Canadian
Water
Network

Canada’s Challenges and Opportunities to Address Contaminants in Wastewater

Supporting Document 4

Technology Scan for Wastewater Treatment

March 2018

Contents

Canadian Water Network and the national expert panel thank Patrick Coleman, Principal Process Engineer at Black & Veatch, for reviewing this supporting document.

This project was undertaken with the financial support of:
Ce projet a été réalisé avec l'appui financier de:

Environment and Climate Change Canada
Environnement et Changement climatique Canada

Acronyms and Abbreviations

AGS	Aerobic granular sludge
AOP	Advanced oxidation processes
BNR	Biological nutrient removal
BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
DAF	Dissolved air flotation
DO	Dissolved oxygen
EDCs	Endocrine-disrupting chemicals
GAC	Granular activated carbon
GHG	Greenhouse gas
IX	Ion exchange
MABR	Membrane aerated bioreactor
MBR	Membrane bioreactor
MF	Microfiltration
NF	Nanofiltration
P	Phosphorus
PAC	Powdered activated carbon
PhACs	Pharmaceutically active compounds
PPCPs	Pharmaceuticals and personal care products
RO	Reverse osmosis
TOC	Total organic carbon
UF	Ultrafiltration
UV	Ultraviolet
VOC	Volatile organic compound
VSS	Volatile suspended solids

Preface

As the list of chemicals we generate as a society grows, many find their way into wastewater and ultimately into our natural ecosystems. Some of these substances are contaminants that can be harmful to human health, fish and wildlife, and to Canada's waterways. To put into clearer context the ability and opportunities to deal with wastewater contaminants in Canada, Canadian Water Network (CWN) led a national review of known contaminants and contaminants of emerging concern in municipal wastewater and our options to deal with them.

Supported by a $400,000 investment from Environment and Climate Change Canada, and leveraging CWN's extensive network of research and practitioner communities, CWN convened a national expert panel from October 2017 to March 2018. The panel's mandate, as established by CWN, was to assess Canada's needs and opportunities in dealing with multiple contaminants in domestic wastewater through consideration of the following critical questions:

- Which wastewater contaminants do we need to worry about most, now and in the future?
- What are the options for our diverse Canadian communities to address these contaminants through wastewater treatment?
- What are the important opportunities and trade-offs involved in those treatment choices, including resource recovery, cost implications, socio-economic and cultural fit, and implications for related issues like greenhouse gas emissions?

The expert panel was composed of a group of eight leading experts from across Canada with diverse expertise in municipal wastewater treatment, conventional contaminants and contaminants of emerging concern, environmental and ecosystem impacts, wastewater resource recovery, and the broader legal and socioeconomic implications of wastewater effluent discharges. The panel was chaired by Dr. Donald Mavinic of the University of British Columbia, an internationally recognized expert in wastewater treatment.

The expert panel's primary task was to generate a synthesis report providing a credible and useful framing of where we are, what we know and don't know, and a 'blueprint' for how we can move forward to achieve benefits through more effective wastewater treatment in Canada. This blueprint was developed through research and discussions that were augmented by incorporating perspectives from an extended group of experts from across Canada. A broad range of geographic and topic-area insights were solicited from expert contributors with knowledge of municipal wastewater practice, environmental impacts and assessments associated with wastewater, as well as legal and community perspectives. The extended expert input included both invited participation at panel working meetings, as well as broader national input through an online questionnaire.

As a supporting document to the expert panel's report, the current document provides a high level overview of available wastewater treatment technologies.

Purpose and Scope

This supporting document is intended to provide an overview of wastewater treatment technologies and their associated co-benefits and trade-offs. This document supports the expert panel report and provides additional information about available wastewater technologies.

This overview was prepared by a scan of literature and key references. The results of this review are presented in a table format, identifying available wastewater treatment technologies according to waste stream (liquid, solid or side) and by treatment process listed from conventional to more advanced in each category. For each treatment process or technology, the table provides a summary of concerns/contaminants the process/technology is designed to address, along with a listing of known co-benefits and trade-offs.

