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Discussion

Estimated scale of costs to remove PFAS from the environment at current emission rates

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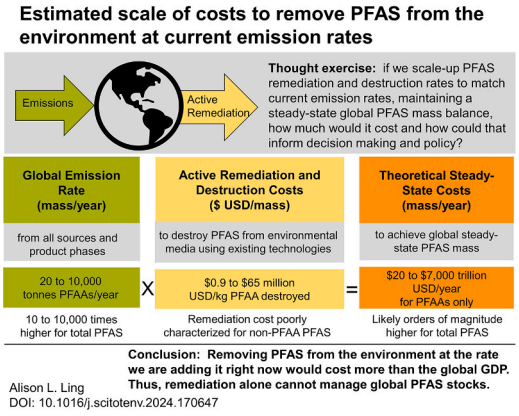
HIGHLIGHTS

- PFAS remain and cycle in the natural environment until actively destroyed
- Managing environmental stocks of PFAS through treatment alone is unaffordable
- Reduced PFAS emissions is needed to avoid increasing environmental accumulation
- PFAS use restrictions should regulate PFAS as a class and consider "essential uses"

GRAPHICAL ABSTRACT



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ABSTRACT

This discussion article builds upon existing data to ask whether environmental remediation and treatment is an economically viable solution to manage global environmental stocks of per- and polyfluoroalkyl substances (PFAS) without extensive use restrictions. Their environmental persistence means that PFAS released into the environment will remain there until actively removed and destroyed. Thus, removing and destroying PFAS from the global environment at the same rate they are currently being added reflects a theoretical steady-state condition where global PFAS stocks remain constant. Current costs to remove perfluoroalkyl acids (PFAAs), a subclass of PFAS, from the environment at the same rate they are being added were estimated here at 20 to 7000 trillion USD per year. If the ratio of total PFAS emissions to PFAAs emissions matches current production ratios, total PFAS release rates and associated treatment costs could be 10 to 10,000 higher than presented above for PFAAs only. Thus, current costs to remove and destroy the total PFAS mass released annually into the environment would likely exceed the global GDP of 106 trillion USD. While this level of treatment is not technically or economically achievable, it highlights the unaffordability of using environmental remediation alone to manage environmental PFAS stocks. Without significant reductions in production and emissions, the mass of PFAS present in the global environment will continue to rise. Treating targeted environmental media will be needed to manage human and environmental health impacts, but we are limited to the level of treatment that is practical and affordable.

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1. Introduction

1.1. Knowledge status: PFAS occurrence, toxicity, and regulations

PFAS are a broad class of over 10,000 chemicals used in manufacturing processes and consumer products, across many industries, including electronics, automotive, textiles, pulp and paper, metal finishing, and personal care products (Brunn et al., 2023; ECHA, 2023). The definition used by the European Chemicals Agency (ECHA) states that PFAS contain "at least one fully fluorinated methyl or methylene carbon atom" without a halogen attached to it, and excludes certain fully degradable subgroups (ECHA, 2023). The PFAS most frequently studied and targeted by regulations are perfluoroalkyl acids (PFAAs), including legacy compounds perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS). As PFAS attract increasing regulatory and public attention, industries have pivoted to replace these legacy PFAS with alternate "replacement" chemicals. Many of these replacements are also PFAS despite the fact that uses in many consumer products have PFAS-free alternatives (Glüge et al., 2022). Environmental fate and health impacts of newer, replacement PFAS are less understood, complicating efforts to characterize the risks and remediation options for PFAS in active use (Ruan et al., 2022; Wang et al., 2017).

PFAS are globally ubiquitous in the environment and continue to be discharged and disseminated via global transport of products and wastes, atmospheric dispersion, surface water transport, and groundwater flow (D'Ambro et al., 2021; Kurwadkar et al., 2022; Stoiber et al., 2020b). They have been reported in soil, water, and air samples across the world (Abunada et al., 2020; Cousins et al., 2022; Rauert et al., 2018; Valsecchi et al., 2013; Xu et al., 2021), and in human blood serum (DeLuca et al., 2021; Sunderland et al., 2019). The environmental fate of PFAS is complicated by transformations that can convert "precursor" PFAS into other PFAS. For example, some fluorinated gases and side-chain fluorinated polymers have been shown to degrade to PFAAs, such as highly persistent and mobile trifluoroacetic acid (TFA) (Brunn et al., 2023; Freeling and Björnsdotter, 2023; OECD, 2022; Sun et al., 2020). So even if PFAAs are not produced commercially in the future, they can still be produced in the environment via degradation of other PFAS, including through environmental photolysis and oxidation (Armitage et al., 2006; Martin et al., 2006; Thackray and Selin, 2017), biological processes (Kolanczyk et al., 2023; Liu and Mejia Avendaño, 2013), and wastewater treatment (Houtz et al., 2016; Thompson et al., 2022).

The ubiquity and increasing environmental stocks of PFAS raise concerns due to reported toxicity impacts to wildlife and humans (Brunn et al., 2023; Espartero et al., 2022; Jones et al., 2022; Sunderland et al., 2019). A recent National Academies review found sufficient evidence for decreased antibody response to vaccines, dyslipidemia (including increased cholesterol), decreased birthweight, and increased risk of kidney cancer (National Academies of Sciences, Engineering, and Medicine, 2022). Household use of PFAS-containing products can expose humans to PFAS through skin exposure or inhalation of household dust and volatilized PFAS in indoor spaces (DeLuca et al., 2021; Kissel et al., 2023; Sunderland et al., 2019). PFAS in groundwater and surface waters can also impact human health through drinking water supplies and agricultural uptake (Andrews and Naidenko, 2020; Stoiber et al., 2020a; Wang et al., 2020).

