Canadian Water Network

Investigation of green chemistry treatment options to address Chemicals of Mutual Concern in landfill leachate

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Contents

This publication has been prepared for the Great Lakes Harmful Pollutants section of Environment and Climate Change Canada team using a diverse range of source materials, including inputs from Canadian municipalities, water utilities, academic institutions, and technology companies based in Canada and the U.S., as well as a comprehensive scan of relevant literature. It is intended to serve as non-authoritative guidance, developed with the best knowledge and expertise available. CWN and the authors have made reasonable effort to ensure the accuracy of the information within but have not performed independent technical evaluations of the technologies mentioned in this report. The inclusion of any technology does not constitute an endorsement or recommendation. Any decision related to the selection or use of any technology mentioned in this report is the sole responsibility of the reader. CWN and the authors do not assume responsibility or liability for any consequences, direct or indirect, that may arise from such use.

Glossary

Ammonia nitrogen (NH_3-N): Includes both ammonium (NH_4^+) and ammonia (NH_3). Ammonia is a common toxicant derived from wastes, fertilizers and natural processes. Ammonia is a common cause of fish kills and can cause eutrophication (heavy plant growth) (EPA, 2024).

Biological Oxygen Demand (BOD): The amount of oxygen consumed by microorganisms while they are breaking down organic matter under aerobic conditions (e.g. wastewater) (EPA, 2012). BOD is used in wastewater treatment plants as an index of the degree of organic pollution in water (Tuser, 2021).

Chemical Oxygen Demand (COD): The amount of oxygen required to oxidize soluble and particulate organic matter in water. Higher COD levels will reduce DO levels, which can be detrimental to aquatic health (Real Tech, 2017). COD is used in wastewater treatment plants as an index of the effect discharged wastewater will have on the receiving environment.

Dissolved Oxygen (DO): Oxygen measured in its dissolved form; if more oxygen is consumed than is produced, DO levels decline and can cause sensitive aquatic animals to move away, weaken or die (EPA, 2012).

Dissolved Organic Carbon (DOC): Organic matter that can pass through a filter size ranging from 0.7 to 0.22 microns (Bruckner, n.d.). DOC can cause issues in wastewater when it provides precursors for disinfection by-product formation. DOC can also provide a carbon or energy sources for microorganisms and biofilms in receiving water (Pipe-Martin, 2008).

Fouling: Fouling is the adsorption and accumulation of organics on surfaces, for example, resins, membranes, and leachate collection systems. This accumulation of organics reduces the function of the material or equipment being used (Tuser, 2021). Biofouling is fouling caused by the attachment of microorganisms following the development of biofilm layers on surfaces (Bachosz et al., 2022).

Green chemistry: The design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances. Green chemistry applies across the life cycle of a chemical product, including its design, manufacture, use, and ultimate disposal (EPA, 2023).

Green engineering: Practices that reduce waste and hazards during the entire life cycle of a material, product, process or system (EPA, 2023)

Green technology standards: CWN streamlined the 24 principles of green chemistry and green engineering into seven standards. Each standard encapsulates one or several green chemistry or green engineering principles, and this was done to simplify the process of analysis of each technology.

Humic substances (HS): Naturally occurring mixture of organic compounds that can be derived from any organic materials, including plant and animal debris, microfauna, biowastes, and pesticides. Humic substances are considered refractory organic compounds, and include humic acids, fulvic acids, and humin (International Humic Substances Society, 2007). HS can significantly affect the behaviour of some pollutants – for example, toxicity, adsorption, and disinfection. HS extracted from leachates may have a higher content of carbon, hydrogen and nitrogen (Kang et al., 2002).

Landfill leachate treatment: Biological, chemical, or physical-chemical processes that remove or destroy contaminants from landfill leachate. Individual treatment technologies may be combined as part of a "treatment train" to more effectively remove or destroy contaminants.

Refractory organic compounds: Also called recalcitrant organic compounds, these refer to a variety of organic compounds that are poorly biodegradable and/or exhibit a low value for the ratio of BOD to COD (Copa et al., 2004). Refractory organic compounds are not always broken down following leachate treatment, and include fulvic and humic-like acid substances, (Jiang et al., 2019).

Total Suspended Solids (TSS): Waterborne particles that exceed 2 microns in size. TSS are comprised mostly of inorganic materials, as well as some algae and bacteria. High TSS may decrease DO levels and increase water temperature, which can be detrimental to aquatic life. TSS in drinking water can negatively impact human health in various ways (Campbell, 2021).

1. Executive summary

In Canada, landfill waste produces leachate, a liquid concentrated in contaminants that is often treated at local municipal wastewater treatment plants. However, treatment levels vary and can still leave harmful contaminants in the wastewater effluent. Rather than focusing solely on wastewater treatment of contaminants, there are opportunities to address concentrated sources of priority contaminants at point sources, such as in landfill leachate. In support of the Great Lakes Water Quality Agreement to protect water quality, Environment and Climate Change Canada contracted CWN to explore landfill leachate treatment technologies that can treat Chemicals of Mutual Concern while considering green technology standards. This project involved communicating with experts from Canadian municipalities and water utilities, academia, and Canada and U.S.-based technology companies to understand leachate management trends and considerations and information on leachate treatment technologies that address Chemicals of Mutual Concern, in particular PFAS.

