Failure to act on PFAS in landfill leachate threatens to derail biosolids management programs

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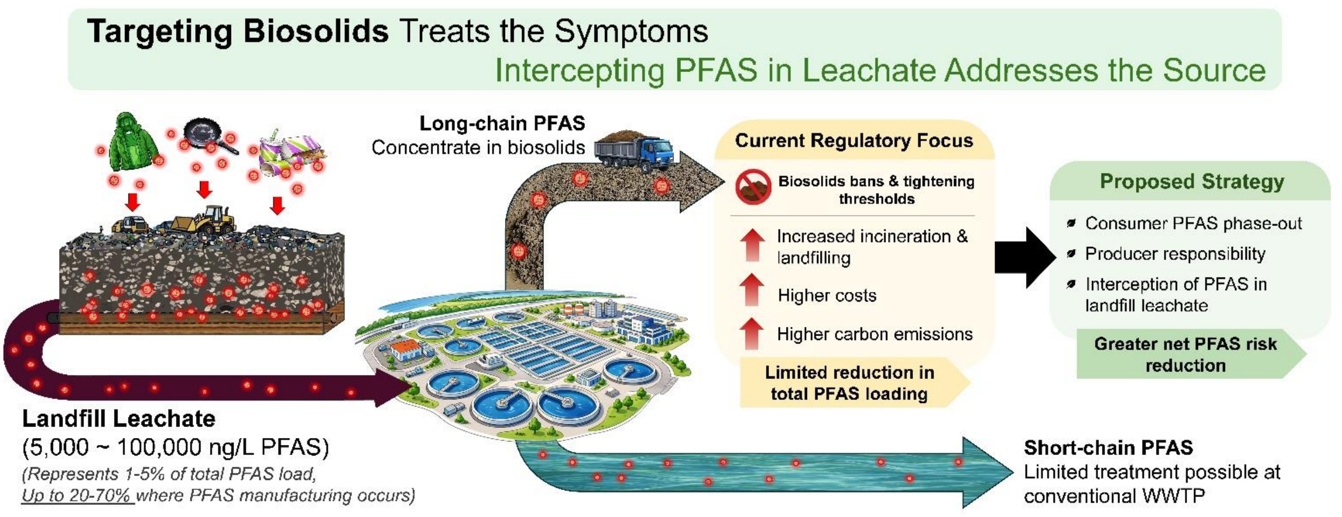
Highlights

- Landfill leachate can drive disproportionate PFAS loading to biosolids
- Biosolids bans may not reduce net environmental PFAS loading
- Few binding PFAS limits exist for landfill leachate globally
- WWTPs redistribute PFAS rather than eliminate them
- Upstream control and LL treatment offer a stronger policy pathway

Graphical Abstract



Abstract

Land application of biosolids has long been an accepted and important part of circular nutrient management, returning carbon, nitrogen, and phosphorus from wastewater treatment plants to agricultural soils. However, recent and growing concerns over per- and polyfluoroalkyl substances (PFAS) have placed biosolids programs under increasing regulatory pressure, resulting in outright bans in several jurisdictions. This perspective surveys current PFAS regulations, bans, and monitoring requirements for biosolids across major global jurisdictions and argues that prevailing regulatory responses are potentially misdirected. While public and regulatory attention has focused on biosolids, addressing and intercepting concentrated upstream PFAS sources such as industrial wastewaters and landfill leachate (LL) remains largely unmanaged prior to discharge to publicly owned wastewater treatment plants. LL frequently contains PFAS concentrations orders of magnitude higher than municipal wastewater influent and, where co-treated, can contribute to a disproportionately large PFAS mass loading to biosolids despite representing a relatively small fraction of total influent flow. In the absence of upstream controls, increasingly restrictive biosolids standards risk dismantling effective nutrient recycling programs without delivering meaningful reductions in environmental PFAS loading. Source control, targeted monitoring, and treatment of LL offer a more balanced and effective policy pathway.