Regulations regarding PFAS are rapidly evolving. Drinking water in the U.S. is currently subjected to health guidance values in 30 U.S. states (ITRC, 2023), with proposed Federal maximum contaminant limits (MCLs) for specific compounds (U.S. EPA, 2023b). PFOA and PFOS could soon be classified as a hazardous substance in the United States (U.S. EPA, 2022), which would impact production and remediation costs. In addition to these environmental regulations, regulations restricting PFAS production and use are being implemented in the EU and the United States (ECHA, 2023; Minnesota PFAS Ban, 2023; Vermont Legislature, 2021). PFOA, PFOS, and perfluorohexane sulfonic acid (PFHxS) are specifically addressed by the Stockholm Convention on Persistent Organic Pollutants, targeting international use limitations (OECD, 2023).

European PFAS regulations are generally based on chemical characteristics rather than specific compounds (ECHA, 2023; European Drinking Water Directive, 2020). has Specific U.S. states have also passed PFAS use restrictions addressing PFAS as a group rather than on a chemical-by-chemical basis (California Safer Food Packaging and Cookware Act, 2021; Maine Legislature, 2021; Minnesota PFAS Ban, 2023; Vermont Legislature, 2021). However, Federal regulations in the United States have largely focused on individual PFAS such as PFOA and PFOS rather than defining and restricting PFAS as a group (U.S. EPA, 2021, 2022; U.S. EPA, 2023b). Regulations addressing PFAS as a class rather than as individual compounds accommodates the potential for environmental transformation of precursors to other PFAS, despite analytical constraints (Kwiatkowski et al., 2020).

1.2. The problem with persistence

The same chemistry that makes PFAS useful – the thermodynamic strength and short length of carbon-fluorine bonds – also makes them difficult to degrade. Very few PFAS in use today readily degrade to non-fluorinated end products by any known environmental process (ITRC, 2022b). Thus, persistent PFAS entering soils, groundwater, surface water, and the atmosphere remain in the environment until actively removed and destroyed. Our society has previously attempted remediation of persistent and toxic contaminants in the environment, including polychlorinated biphenyl (PCBs) and chlorinated pesticides. However, PFAS, especially emerging short-chain compounds, can be both more persistent and more mobile than these legacy contaminants (Hale et al., 2020), enabling ongoing dispersion and cycling in environmental air and water resources with ongoing risk of human exposure.

Recent work argues that environmental persistence alone should be sufficient justification to regulate production of a chemical, because stocks of persistent chemicals added to the environment consistently increase, with increasing potential for known and unknown human health risks (Cousins et al., 2020; Cousins et al., 2019b). These risks are exacerbated by the very high societal cost of removing persistent chemicals from the environment once released (Barr Engineering Co., and Hazen and Sawyer, 2023; Brunn et al., 2023; U.S. Chamber of Commerce, 2022), by degradation of precursor PFAS into other PFAS, and by unknown health effects of replacement PFAS and PFAS mixtures (De Silva et al., 2021). Despite the challenges with environmental persistence, PFAS are still being produced and integrated into consumer products in "non-essential uses," exacerbating the problem for future generations (Glüge et al., 2022; Ritscher et al., 2018). "Essential use" reflects chemical use that is "necessary for health, safety or is critical to the functioning of society" with "no available technically and economically feasible alternatives," while "non-essential uses" are primarily market driven (Cousins et al., 2019a).

The problem of persistence also means that active treatment to remove and destroy PFAS from the environment is difficult and expensive. An U.S. EPA-sponsored, 2022 study evaluated the efficacy and readiness of non-combustion-based technologies to mineralize PFAS associated with spent granular activated carbon (GAC) and anion exchange (AIX) media, soils, wastewater biosolids, aqueous film forming foams (AFFF), and landfill leachate. This study found limited technological readiness other than high-temperature incineration, except potentially for applying supercritical water oxidation (SCWO) for AFFF destruction and pyrolysis for biosolids treatment (Berg et al., 2022). However, high-temperature incineration is expensive and primarily available at hazardous waste incinerators. The U.S. EPA reported typical costs for hazardous waste incineration at 1110 to 1610 USD per tonne of PFAS-containing liquids, sludges, and solids (U.S. EPA, 2020), orders of magnitude higher than the 55 USD per tonne national average for municipal solid waste tipping fees (Environmental Research and

Education Foundation, 2023).

1.3. Mass balance on global PFAS stocks

Environmental accumulation of PFAS is best understood by considering a mass balance of PFAS stocks in the global environment. The primary sources of PFAS to the environment include production-phase emissions from PFAS production and product manufacturing facilities and use-phase emissions either released to the ambient environment near the point of use or routed through waste management facilities that receive PFAS from industrial, commercial, and municipal sources (Armitage et al., 2006; ECHA, 2023; Ehsan et al., 2023; Evich et al., 2022; Schellenberger et al., 2022; Thompson et al., 2022) (Fig. 1). The ubiquity of PFAS in consumer products, associated diffuse nature of use-phase emissions, and environment mobility all contribute to the ubiquity of PFAS in environmental media worldwide. A mass balance showing current PFAS emission sources and destruction routes is illustrated in Fig. 1.

