS and PFOA levels detected in our study are within the range detected in several studies investigating PFOS soil deposition near PFAS releasing sources (Conservation 2021; Zhu et al. 2019); however, our mean PFOS level of 1,225 ng/kg was greater than the hypothesized background PFOS level of approximately 610 ng/kg in a study near an industrial source in the northeastern US (Schroeder et al. 2021). We cannot link the observed PFOS and PFOA levels in our study to the hazardous waste incinerator. It is possible that there are other sources of PFAS in the area that have not been reported, similar to the observations made in nearby Wooster, OH (Pike et al. 2021).

The US EPA has listed both PFOS and PFOA as emerging contaminants of concern (Environmental Protection Agency 2017) and in 2016 established a chronic reference dose (RfD) for PFOA of 0.00002 mg/kg-day and a chronic RfD for PFOS of 0.00002 mg/kg-day. These RfDs are currently under reevaluation with the US EPA and may be updated in the future (Environmental Protection Agency 2021c). Due to the documented human health effects associated with PFOA and PFOS exposure, the bioaccumulation of the chemicals, and environmental persistence, these long-chain PFAS have been phased out of production in the United States; however, industry has shifted to producing short-chain PFAS as replacements with limited data to support safety. Additionally, despite the fact that PFOS and PFOA are being phased out of production in the US, these substances are ubiquitous in the environment, making safe and effective disposal a challenge.

Soil levels of replacement PFAS including GenX

In East Liverpool, OH, we detected quantifiable perfluorobutanesulfonic acid (PFBS) levels in 12 of our soil samples. In 2002, the production of PFOS was phased out and replaced by PFBS due to its shorter carbon chain length and, thus, subsequent shorter half-life in human serum (approximately 44 days vs. approximately 1,200 days) (Li et al. 2018; Xu et al. 2020). In addition to PFBS-containing products, PFBS may also be a byproduct of the degradation of longer-chain PFAS. Notably, previous research suggests that PFBS does not readily adsorb to soil; therefore, concentrations are more likely to be detected in water (Norwegian Geotechnical Institute 2018). While there is limited health data on PFBS, animal studies suggest that PFBS is associated with adverse fetal, reproductive, renal, hepatic, and endocrine health outcomes (Bogdan 2019; Environmental Protection Agency 2018). Questions surrounding the carcinogenicity of PFBS remain. Although the current literature suggests that PFBS is less toxic than PFOA and PFOS, the US EPA has established a RfD of 0.0003 mg/kg-day for PFBS based on oral exposure (Environmental Protection Agency 2021e).

Quantifiable levels of HFPO-DA (GenX) were detected in 12 of the sampling locations (range: 150 ng/kg and 1100 ng/kg). The majority of the soil samples with quantifiable GenX concentrations were to the east of the incinerator. According to the US EPA's Toxic Release Inventory (TRI), no facilities located near these sampling locations

