



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

Prepared for
Minnesota Pollution Control Agency

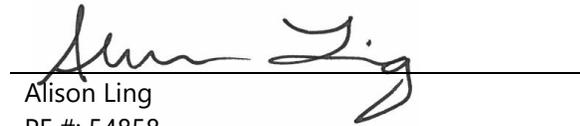


May 2023

Prepared by:
Barr Engineering Co., Hazen and Sawyer

Certifications

I hereby certify that this report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Engineer under the laws of the state of Minnesota.



Alison Ling
PE #: 54858
Date: May 10, 2023

Responsible for Sections 1, 2, 3, 4, 10 (except 10.5), and 11; Appendices A, B, C, and D

I hereby certify that this report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Engineer under the laws of the state of Minnesota.



Kathryn Wolohan
PE #: 54881
Date: May 10, 2023

Responsible for Sections 5, 6, 8, and 9;
Appendix E

I hereby certify that this report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Engineer under the laws of the state of Minnesota.



Anna Munson
PE #: 51711
Date: May 10, 2023

Responsible for Sections 7 and 10.5

Contributors

This report was developed by Barr Engineering Co. and Hazen and Sawyer in collaboration with the Minnesota Pollution Control Agency.

Barr Engineering Co.

Katie Wolohan, PE
Ali Ling, PhD, PE
Andy McCabe, PhD
Becca Vermace, PE
Don Richard, PhD, PE
Charles Gantzer, PhD, PE
Sorel Nelson

Hazen and Sawyer

Anna Munson, PE
Derya Dursun, PhD, PE
Micah Blate, PE
Mohammed Abu-Orf, PhD

Minnesota Pollution Control Agency

Scott Kyser, PE

The following manufacturers and technology providers contributed information used in this report:

- 374Water (supercritical water oxidation)
- ECT2 (foam fractionation and anion exchange)
- SUEZ, now a part of Veolia Water Technologies & Solutions (RO)
- Calgon Carbon Corporation (GAC and GAC reactivation)
- Vadose Remediation, LLC (modified clay media)
- EPOC Enviro (foam fractionation)
- Clean Harbors Environmental Services (waste incineration)
- Evoqua Water Technologies, LLC (GAC and anion exchange)
- H2K Technologies, Inc. (GAC vessels)
- Purolite (anion exchange resin)
- ROChem Americas, Inc. (wide-spaced RO)

The authors would also like to thank the following people for their valuable feedback, reviews, comments, and discussions. Their contributions greatly improved this report.

- Clifford Shierk, Minnesota Pollution Control Agency
- Rebecca Higgins, Minnesota Pollution Control Agency
- Ginny Black, Minnesota Composting Council

- Bryan Oakley, Barr Engineering Co.
- Ryan Schipper, Barr Engineering Co.
- Phil Fish, Barr Engineering Co.
- Tim Sperfslage, Barr Engineering Co.

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

May 2023

Contents

- Executive Summary..... 1
- 1 Introduction 6
 - 1.1 Background..... 6
 - 1.2 Study Objectives 7
 - 1.3 Use of Report 8
 - 1.4 Report Structure and Study Scope 9
 - 1.5 Definitions..... 11
 - 1.5.1 Waste Streams..... 11
 - 1.5.2 Treatment and Destruction 11
- 2 PFAS Chemistry and Selection of PFAS Considered in this Study..... 13
 - 2.1 PFAS Classes and Chemical Characteristics..... 13
 - 2.2 PFAS Precursors and Transformations 14
 - 2.3 Selection of PFAS Considered for this Study..... 16
 - 2.4 Treatment Target Selection 18
- 3 Selection of Currently Feasible Treatment Technologies for PFAS Removal..... 20
 - 3.1 Technology Screening Approach 20
 - 3.2 Technology Screening Results—PFAS Liquid-Liquid Separation 20
 - 3.2.1 NF/RO Membrane Separation..... 21
 - 3.2.2 Foam Fractionation..... 22
 - 3.2.3 Comparison of PFAS Liquid Separation Technologies 23
 - 3.3 Technology Screening Results—PFAS Liquid-Solid Separation..... 23
 - 3.3.1 Granular Activated Carbon Adsorption 23
 - 3.3.2 Reactivated Granular Activated Carbon 25
 - 3.3.3 Single-Use Anion Exchange Resin 25
 - 3.3.4 Regenerable Anion Exchange Resin and Solvent Regeneration 26
 - 3.3.5 Modified Clay Adsorption..... 27
 - 3.3.6 Comparison of PFAS Phase Separation Technologies for Liquid Streams 28