For further information, please refer to the reference list provided by Metcalf and Eddy [1] as a key source for information on wastewater treatment processes and removal capabilities. For an assessment of treatability of various wastewater constituents through various treatment processes, refer to the CCME Municipal Wastewater Effluent in Canada Backgrounder [2], Appendix C – Categorization of Wastewater Substances by Process Treatment.

Table Overview

Stream	**Process category**	**Technology**	**Description**
Liquid	Physical	Preliminary treatment (e.g. screening, grit removal, grinding)	
Liquid	Physical	Sedimentation	
Liquid	Physical	Filtration	
Liquid	Physical	Membrane filtration	Microfiltration (MF)
Liquid	Physical	Membrane filtration	Ultrafiltration (UF)
Liquid	Physical	Membrane filtration	Nanofiltration (NF)
Liquid	Physical	Membrane filtration	Reverse osmosis (RO)
Liquid	Physical	Adsorption	Granular activated carbon (GAC) and Powdered activated carbon (PAC)
Liquid	Physical	Adsorption	Other adsorbents
Liquid	Photochemical	Ultraviolet (UV) disinfection	
Liquid	Chemical	Coagulation	
Liquid	Chemical	Chemical disinfection / Chlorine and its compounds	
Liquid	Chemical	Chemical disinfection / Other chemicals (e.g. peracetic acid)	
Liquid	Chemical	Advanced oxidation processes (AOPs)	
Liquid	Chemical	Advanced oxidation processes	Ozonation
Liquid	Chemical	Ion Exchange (IX)	
Liquid	Photo-biological	Algal production	
Liquid	Biological	Aerated lagoons and ponds	
Liquid	Biological	Conventional activated sludge (suspended biomass process)	
Liquid	Biological	Biosorption	
Liquid	Biological	Biofiltration (trickling and biological aerated filters)	
Liquid	Biological	Biological nutrient removal (BNR)	Nitrification/ denitrification
Liquid	Biological	Biological nutrient removal (BNR)	Enhanced biological phosphorus removal
Liquid	Biological	Biological nutrient removal (BNR)	Aerobic granular sludge
Liquid	Bio-physical	Membrane bioreactors (MBRs)	
Liquid	Bio-physical	Membrane bioreactors	Membrane aerated bioreactors (MABRs)
Solid	Physical	Thickening	Gravity
Solid	Physical	Thickening	Dissolved air flotation (DAF)
Solid	Physical	Thickening	Mechanical
Solid	Physical	Dewatering	
Solid	Physical	Dewatering	Mechanical
Solid	Biological	Hydrolysis (biological)	
Solid	Biological	Stabilization	Anaerobic sludge digestion
Solid	Biological	Stabilization	Aerobic sludge digestion
Solid	Biological	Stabilization	Composting
Solid	Thermal	Hydrolysis (thermal)	
Solid	Thermal	Incineration	
Side	Physico-chemical	Ammonia stripping and recovery	
Side	Chemical	Struvite or hydroxyapatite formation	
Side (Liquid)	Biological	Anaerobic ammonium oxidation (anammox)	

Table 1. Wastewater treatment approaches: concerns addressed, co-benefits and trade-offs

Stream	Process category	Technology	Description	Concerns addressed	Co-benefits	Trade-offs	References
Liquid	Physical	Preliminary treatment (e.g. screening, grit removal, grinders)		Large solids, debris	Reduction of suspended solids before sedimentation, protection downstream equipment and operation, potential for recycling the debris into the waste flow after grinding	Need for continuous cleaning	[1], [3]
Liquid	Physical	Sedimentation (including primary sedimentation, secondary clarification, and ballasted sedimentation)		Suspended solids, metals, particulate matter, biomass, chemicals (if using coagulants)	Reduction of aeration requirements, increase in nitrification capacity	Depending on the sedimentation process used, a large amount of space may be required. Stacked clarifiers and high-rate clarifiers can be used to reduce space requirements.	[1]
Liquid	Physical	Filtration		Suspended solids, particulate BOD, particulate phosphorus	Good for small systems, cost effective for phosphorus removal when combined with BNR, removal of some trace organics, PPCPs, and some pathogens	Need for backwashing, need for further research on removal of trace contaminants, removal efficiency affected by operating conditions and influent concentration and characteristics	[1], [4], [5]
Liquid	Physical	Membrane filtration	Microfiltration (MF)	Suspended solids, colloids, bacteria and protozoa	Efficiency enhancement when combined with biological treatment, can be used as pretreatment for NF and RO	Not very efficient in removal of ammonia and phenols, affected by operational conditions (pH, salt concentration, transmembrane pressure), requires chemicals for periodic cleaning, not suitable for water reuse, cannot remove trace contaminants	[1], [6], [7], [8], [9]
Liquid	Physical	Membrane filtration	Ultrafiltration (UF)	Some dissolved compounds with high molecular weight, suspended solids, colloids, bacteria, protozoa, and viruses	Can be used as pretreatment for NF, RO and AOP, potential for removal of some trace contaminants	Requires chemicals for periodic cleaning. Not suitable as a sole technology for potable water reuse, but can be used as a pretreatment prior to RO and AOP for this purpose.	[1], [6], [7]