Table 2 PFAS concentrations in soil (ng/kg) near the WTI incinerator

PFAS		Perfluorooctanesulfonic acid (PFOS)	Perfluorooctanoic acid (PFOA)	Perfluorobutanesulfonic acid (PFBS)	Hexafluoropropylene oxide dimer acid (HFPO-DA or GenX)	Perfluorononanoic acid (PFNA)	N-Methylperfluorooctane-sulfonamidoacetic acid	Perfluorodecanesulfonic acid (PFDS)	Perfluorodecanoic acid (PFDA)	Perfluorododecanoic acid (PFDoA)
Collected January 30, 2021	Site A	**300**	**110**	**43**	<210	**60**	<210	<43	<210	<210
	Site B1	**460**	**200**	<48	<240	**85**	<240	<48	<240	<240
	Site B2	**490**	**250**	<49	<250	**79**	<250	<49	<250	<250
	Site C	**8,300**	**210**	**39**	<180	**180**	**230**	<35	**620**	**240**
	Site D	**1,000**	**570**	<38	<190	**190**	<190	<38	<190	<190
	Site E	**580**	**170**	<37	<180	**120**	<180	<37	ND	<180
	Site F	**220**	<41	<41	<210	<41	<210	<41	<210	<210
	Site G	**110**	**150**	<45	<220	**100**	<220	<220	<220	<220
	Site H	**4,600**	**970**	<31	<150	**360**	<150	<31	**160**	<150
	Site I	**700**	**86**	<52	<260	**91**	<260	<52	<260	<260
	Site J1	**2,000**	**320**	<55	<280	**230**	<280	**65**	**320**	<280
	Site J2	**1,100**	**120**	<35	<170	**150**	<170	<35	**200**	<170
	Site K	**110**	**51**	<32	<160	**35**	<160	<32	<160	<160
	Site L	**160**	**76**	<33	**470**	**48**	<170	<33	<170	<170
	Site M	**890**	**230**	<59	**1,100**	**110**	<300	**60**	<300	<300
Collected December 29, 2021	Site N	<12	<14	<20	<120	<15	<37	<16	<23	<32
	Site O	**530**	**200**	**41**	**150**	**120**	<44	**21**	**71**	<38
	Site P	**620**	**400**	<27	<160	**270**	<49	<21	**190**	<42
	Site Q	**3900**	**500**	**55**	<150	**270**	<47	<20	**240**	**86**
	Site R	**720**	**1300**	**46**	<160	**190**	<50	<21	**62**	<43
	Site S	**3000**	**180**	**36**	<180	**130**	<55	<23	**65**	<47
	Site T	**200**	**82**	<26	<160	**67**	<48	<20	**63**	<41
	Site U	**200**	**250**	<28	<170	**82**	<51	<22	**56**	<44
	Site V	**1000**	**460**	**41**	**600**	**220**	<52	<22	**290**	**88**
	Site W	**810**	**610**	**33**	**170**	**150**	<47	<20	**82**	<40
	Site X	**2300**	**880**	**39**	**390**	**250**	<46	<20	**240**	**63**
	Site Y	**2800**	**720**	**39**	**280**	**200**	<45	<19	**160**	**61**
	Site Z	**750**	**280**	<22	<130	**110**	<40	**65**	**96**	**41**
	Site AA	**1200**	**430**	<28	**350**	**310**	<51	<22	**230**	**87**
	Site BB	**50**	**130**	<24	<140	**39**	<44	<19	**37**	<38
	Site CC	**350**	**170**	<24	<150	**140**	<44	<19	**140**	**42**
	Site DD	**560**	**380**	**27**	**230**	**190**	<40	<17	**130**	**76**
	Site EE	**690**	**1100**	**46**	**850**	**360**	<51	<22	**190**	**46**
	Site FF	**330**	**390**	<23	**190**	**120**	<42	<18	**47**	<36
	Site GG	**630**	**540**	<25	**1500**	**270**	<45	<19	**200**	**60**

Table 2 (continued)

PFAS		Perfluorononanesulfonic acid (PFNS)	Perfluorooctanesulfonamide (PFOSA)	Perfluoropentanoic acid (PFPeA)	Perfluoroundecanoic acid (PFUnA)	Perfluorobutanoic acid (PFBA)	Perfluorohexanoic acid (PFHXA)	Perfluoroheptanoic acid (PFHPA)	Perfluorotridecanoic acid (PFTRIA)	Total PFAS (ng/kg)
Collected January 30, 2021	Site A	<210	<43	<210	<210	<210	<210	<210	<210	513
	Site B1	<240	<48	<240	<240	<240	<240	<240	<240	745
	Site B2	<250	<49	<250	<250	<250	<250	<250	<250	819
	Site C	**620**	**69**	**220**	**180**	<180	<180	<180	<180	10,908
	Site D	<190	<38	<190	<190	<190	<190	<190	<190	1760
	Site E	<180	<37	<180	<180	<180	<180	<180	<180	870
	Site F	<210	<41	<210	<210	<210	<210	<210	<210	220
	Site G	<220	<45	<220	<220	<220	<220	<220	<220	360
	Site H	<150	<31	<150	<150	<150	<150	<150	<150	6090
	Site I	<260	<52	<260	<260	<260	<260	<260	<260	877
	Site J1	<280	<55	<280	<280	<280	<280	<280	<280	2935
	Site J2	<170	<35	<170	<170	<170	<170	<170	<170	1570
	Site K	<160	<32	<160	<160	<160	<160	<160	<160	196
	Site L	<170	<33	<170	<170	<170	<170	<170	<170	754
	Site M	<300	<59	<300	<300	<300	<300	<300	<300	2390
Collected December 29, 2021	Site N	<26	<10	<20	<26	**61**	**49**	<20	<34	110
	Site O	<31	**13**	**81**	**98**	**370**	**94**	**110**	<41	1899
	Site P	<34	<13	**78**	**210**	**460**	**120**	**120**	<45	2468
	Site Q	<33	**28**	**130**	**120**	**330**	**200**	**190**	**<44**	6049
	Site R	<35	<14	**150**	**74**	**470**	**190**	**140**	**<46**	3342
	Site S	<39	**35**	**36**	**110**	**210**	**87**	**56**	**<51**	3945
	Site T	<34	<13	**31**	**43**	**140**	**71**	**44**	<44	741
	Site U	<36	**16**	**29**	**69**	**130**	**83**	**49**	<47	964
	Site V	<37	**28**	**92**	**200**	**370**	**130**	**180**	56	3755
	Site W	<33	<13	**160**	**200**	**430**	**170**	**160**	<43	2975
	Site X	<33	<13	**230**	**140**	**580**	**290**	**220**	<43	5622
	Site Y	<32	**35**	**110**	**91**	**250**	**150**	**100**	**45**	5041
	Site Z	<28	**12**	**31**	**67**	**120**	**110**	**60**	**<37**	1742
	Site AA	<36	<14	**120**	**240**	**490**	**110**	**160**	**64**	3791
	Site BB	<31	<12	**43**	**46**	**170**	**64**	**51**	<41	630
	Site CC	<31	**12**	**74**	**110**	**210**	**81**	**54**	<41	1383
	Site DD	<28	**12**	**76**	**140**	**330**	**100**	**96**	58	2405
	Site EE	<36	<14	**120**	**140**	**590**	**190**	**230**	<48	4552
	Site FF	<30	**12**	**43**	**58**	**170**	**100**	**62**	<39	1522
	Site GG	<32	<12	**130**	**160**	**340**	**160**	**160**	<42	4150