3.4	Technology Screening Results—PFAS Destruction.....	28
3.4.1	High-Temperature Incineration (retained for disposal of Sorption Media and Concentrates).....	29
3.4.2	Thermal Reactivation of Granular Activated Carbon (retained for disposal of Sorption Media).....	30
3.4.3	Supercritical Water Oxidation (retained for disposal of Biosolids).....	30
3.4.4	Pyrolysis with Thermal Oxidation (retained for disposal of Biosolids).....	31
3.4.5	Gasification with Thermal Oxidation (retained for disposal of Biosolids).....	33
4	Assembly of Currently Feasible Management Alternatives for PFAS Removal.....	35
4.1	Liquid Waste Streams (Municipal WRRF Effluent, Mixed MSW Landfill Leachate, and Compost Contact Water).....	35
4.2	Biosolids	38
5	PFAS Management Alternatives Evaluation and Cost Curve Methods	39
5.1	Goals and Approach to Alternative Evaluation Criteria Development and Weighting.....	39
5.1.1	Technical Feasibility.....	39
5.1.1.1	PFAS Separation Efficiency (Ability to Meet 5 ng/L or 5 ng/g)	39
5.1.1.2	PFAS Destruction Efficiency.....	40
5.1.1.3	Degree of Commercialization.....	40
5.1.1.4	Reliability of Performance.....	41
5.1.1.5	Simplicity of Operation and Maintenance.....	41
5.1.1.6	Operator and Public Health.....	41
5.1.2	Economic Feasibility.....	42
5.1.2.1	Relative Capital Costs	42
5.1.2.2	Relative Operation and Maintenance Costs (Not Including Energy Costs).....	42
5.1.2.3	Relative Energy Consumption	42
5.1.2.4	Relative Complexity and Cost of Pretreatment	43
5.1.2.5	Relative Energy Recovery from Biosolids Alternatives.....	43
5.1.2.6	Applicability at Scale	43
5.1.3	Byproducts Management.....	44
5.1.3.1	Beneficial Reuse Opportunity for Water or Byproducts.....	44
5.1.3.2	Potential for Media Shifting of PFAS Pollutants.....	44
5.1.4	Evaluation Criteria Selection and Weighting by Waste Stream	45
5.2	Goals and Approach for Preliminary Design and Costing of Example Pretreatment Facilities.....	46
5.3	Goals and Approach for Preliminary Design and Costing of Site-Specific Facilities.....	48
5.3.1	Preliminary Design.....	48

5.3.2	Cost Estimate Approach and Limitations.....	49
5.3.3	Capital Cost Support.....	50
5.3.4	Operation and Maintenance Cost Support.....	51
5.4	Goals and Approach for Regional Facility Evaluation	53
6	Municipal Wastewater	55
6.1	Project Assumptions for Municipal Wastewater	55
6.1.1	Description and Scale of Required Treatment.....	55
6.1.2	PFAS Influent Concentrations and Treatment Targets	56
6.1.3	Water Quality Assumptions for Pretreated WRRF Effluent.....	57
6.2	PFAS Management Alternatives Evaluation Results	58
6.2.1	Evaluation Scoring Results.....	58
6.2.2	Technical Feasibility.....	61
6.2.3	Economic Feasibility.....	62
6.2.4	Byproducts Management.....	63
6.2.5	PFAS Management Alternatives for Preliminary Design.....	63
6.3	Alternative Preliminary Design and Cost Curve Development.....	63
6.3.1	Alternative 1a (Municipal Wastewater).....	63
6.3.2	Alternative 2a (Municipal Wastewater).....	65
6.3.3	Alternative 6a (Municipal Wastewater).....	68
6.3.4	Alternative 6b (Municipal Wastewater)	71
6.4	PFAS Removal Performance and Reliability	74
6.5	Example Pretreatment and Retrofit Options for PFAS Separation Technologies Applied to WRRF Effluent.....	75
6.5.1	Example Pretreatment Retrofit for Existing Activated Sludge Treatment.....	76
6.5.2	Example Pretreatment Retrofit for Existing Stabilization Ponds.....	77
6.6	Other Considerations for Municipal WRRF Effluent.....	79
7	Municipal Wastewater Biosolids.....	80
7.1	Project Assumptions for Municipal Wastewater Biosolids.....	80
7.1.1	Description and Scale of Required Treatment.....	80
7.1.2	Biosolids PFAS Concentrations and Treatment Targets.....	81
7.1.3	Biosolids Composition and Characteristics	81
7.2	PFAS Management Alternatives Evaluation Results	82
7.2.1	Evaluation Scoring Results.....	82
7.2.2	Technical Feasibility.....	83