Current destruction of PFAS from environmental sources in the U.S. is limited to <15 hazardous waste incineration and GAC reactivation facilities, accepting a total of <3 million tonnes of mixed material per year (U.S. EPA, 2019). If that total capacity was dedicated to PFAS-containing wastes, the PFAS content of that waste matched PFAS-laden GAC reported at 10 to 55,000 ng/g (DiStefano et al., 2022), and capacity is scaled to the entire world based on gross domestic product (GDP), then current global PFAS destruction from environmental sources would fall between 0.15 and 820 t/year. In contrast, global PFAS emissions likely exceed 100,000 tons per year (ECHA, 2023; Evich et al., 2022). Thus, the mass rate of PFAS currently entering the environment vastly exceeds the mass rate being removed and destroyed.

A steady-state condition with constant mass of PFAS in the global environment could theoretically be achieved by either increasing the amount of PFAS removed from the environment via active environmental remediation and destruction, reducing input sources of PFAS to the environment via PFAS use restrictions, or both. This paper presents a thought experiment evaluating costs to reach steady-state conditions by increasing environmental remediation and destruction to match current PFAS emission rates, acknowledging that those treatment rates are not actually feasible. This steady-state reference point could inform relative prioritization of environmental remediation and use restriction to manage PFAS in the global environment.

This simplified, theoretical model does not consider the varying turnaround time of different environmental stocks, instead taking a holistic, long-term view of the global environment, where PFAS in medium-term and long-term environmental sinks can be recycled back into other stocks. Medium-term sinks include open ocean water, landfills, and sediment burial, while long-term sinks include deep ocean burial and deep-well injection. A steady-state mass of PFAS in the global environment would not reflect steady-state conditions in all environmental stocks, as medium- and long-term sinks may take on more PFAS mass while media with shorter turnaround times and more potential for human exposure like the atmosphere and freshwaters may see reduced PFAS mass during global steady-state conditions.

1.4. Why we need to better understand remediation costs

The goal of this study is to contribute to discussion of long-term economic costs and benefits of PFAS use restrictions and environmental regulations. Societal costs will be incurred regardless of the future balance between 1) ongoing PFAS accumulation due to limited action, 2) reduced emissions through PFAS use and emission restrictions, and 3) increased treatment through environmental regulations. The future balance between these actions will dictate the balance of negative effects, including 1) increasing human and environmental impacts from compounding environmental PFAS stocks, 2) economic impacts of use restrictions, and 3) remediation costs and associated

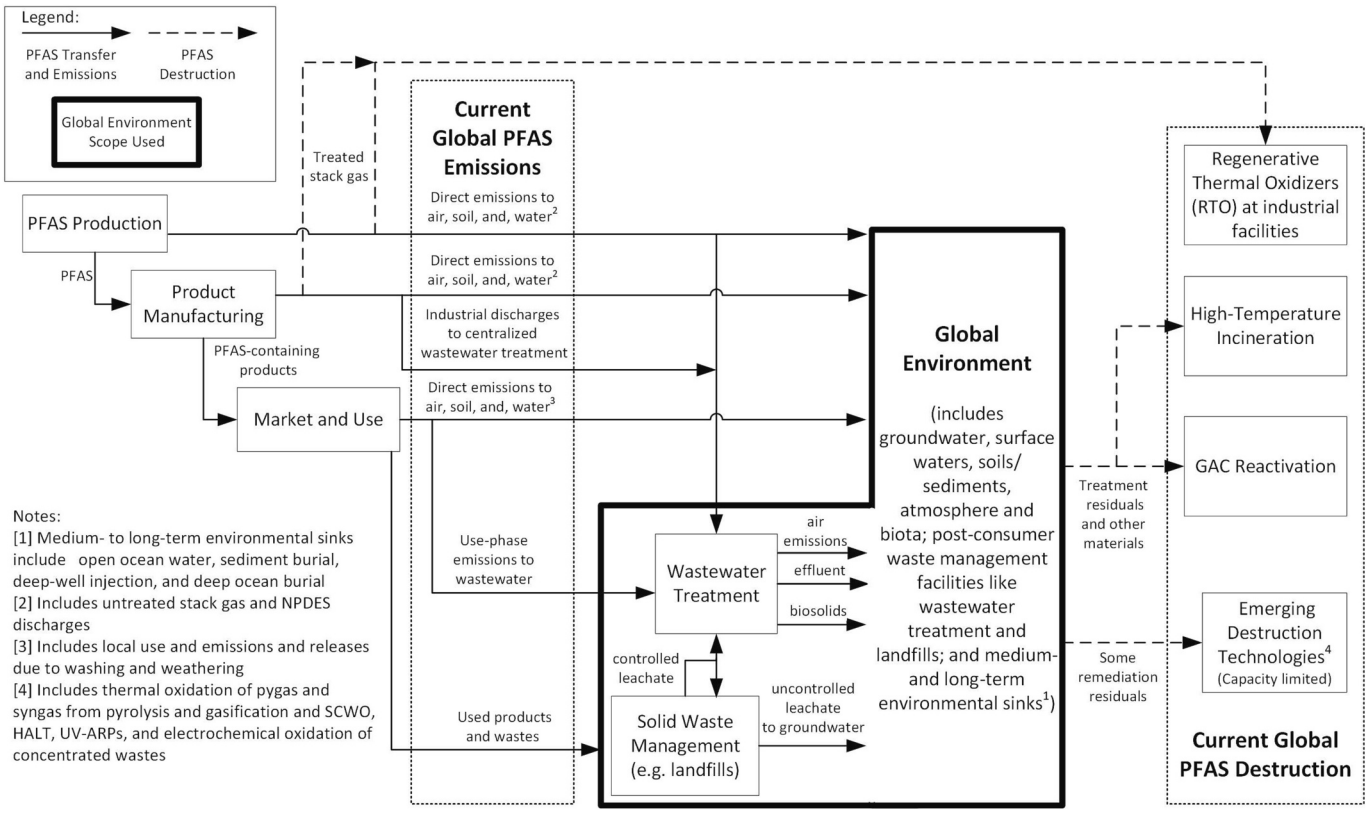

Fig. 1. Simple mass balance on PFAS in the global environment, including boundaries used in this study for the global environment, current emissions, and current destruction.

