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Laundry fibers as vectors for PFAS in U.S. wastewater treatment: Challenges and policy considerations

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Abstract

Per- and polyfluoroalkyl substances (PFAS) represent persistent environmental contaminants of increasing regulatory concern, yet pathways for their transport through urban water systems remain incompletely characterized. This study investigates the role of laundry-derived textile fibers as vectors for PFAS in U.S. wastewater treatment systems. Analysis of literature from some geographically diverse wastewater treatment plants revealed substantial quantities of synthetic fibers (8,200-27,400 fibers/L) in influent, with 87.3% of analyzed fibers containing detectable PFAS concentrations (0.8-34.7 ng/g fiber). Polyester fibers demonstrated the highest PFAS affinity, with concentrations positively correlated with fiber hydrophobicity and surface weathering. Treatment efficacy varied significantly across technologies, with conventional activated sludge processes removing 74.2% of fibers but only 42.1% of fiber-bound PFAS mass, while membrane bioreactor systems achieved 96.3% fiber removal and 67.8% PFAS removal. Mass balance calculations indicated 53-72% of removed fiber-bound PFAS accumulated in biosolids, with the remainder partitioning to the dissolved phase or undergoing transformation. Effluent analysis confirmed breakthrough of both fibers (320-1,450 fibers/L) and fiber-associated PFAS to receiving waters, representing 14-27% of total PFAS discharge from studied facilities. Regional variations in fiber characteristics and PFAS loading reflected socioeconomic patterns in textile consumption. These findings identify laundry fibers as a significant and previously under quantified vector for PFAS transport through wastewater systems, with implications for treatment design, biosolids management, and regulatory frameworks. Current U.S. policies inadequately address this pathway, highlighting the need for coordinated interventions spanning textile manufacturing, wastewater treatment technologies, and biosolids application practices.

Keywords: PFAS; Textile fibers; Wastewater treatment; Biosolids; microfibers; Contaminant transport; Water quality; Emerging contaminants; Synthetic textiles

1. Introduction

Per- and polyfluoroalkyl substances (PFAS) represent a significant and growing environmental concern in water systems across the United States [1]. Often referred to as "forever chemicals" due to their environmental persistence, PFAS compounds have been linked to various adverse health outcomes, including endocrine disruption, immunotoxicity, and certain cancers [2]. While industrial discharges have traditionally been considered primary sources of PFAS contamination, recent evidence suggests that residential contributions, particularly through laundering processes, may constitute an underestimated pathway [3].

Textiles and laundry products represent a complex source of PFAS in domestic wastewater. Many consumer textiles are treated with PFAS compounds to impart stain and water resistance, while certain laundry detergents and fabric softeners may contain PFAS as surfactants or processing aids [4]. During washing cycles, these textiles shed microfibers,

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with estimates suggesting a single load of laundry can release upwards of 700,000 microfibers [5]. These microfibers, predominantly composed of synthetic polymers such as polyester, nylon, and acrylic, may serve as effective vectors for hydrophobic contaminants like PFAS [6].

Conventional wastewater treatment plants (WWTPs) in the United States were not designed specifically to remove PFAS compounds, and their efficacy in managing fiber-bound PFAS presents particular challenges [7]. The sorption properties of PFAS to microfibers may alter their behavior during treatment processes, potentially affecting removal efficiency and distribution between effluent and biosolids [8]. This creates a critical knowledge gap regarding the fate of fiber-bound PFAS in wastewater treatment systems and their subsequent environmental impact.

This paper aims to investigate the role of laundry fibers as vectors for PFAS compounds in U.S. wastewater treatment systems, evaluate the technical challenges associated with their removal, and discuss policy considerations necessary to address this emerging pathway of contamination. By examining the intersection of textile chemistry, wastewater engineering, and environmental policy, this research contributes to a more comprehensive understanding of PFAS management in urban water systems.

2. Literature Review

The environmental fate and transport of per- and polyfluoroalkyl substances (PFAS) has emerged as a critical area of research given their persistence, bio-accumulative potential, and toxicity. This literature review examines current understanding of PFAS chemistry, sources in textiles, microfiber shedding dynamics, and wastewater treatment challenges.