7.2.3	Economic Feasibility.....	84
7.2.4	Byproducts Management.....	85
7.2.5	PFAS Management Alternatives for Preliminary Design.....	85
7.3	Alternative Preliminary Design and Cost Curve Development.....	85
7.3.1	Supercritical Water Oxidation (Wastewater Biosolids).....	85
7.3.2	Pyrolysis/Gasification with Thermal Oxidation (Wastewater Biosolids).....	89
7.4	PFAS Removal Performance and Reliability.....	92
7.5	Example Pretreatment for PFAS Destruction Technologies Applied to Biosolids.....	92
7.5.1	Example Pretreatment for SCWO.....	93
7.5.2	Example Pretreatment for Pyrolysis/Gasification.....	94
7.6	Other Considerations for Municipal Wastewater Biosolids.....	95
8	Mixed MSW Landfill Leachate.....	97
8.1	Project Assumptions for Mixed MSW Landfill Leachate.....	97
8.1.1	Description and Scale of Required Treatment.....	97
8.1.2	PFAS Influent Concentrations and Treatment Targets.....	97
8.1.3	Water Quality Assumptions for Pretreated Mixed MSW Landfill Leachate Quality.....	98
8.2	PFAS Management Alternatives Evaluation Results.....	99
8.2.1	Evaluation Scoring Results.....	99
8.2.2	Technical Feasibility.....	101
8.2.3	Economic Feasibility.....	102
8.2.4	Byproducts Management.....	103
8.2.5	PFAS Management Alternatives for Preliminary Design.....	104
8.3	Alternative Preliminary Design and Cost Curve Development.....	104
8.3.1	Alternative 1a (Landfill Leachate).....	104
8.3.2	Alternative 1b (Landfill Leachate).....	106
8.3.3	Alternative 5a (Landfill Leachate).....	109
8.3.4	Alternative 8a (Landfill Leachate).....	112
8.4	PFAS Removal Performance and Reliability.....	114
8.5	Example Pretreatment for PFAS Separation Technologies Applied to Mixed MSW Landfill Leachate.....	115
8.6	Other Considerations for Mixed MSW Landfill Leachate.....	117
9	Compost Contact Water.....	119
9.1	Project Assumptions for Compost Contact Water.....	119
9.1.1	Description and Scale of Required Treatment.....	119

9.1.2	PFAS Influent Concentrations and Treatment Targets	120
9.1.3	Water Quality Assumptions for Pretreated Compost Contact Water.....	120
9.2	PFAS Management Alternatives Evaluation Results	122
9.2.1	Evaluation Scoring Results.....	123
9.2.2	Technical Feasibility.....	124
9.2.3	Economic Feasibility.....	125
9.2.4	Byproducts Management.....	126
9.2.5	PFAS Management Alternatives for Preliminary Design.....	126
9.3	Alternative Preliminary Design and Cost Curve Development.....	127
9.3.1	Alternative 1a (Compost Contact Water).....	127
9.3.2	Alternative 5a (Compost Contact Water).....	129
9.3.3	Alternative 8a (Compost Contact Water).....	132
9.4	PFAS Removal Performance and Reliability	134
9.5	Example Pretreatment for PFAS Separation Technologies Applied to Compost Contact Water	134
9.6	Other Considerations for Compost Contact Water.....	136
10	Regional PFAS Management Facility Evaluation	139
10.1	Products for Regional Facility PFAS Destruction by Waste Stream	139
10.2	Technologies for Regional Facility PFAS Destruction.....	139
10.3	Specific Considerations for Regional Facilities.....	140
10.3.1	Summary of Existing Regional Facility Networks.....	140
10.3.2	Potential New Regional Facility Concepts	140
10.4	Sorption Media High-Temperature Incineration Facility Concept-Level Design	142
10.4.1	Design Basis and Equipment Needs	142
10.4.2	Cost Estimates	143
10.4.3	Economic Analysis.....	145
10.5	Biosolids Pyrolysis/Gasification Facility Concept-Level Design	148
10.5.1	Design Basis and Equipment Needs	148
10.5.2	Cost Estimates	150
10.5.3	Economic Analysis.....	152
10.6	Permitting and Siting Considerations.....	155
11	PFAS Management Themes and Conclusions.....	157
11.1	Breaking the Cycle.....	157
11.2	Costs per Mass of PFAS Removed	157