externalities. Understanding the relative and ultimate costs of all three options can support development and prioritization of regulatory actions regarding PFAS.

The estimated annual health burden of current PFAS exposures were recently estimated at tens of billions of USD both in the United States and in the European Economic Area (Goldenman et al., 2019; Obsekov et al., 2023). These reflect a portion of societal costs associated with current environmental PFAS stocks and would be expected to increase as global PFAS stocks increase. Likewise, economic impacts of PFAS use restrictions are also starting to be characterized, with the European Chemical Agency estimating qualitative and quantitative cost impacts of recently proposed use restrictions (ECHA, 2023).

However, reported cost estimates for removing and destroying PFAS from environmental media remain limited, especially at scales relevant to the global mass balance. The environmental media most widely treated for PFAS at full-scale is drinking water, where GAC, AIX, or reverse osmosis (RO) have been applied to separate PFAS from the water phase (AWWA, 2019). Reported removal efficiencies are primarily for PFAAs. As a result, full-scale cost estimates for separating PFAS from media other than drinking water or for separating non-PFAA PFASs from any media are not widely available. Furthermore, full-scale PFAS destruction remains limited to high-temperature thermal technologies with high costs (U.S. EPA, 2020), limited capacity (U.S. EPA, 2019), greenhouse gas emissions, and uncertain regulatory status (PFAS, 2022; NY Senate, 2020; US Department of Defense, 2023).

The demonstrated human health impacts of PFAS will require environmental remediation in targeted applications to protect human health. However, resources available to address environmental PFAS are limited. For example, the Bipartisan Infrastructure Law in the U.S. set aside $9 billion USD over five years to treat PFAS in drinking water (The White House, 2023), but meeting proposed drinking water regulations was recently estimated at $55 billion USD and $24 billion USD by separate studies (Black and Veatch, 2023; U.S. EPA, 2023a). Funding sources to remediate landfills, wastewater effluent and biosolids, and contaminated soils and sediments are more uncertain, especially for facilities without an identified, liable polluter. Improved understanding of how much it costs to remove and destroy PFAS from the environment could help inform discussion of potential costs to implement regulatory criteria for drinking water, wastewater, and other media as well as potential societal cost savings from PFAS use restrictions.

This discussion article addresses that need by considering approximate cost estimates to remove PFAS from the environment as fast as they are being added. For the conceptual framework, order-of-magnitude estimates were developed for technology costs per mass PFAS destroyed and current global emission rates of PFAS mass per year, which were then multiplied together for an estimated annual cost to achieve theoretical steady-state conditions.

2. Costs to remove and destroy PFAAs from environmental media

2.1. Scope and assumptions

The majority of PFAS removal projects with published treatment costs target long-chain PFAAs, such as PFOS and PFOA. These are also among the easiest PFAS to remove from the water phase due to their relative hydrophobicity (Neuwald et al., 2022; Westreich et al., 2018). Some PFAS, such as TFA and fluorinated gasses, do not have clear technologies available to reliably remove and destroy them from environmental media (Hale et al., 2022; Sheldon and Crimmin, 2022) and thus do not have established cost estimates for environmental remediation. As a result, this order-of-magnitude cost analysis focused on PFAAs specifically, due to limited technology options, demonstrated projects, and associated cost estimates available for remediation and destruction of other PFAS.

Because this discussion focuses on a global mass balance, treatment costs per mass of PFAS removed and destroyed are more relevant than costs per volume of media treated. This analysis considered published cost estimates that included both PFAS destruction costs and sufficient metadata to estimate mass of PFAA removed. Required metadata for use in this analysis included media type(s) treated, media treatment rates, technology design and arrangement, PFAS concentrations, and cost estimate inclusions. Technologies that transfer, separate, or encapsulate PFAS without destroying them were not considered, except as preconcentration steps for PFAS destruction processes. While sequestration options like landfill leachate recycling, in situ sequestration, deep well injection, and deep ocean burial have the potential to be environmental PFAS sinks, mass flows have not been quantified and are likely small in scale relative to total emissions. One study estimated loss to deep ocean waters – a prerequisite for deep ocean burial – at about 0.1 to 10 % of total estimated emissions of perfluorocarboxylic acids (PFCAs), a subset of PFAAs (Prevedouros et al., 2006), which is a low enough percentage to not affect this order-of-magnitude estimate.

