Evaluation of Current Alternatives and Estimated Cost Curves for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water

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Certifications

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Abbreviations

ADONA	8-dioxa-3H-perfluorononanoate
AFFF	aqueous film-forming foam
AIX	anion exchange
Barr	Barr Engineering Co.
BOD_5	five-day biochemical oxygen demand
CAA	Clean Air Act
$CaCO_3$	calcium carbonate
CCI	Construction Cost Index
CEPCI	Chemical Engineering Plant Cost Index
CO_2	carbon dioxide
COD	chemical oxygen demand
DOC	dissolved organic carbon
dtpd	dry tons of wastewater solids per day
EBCT	empty bed contact time
EIS	Environmental Impact Statement
ENR	Engineering News Record
FASA	perfluoroalkane sulfonamide
FTE	full-time employees
FTOH	fluorotelomer alcohol
FTS	fluorotelomer sulfonate
GAC	granular activated carbon
GHG	greenhouse gas
gpd	gallons per day
gpm	gallons per minute
HALT	high-temperature alkaline treatment
Hazen	Hazen and Sawyer
HBV	Health-Based Value
HF	hydrofluoric acid
HFPO-DA	propanoate
HRL	Health Risk Limit
HLR	hydraulic loading rate
HSDM	homogenous surface diffusion model
HWI	hazardous waste incinerator
ITRC	interstate technology regulatory council
kSCF	thousand standard cubic feet
lb	pound
MBR	membrane bioreactor
MC	modified clay
MF	microfiltration

mg/L	milligrams per liter
MGD	million gallons per day
min	minute
MPCA	Minnesota Pollution Control Agency
MSW	municipal solid waste
N-EtFOSA	N-ethyl perfluorooctane sulfonamide
N-EtFOSAA	N-ethyl perfluorooctane sulfonamido acetic acid
N-EtFOSE	N-ethyl perfluorooctane sulfonamidoethanol
NF	nanofiltration
ng/L	nanogram per liter
N-MeFOSAA	N-methyl perfluorooctanesulfonamido-acetic acid
NPDES	National Pollutant Discharge Elimination System
NPV	net present value
O&M	operations and maintenance
PASF	perfluoroalkane sulfonamido substance
PFAA	perfluoroalkyl acid
PFAS	per- and polyfluoroalkyl substances
PFBA	perfluorobutanoic acid
PFBS	perfluorobutane sulfonic acid
PFCA	perfluoroalkyl carboxylate
PFHpA	perfluoroheptanoate, perfluoroheptanoic acid
PFHxA	perfluorohexanoate, perfluorohexanoic acid
PFHxS	perfluorohexanesulfonic acid
PFOA	perfluorooctanoic acid
PFOS	perfluorooctane sulfonic acid
PFSA	perfluoroalkane sulfonate
PICs	products of incomplete combustion
Report	*Evaluation of Current Alternatives and Estimated Cost Curves for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water*
RO	reverse osmosis
SCWO	supercritical water oxidation
sq. ft.	square feet
SSI	sewage sludge incineration
SSOM	source-separated organic material
STU	standard treatment units
TDS	total dissolved solids
TOC	total organic carbon
TOP	total oxidizable precursors
TS	total solids
TSS	total suspended solids

UF	ultrafiltration
USD	United States Dollars
U.S. DOD	United States Department of Defense
U.S. EPA	United States Environmental Protection Agency
WRRF	water resource recovery facility

Executive Summary

This study develops alternatives to remove and destroy per- and polyfluoroalkyl substances (PFAS) from water resource recovery facility (WRRF) effluent, biosolids, mixed municipal solid waste (MSW) landfill leachate, and compost contact water (waste streams) using currently feasible technologies (i.e., could be built today). Barr Engineering Co. (Barr) and Hazen and Sawyer (Hazen) screened over 50 PFAS separation and destruction technologies for their ability to remove and destroy select PFAS to below current analytical reporting limits (a non-regulatory target established by the Minnesota Pollution Control Agency [MPCA] specifically for this study) and for their demonstrated commercial status. Thirteen technologies were retained for detailed consideration and assembled into alternatives, including destroying PFAS in final waste products. Assembled alternatives were ranked for criteria related to technical feasibility, economic feasibility, and byproducts management. Barr and Hazen retained two-to-four alternatives for each waste stream for preliminary design and cost estimating.

Currently, feasible technologies to separate PFAS from liquid waste streams are limited to sorption processes in pressure vessels (including granular activated carbon [GAC], anion exchange [AIX], and modified clay), reverse osmosis (RO) membrane separation, and foam fractionation. Feasible technologies to destroy PFAS from liquid media are currently limited to high-temperature incineration, thermal oxidation, and supercritical water oxidation (SCWO). Management of PFAS in biosolids remains a developing field with significant public and regulatory interest. Technologies selected as feasible at this time include SCWO, pyrolysis followed by thermal oxidation, and gasification followed by thermal oxidation.