11.3	PFAS Management Options for Minnesota	158
11.4	Energy Use and Associated Carbon Dioxide Emission Equivalents	161
11.5	Limitations on Use of Cost Estimates	164
11.6	Costs to Manage Short-Chain versus Long-Chain PFAS.....	164
11.7	Technology Readiness	165
11.8	Future Research Needs.....	166
12	References	167

List of Tables

Table 2-1	Summary of target PFAS and representative concentrations for this study	18
Table 4-1	Summary of liquid phase PFAS management alternatives.....	37
Table 4-2	Summary of PFAS management alternatives for biosolids	38
Table 5-1	Evaluation criteria weightings by waste stream.....	46
Table 5-2	Targeted pretreated water quality for PFAS management alternatives with RO or sorption media vessels.....	47
Table 6-1	Assumed influent concentrations and treatment goals for target PFAS in municipal WRRF effluent (all units in ng/L)	56
Table 6-2	Assumed initial and pretreated municipal wastewater quality	58
Table 6-3	Alternatives evaluation results for municipal WRRF effluent.....	60
Table 6-4	Summary of design basis assumptions for Alternative 1a for municipal wastewater	64
Table 6-5	Summary of design basis assumptions for Alternative 2a for municipal wastewater	66
Table 6-6	Summary of design basis assumptions for Alternative 6a for municipal wastewater	69
Table 6-7	Summary of design basis assumptions for Alternative 6b for municipal wastewater.....	72
Table 6-8	PFAS removal performance and reliability for municipal WRRF effluent treatment alternatives.....	74
Table 7-1	Assumed influent concentrations and treatment goals for target PFAS for municipal WRRF biosolids (all units in ng/g)	81
Table 7-2	Assumed composition and characteristics of municipal WRRF biosolids feed to PFAS destruction technologies	82
Table 7-3	Alternatives evaluation results for municipal WRRF biosolids.....	83
Table 7-4	SCWO system sizing	86
Table 7-5	Summary of design basis assumptions for supercritical water oxidation for biosolids.....	87
Table 7-6	Summary of design basis assumptions pyrolysis/gasification with thermal oxidation for biosolids.....	91
Table 8-1	Assumed influent concentrations and treatment goals for target PFAS for mixed MSW landfill leachate (all units in ng/L).....	98
Table 8-2	Assumed initial and pretreated mixed MSW landfill leachate quality	99
Table 8-3	Alternatives evaluation results for mixed MSW landfill leachate.....	101
Table 8-4	Summary of design basis assumptions for Alternative 1a for landfill leachate	105
Table 8-5	Summary of design basis assumptions for Alternative 1b for landfill leachate	108
Table 8-6	Summary of design basis assumptions for Alternative 5a for landfill leachate	110
Table 8-7	Summary of design basis assumptions for Alternative 8a for landfill leachate	113
Table 8-8	PFAS removal performance and reliability for mixed MSW landfill leachate alternatives	115
Table 9-1	Assumed influent concentrations and treatment goals for target PFAS for compost contact water (all units in ng/L).....	120
Table 9-2	Assumed initial and pretreated compost contact water quality	122
Table 9-3	Alternatives evaluation results for compost contact water.....	124
Table 9-4	Summary of design basis assumptions for Alternative 1a for compost contact water.....	128