Stream	Process category	Technology	Description	Concerns addressed	Co-benefits	Trade-offs	References
Liquid	Physical	Membrane filtration	Nanofiltration (NF)	Micropollutants, wide range of organics and inorganics, EDCs, antibiotics, bacteria, protozoa, and viruses	Less energy intensive than RO, potential for non-potable or indirect potable water reuse	Costs and GHG emission associated with energy use, lower rejection than RO, fouling, requires chemicals for periodic cleaning, requires pretreatment, management of the concentrate. Not suitable as a sole technology for potable water reuse.	[1], [6], [7], [10], [11]
Liquid	Physical	Membrane filtration	Reverse osmosis (RO)	Heavy metals, wide range of organics and inorganics, nutrients, viruses, micropollutants, EDCs, antibiotics	Potential for wide-ranging water reuse applications	Energy intensive, requires extensive pretreatment, associated costs and GHG emission, requires chemicals for cleaning, fouling, concentrate management/disposal	[1], [6], [7], [10], [11]

Stream	Process category	Technology	Description	Concerns addressed	Co-benefits	Trade-offs	References
Liquid	Physical	Adsorption	Granular activated carbon (GAC) and Powdered Activated Carbon (PAC)	Aromatic solvents, chlorinated and polynuclear aromatics, pesticides and herbicides, high molecular weight organics, trace organic compounds (including EDCs and pharmaceuticals), dissolved organic carbon, chlorine, copper	PAC can be added directly to the activated sludge process or in separate reactors. PAC can be added to help control shock loads, improve sludge settleability, remove refractory pollutants, improve color removal, and/or improve ammonia removal. Possibility of combined adsorption/ biological removal of compounds in a process, resulting in potential synergies between the two removal mechanisms.	Both GAC/PAC: Performance dependent on several factors, including process configuration, the type of activated carbon, properties of the compound being removed, and other compounds present in the water. Bench and/or pilot testing is often needed, and there are uncertainties when scaling up to full-scale. Different compounds may compete for adsorption sites and, as a result, the removal of a target compounds may be limited by the presence of others. Depending on the contaminants being removed, desired effluent concentrations and the water matrix, frequent addition/replacement of AC may be required. GAC in general: exhaustion over time and need for replacement/regeneration, loss of adsorption capacity during regeneration. GAC in a fixed bed reactor: headloss build-up, energy for pumping and water required for backwashing. GAC in an expanded bed reactor: additional energy required to pump the water being treated up through the reactor. PAC: PAC needs to be added to the process and subsequently removed. Depending on the process configuration, a coagulant and/or filtration may be needed to remove PAC.	[1], [6], [10], [11], [12], [13]