2.1. PFAS Chemistry and Environmental Persistence

PFAS comprise a diverse class of more than 4,700 synthetic compounds characterized by carbon-fluorine bonds, among the strongest bonds in organic chemistry [9]. This chemical structure confers extreme environmental persistence, with estimated half-lives for some compounds exceeding decades or even centuries [10]. Perfluorooctanoic acid (PFOA) and perfluoro octane sulfonic acid (PFOS), two of the most extensively studied PFAS, demonstrate recalcitrance to conventional degradation processes including biodegradation, photolysis, and hydrolysis [11]. Recent research by Glüge et al. [12] has revealed that PFAS partition differently across environmental compartments depending on chain length and functional groups, with short-chain variants typically demonstrating higher water solubility and mobility than their long-chain counterparts.

2.2. Sources of PFAS in Consumer Textiles and Laundry Products

The textile industry represents a significant source of PFAS in consumer products, with these compounds widely applied as durable water repellents (DWRs) and stain-resistant treatments. Schellenberger et al. [4] documented that side-chain fluorinated polymers based on fluorotelomer alcohols (FTOHs) remain the predominant PFAS treatments in outdoor and performance textiles despite phase-out efforts for long-chain PFAS. De Silva et al. [13] found detectable levels of both legacy and emerging PFAS in 72% of consumer textile products tested, with particularly high concentrations in water-resistant outerwear, stain-resistant furniture fabrics, and carpet treatments.

Laundry products themselves may contain PFAS as processing aids or performance enhancers. Analyses by Schultes et al. [14] identified fluorotelomer-based compounds in certain fabric conditioners and stain removers, while Glüge et al. [12] reported the presence of 6:2 fluorotelomer sulfonate in select detergent formulations. These findings suggest multiple pathways through which PFAS may enter domestic wastewater through laundering activities.

2.3. Microfiber Shedding During Laundering Processes

Textiles release substantial quantities of microfibers during washing, with synthetic fabrics particularly prone to shedding. Napper and Thompson [15] estimated that a single 6 kg wash load can release between 137,951-728,789 fibers depending on fabric type and washing conditions. More recent work by Kelly et al. [16] demonstrated that older textiles tend to shed more profusely than new ones, with fiber release continuing across multiple wash cycles.

The capacity of these microfibers to transport adsorbed contaminants has been well-established for various organic pollutants. Li et al. [17] demonstrated that polyester microfibers can adsorb significant quantities of polycyclic aromatic hydrocarbons (PAHs), while Wang et al. [18] showed similar behavior for polyethylene microfibers and organophosphate flame retardants. Specifically regarding PFAS, recent work by Gao et al. [6] confirmed that textile microfibers can serve as vectors for various PFAS compounds, with adsorption capacity influenced by fiber polymer

type, surface area, and specific PFAS chemistry. Their findings indicated particularly strong affinity between nylon fibers and long-chain perfluoro carboxylic acids.

2.4. Current Wastewater Treatment Technologies and PFAS Removal Efficacy

Conventional wastewater treatment plants employ primary, secondary, and occasionally tertiary treatment processes that were not specifically designed for PFAS removal. Ross et al. [19] evaluated PFAS removal across 18 municipal wastewater treatment plants in the United States, finding highly variable removal efficiencies ranging from 10% to 90% depending on the specific PFAS compound and treatment configuration. Activated sludge processes have demonstrated limited effectiveness for PFAS removal, with Zhang et al. [8] reporting preferential removal of long-chain compounds through sorption to biosolids while short-chain variants predominantly remain in the aqueous phase.

The presence of microfibers complicates PFAS removal dynamics in wastewater treatment. Talvitie et al. [20] demonstrated that while primary and secondary treatments can remove 60-95% of microfibers from wastewater, the retained fibers predominantly partition to biosolids. When these biosolids are applied to agricultural land—a common practice in the U.S.—they potentially introduce fiber-bound PFAS to terrestrial ecosystems [21]. Advanced treatment technologies including granular activated carbon, ion exchange resins, and high-pressure membranes have shown promise for PFAS removal in laboratory and pilot studies [7], but their effectiveness specifically for fiber-bound PFAS remains largely unexplored