The costs to remove and destroy PFAS from environmental media depend on targeted media and technologies used. However, this current analysis is limited to environmental media where treatment applications have been implemented or envisioned in enough detail to accurately estimate costs and PFAS destruction rates at large scales. Removing and destroying PFAS from environmental soils and sediments is complicated by a lack of demonstrated in situ destruction methods and the high costs of excavation (Mahinroosta and Senevirathna, 2020). Numerous studies report soil remediation costs for sites contaminated with PFAS (Drenning et al., 2023; Quinnan et al., 2022; U.S. Chamber of Commerce, 2022), but they either do not include PFAS destruction costs or do not report data to inform the mass of PFAS removed. Similarly, environmental remediation of atmospheric PFAS has not been widely tested or evaluated and is not practical due to low atmospheric PFAS concentrations (1–100 pg/m^3) (Rauert et al., 2018). While PFAS accumulate in and transfer through biota, including plants and animals (Houde et al., 2008; Zhu et al., 2022), removing PFAS mass from the environment should not target biomass, because destroying biomass to destroy bioaccumulated PFAS will negatively impact ecosystems and their services. In addition, the mass of biota in the environment is negligible compared to the mass of other environmental media. Costs to remove and destroy PFAS from environmental soils, sediments, atmosphere, or biota remain either poorly characterized or impractical, and are thus not included in this analysis.

Costs per mass of PFAAs removed and destroyed were estimated based on recent studies reporting costs, focusing on projects that included PFAA destruction at a scale relevant to the global mass balance (here assumed to be 4000 m^3/day for liquid treatment and 10 dry tonnes per day for solid treatment). The realm of available large-scale cost estimates addresses drinking water, landfill leachate, and wastewater effluent using GAC, AIX, or foam fractionation to separate PFAS for destruction by high-temperature incineration or GAC reactivation. One cost estimate to destroy PFAS from wastewater biosolids using pyrolysis or gasification with thermal oxidation was also available and included. While post-consumer waste management discharges like landfill leachate and wastewater effluent and biosolids are not typically considered environmental media, they are included in the "global environment" box for this analysis because they are downstream of production and use phases (Fig. 1). Because both contain higher concentrations of PFAS than typical environmental surface and groundwaters, less volume needs to be treated to destroy a given mass of PFAS. Thus, costs to remove and destroy a given mass of PFAS from landfill leachate, wastewater effluent, and wastewater biosolids are conservatively low relative to environmental media with lower PFAS concentrations.

Costs estimated in this analysis are intended to reflect present value, life-cycle project costs for PFAS remediation projects over a 20-year service life, including equipment costs, direct costs, indirect costs, and operation and maintenance (O&M) costs. Reported annual O&M costs

were adjusted to present value and added to reported capital costs using Eq. 1. In this calculation, n reflects a 20-year life-span of initial equipment investment, and r reflects an annual discount rate of 7.0 %, an intermediate value between 20-year nominal interest rates of 4.2 % (Office of Management and Budget, 2023b) and the current prime interest rate of 8.5 %. Costs estimated here were not intended to be exhaustive of available data. Instead, they reflect a conceptual range for current environmental remediation technologies across multiple media. Differences in costs within one to two orders-of-magnitude are not expected to change the conclusions presented here.

$$20-year\ Present\ Value\ Cost = Capital\ Cost + \sum_{i=0}^{n} \frac{Annual\ O\&M\ Cost}{(1+r)^i} \quad (1)$$

2.2. Remediation cost estimates for PFAAs

Estimated 20-year costs were recently developed for drinking water systems in the United States to comply with proposed drinking water standards of 4 parts per trillion (ppt) for PFOA and PFOS (Black and Veatch, 2023) using GAC adsorption with high-temperature incineration of spent media. Assuming an average PFAA concentration of 21.4 ng/L from a separate study of typical drinking water concentrations (Boone et al., 2019), mass-normalized costs for these applications ranged from 16 to 65 million USD per kg PFAA removed and destroyed, depending on facility size (Table 1). A separate case study for a water treatment plant built in 2006 reported project costs and PFAA treatment rates supporting an inflation-adjusted cost of 67 million USD per kg PFAA (ITRC, 2022a). Other drinking water case studies from completed or planned projects report costs as low at 0.2 million USD per kg of PFAA but do not specifically include costs for final residuals disposal that included PFAS destruction, so costs per mass PFAS removed and destroyed could not be estimated for use here (Barton, 2019; Cordner et al., 2021; U.S. EPA, 2023a). On the waste management side, two studies included estimated costs for PFAA removed and destroyed from treated wastewater effluent, wastewater biosolids, or landfill leachate. When combined with study metadata, costs for these theoretical projects spanned 0.9 to 41 million USD per kg of PFAA over a 20-year operating period (Barr Engineering Co., and Hazen and Sawyer, 2023; Malovanyy et al., 2023). Thus, order-of-magnitude cost estimates per kg PFAS removed and destroyed from environmental media ranged from 0.9 to 67 million USD, as detailed in Table 1.

The cost per mass of PFAA destroyed estimated here varied with project scale, target media, technologies used, PFAAs measured, PFAA concentration, and costs of upstream pretreatment technologies. Project scale was a major driver of cost variation with a 100-fold increase in treatment rate reducing costs per mass PFAS removed and destroyed by a factor of 7 to 35 for WRRF effluent and landfill leachate. Variations in treatability among PFAAs also contributes uncertainty to the estimated costs per mass PFAA removed, as compounds with reported removal varied by study. The cost per mass of short-chain PFAA destroyed is higher than the cost per mass of long-chain PFAA destroyed due to their higher mobility and associated treatment complexities (Barr Engineering Co., and Hazen and Sawyer, 2023; Malovanyy et al., 2023).