Table ES-1 summarizes estimated capital and operations and maintenance (O&M) cost ranges for the two highest-ranking PFAS management alternatives for each waste stream for illustrative purposes. These estimates do not include pretreatment costs to achieve specified PFAS treatment process requirements. Pretreatment costs can, in some cases, be more expensive than PFAS removal and destruction. Requirements for both pretreatment and PFAS removal will vary significantly among sites and will need site-specific evaluations. Site-specific goals, conditions, and limitations may impact technology selection and implementation costs. Detailed PFAS removal cost estimates and cost curves for three facility sizes are included in this report. Based on our analyses, capital costs for removing PFAS from WRRF effluent and biosolids are similar, but O&M costs are significantly lower for biosolids treatment.

Table ES-1 Select capital and O&M cost ranges for highest-ranking alternatives

Waste Stream	Facility Size	Highest-Ranking Alternatives	Capital Cost Range (by facility)	Annual O&M Cost Range (by facility)	Relative Confidence in Ability to Reliably Meet PFAS Targets[2]
Municipal WRRF effluent	10 million gallons per day (MGD) (6,940 gpm) (similar to Mankato or Moorhead with a population of 45,000)	GAC with reactivation (Alt 1a)[1]	\$41M–\$88M	\$4.5M–\$9.6M	Medium-high (breakthrough of short-chain PFAS may limit reliability)
		GAC, single-use AIX with GAC reactivation and AIX high-temperature incineration (Alt 6a)[1]	\$80M–\$170M	\$6.1M–\$13M	High (two processes provide more controlled breakthrough)
Municipal WRRF biosolids	10 dry tons per day (estimated for 10 MGD WRRF)	SCWO[3]	\$40M–\$85M	\$0.47M–\$0.99M	Medium-high (limited testing at full-scale)
		Pyrolysis or gasification with thermal oxidation of pyrogas[1,3]	\$53M–\$110M	\$0.55M–\$1.2M	Medium-high high (limited testing at full scale)
Mixed MSW landfill leachate	0.014 MGD (10 gpm)	GAC with high-temperature incineration (Alt 1a)[1]	\$0.30M–\$0.60M	\$0.23M–\$0.48M	Medium (breakthrough of short-chain PFAS may limit reliability)
		Foam fractionation with high-temperature incineration of foamate (Alt 8a)	\$5.0M–\$11M	\$0.20M–\$0.42M	Low (limited removal of short-chain PFAS)
Compost contact water	0.014 MGD (10 gpm)	GAC with high-temperature incineration (Alt 1a)[1]	\$0.30M–\$0.60M	\$0.21M–\$0.44M	Medium (breakthrough of short-chain PFAS may limit reliability)
		Foam fractionation with high-temperature incineration of foamate (Alt 8a)	\$5.0M–\$11M	\$0.20M–\$0.42M	Low (limited removal of short-chain PFAS)

[1] Alternatives indicated likely need pretreatment processes to operate PFAS separation and destruction technologies. Pretreatment costs are not included in this table but are discussed in report sections for each waste stream.

[2] Relative ability to reliably meet PFAS targets reflects a combination of technology performance and reliability. For example, foam fractionation alternatives receive a “low” score because they are not expected to meet short-chain PFAS treatment targets. Alternately, single-process media filtration is expected to meet targets most of the time, except when a breakthrough event occurs. Hence, it receives a “medium” to “medium-high” score for reduced reliability. Breakthrough can be monitored and managed to limit PFAS reporting to effluent; however, targeting levels below analytical reporting limits for PFBA in high-concentration waste streams like landfill leachate could require media changeout every 2–4 weeks, which is on a similar time frame as analytical turnaround time for PFAS. Thus, PFAS breakthrough may not be detected in time for changeout, resulting in a lower reliability score for single-process media filtration for high PFAS concentration waste streams. Compared to single-process media filtration, dual-process media filtration receives a score of “high” because it is expected to allow for more time for monitoring breakthrough across four vessels instead of two and thus to more reliably meet PFAS targets.

[3] Biosolids costs are extrapolated from cost curves developed for this study.

Capital costs are driven by the recalcitrant and water-soluble nature of PFAS, which requires multiple additional processes, including pretreatment ahead of designated PFAS separation and destruction alternatives. Most currently available PFAS removal systems are modular, with limited economy-of-scale benefits for large facilities. O&M costs are driven by operational labor, energy use of high-temperature destruction technologies, and frequent sorption media changeout needed to achieve concentrations of short-chain PFAS below current method reporting limits (for alternatives with sorption media).

Costs were also evaluated with a lens on the cost per benefit provided by comparing the cost per mass of target PFAS removed between different waste streams and technologies over 20 years (detailed in Table 11-1). Treating wastewater biosolids or landfill leachate had the lowest cost per mass of target PFAS removed over 20 years (approximately $0.7 million to $4.0 million per pound of PFAS removed from biosolids and $0.2 million to $18 million per pound of PFAS removed from leachate). These costs are further described in Section 11.2. This cost range reflects the range of facility sizes analyzed here and the design basis influent PFAS concentrations established for this study.