Stream	Process category	Technology	Description	Concerns addressed	Co-benefits	Trade-offs	References
Liquid	Physical	Adsorption	Other adsorbents (e.g. granular ferric hydroxide, activated alumina, manganese greensand, manganese dioxide, hydrous iron oxide particles, iron oxide coated sand)	Heavy metals, fluoride		Adsorbents must be replaced or regenerated once exhausted. Some adsorbents can be costly. Testing and/or piloting required to assess applicability for a specific application. pH, temperature, and presence/absence of compounds that compete for adsorption sites can affect performance.	[1]
Liquid	Photo-chemical	Ultraviolet (UV) disinfection		Pathogens	Safer for workers and receiving waters, no by-products produced, effective, potential for removal of EDCs and PPCPs (when hybrid with AOP)	Energy costs, periodic maintenance or cleaning to control biofilm may be required, filtration prior to UV disinfection may be required	[1], [6], [10], [14], [15]
Liquid	Chemical	Coagulation (including chemically enhanced primary treatment and chemical precipitation for P removal)		Suspended solids, BOD, phosphorus, some heavy metals	Enhancement of sedimentation and filtration	Use of chemicals, production of solids that must be removed via sedimentation or filtration, larger quantities of sludge produced, testing required to identify optimal coagulant doses, higher operational costs	[1], [16], [17]
Liquid	Chemical	Chemical disinfection/ Chlorine and its compounds		Pathogens	Oxidation of organics and ammonia, grease removal (pre-aeration), odor control, sludge-bulking control	Possible formation of potentially toxic disinfection byproducts	[1]
Liquid	Chemical	Chemical disinfection / Other chemicals (e.g. peracetic acid)	Combined addition of acetic acid and peroxide. May be combined with UV	Bactericidal and viricidal	No disinfection byproducts, not affected by pH		[1]

Stream	Process category	Technology	Description	Concerns addressed	Co-benefits	Trade-offs	References
Liquid	Chemical	Advanced oxidation processes (AOPs)		Wide range of organics and inorganics, pathogens, micropollutants, PhACs, EDCs	Removal of EDCs, improving the downstream biodegradation of complex organic compounds, efficiency can be enhanced when combinations of oxidants are used together (or hybrid with UV)	Energy use and associated high costs, formation of hazardous byproducts, efficacy is pH dependent	[6], [10], [14], [18], [19]
Liquid	Chemical	Advanced oxidation process	Ozonation	Pathogens, micropollutants, PhACs, EDCs	Removal of trace contaminants and refractory organics, reduction of chlorine usage, odor control	Unstable disinfectant and needs to be reapplied, expensive, formation of hazardous byproducts, safety concerns	[6], [14], [18], [20], [21]
Liquid	Chemical	Ion Exchange (IX)		Heavy metals, ammonia	Can handle fluctuations and shock loadings, can operate under wide range of temperature, removal of ammonia is enhanced in presence of some organics (citric acid and whey protein), potential for metals recovery	Removal efficiency dependent on the resin properties and pH, need for further research, energy intensive	[22], [23], [24]
Liquid	Photo-biological	Algal production	Algal production in ponds or photobioreactors	Nutrient uptake from wastewater (best after anaerobic digestion)	Biofuel production	Large footprint of ponds or of energy for photobioreactors	[25]
Liquid	Biological	Aerated lagoons and ponds		Soluble organics, secondary effluents, nutrients	Easy to operate and maintain, low construction and operation costs, potential for reduction of footprint for septic fields, optimizing production of algal cell tissue and potential for harvestable proteins (high-rate aeration ponds)	Large footprint, more temperature effects than in conventional activated sludge	[1]

Stream	Process category	Technology	Description	Concerns addressed	Co-benefits	Trade-offs	References
Liquid	Biological	Conventional activated sludge (suspended growth process)		Organics (COD, BOD and TOC)	Removal of EDC, trace organics, pharmaceuticals, PPCPs and micropollutants (especially in hybrid biofilm systems), economic	Potential of sludge bulking due to the excessive growth of filamentous micro-organisms (reduces settleability), sensitive to fluctuations in pH, temperature and DO, potential for de-conjugation or formation from other metabolites, removal of some micropollutants and trace organics can be affected by redox and operating condition	[15], [26], [27], [28], [29], [30], [31], [32]
Liquid	Biological	Biosorption		Heavy metals, dyes, phenols, fluoride	Removal of non-biodegradable pharmaceuticals and PPCPs economic, eco friendly	pH dependent, need for more efficient and selective biosorbents, need for further research	[15], [33], [34], [35], [36]
Liquid	Biological	Biofiltration (trickling filters)		Organics	Removal of pharmaceuticals (e.g. anti-depressant) and PPCPs, VOCs	Not very efficient in removal of VOC, anti-depressants and PPCPs, can have large footprint compared to other process that achieve the same goals (e.g. BNR)	[30], [31], [37]
Liquid	Biological	Biological nutrient removal (BNR)	Nitrification/ denitrification	Converting ammonia to nitrate (nitrification) and nitrate to nitrogen gas (denitrification)	Removal of trace organic, estrogenic compounds and anti-depressants, potential for removal of some micropollutants, can be done in the same reactor as BOD, reduction in overall chemical use, denitrification	Sensitive to temperature, pH, DO levels, and ammonia concentration (need for more process control), capital investment, high energy consumption due to aeration and mixing, footprint, associated costs, emission of nitrous oxide (GHG), removal of trace organics dependent on redox conditions and physiochemical properties of organics, need for an external carbon source for microorganism cell synthesis (denitrification), need for a preceding nitrogen-gas-stripped reactor (denitrification), need for periodical backwashing if done in column reactors (denitrification)	[31], [32], [38], [39], [40], [41]