Table 9-5	Summary of design basis assumptions for Alternative 5a for compost contact water.....	130
Table 9-6	Summary of design basis assumptions for Alternative 8a for compost contact water.....	132
Table 9-7	PFAS removal performance and reliability for compost contact water treatment alternatives.....	134
Table 10-1	Estimated capital costs for a regional high-temperature incineration facility in Minnesota	144
Table 10-2	Annual estimated operational and maintenance costs and income for a regional high-temperature incineration facility handling spent GAC in Minnesota	145
Table 10-3	Economic analysis for regional high-temperature incineration facility in Minnesota, in millions of USD—sensitivity of NPV to incineration fees and real interest rate	147
Table 10-4	Economic analysis for regional high-temperature incineration facility in Minnesota, in millions of USD—sensitivity to incineration fees and capital and O&M cost ranges (3% interest, 20 years) ^[1]	147
Table 10-5	Estimated economic externalities for regional high-temperature incineration in Minnesota (compared to out-of-state incineration).....	148
Table 10-6	Summary of design basis assumptions for regional biosolids pyrolysis/gasification facility.....	149
Table 10-7	Estimated capital cost for a regional biosolids pyrolysis/gasification facility in Minnesota	151
Table 10-8	Economic analysis for regional pyrolysis/gasification facility in Minnesota, in millions of USD—sensitivity of NPV to biosolids tipping fees and real interest rate.....	153
Table 10-9	Economic analysis for regional pyrolysis/gasification facility in Minnesota, in millions of USD - sensitivity to tipping fees and capital and O&M cost ranges (3% interest, 20 years).....	153
Table 10-10	NPV of a regional pyrolysis/gasification facility in Minnesota with capital cost and O&M contributions from individual WRRFs.....	154
Table 10-11	Comparison of cost to utility for construction and operation of an independent pyrolysis/gasification facility versus a regional facility.....	155
Table 11-1	Estimated cost per mass of PFAS removed from targeted waste streams over 20 years ^[1]	158
Table 11-2	Estimated 20-year costs for PFAS removal from targeted waste streams in Minnesota, in million USD ^[1]	160
Table 11-3	Estimated energy use and CO ₂ equivalents for PFAS management alternatives.....	163

List of Figures

Figure 1-1	PFAS use and disposal and target waste streams in this Report.....	7
Figure 1-2	Summary of steps used to develop treatment alternatives and cost analyses	10
Figure 1-3	Distinction between PFAS separation and PFAS destruction mechanisms.....	12
Figure 2-1	Example PFAS precursor breakdown pathway to perfluoroalkyl end products.....	15
Figure 3-1	Example SCWO process flow diagram.....	31

Figure 3-2	Example pyrolysis process flow diagram.....	32
Figure 3-3	Example thermal oxidizer process flow diagram.....	33
Figure 3-4	Example gasification process flow diagram	34
Figure 6-1	Conceptual process flow diagram for Alternative 1a for municipal wastewater.....	64
Figure 6-2	Capital cost curve for Alternative 1a for municipal wastewater.....	65
Figure 6-3	O&M curve for Alternative 1a for municipal wastewater	65
Figure 6-4	Conceptual process flow diagram for Alternative 2a for municipal wastewater.....	66
Figure 6-5	Capital cost curve for Alternative 2a for municipal wastewater.....	67
Figure 6-6	O&M cost curve for Alternative 2a for municipal wastewater.....	67
Figure 6-7	Conceptual process flow diagram for Alternative 6a for municipal wastewater.....	68
Figure 6-8	Capital cost curve for Alternative 6a for municipal wastewater.....	70
Figure 6-9	O&M cost curve for Alternative 6a for municipal wastewater.....	70
Figure 6-10	Conceptual process flow diagram for Alternative 6b for municipal wastewater.....	71
Figure 6-11	Capital cost curve for Alternative 6b for municipal wastewater.....	73
Figure 6-12	O&M cost curve for Alternative 6b for municipal wastewater	73
Figure 6-13	Capital cost curve for retrofitting conventional activated sludge to MBR.....	77
Figure 6-14	Capital cost curve for new MBR installation for a stabilization pond system, including the cost to replace stabilization ponds	78
Figure 7-1	Conceptual process flow diagram for biosolids supercritical water oxidation.....	86
Figure 7-2	Capital cost curve for biosolids SCWO.....	87
Figure 7-3	O&M cost curve for biosolids SCWO.....	88
Figure 7-4	Conceptual process flow diagram for biosolids pyrolysis/gasification with thermal oxidation.....	90
Figure 7-5	Capital cost curve for biosolids pyrolysis/gasification with thermal oxidation	91
Figure 7-6	O&M costs for biosolids pyrolysis/gasification with thermal oxidation	92
Figure 7-7	Capital cost curve for screw press dewatering to 15% solids for SCWO.....	94
Figure 7-8	Capital cost curve for dewatering to 25% solids for pyrolysis/gasification	95
Figure 8-1	Conceptual process flow diagram for Alternative 1a for landfill leachate.....	104
Figure 8-2	Capital cost curve for Alternative 1a for landfill leachate.....	105
Figure 8-3	O&M cost curve for Alternative 1a for landfill leachate.....	106
Figure 8-4	Conceptual process flow diagram for Alternative 1b for landfill leachate.....	107
Figure 8-5	Capital cost curve for Alternative 1b for landfill leachate.....	108
Figure 8-6	O&M cost curve for Alternative 1b for landfill leachate.....	109
Figure 8-7	Conceptual process flow diagram for Alternative 5a for landfill leachate	110
Figure 8-8	Capital cost curve for Alternative 5a for landfill leachate.....	111
Figure 8-9	O&M cost curve for Alternative 5a for landfill leachate.....	111
Figure 8-10	Conceptual process flow diagram for Alternative 8a for landfill leachate	112
Figure 8-11	Capital cost curve for Alternative 8a for landfill leachate.....	113
Figure 8-12	O&M cost curve for Alternative 8a for landfill leachate.....	114
Figure 8-13	Conceptual process flow diagram for landfill leachate pretreatment	116