When costs for individual facilities were extrapolated to the estimated number of WRRFs in Minnesota accepting greater than 0.05 MGD and mixed MSW landfills and composting sites, estimated costs for Minnesota could be at least $14 billion for removing and destroying PFAS from WRRF effluent and biosolids, and at least $105 million for removing and destroying PFAS from mixed MSW landfill leachate and compost contact water. These estimates, which include pretreatment, are summarized in Table ES-2 and further discussed in Section 11.3.

Table ES-2 Summary of estimated 20-year costs for managing PFAS in targeted waste streams in Minnesota[1]

Waste Stream	Estimated Number of Facilities	Range of Flows	Estimated 20-year costs for Minnesota (Millions of USD)[2]
Municipal WRRF effluent[3]	283	0.1–300 MGD	$12,000–$25,000
Municipal WRRF biosolids[4]	1 regional facility, plus 50 on-site facilities	50 dry tons of wastewater solids per day (dtpd) regional facility, on-site for 1–10 dtpd	$1,600–$3,300
Mixed MSW landfill leachate[5]	24	1–100 gpm	$77–$160
Compost contact water[6]	9	1–100 gpm	$28–$60

[1] This statewide evaluation carries additional uncertainty related to approximations for facility sizing, number of facilities, and degree of pretreatment needed. Costs are rounded to two significant figures. Costs are based on design basis concentrations selected to be typical of those reported in WRRF effluent (Helmer, Reeves, and Cassidy 2022; Coggan et al. 2019; Thompson et al. 2022), biosolids (Venkatesan and Halden 2013; Helmer, Reeves, and Cassidy 2022), landfill leachate (Lang et al. 2017), and compost contact water (Wood Environment & Infrastructure Solutions Inc. 2019).

[2] Twenty-year costs reflect net present value calculations using an interest rate of 7%.

[3] WRRF upgrade costs for effluent treatment are for PFAS separation and destruction using GAC adsorption with high-temperature incineration of media at flow rates below 1.1 MGD and GAC reactivation at higher flow rates. These include approximate costs for tertiary treatment retrofits (at WRRFs) or pretreatment processes (at landfill leachate and composting sites) likely needed at most facilities to provide the water quality required for GAC or RO feed. This analysis excludes WRRFs below 0.05 MGD.

[4] WRRF upgrade costs are for PFAS destruction in biosolids using pyrolysis or gasification with thermal oxidation of produced gasses. Costs include centrifuge dewatering to provide 25% solids material for process feed for each facility. These assume that WRRFs treating more than 0.1 MGD but producing less than 1 dtpd biosolids would ship to one regional, 50-dtpd pyrolysis facility. The costs shown here do not include transporting biosolids to that facility. These costs also do not include a pyrolysis/gasification facility with thermal oxidation for Minnesota's largest WRRF because costs for a facility of this size are not available.

[5] Costs are presented for 24 landfills, but the total number of landfills accepting mixed MSW in Minnesota is difficult to estimate due to mixed-use. Assumed equalization is present to limit peak leachate flows to twice the annual average leachate flow. Facility sizes are estimated based on publicly available data.

[6] Costs are presented for nine composting sites, but the total number of source-separated organic material (SSOM) composting sites is difficult to estimate due to mixed-use. Facility sizes are estimated based on publicly available data.

Most currently available PFAS destruction technologies are designed to treat concentrated waste streams rather than WRRF effluent water and are unlikely to be economically viable for most individual facilities. Regionalization of PFAS destruction may make financial sense for managing concentrated PFAS waste streams such as biosolids, foam fractionation foamate, GAC, and AIX resin. It may also be beneficial for treating high-concentration waste streams like landfill leachate, compost contact water, and biosolids from smaller facilities where on-site destruction is not economically viable. Evaluation of a regional high-temperature incineration facility for sorption media and a regional biosolids pyrolysis or gasification facility suggests that such facilities could potentially be economically viable when the fee structure is set appropriately to benefit the individual utilities and the regional facility. Other regionalization options that may become feasible include regional disposal of smaller volumes of foamate from foam fractionation using emerging destruction technologies such as SCWO, high-temperature alkaline treatment (HALT), or electrochemical oxidation.

Except for foam fractionation, liquid treatment technologies currently available at commercial scales are conventional water treatment technologies used in the water treatment industry for many years to treat other substances. While these technologies have been adapted at the commercial scale for PFAS treatment, many were not specifically designed for PFAS removal. New, targeted technologies to concentrate and destroy PFAS exist and have been demonstrated at bench- and pilot-scale. These newer technologies have the potential to reduce future capital and operating costs. However, these technologies are currently applied at small scales; for many of these newer technologies, performance and long-term maintenance needs have not been proven in full-scale implementations. In the future, these technologies may potentially be implemented at individual facilities rather than relying on regional or out-of-state high-temperature incineration facilities.