*Quantification limits varied. Values in bold refer to values greater than the detection limit. *Perfluorotetradecanoic acid, perfluoropentanesulfonic acid, perfluoroheptanesulfonic acid, fluorotelomer sulphonic acid 4:2, fluorotelomer sulphonic acid 8:2, N-ethylperfluorooctanesulfonamidoacetic acid, and 4,8-dioxa-3H-perfluorononanoic acid were not detected in any soil samples

(Beaver County, Pennsylvania; Columbiana County, Ohio; and Hancock County, West Virginia) have reported GenX releases due to the self- report nature and recent addition of PFAS to the TRI (EPA Toxic Release Inventory 2021). GenX was developed to be a safer alternative to replace the longer-chain PFOA. GenX can be generated as a byproduct of manufacturing processes. The concentrations observed in East Liverpool, OH, are similar to the 2018 GenX levels (1.00 ng/g and 1.20 ng/g) measured in soil near Veto Lake in Washington County, OH, located approximately 8 km from a fluorochemical facility (Galloway et al. 2020). However, it is important to note that the emissions near Veto Lake were attributed to the use of GenX in the manufacturing process. While data on human exposure to GenX is lacking, animal studies have linked GenX exposure with adverse health outcomes similar to those observed with PFOA and PFOS exposure such as gestational (Blake Bevin et al. 2020), developmental (Conley et al. 2021), gut microbiota (Xie et al. 2021), hepatic, renal, hematologic, and immune health effects (Environmental Protection Agency 2018, 2021c). In 2021, the US EPA established a subchronic (0.00003 mg/kg-day) and chronic (0.000003 mg/kg-day) RfD for GenX chemicals (Environmental Protection Agency 2021c). The RfD for GenX is lower than the RfDs established in 2016 for PFOS and PFOS. Markedly, the chronic RfD for GenX is 100 times lower than the established RfD for PFBS (Environmental Protection Agency 2021c). Interestingly, GenX is not known to be a component of AFFF. GenX is produced by Chemours in Fayetteville, NC. We are unable to determine the source of GenX at the sampling sites; it is possible that aside from AFFF, other sources of PFAS are being incinerated at Heritage WTI. Additionally, there may be other GenX sources such as waste disposal sites or other PFAS-releasing industrial sites; however, our research team has been unable to identify other potential PFAS sources (EPA Toxic Release Inventory 2021).