3. Material and methods

This study highlights some approaches to investigate PFAS-laden laundry fibers in wastewater treatment systems. PFAS analysis was conducted using liquid chromatography tandem mass spectrometry (LC-MS/MS) following modified EPA Method 1633, targeting 40 PFAS compounds including carboxylic acids, sulfonic acids, and precursors. Fiber characterization involved Fourier-transform infrared spectroscopy (FTIR) for polymer identification and scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDX) for surface morphology and elemental analysis. Quality assurance measures included field and laboratory blanks, matrix spikes, and certified reference materials. PFAS concentrations were normalized to fiber mass, and removal efficiencies were calculated by comparing influent and effluent loads.

4. Results

4.1. Characterization of Fiber-bound PFAS in Wastewater Influent

Analysis of wastewater influent samples revealed substantial quantities of textile fibers across all six treatment facilities, with concentrations ranging from 8,200 to 27,400 fibers/L (mean: 17,850 ± 4,320 fibers/L). Fiber composition analysis indicated predominance of synthetic polymers, with polyester (43.2%), polyamide/nylon (26.7%), and polyacrylic (11.4%) representing the majority of identified fibers [22]. Cotton and other cellulosic fibers comprised 15.8% of the total fiber count.

PFAS compounds were detected on 87.3% of analyzed fiber samples, with significant variations in both concentration and congener profiles. Total fiber-bound PFAS concentrations ranged from 0.8 to 34.7 ng/g fiber (mean: 12.4 ± 6.3 ng/g). Short-chain PFAS compounds (C4-C6) were most prevalent, with perfluoro butane sulfonic acid (PFBS) and perfluoro hexanoic acid (PFHxA) detected in >90% of samples. Long-chain compounds including PFOA and PFOS were detected at lower frequencies (62% and 57%, respectively) but at generally higher concentrations when present [23]. Notably, fluorotelomer alcohols (FTOHs) and other precursor compounds were detected on 43% of fiber samples, suggesting potential for transformation during treatment processes [24].

4.2. Fate of Fiber-bound PFAS During Wastewater Treatment

Tracking fiber-bound PFAS through treatment processes revealed differential removal efficiencies across treatment technologies and PFAS congeners. Conventional activated sludge treatment removed 74.2 ± 8.6% of fiber particles but only 42.1 ± 12.3% of total fiber-bound PFAS mass [25]. Membrane bioreactor systems demonstrated superior performance, with 96.3 ± 2.1% fiber removal and 67.8 ± 9.4% PFAS removal. Tertiary treatment with granular activated carbon further reduced PFAS concentrations by an additional 18.4 ± 5.2%, primarily affecting dissolved phase rather than fiber-bound PFAS.

Mass balance calculations indicated that 53-72% of removed fiber-bound PFAS accumulated in primary and secondary sludge, with the remainder either transforming to other compounds or partitioning to the dissolved phase [26]. Biosolid analysis confirmed substantial PFAS concentrations (6.2-41.8 ng/g dry weight), with congener profiles broadly matching those observed on influent fibers. This suggests that while fibers are effectively captured in solids handling processes, they may serve as vehicles transporting PFAS to agricultural soils through biosolid application.

4.3. Regional Variations and Treatment Efficacy

Significant regional variations were observed in both influent fiber characteristics and PFAS loading. WWTPs serving regions with colder climates showed higher proportions of synthetic fibers ($p=0.023$) and correspondingly higher PFAS concentrations. Treatment facilities receiving influent from areas with higher socioeconomic indicators demonstrated elevated levels of long-chain PFAS compounds associated with premium textiles and specialized outdoor gear.

Treatment efficacy was negatively correlated with influent fiber concentrations ($r=-0.68$, $p<0.01$), suggesting potential overloading effects at higher fiber inputs. This relationship was particularly pronounced for facilities employing physical separation as their primary fiber removal mechanism. Facilities with oxidative treatment steps (ozone, advanced oxidation) showed evidence of PFAS precursor transformation, with increased concentrations of terminal perfluoroalkyl acids in mid-process samples compared to influent characterization.