The liquid-phase treatment costs used in this analysis were based on available case studies, many of which targeted very low PFAA concentrations (<10 ng/L) (Barr Engineering Co., and Hazen and Sawyer, 2023; Black and Veatch, 2023). While treating to these low targets is not needed for the goal of reducing global PFAA stocks, the GAC adsorption and ion exchange processes used in those projects achieve low treatment targets until media breakthrough occurs (Boyer et al., 2021; Franke et al., 2019; Westreich et al., 2018). Thus, actual costs per mass PFAA destroyed for these technologies depended primarily on influent concentration and media changeout frequency, with limited influence from treatment targets.

Table 1
Estimated costs per mass targeted PFAAs removed and destroyed from environmental media.

Media treated	Flow rate[a]	Technologies used	PFAA concentrations removed and destroyed	Estimated 20-year costs (USD)[b]	Estimated costs (USD)/kg PFAA	Reference and cost type
Drinking water	3.6 MGD	GAC, destruction not stated	5.4 ng/L (sum of 7 PFAAs)	$7.0M[c]	$67M	Constructed costs (ITRC, 2022a)
	0.16 MGD	Multiple locations, Varied technology, includes media incineration	21.4 ng/L (sum of 17 PFAAs)	$6.2M[d]	$65M	Estimated costs averaged across 858 systems (Black and Veatch, 2023), using median PFAS concentrations in drinking water sources (Boone et al., 2019)
	5.6 MGD	Multiple locations, Varied technology, includes media incineration	21.4 ng/L (sum of 17 PFAAs)	$49M[d]	$16M	Estimated costs averaged across 64 systems (Black and Veatch, 2023), using median PFAS concentrations in drinking water sources (Boone et al., 2019)
Waste-water effluent	0.1 MGD	MBR pretreatment[e], GAC, incineration	110 ng/L (sum of 7 PFAAs)	$13M	$41M	Estimated costs for theoretical facility (Barr Engineering Co., and Hazen and Sawyer, 2023)
	10 MGD	MBR pretreatment, GAC, incineration	110 ng/L (sum of 7 PFAAs)	$190M	$6M	
Landfill leachate	1 gpm	MBR pretreatment, GAC, incineration	4,700 ng/L (sum of 7 PFAAs)	$4.6M	$35M	
	100 gpm	MBR pretreatment, GAC, incineration	4,700 ng/L (sum of 7 PFAAs)	$12M	$0.9M	
	66 gpm	GAC, incineration	794 ng/L (sum of 10 PFAAs)	$4.6M[f]	$3.5M	Costs estimated for theoretical facility (Malovanyy et al., 2023)
	66 gpm	AIX, incineration	794 ng/L (sum of 10 PFAAs)	$2.3M[f]	$1.7M	
Waste-water biosolids	10 dtpd	Pyrolysis and thermal oxidation	550 ng/g (sum of 7 PFAAs)	$94M	$2.6M	Costs estimated for theoretical facility (Barr Engineering Co., and Hazen and Sawyer, 2023)

[a] MGD = million gallons per day, gpm = gallons per minute, dtpd = dry (English) tons per day, and $M reflects millions of USD per day.
[b] 20-year present value costs assume an interest rate of 7%, as described in Section 2.1 and Eq. 1
[c] 2006 capital cost adjusted to 2023 costs using Engineering News-Record Construction Cost Indices (Engineering News-Record, 2024).
[d] Assumed 75 gal/day usage for two population ranges presented: 1,001-3,300 (average 2,151) and 50,001-1,000,000 (average 75,000), reflects costs to reach 4 ppt PFOA and PFOS
[e] Costs include tertiary treatment using a membrane bioreactor (MBR) to remove solids from WRRF effluent prior to GAC pressure vessels.
[f] Costs per volume terated were estimated for 72% removal of 10 PFAAs based on provided data, then adjusted to 20-year life-cycle costs at 7% interest based on flow rate, depreciation period, and interest rate presented in source.

3. Global PFAA emission estimates

3.1. Sources, scope, and assumptions

Release of PFAS to the environment can be characterized by product life phases: PFAS production, product manufacturing, product use, and waste management. Most existing PFAS emission estimates focus on production, manufacturing, and immediate use phases, which reflect short-term emissions but neglect emissions after storage, waste management, and re-release. One previous study estimated global emissions of perfluorocarboxylic acids (PFCAs), a subset of PFAAs, across all product life phases at 237 t/year in 2000 (Prevedouros et al., 2006). Fig. 1 illustrates major emission pathways, including industrial air emissions, use-phase emissions not routed to wastewater, wastewater discharges, and landfill leachate to groundwater.

Production and manufacturing phase emissions from industrial facilities can add PFAS to water, soils, and the atmosphere, sometimes leading to long-range atmospheric dispersion and transport (Armitage et al., 2006; D'Ambro et al., 2021). One PFAS production facility reported air emissions near 100 t/year of PFAS, based on 26 measured compounds (D'Ambro et al., 2021), but recently upgraded stack gas treatment to include regenerative thermal oxidation (RTO) to destroy PFAS from air emissions (Focus Environmental Inc, 2020). Regulation of PFAS in direct industrial wastewater discharges varies by country, and this emission route has not been previously compiled. The total number of PFAS production and manufacturing facilities contributing emissions is unknown. A 2022 study used industry classification codes to flag 49,145 industrial facilities as presumptive PFAS release sites in the United States (Salvatore et al., 2022). Since this count was recent and based on industry type, most of these facilities are likely ongoing emission sources. Thus, direct emissions from PFAS production and manufacturing facilities are likely a major source. One 2014 paper estimated global, production-phase estimate of 75 to 500 t/year for PFCAs only (Wang et al., 2014).