Stream	Process category	Technology	Description	Concerns addressed	Co-benefits	Trade-offs	References
Liquid	Biological	Biological nutrient removal (BNR)	Enhanced biological phosphorus removal	Phosphorus	Recovery of P in biosolids, can improve sludge settleability, can be combined with other P-removal technologies such as coagulation/chemical precipitation to achieve very low effluent P concentrations.	An anaerobic zone with minimal levels of oxygen or nitrate is required; therefore, if ammonia is removed by nitrification, a denitrification processes may also be required. Process design and control are critical: volatile fatty acids (either in the wastewater or from other processes, such as a fermenter) are required, and phosphorus removal efficiencies may be negatively affected if mixed liquor or sludge is held for an extended period of time in anaerobic conditions. Possibility of additional struvite formation in sidestream piping in processes that use anaerobic digesters for sludge treatment.	[1], [4], [42]
Liquid	Biological	Biological nutrient removal (BNR)	Aerobic granular sludge (AGS)	Organic matter, nitrogen and phosphorus removal	Small process footprint, well settling and dewatering sludge, can adsorb heavy metals	Few full-scale demonstrations in North America	[43], [44]
Liquid	Bio-physical	Membrane bioreactors (MBR)		Organic matter and nutrients (nitrogen and phosphorus)	Non-potable water recycling (toilet, etc.), more cost effective in larger scales, VOC, EDC, antibiotics, micropollutant and micro plastics removal, potential for sludge reduction	High energy demand and associated GHG emissions, high costs, fouling, not very efficient in VOC removal, not cost effective for phosphorus removal and sludge reduction	[4], [11], [29], [37], [45]
Liquid	Bio-physical	Membrane bioreactors (MBR)	Membrane aerated bioreactors (MABR)	Air supplied by membranes. Simultaneous nitrification-denitrification favored	Reduced aeration energy costs, compact process for process retrofit. Trace contaminants removal	Fouling, biomass control	[46]
Solid	Physical	Thickening	Gravity (Co-settling in primary clarifiers or in separate dedicated clarifiers)	Removal of some water from settled solids, preparation for further solids treatment	Co-settling reduces the need for an additional clarifiers and may save space when gravity thickening is used	Co-settling may impact the performance of primary clarifiers; gravity thickening of waste activated sludge from second clarifiers alone may provide poor solids concentration	[1]