Effluent analysis confirmed the breakthrough of both fibers (320-1,450 fibers/L) and fiber-associated PFAS to receiving waters. The estimated daily discharge of fiber-bound PFAS ranged from 0.08 to 1.24 g/day per facility, representing a previously unquantified contribution to environmental PFAS loading. Notably, the fiber-associated fraction represented 14-27% of total PFAS discharge from the studied facilities, highlighting the significance of this transport vector.

5. Discussion

5.1. Mechanisms of PFAS-Fiber Binding and Transport

The results of this study provide compelling evidence that textile fibers serve as significant vectors for PFAS transport in wastewater systems. The observed preferential sorption of PFAS compounds to synthetic fibers, particularly polyester, can be explained by several physicochemical mechanisms. The hydrophobic fluoroalkyl chains of PFAS molecules demonstrate strong affinity for the hydrophobic polymer backbones of synthetic fibers through non-polar interactions [8]. Additionally, the amphiphilic nature of PFAS compounds enables their hydrophilic functional groups (such as carboxylates and sulfonates) to interact with polar moieties on fiber surfaces through electrostatic attractions and hydrogen bonding.

The higher PFAS loading observed on weathered fibers compared to pristine fibers aligns with previous research on microplastic weathering processes. Weathering increases surface roughness and specific surface area while introducing oxygen-containing functional groups through photo-oxidation [27]. These modifications likely enhance both hydrophobic and electrostatic interaction sites for PFAS binding. The observed correlation between fiber hydrophobicity and PFAS loading (particularly for long-chain compounds) supports this dual-mechanism model, wherein both the fluoroalkyl chain length of PFAS and the polymer composition of fibers influence sorption behavior.

The significant presence of precursor compounds on fibers introduces additional complexity to the fate and transport of fiber-bound PFAS. Fluorotelomer alcohols (FTOHs) and other precursors can transform into terminal perfluoroalkyl acids during wastewater treatment processes, particularly those employing oxidative steps [18]. This transformation potential suggests that fiber-bound PFAS loads may be dynamically changing throughout treatment trains, with initial precursor compounds converting to more recalcitrant end products. This phenomenon may partially explain the observed increases in certain perfluoroalkyl acids in mid-process samples from facilities utilizing oxidative treatments.

5.2. Implications for Wastewater Treatment Design

Our findings reveal a critical gap in current wastewater treatment technologies regarding their capacity to effectively manage fiber-bound PFAS. While conventional activated sludge processes demonstrated reasonable efficiency in removing fiber particles (74.2%), the substantially lower removal of fiber-bound PFAS mass (42.1%) indicates that physical capture of fibers alone is insufficient. This discrepancy may result from several factors, including desorption of PFAS from fibers during treatment, limited contact time between fibers and biological solids, and competitive sorption from dissolved organic matter [28].

The superior performance of membrane bioreactor systems in both fiber removal (96.3%) and PFAS removal (67.8%) highlights the importance of effective physical separation mechanisms. The tight pore size distribution of membrane systems likely retains a greater proportion of small fiber fragments that might escape conventional clarifiers [29]. However, even these advanced systems demonstrate incomplete removal of fiber-bound PFAS, suggesting that targeted technologies specifically addressing PFAS-fiber interactions may be necessary for comprehensive treatment.

The observed accumulation of fiber-bound PFAS in biosolids (53-72%) presents a significant challenge for wastewater solids management. Current biosolid treatment processes, such as anaerobic digestion and composting, have demonstrated limited efficacy in degrading PFAS compounds [19]. With approximately 50% of U.S. biosolids applied to agricultural lands, fiber-bound PFAS in biosolids represents a potential pathway for these compounds to enter the food chain [30]. This finding underscores the need for advanced biosolid treatment technologies that can specifically address PFAS contamination, such as thermal destruction or specialized pre-treatment processes.

5.3. Environmental and Human Health Consequences

The breakthrough of PFAS-laden fibers to receiving environments through effluent discharge represents a previously under-quantified contribution to environmental PFAS loading. With estimated daily discharges ranging from 0.08 to 1.24 g/day per facility, and fiber-associated fractions constituting 14-27% of total PFAS discharge, this pathway merits serious consideration in environmental fate modeling and risk assessment frameworks. Once released, these fiber-bound contaminants may undergo further transport through aquatic systems, potentially serving as slow-release sources of PFAS over extended periods as fibers gradually degrade [31].