Concentrations of "other quanitifiable PFAS"

Perfluorononanoic acid (PFNA) was quantifiable in 33 of the 35 soil samples collected in our study. Additional PFAS compounds were quantifiable in our soil sampling and are indicated by the gray shading in Fig. 1. Perfluorodecanoic acid (PFDA) was detected in 23 of the 35 sampling sites. Perfluorodecanesulfonic acid (PFDS) was quantifiable at 4 samplings sites. Detectable concentrations of n-methylperfluorooctanesulfonamidoacetic acid (NMeFOSAA), perfluorododecanoic acid (PFDoA), perfluorononanesulfonic acid (PFNS), perfluorooctanesulfonamide (PFOSA), perfluoropentanoic acid (PFPeA), and perfluoroundecanoic acid (PFUnA) were observed in several locations.

The epidemiologic literature regarding these PFAS is limited. A cross-sectional study using National Health and Nutrition Examination Survey (NHANES) data described an association between PFNA serum concentrations and cholesterol levels (Nelson et al. 2010). Moreover, animal studies suggest a relationship between PFNA and immune response (Fang et al. 2008). The US EPA is in the process of conducting human health toxicity assessments for PFNA and PFDA (Environmental Protection Agency 2019). NMeFOSAA, PFDoA, PFNS, PFOSA, PFPeA, PFUnA, and PFDS are currently included on the US EPA's working list of PFAS chemicals with research interest (Environmental Protection Agency 2019, 2021e). Over 4,700 PFAS currently exist, with this number growing as industry generates new substances (National Institute of Environmental Health Sciences), creating a burdensome challenge for epidemiologic research.

Surface water concentrations of PFAS

In our study, we collected surface water samples in addition to soil samples. The majority of the surface water samples had quantifiable levels of PFOS and PFOA (Supplemental Table 2 and Supplemental Fig. 1). Quantifiable PFOS concentrations ranged from 4.5 ng/L to 19 ng/L, and quantifiable PFOA concentrations ranged from 2.1 ng/L to 11 ng/L. We also detected quantifiable levels of PFHxS at site W-5 at a concentration of 8.8 ng/L. No other PFAS were detected in the surface water samples. Overall, the PFOS concentrations were higher than the PFOA concentrations. Previous research examining surface waters near US Air Force Installations with histories of AFFF use suggests that PFOS is the most critical PFAS related to AFFF (East et al. 2021). The PFOS levels in our study are similar to those observed in a recent study investigating PFAS in surface water collected from the Truckee River near Reno, Nevada (range: not detectable to 17.4 ng/L) (Bai & Son 2021). Notably, in our study, we more readily detected quantifiable levels of PFAS in soil than in surface water samples. This finding aligns with previous research that has demonstrated that PFAS are more prominent in soil when compared to other media such as surface water (Abunada et al. 2020).

Challenges with PFAS incineration

Properties such as high thermal stability and persistence that make PFAS ideal for use also make PFAS disposal an extremely complex issue. An investigation into three Chinese municipal solid waste incineration plants found low concentrations of PFAS present in fly ash and bottom ash and higher levels in the leachates (Liu et al. 2021). Interestingly, short chain PFAS comprised the majority of the PFAS

in the leachate. This study concluded that while incineration destroyed the majority of the PFAS, incomplete incineration resulted in the production of byproducts. Among the incinerators, PFAS concentrations were correlated with site-specific conditions such as the type of incinerator, temperature, and time. A study in Sweden found that ash from municipality incineration facilities contained PFAS and may be a source of environmental pollution (Wohlin 2020). While we detected PFAS concentrations near a hazardous waste incinerator, our study did not directly evaluate the safety and effectiveness of PFAS incineration. More research is needed to address the concerns surrounding PFAS incineration including the formation of products of incomplete combustion, incineration ash containing PFAS, and the emission of air pollutants such as greenhouse gasses (Environmental Protection Agency 2020; Stoiber et al. 2020).

Hazardous waste incineration and environmental justice

Poverty rates are greater than the US average for half of the communities with hazardous waste incinerators receiving PFAS for incineration (Table 1). Three of which have poverty rates more than two times greater than the national average. Seven of the eight communities have populations with a lower educational attainment (< Bachelor's degree) than the US estimate. 62 percent of the communities have a higher disability rate compared to the US. The populations of all of the included communities are 50 percent or more White, and three (37.5%) of the communities have populations between 30 and 50 percent Black, Indigenous, and people of color (BIPOC).