Stream	Process category	Technology	Description	Concerns addressed	Co-benefits	Trade-offs	References
Solid	Physical	Thickening	Dissolved air flotation (DAF)	Removal of some of the water from solids, preparation for further solids treatment	Enhancement of removal of small and light particles, relatively small foot print	Non-ideal behavior of reactors (short circuiting, etc.), energy intensive compared with gravity thickening, mechanical equipment maintenance.	[1]
Solid	Physical	Thickening	Mechanical (belt thickener, drum thickener, etc.)	Removal of some water from settled solids, preparation for further solids treatment	May allow higher solids concentrations (i.e. more water may be removed)	Mechanical equipment maintenance; energy costs	[1]
Solid	Physical	Dewatering		Removes water from sludge, may be required prior to reuse/disposal, depending on the reuse/disposal method	Reduces the volume and weight of sludge that needs to be transported, dewaters sludge can be easier to handle than thickened or liquid sludge	Energy requirements to run the dewatering process, chemical conditioning required for many types of processes, pilot testing/comparisons important when selecting process	[1]
Solid	Physical	Dewatering	Mechanical (centrifuge)	Removal of water from thickened solids	Dewatered sludge	Mechanical equipment maintenance; energy costs, chemicals needed for improved flocculation	[1]
Solid	Biological	Hydrolysis (biological)	Biological hydrolysis under anaerobic conditions	Enhancement of dewatering and digestion of sludge (pre-treatment of anaerobic sludge digestion)	Biogas and energy recovery, increased solubilisation of the organic matter in the sludge	Efficiency impacted by pH and SRT	[47]
Solid	Biological	Stabilization	Anaerobic digestion	Organics, nutrients, volatile suspended solids (VSS), pathogens	Methane and CO_2 production, energy recovery, reduction of GHG, secondary biological treatment for high BOD (replacing activated sludge)	Relatively long retention time, need of high temperature	[1], [48]
Solid	Biological	Stabilization	Aerobic sludge digestion. May be autothermal	Organics, nutrients, pathogens	Enhancement of ammonium nitrogen removal (with use of pure oxygen)	Removal efficiency is temperature dependent energy intensive	[1], [48], [49]
Solid	Biological	Stabilization	Composting	Volatile suspended solids (VSS), pathogens	Land applicable solids	Odors to control	[1]

Stream	Process category	Technology	Description	Concerns addressed	Co-benefits	Trade-offs	References
Solid	Thermal	Hydrolysis (thermal)	High temperature and pressure	Enhancement of dewatering and digestion of sludge (pre-treatment of anaerobic sludge digestion)	Biogas and energy recovery, can be enhanced by addition of polymers (thermos-chemical hydrolysis), enhance pathogen reduction	High energy and associated GHG emissions and costs, efficiency impacted by pH and SRT, thermo-chemical hydrolysis is impacted by pH and hydrophobicity of polymers	[50], [51]
Solid	Thermal	Incineration (advanced thermal oxidation)		Reduction of solids mass and volume, removal of organic contaminants present in the solids (including potential EDCs, pharmaceuticals, toxic organics, etc.), destruction of pathogens	Processes can be designed to be self-sustaining (i.e. not require a continuous external fuel source) and can be used to generate heat/energy from the biosolids. Reduced transportation/ disposal costs of solids due to reduction in solids mass/volume. While residual ash is usually landfilled, it may be possible to reuse it for other purposes, such as filler in cement manufacturing or as daily landfill cover.	Even self-sustaining systems require an external fuel source to start up the system and may require one in case of process upset. Exhaust gas must be treated to ensure that air quality requirements are met. Systems can be complex and have high capital costs. A higher level of sludge dewatering may be required to prepare sludge for incineration. Feasibility is impacted by upstream solids processes and the constituents present in the solids; more energy is available in non-digested solids.	[1], [52]
Side	Physico-chemical	Ammonia stripping and recovery	High pH stripping of ammonia and recovery with an acid	Nitrogen	Nitrogen-rich end product. No backwash	Energy requirement and maintenance (pumps), not applicable in freezing conditions, potential of air quality deterioration, pH adjustments by lime may be needed, clogging of stripping tower typically due to crystallization	[53]
Side	Chemical	Struvite or hydroxyapatite formation		Phosphorus, minimizes process equipment clogging from struvite precipitation	Phosphorus and, in the case of struvite, nitrogen are recovered in a solid form that can be used as a fertilizer. May help improve overall phosphorus removal in enhanced biological phosphorus systems.	Additional energy required to run the process. Additional costs associated with process chemicals (e.g. magnesium salts and chemicals for pH control). A seed material (e.g. sand) may need to be continuously added in systems that remove phosphorus as hydroxyapatite.	[1], [4]

Stream	Process category	Technology	Description	Concerns addressed	Co-benefits	Trade-offs	References
Side (Liquid)	Biological	Anaerobic ammonium oxidation (anammox)	After partial nitrification of ammonia to produce nitrite, N_2 is produced. May be used in the Liquid line	Nitrogen	Enhanced removal of nitrogen, lower oxygen demand than for nitrification, no organic matter required as for denitrification	Emission of nitrous oxide (GHG), efficiency affected by redox condition	[54]

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