PFAAs and PFAA precursor emissions from product use were recently characterized by the European Chemical Agency (ECHA, 2023) and estimated at 2800 to 12,600 t/year within the European Union (ECHA, 2023). The estimates reflect use-phase emissions only and do not include emissions during production, manufacturing, or waste management, and is thus underestimates total European emissions. However, since this is the most recent emissions estimate and it includes both PFAAs and precursors that can transform to PFAAs in the environment, the ECHA use-phase estimate was used as the primary source to support a total, global emissions estimate.

Municipal waste management facilities are passive receivers of PFAS emissions from municipal, commercial, and industrial sources. Municipal wastewater treatment processes used today do not remove PFAS. In fact, total measured PFAS mass can increase across a wastewater plant due to transformation of unmeasured, precursor PFAS in the influent into measured PFAS in the effluent and biosolids (Houtz et al., 2016; Thompson et al., 2022). Global PFAA emissions routed through treated wastewater effluent or biosolids have been reported for varying geographies and subsets of PFAAs reported (Kwon et al., 2017; Murakami et al., 2008; Pistocchi and Loos, 2009; Venkatesan and Halden, 2013), with estimates for just PFOA and PFOS ranging from 4 t/year for effluent and biosolids in the whole of South Korea to 50 t/year for effluent only across the European continent. Landfills and contaminated sites can act as medium-term sinks and sources of PFAS. PFAS in landfilled materials may be sequestered short-term but can be transformed and re-released through leachate routed to wastewater treatment or groundwater (Hamid et al., 2018; Lang et al., 2017). PFAS emissions through wastewater treatment are just a fraction of total releases, and releases from landfills and contaminated sites are poorly characterized on a global scale, so waste management phase data was not used to estimate total global emissions. However, future efforts to characterize global PFAS emissions should consider waste management, especially landfills and contaminated sites as time-delayed sources.

3.2. Emissions estimate

The 2023 ECHA use-phase emissions estimate was used to estimate global PFAA and precursor emissions, because it is the most recent and also includes PFAA precursors. Scaling the ECHA estimate of European, use-phase emissions to the entire world based on GDP suggests worldwide, use-phase emissions of approximately 19,000 to 84,000 t/year. This range was then increased slightly based on the knowledge that significant production-phase and waste management phase emissions were not included. A resulting, order-of-magnitude estimate for total, global, long-term emissions across all product life phases resulting from current production of PFAA and precursors is 20,000 to 100,000 t/year.

4. Annual costs to achieve steady-state global PFAS

4.1. Theoretical cost estimate for steady-state global PFAAs

Costs per mass PFAA removed and destroyed were applied to estimated global PFAA emission rates to reflect theoretical steady-state conditions where destruction rates match current emission rates. Using estimated emission rates of 20,000 to 100,000 metric tonnes per year of PFAAs and precursors and applying estimated unit costs of 0.9 million to 67 million USD per kg PFAA removed and destroyed, cost to achieve steady-state global PFAA stocks would be between 20 and 7000 trillion USD per year. This range brackets the estimated global GDP of 106 trillion USD (International Monetary Fund, 2023). This order-of-magnitude cost estimate is subject to significant, compounding uncertainties, including those associated with variations in treatment efficacy, characteristics and concentrations of specific PFAA, which PFAA are reported, and site-specific constraints that cannot be captured in a broad survey. However, the estimated scale of costs (tens to thousands of trillions of USD per year) provides a useful benchmark highlighting the impracticality of relying on environmental remediation alone to control global stocks of PFAAs in the environment.

4.2. Cost considerations for Total PFAS

The cost estimate presented above reflects a theoretical scale-up of PFAA destruction from the environmental sources at a rate similar to current estimated emission rates. But what about other PFAS? Total PFAS production, including fluorotelomers, fluoropolymers, and fluorinated gases, is estimated to be 10 to 10,000 times higher than PFAA production (ECHA, 2023; Evich et al., 2022). If the ratio of total PFAS emissions to PFAA emissions is similar, total PFAS emission rates and associated costs to remove and destroy them from the environment could also be 10 to 10,000 times the emission rates and costs presented above for PFAAs only. Additionally, since long-chain PFAAs are among the easiest PFAS to remove from the environment, mass-normalized costs to remove other PFASs will likely be higher, further increasing the global steady-state cost for all PFAS. One study estimated that achieving 95 % removal of 11 targeted PFAS from landfill leachate would cost over six times >95 % removal of only PFOS and PFOA (Malovanyy et al., 2023). Many non-PFAA PFAS do not have technologies demonstrated to effectively remove them from the environment, suggesting that treatment may not be achievable and if achievable, costs will likely be higher than for PFAAs (Hale et al., 2022; Sheldon and Crimmin, 2022).

Considering these compounding factors along with the PFAA-specific cost estimate of 20 to 7000 trillion USD, removing and destroying the same amount of total PFAS we are currently adding to the environment would likely require investment exceeding the entire global GDP of 106 trillion USD, if even technologically achievable. This means there is not enough money in the world for environmental remediation to keep up with current PFAS production and emission rates. Thus, relying on

environmental remediation alone without PFAS use restrictions would result in ever-increasing environmental PFAS stocks and potential human health risks.