Figure 8-14	Capital cost curve for new MBR installations with pre-aeration, sedimentation, and chemical addition for landfill leachate pretreatment	117
Figure 9-1	Conceptual process flow diagram for Alternative 1a for compost contact water	127
Figure 9-2	Capital cost curve for Alternative 1a for compost contact water	128
Figure 9-3	O&M cost curve for Alternative 1a for compost contact water	129
Figure 9-4	Conceptual process flow diagram for Alternative 5a for compost contact water	130
Figure 9-5	Capital cost curve for Alternative 5a for compost contact water	131
Figure 9-6	O&M cost curve for Alternative 5a for compost contact water	131
Figure 9-7	Conceptual process flow diagram for alternative 8a for compost contact water	132
Figure 9-8	Capital cost curve for Alternative 8a for compost contact water	133
Figure 9-9	O&M cost curve for Alternative 8a for compost contact water	133
Figure 9-10	Conceptual pretreatment process flow diagram for compost contact water.....	135
Figure 9-11	Capital cost curve for new MBR installations with pre-aeration, sedimentation, and chemical addition for compost contact water pretreatment.....	136
Figure 10-1	Conceptual process flow diagram for sorption media regional high-temperature incineration facility	143
Figure 10-2	Estimated 20-year NPV and income ranges for regional high-temperature incineration facility.....	146
Figure 10-3	Conceptual process flow diagram for regional biosolids pyrolysis/gasification facility....	150
Figure 10-4	Construction cost in millions USD for a biosolids drying and pyrolysis/gasification facility with a capacity of up to 50 dtpd	151
Figure 10-5	Estimated O&M cost per mass for biosolids pyrolysis/gasification with thermal oxidation.....	152
Figure 11-1	Estimated O&M cost multiplier for GAC treatment targeting short-chain (PFBA or PFBS) removal versus long-chain (PFOA) removal for municipal WRRF effluent, mixed MSW landfill leachate, and compost contact water.....	165

List of Appendices

Appendix A	PFAS Chemical Characteristics and Most Similar "Target PFAS" Used in this Study
Appendix B	PFAS Separation and Destruction Technology Screening Table
Appendix C	PFAS Removal Performance by Technology
Appendix D	Media Breakthrough Curve Estimates
Appendix E	Detailed Design Basis and Cost Tables

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	<i>Evaluation of Current Alternatives and Estimated Cost Curves for PFAS Removal and Destruction from Municipal Wastewater, Biosolids, Landfill Leachate, and Compost Contact Water</i>
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)	GAC with reactivation (Alt 1a) ^[1]	\$41M–\$88M	\$4.5M–\$9.6M	Medium-high (breakthrough of short-chain PFAS may limit reliability)
	(similar to Mankato or Moorhead with a population of 45,000)	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.