In Cohoes, New York, a designated environmental justice area by the New York State Department of Environmental Conservation, the Norlite Hazardous Waste Incinerator is located within 400 feet from public housing (Bennington College 2021). Due to unknown risks and vocal public concern, the city of Cohoes banned the incineration of AFFF in 2020 (Times Union 2020). Several months later, the state of New York followed suit, citing environmental health concerns (Times Union 2020). Due to this success, the Norlite Incinerator has received few shipments of PFAS; therefore, the city is not included in Table 1. Other communities have expressed similar concerns surrounding potential PFAS contamination stemming from incineration (Flaherty 2020). While these facilities have received PFAS shipments intended for incineration (Environmental Protection Agency 2021d), the amount that has been incinerated at each site is unknown.

East Liverpool residents have raised concern about the environmental health risks associated with the hazardous waste incinerator since its inception in 1982, as well as expressing concerns about a local warehouse facility that emits air pollutants, primarily manganese (Haynes et al. 2018). The poverty rate in East Liverpool, OH, is more than 2 times that of the US (27.9% vs. 11.4%) and the local median income level is nearly half of the US estimate ($32,119 vs. $62,843). It has been well-established that poverty is associated with health inequities such as increased risk of chronic disease (Braveman et al. 2010) and reduced life-expectancy (Chetty et al. 2016). In East Liverpool, approximately 2,500 children are under the age of 18 years. Two schools are located within two kilometers of the incinerator, and many houses are located even closer. Children are especially vulnerable to environmental insults (Landrigan et al. 2004), and PFAS exposure has been associated with pediatric asthma, early puberty onset, neurodevelopmental effects, decreased vaccine response, and cardiometabolic outcomes (Rappazzo et al. 2017). In a nearby community in Appalachian Ohio, the introduction of unconventional natural gas development, an industry with similar uncertain environmental health impacts, has been linked with heightened psychological and social stress among the residents (Fisher et al. 2018). It is important to examine how the compounding effects of environmental and socioeconomic inequities in communities such as East Liverpool contribute to heightened health and psychosocial impacts.

PFAS legislation

The US House of Representatives passed the PFAS Action Act of 2021, a comprehensive initiative aimed at limiting the use of PFAS and remediating contamination. This legislation would require the US EPA to designate PFOA and PFOS chemicals as "hazardous substances" under CERCLA or the Superfund law within one year of enactment of the legislation (PFAS Action Act of 2021 (H.R. 2467)). Within five years of enactment of the legislation, the agency would have to determine whether to designate all other PFAS chemicals as hazardous substances. The US EPA would be required to determine if PFAS are toxic pollutants under the Clean Water Act and/or considered hazardous air pollutants. Additionally, the Agency would regulate the disposal of all products containing PFAS. Further, in October 2021, the US EPA proposed plans to add PFOA, PFOS, PFBS, and GenX as hazardous waste under the Resource and Conservation and Recovery Act (Environmental Protection Agency 2021a). Thus, research is needed to determine the efficacy of burning PFAS and the extent to which communities are at risk of exposure to unburned PFAS or other chemicals resulting from the incineration or partial incineration process.

Limitations

While quantifiable levels of PFAS were detected in every soil sample in our pilot study, we are unable to pinpoint

the direct source of contamination. In 2020, the US EPA Toxics Release Inventory was updated to include the reporting of 172 PFAS (Gillespie 2020); thus, industrial sources of PFAS releases will be more apparent in the future. Therefore, it is possible that the PFAS concentrations quanitified in our study may be attributed to other pollution sources such as wastewater discharges or other industrial sites. Additionally, we were unable to collect soil samples before the incinerator began accepting AFFF; therefore, we do not have comparison samples.. Future research is critical to investigate timely research questions related to PFAS distribution in the environment as a result of attempted incineration.

Conclusions

In summary, all soil samples in our study had measurable amounts of PFAS, including PFBS, PFNA, PFOS, PFOA, and GenX. The concentrations of PFOS were the highest in our soil samples. It is noteworthy that GenX was found in nearly half of our soil samples. More research is necessary to determine the source of the GenX. Critical and timely research on the disposal of PFAS could contribute to informed policy determinations about its safety. Specifically, the US EPA has stated the need to evaluate the effectiveness of PFAS disposal (Gillespie 2020). Importantly, if PFAS are determined to be hazardous in the PFAS Action Act of 2021, further research on disposal safety could increase knowledge about potential risks and inform the evolution of regulatory requirements, ultimately expanding opportunities to protect vulnerable individuals and communities from PFAS exposure.

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