5. Discussion

5.1. Implications for environmental PFAS remediation

PFASs negatively impact human health at concentrations currently found in some environments (Sunderland et al., 2019). Where we have available, effective, and economic technologies and the human health benefit is clear, environmental remediation to remove PFAS makes sense. The need for remediation is especially true for drinking water sources with high PFAS concentrations where the human health benefit exceeds potential downsides, as supported by a recent cost-benefit analysis (U.S. EPA, 2023a). However, not all environmental media can or should be treated for PFAS. For example, some soils, sediments, and water resources experience limited human contact and thus impart limited health risks. Similarly, not every PFAS can be effectively removed from environmental media using existing remediation and destruction technologies. Some, such as TFA and fluorinated gasses, are difficult or impossible to remove and destroy from the environment using current technologies (Hale et al., 2022; Scheurer et al., 2017; Sheldon and Crimmin, 2022). Others can be removed, but at higher costs than those estimated for select PFAAs here (Hale et al., 2022; Li et al., 2020; Riegel et al., 2023).

While this analysis evaluated economic costs for remediating PFAS from environmental sources, environmental remediation has numerous non-quantified externalities, including material use, greenhouse gas emissions, and environmental justice issues, that should be considered when weighing costs and benefits of specific remediation projects. As a result, remediation costs for a specific project will depend on which PFAS are present and the efficacy and economics of removing and destroying targeted compounds. If environmental remediation is undertaken for the purpose of removing PFAS from the environment without immediate health outcomes, engineers should target media with high PFAS concentrations and design treatment processes to concentrate PFAS into a small volume prior to destruction to maximize PFAS destruction for the funds invested. Prioritization of remedial activities should consider stakeholder priorities, available funding, health and environmental impacts, and externalities of treatment across project life cycles and could follow established benefit-cost analysis frameworks (EC, 2015; Office of Management and Budget, 2023a).

The technology landscape for PFAS remediation is changing rapidly, with multiple emerging technologies having the potential to be less expensive than those currently demonstrated. Promising technologies currently undergoing demonstration and scale-up include concentration technologies regenerable ion exchange (Ellis et al., 2022) and foam fractionation (Burns et al., 2021; McCleaf et al., 2021; Vo et al., 2023) and destruction technologies supercritical water oxidation (SCWO), electrochemical oxidation (EO), advanced reduction processes (ARP), and hydrothermal alkaline treatment (HALT) (Cui et al., 2020; Hao et al., 2021; Krause et al., 2022; Li et al., 2022). These advances need to continue, especially for very persistent, very mobile substances like TFA. As these and other environmental PFAS remediation technologies continue to develop and scale up, estimated costs per mass of PFAS destroyed are likely to decrease from those estimated here. However, given that costs estimated here for existing treatment technologies exceed the global GDP, future technologies would need to be cheaper per mass of PFAS destroyed by multiple orders of magnitude to change the conclusions presented here. So, while new technology validation, scale-up, and cost optimization can reduce future treatment costs, they will not obviate the need to reduce PFAS emissions anytime soon.

5.2. Implications for restricted PFAS use

While environmental remediation can only target a limited range of PFAS due to efficacy and economic limitations, PFAS use restrictions can and should target a wider array of compounds by regulating PFAS as a class based on their persistence rather than individual compounds based on their toxicity (Cousins et al., 2020; Kwiatkowski et al., 2020). In fact, this approach may be the most feasible way to control environmental stocks of TFA and fluorinated gasses without clear, economical treatment options (Hale et al., 2022; Scheurer et al., 2017; Sheldon and Crimmin, 2022).

While the economic impacts of using remediation to control global PFAS stocks were demonstrated here to rival the global GDP, PFAS use restrictions will also impact economies. Immediate impacts can be partially mitigated through “essential use” evaluations. While PFAS used in consumer products are often replaceable by non-fluorinated alternatives (Cousins, Goldenman et al., 2019; ECHA, 2023; Glüge et al., 2022), some industries may merit a more detailed, essential use evaluation to better understand availability and development routes for non-PFAS alternatives and associated economic implications of restrictions. For example, proposed European PFAS use restrictions consider essential uses with specific derogations (exemptions) based primarily on an analysis of available alternatives (ECHA, 2023). The essential-use framework can support evolving regulations that incentivize development of readily degradable replacement chemicals and update derogations based on current availability of viable, non-PFAS alternatives. Ongoing progress under an essential use approach will require investments and innovations in chemical development and engineering (Hale et al., 2022). The Royal Society of Chemistry recently published useful guidance regarding chemical alternatives to PFAS (Balan et al., 2023).

6. Conclusion

Ever-increasing PFAS mass in the global environment can only be addressed by changing the mass balance though either increased remediation, reduced emissions, or both. This study contributes to the broader PFAS policy discussion by conducting a thought experiment to estimate potential costs of relying on increased remediation alone without reduced use and emissions. Estimated annual costs to remove PFAS from the environment as fast as it is being added right now using current, large-scale treatment technologies are on the scale of the current global GDP of 106 trillion USD. This estimate addresses an arbitrary interim target of steady-state global PFAS mass and is not intended to reflect realistic treatment rates. While some environmental PFAS remediation will be needed to protect public health, this finding indicates that treatment alone cannot solve our environmental PFAS problem.

A group of European academics, regulators, and utility representatives recommended management of persistent, mobile, and toxic (PMT) substances like PFAS through restricting their production and use, reducing their emissions, and conducting environmental remediation, in that order (Hale et al., 2022). The unaffordable remediation costs estimated here further support prioritization of restricted PFAS use and emission to manage global, environmental PFAS stocks.

CRediT authorship contribution statement

Alison L. Ling: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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