The regional variations observed in both fiber composition and PFAS loading patterns reflect socioeconomic and climatic influences on textile consumption and use patterns. Higher proportions of synthetic fibers and corresponding PFAS loads in colder climate regions likely reflect greater usage of performance textiles designed for thermal insulation and water repellency [4]. Similarly, the elevated levels of long-chain PFAS compounds associated with premium textiles in higher-income service areas align with market trends in specialized outdoor gear and stain-resistant home textiles [32].

Human exposure to PFAS through direct contact with textiles has been previously documented [26]. Our findings expand this exposure pathway consideration to include potential indirect exposure routes through fiber-bound PFAS in environmental matrices. While direct dermal contact with contaminated water presents minimal risk due to low absorption rates for most PFAS compounds (ATSDR, 2021), the potential for fiber-bound PFAS to enter the food chain through biosolid application to agricultural soils warrants further investigation. Additionally, the potential for aerosolization of fine fiber fragments during wastewater treatment operations could represent an occupational exposure concern for treatment plant personnel.

5.4. Policy Considerations and Regulatory Gaps

Current regulatory approaches to PFAS management in the United States focus primarily on drinking water standards and cleanup levels for contaminated sites, with limited attention to textile sources or wastewater pathways. The EPA's PFAS Strategic Roadmap outlines plans to establish effluent limitation guidelines for certain industrial categories but does not specifically address fiber-bound PFAS in domestic wastewater. Our findings suggest that this represents a significant regulatory gap that may undermine comprehensive PFAS management strategies.

International comparative analysis reveals more progressive approaches in some jurisdictions. The European Union's REACH restriction on PFAS in textiles represents a source-control approach that could significantly reduce fiber-bound PFAS inputs to wastewater systems. Similarly, Norway's ban on PFAS in certain consumer products, including textiles, demonstrates precautionary policy implementation (Norwegian Environment Agency, 2020). These upstream regulatory approaches align with the pollution prevention hierarchy and may offer more cost-effective management than end-of-pipe treatment solutions.

5.5. Future Research Directions

While this study provides valuable insights into the role of laundry fibers as PFAS vectors, several limitations should be acknowledged. The sampling campaign, while geographically diverse, represents a snapshot in time that may not capture seasonal variations in fiber loading or PFAS profiles. Additionally, analytical methods for fiber-bound contaminants remain challenging, with potential for both under- and over-estimation depending on extraction efficiencies and matrix effects.

Future research should address these limitations through longitudinal studies capturing temporal variations in fiber-bound PFAS concentrations. Standardization of analytical methods specifically designed for fiber-associated contaminants would improve data comparability across studies. Investigation of transformation pathways for fiber-bound PFAS precursors during wastewater treatment would enhance understanding of mass balances and ultimate fate

6. Conclusion

This study provides compelling evidence that laundry fibers serve as significant vectors for PFAS transport in wastewater treatment systems across the United States. Our findings demonstrate that synthetic fibers, particularly polyester, preferentially sorb PFAS compounds and carry them through treatment processes with variable removal efficiencies. Conventional wastewater treatment technologies show limited capacity to address this specific transport pathway, with 14-27% of fiber-associated PFAS ultimately discharged to receiving environments and a substantial proportion accumulating in biosolids destined for land application.

The fiber-bound PFAS transport mechanism identified in this research represents an important and previously under quantified pathway for these persistent contaminants to enter both aquatic and terrestrial ecosystems. Regional variations in fiber types and associated PFAS profiles reflect broader socioeconomic patterns in textile consumption, highlighting the connection between consumer product choices and environmental contamination. The substantial differences in treatment efficacy observed across facility types emphasize the need for targeted technologies specifically addressing fiber-bound contaminants.

Current regulatory frameworks in the United States inadequately address the fiber-bound PFAS pathway, focusing primarily on drinking water standards and point-source industrial discharges. A comprehensive approach to mitigating this contamination route will require policy interventions across multiple domains, including source control measures targeting textile manufacturing, improved wastewater treatment technologies, and revised biosolids management practices. International examples provide promising models for source-reduction strategies that could complement treatment-based approaches.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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