Keywords: PFAS, biosolids management, landfill leachate, wastewater treatment, environmental regulations, policy

Introduction

For decades, the land application of biosolids, treated sewage sludge produced at wastewater treatment plants (WWTPs), has been one of the most effective circular nutrient management practices. Land-application of biosolids aims to recycle carbon, nitrogen, and phosphorus from crops consumed in cities back to agricultural soils, thus helping to close the nutrient loop (*1*); in addition, the carbon content of biosolids is viewed as a valuable soil amendment. Without viable biosolids programs, WWTP operators face generally costlier options, such as landfilling (~ 2.0 x more expensive) or incineration (~ 2.8 x more expensive) (Figure 1) (*2*–*7*). These alternatives not only increase carbon emissions but also increase agricultural operational costs by removing valuable nutrients such as phosphorus, potassium, and nitrogen from the agricultural cycle, increasing farmers' reliance on commercial fertilizers and soil amendments. Compounding the issue, additional treatments might need to be implemented to prevent nutrients and other pollutants re-entering the system through landfill leachate (LL) (*8*). As a result, the practice of land-applying biosolids to recycle nutrients recovered from wastewater treatment is typically framed as an environmental success (*1*, *9*, *10*).

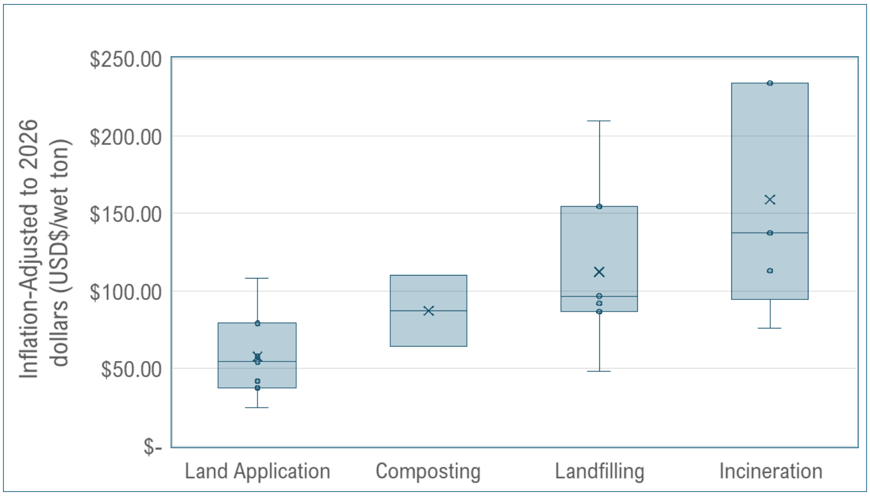


Figure 1. Inflation-adjusted costs (in 2026 USD per wet ton) for biosolids management methods: land application, composting, landfilling, and incineration. Land application remains the lowest-cost option on average, while incineration shows the highest variability.

Growing concern over threats of per- and polyfluoroalkyl substances (PFAS) contamination has placed biosolids programs under intense regulatory pressure, due to the risk of contaminating crops, livestock and groundwater (*11*, *12*). In 2024 alone, multiple jurisdictions in the U.S., Canada, and Europe proposed or enacted restrictions, including outright bans, on land application of biosolids (*13*–*16*). PFAS are persistent, environmentally bioaccumulative and have triggered justified alarm with environmental scientists and activists, but an over-response threatens to dismantle established biosolids systems, essential for nutrient recovery and climate-resilient agriculture. Public discourse has focused intensely on industrial and consumer PFAS sources (*17*, *18*), yet LL is an important driver that remains largely unmanaged. PFAS concentrations in biosolids produced in WWTPs accepting LL are often elevated (*19*) as landfills receive the majority of post-consumer materials containing PFAS (*20*). Across North America, potential landfill-derived PFAS loading is large, with approximately 2,600 active municipal landfills in the United States and more than 1,500 in Canada (*21*, *22*). Although not all landfills discharge LL to WWTPs and sewer-connection statistics are unavailable, comprehensive sampling programs in the United States show that LL carries total PFAS concentrations an order of magnitude or more higher than WWTP influent (*23*–*25*), commonly in the 5,000–20,000 ng/L range, with maximum values often exceeding 100,000 ng/L (*26*, *27*). Discarded carpets, waterproof clothing, food packaging, firefighting foam residuals, and countless other consumer and industrial products end up in landfills, where they slowly release these compounds into a concentrated LL that is often sent directly to publicly owned WWTPs (*28*), where it is co-treated. LL typically accounts for 1 - 5 % of the total PFAS mass entering WWTPs nationally, but can contribute up to 20 - 70 % at specific sites where it represents a larger fraction of influent flow, or where solid wastes from PFAS manufacturing activities are actively accepted (*23*, *24*, *27*). Critically, conventional wastewater treatment processes (such as activated-sludge and anaerobic digestion) predominantly move longer-chain PFAS from the aqueous phase to sludge solids via sorption, while short-chain PFAS generally remain mobile and in solution (*24*, *29*). Very little, if any, of the long-chain PFAS are "eliminated" during the treatment within the WWTP, instead some long chain PFAS or polymeric PFAS may undergo breakdown into somewhat shorter PFAS compounds, but a fraction will simply be adsorbed to the solids and end up accumulating in the sewage sludge. Meanwhile, most of the short-chain PFAS end up in the treated effluent of WWTPs and will potentially be released back into the environment. The presence of long-chain PFAS in biosolids has caused regulators to consider limiting, or outright banning their application to agricultural fields (*30*, *31*) due to their environmental persistence and the uncertainty to determine safe threshold to prevent deleterious environmental impacts in the receiving agricultural areas.

Global Regulatory Landscape

Globally, the regulatory landscape reveals various approaches to the issue of PFAS in biosolids, from outright prohibitions to risk-based thresholds, which appear to be shaped by local politics, scientific consensus, and economic pressures. Table 1 below summarizes key policies as of February 2026, highlighting the differences in land application status, numeric limits, and monitoring mandates. This variation not only complicates cross-border trade and transfer of soil-amending biosolids but also risks encouraging cross-border transfers of PFAS-contaminated biosolids to regions with less stringent regulations. Conversely, certain jurisdictions may follow the precautionary principle and ban the use or importation of biosolids until they develop or adopt biosolid PFAS limits of their own. This was the case in the province of Québec (Canada) in 2023, where the land-spreading of all imported biosolids from the United States was banned until the province's regulators adopted PFAS limits (*32*). With the adoption of new PFAS limits in biosolids in November 2025, Québec's ban on U.S. imported biosolids is now set to expire in 2028 unless amended (*16*). Bans in places like Maine and Connecticut have driven up disposal costs threefold or more, adding tens of millions of dollars annually to ratepayer bills for a problem they did not cause, offering no promise of net reduction in environmental PFAS loading (*33*). It has been reported that biosolid disposal fees in eight states (USA) have increased by an average of 40% since the introduction of PFAS-related restrictions, bans and other requirements (*5*).

Table 1. Global PFAS limits, bans, and monitoring requirements for biosolids

Country/Region	Status of Land Application	Numeric Limit in Biosolids/Sludge	Key Date	Key Policy / Law	Import/Export Restrictions	Monitoring/Treatment Required	Notes / Trend
United States of America (Federal)	Allowed (no federal limit yet)	None (draft risk assessment only)	January 2025	EPA Draft Sewage Sludge Risk Assessment PFOA/PFOS (*34*)	None	Voluntary, methods developing	Source-control emphasis; limits expected
Maine (USA)	Banned	Full ban	June 2022	LD 1911 (*13*)	Bans all out-of-state biosolids	Mandated testing	First & strictest U.S. state
Michigan (USA)	Allowed if < threshold	125 µg/kg PFOS	October 2021	EGLE Interim Strategy (*35*)	None	Yes – industrial pretreatment focus	Successful source-control model
New York (USA)	Allowed if < threshold	50 µg/kg PFOS or PFOA	April/September 2023	NYSDEC Interim Strategy	None	Yes – required for land application	Triggers mitigation if exceeded
Connecticut (USA)	Banned	Full ban	June 2024	SB 292 (Public Act 24-59) (*15*)	Likely bans imports (Maine model)	Yes	Phase-out completed
Canada (Federal)	Allowed if certified	50 µg/kg PFOS (interim)	October 2024	CFIA Interim Standard (*14*)	Blocks imports >50 ppb PFOS	Yes – for certification	Applies to domestic + imported
Québec (Canada)	Domestic only	50 µg/kg PFOS; 38 µg/kg PFOA; 600 µg/kg sum 11 PFAS	November 2025	FRM Code + U.S. import ban (*16*)	Bans biosolids from outside Canada until 2028	Yes – required for land application	Protecting against foreign contamination, first provincial limits in Canada
European Union (General)	Varies by country	No EU-wide limit	Ongoing	REACH restriction under review (*36*, *37*)	POP limits (PFOS/PFOA)	Encouraged	Shift to incineration + P recovery
Wallonia (Belgium)	Allowed	40 µg/kg (sum of 6 PFAS), 400 µg/kg (sum of 22 PFAS)	January 2025	Temporary limit instituted (*38*)	EU rules, limits to quantities of biosolids that can be applied	Mandatory testing	Biosolids exceeding temporary limits must be incinerated
Germany (Federal)	Being phased out	Historic 100 µg/kg PFOS+PFOA	2019–2029	Soil Protection Act + 2029 incineration mandate (*39*)	EU rules	Yes – soil-based	Rapid move to full incineration
Denmark (Federal)	Restricted (soil-based)	Soil: 400 µg/kg (sum 22 PFAS); 10 µg/kg (sum of PFOA, PFOS, PFNA, and PFHxS only)	January 2021	Temporary cut-off values (*40*)	EU rules	Very strict soil monitoring	Among Europe's strictest
Sweden (Federal)	Allowed only under REVAQ	≤20 µg/kg d.w. (sum 22 PFAS)	Ongoing (2023 update)	REVAQ voluntary certification (*41*)	None	Yes – extensive	De-facto industry standard
Netherlands (Federal)	Allowed with strict soil limits	Soil ~0.9 µg/kg PFOS	July 2020	Temporary PFAS framework (*42*)	EU rules	Yes – background enforcement	Construction & farming heavily impacted
UK (Federal)	Allowed (no limit yet)	None	January 2025	DEFRA strategy review launched (*43*)	None	Not yet mandated	Pressure mounting
Australia (Federal)	Allowed (state risk-based)	Varies by state	July 2024	PFAS NEMP 3.0 endorsed (*44*)	None	Widespread testing	Strong source-control focus
New Zealand (Federal)	Allowed	None (under review)	2025	Guidelines update in progress (*44*)	None	Case-by-case	Expected to align with Australia
China (Federal)	Allowed (regional variation)	None	2014 onward	National PFOS/PFOA ban (*45*)	Import/use bans on many PFAS	Some WWTP monitoring	High legacy contamination
Japan (Federal)	Mostly incinerated	None (most biosolids are incinerated)	January 2025	138 compounds banned, and drinking water standard added	Controlled substances	Yes – incineration dominant	>90% sludge incinerated
South Korea (Federal)	Mostly incinerated	None	August 2022	PFHxS added to POPs list (*46*)	Stockholm Convention	Monitoring encouraged	Incineration dominant

This table underscores some emerging trends: North America leads in bans and thresholds (e.g., U.S. states and Canada), Europe focuses on soil-centric restrictions (e.g., Denmark, Netherlands), and Asia-Pacific leans towards incineration as the preferred method to deal with biosolids (e.g., Japan, South Korea). Furthermore, in jurisdictions where numerical limits for PFAS concentrations in biosolids were introduced, the allowed concentrations vary significantly (from 20 – 600 µg/kg dry weight in biosolids, and 0.9 – 400 µg/kg in soil). No clear consensus exists on which exact compounds should be included in numerical limits, complicating cross-border comparisons, which range from single-PFAS thresholds to limits based on the sum of up to 22 different compounds. It is important to note that in the context of LL, little to no local, state/provincial or federal guidelines exist anywhere in the world mandating hard thresholds on PFAS concentrations in LL sent to WWTPs for treatment. However, governments have funded periodic PFAS LL surveys (*47–52*) in an attempt to scope the size of the problem and assess risks.

Policy Implications and Recommendations

Even if PFAS are progressively phased out, landfills receiving consumer waste are expected to become the dominant, long-term reservoirs and emitters of PFAS via LL in the medium- to long-term. Without a targeted LL strategy, regulatory tightening on biosolids risks derailing existing biosolids programs. The central policy challenge is therefore not only to phase out PFAS containing products, but also to implement a proactive and more balanced approach to containing and controlling PFAS mobilized through LL systems. This raises a few central policy questions: 1) How should regulators manage persistent, legacy PFAS sources, and in particular landfills and their leachate streams? 2) How can we tighten controls on biosolids and subsequent exposure to PFAS without simply displacing PFAS from one part of the environment to another? And finally, 3) How can we ensure that we protect the health of the public while not unduly penalizing PFAS "receivers" such as landfills and WRRFs, and thus the tax/ratepayers?

To address this, we suggest that policymakers pursue three parallel strategies:

1. Ban the sale and distribution of non-essential PFAS-containing consumer products, which can impact domestic wastewater streams and drive decade-long leaching in landfills. Potential exemptions could be granted for essential applications such as biomedical devices or other strategic technologies such as batteries. This change would eventually eliminate the source of PFAS that contaminates LL.

2. Urgently establish a framework for progressive PFAS guidelines and recommend best-practices for landfills and other commercial and industrial emitters (aqueous & solid waste streams) in consultation with federal, provincial/state regulators, municipal wastewater and solid waste authorities, based on best available technologies. In parallel, establish dedicated funding streams for research, pilot testing, and the deployment of full-scale interception and containment technologies designed to retain PFAS at secure, contaminated sites, preventing their transfer into biosolids, agricultural fields, or the environment.

3. Enact risk-based limits and standards for PFAS in biosolids and other soil amendments used in agriculture using a scientifically grounded, risk-based approach for the sum of pertinent PFAS to prevent both the contamination of groundwater with PFAS, and the transfer of PFAS into the agri-food system and foodstuffs. These should incorporate site-specific factors like soil type, precipitation, risk of subsurface flow and erosion

and crop uptake, avoiding one-size-fits-all bans.

Extending this globally, international bodies like the United Nations Environment Program (UNEP) could work towards harmonizing LL guidance and best practices under the Stockholm Convention. Without the regulatory spotlight shifting upstream to the management of dominant sources, tightening biosolids standards will remain an expensive regulatory exercise with limited effect on net environmental PFAS loading. Thermal treatment of biosolids is not a silver bullet as it remains uncertain whether existing, commercially-deployable incineration approaches can consistently achieve total mineralization without generating by-products or redistributing fluorinated compounds via gaseous emissions (*53*, *54*). Meeting tighter standards will require capital- and energy-intensive processes that will result in limited improvements in overall exposure risk due to non-regulated sources like atmospheric deposition, household products, and other pathways. The current crisis in biosolids programs does not undermine the intrinsic value of biosolids or the circular economy; instead, it highlights the need for stricter control of inputs. Without this correction, PFAS will remain persistent contaminants in the environment and the circular nutrient economy vital to climate-resilient agriculture will become collateral damage. The current crisis is not unlike what happened a few decades ago when we realize that metals where present in sewage sludge (*55*) and that they could accumulate in soils – rules were put in place and metals are no longer such a problem in biosolids.

We shouldn't rush to ban biosolids land application without viable alternatives. Major historical PFAS manufacturers (3M, Dupont, etc.) are the primary sources of environmental PFAS – municipal biosolids are not. Modern engineered landfills, while not perfect, contain PFAS far better than uncontrolled releases, and most LL is recaptured on site. The focus should be shifted to aggressively pursue source-control programs to keep new PFAS out of wastewater, identify the most contaminated biosolids to divert them from land application, and increase research into affordable destruction technologies. Recent developments have led to the development of viable and market-ready PFAS interception and sequestration technologies such as foam fractionation and sorption, which could be used with potentially concentrated streams such as LL, some of which have already been implemented (*56*). Enacted policies should move the responsibility for managing and remediating PFAS contamination to producers, rather than continuing to burden municipalities, landfills, and ultimately the public, with management and remedial costs. Simply banning land-application of biosolids and sending everything to landfills or incineration may raise costs dramatically for ratepayers with no guarantee of lowering overall human exposure and with negative carbon balance further contributing to global warming.

CRediT authorship contribution statement

Patrick M. D'Aoust: Conceptualization, data curation, formal analysis, investigation, writing – original draft, writing – review & editing. **Benoit Barbeau**: Conceptualization, data curation, supervision, supervision, writing – review & editing. **Sébastien Sauvé**: Conceptualization, data curation, supervision, supervision, writing – review & editing. **Dwight Houweling**: Conceptualization, data curation, supervision, writing – review & editing.

Declaration of competing interests

The authors declare that they hold no apparent or actual competing interests that could affect the content of this manuscript or the results of the study.

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Declaration of generative artificial intelligence use

The authors declare that generative artificial intelligence (ChatGPT 5.2) was used to proofread the manuscript.

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