The literature scan from this project has demonstrated that there is very limited research in the field of landfill leachate treatment of Chemicals of Mutual Concern. Insights from the communication with experts and literature scan have helped CWN identify nine technologies that are effective or have the potential to be effective at treating some Chemicals of Mutual Concern, in particular PFAS, in landfill leachate. These technologies follow some green technology standards. The technologies are:

1. Adsorption, ion exchange and anion exchange.
2. Granular activated carbon.
3. Foam fractionation
4. Electrochemical oxidation
5. Advanced oxidative processes
6. Ozonation
7. Reverse osmosis.
8. Natural coagulants
9. Constructed wetlands.

The outcomes from this project reinforce the need for further research and monitoring to identify opportunities for landfill leachate treatment processes and explore sustainable leachate disposal and destruction options.

2. Introduction

In Canadian communities, most of the solid waste is collected and disposed of in landfills. Although most of the material stays on-site, rainfall and snow melt infiltrate and pass through the waste materials, collecting chemical and biological constituents in the form of leachate. This leachate is a complex liquid of concentrated contaminants sometimes treated on-site, but are more commonly transferred to the local municipal wastewater treatment plant.

Across Canada, the level of treatment for the removal of contaminants from wastewater is limited and can vary. As such, wastewater effluent has the potential to have harmful impacts on ecosystem and human health. Further, advanced treatment does not address all contaminants of concern. Upgrading wastewater treatment is expensive and lengthy for municipalities, due to the high investment costs and the effort required to design effective infrastructure that must meet regulatory requirements and achieve a long lifespan. Despite this, regulators and water managers continually strive to better understand how to address these lingering contaminants, in addition to the co-benefits that can accompany new treatments. The presence of contaminants in treated landfill leachate and wastewater treatment plants' effluents indicate there is a need to mitigate and manage harmful chemicals from a point source before they enter natural waterways.

While conventional technologies can be effective at removing contaminants from leachate, concerns remain about the environmental impacts of persistent, bioaccumulative and toxic contaminants found in most leachate. There is growing interest in research and technology development around the applications of green chemistry, representing a more holistic approach to addressing environmental and human health challenges associated with chemical substances used in society.

In 2023, the Great Lakes Harmful Pollutants section of Environment and Climate Change Canada (ECCC) team contracted CWN to undertake a study exploring the current state of green chemistry as it relates to the treatment of landfill leachate, with a particular focus on Chemicals of Mutual Concern (CMCs) in landfill leachate. The objectives of this study were to:

1. Investigate the current state of green chemistry as it pertains to the treatment of landfill leachate prior to its acceptance for co-treatment at a wastewater treatment plant.
2. Create a searchable and sortable inventory of technologies that have the potential to effectively treat landfill leachate while following green technology standards.

This high-level white paper will inform ECCC of opportunities to better protect Canadian waterways (particularly the Great Lakes) by reducing harmful impacts of wastewater. ECCC policy and decision-makers may benefit from the insights shared in this paper to inform on potential technologies that may be studied, piloted or explored in the future.

2.1 Scope and limitations of the study

The paper focuses on technologies that may treat CMCs, in particular PFAS compounds, noting possible co-benefits for the removal of other landfill leachate contaminants. The paper provides an overview of some of the advantages and disadvantages of the technologies but does not include a detailed review or recommendations of the regulatory constraints of municipalities to update new technologies. The paper does not perform calculations or other methods to verify the information from literature scans, surveys, and interviews.

This white paper provides an overview of the main drivers for the study (section 3), the project methodology (section 4), brief background on current approaches to landfill leachate treatment (section 5), overview of green chemistry in the context of landfill leachate treatment (section 6), and findings on landfill leachate treatment technologies that may treat CMCs while following green technology standards (section 7). Also included are opportunities and knowledge gaps that can further inform decision-making and next steps (section 8), and high-level conclusions (section 9). Appendix 1 contains a summary of practice insights, Appendix 2 provides a summary of common landfill leachate treatment approaches, and Appendix 3 refers to the Technology Database.

The practices and perspectives shared by the fourteen surveyed municipalities are their own insights and do not necessarily represent the entire Canadian municipal landscape. While CWN uses reasonable efforts to provide accurate information in this white paper, the insights shared by experts, practitioners and company information materials have not been independently verified. Although the information discussed has been provided from sources believed to be reliable, the scope of this project does not verify its accuracy or reliability.

3. Background

3.1 Great Lakes Water Agreement

The Great Lakes Water Quality Agreement (GLWQA), signed in 1972 and modernized in 2012, is an agreement between Canada and the U.S. Through the GLWQA, the two countries work together through various levels of government, First Nations and Métis organizations, businesses, non-governmental organizations, and the public to restore and protect the water quality of the Great Lakes (Binational.net, 2024). The 2012 agreement focuses on restoring and protecting the Great Lakes with the objectives of being a source of safe, high-quality drinking water, allowing for recreational use, and allowing for human consumption of fish and wildlife (ECCC, 2022).

3.2 Chemicals of Mutual Concern

In consideration of the GLWQA objectives, eight chemicals have been designated under the GLWQA as Chemicals of Mutual Concern (CMCs). These chemicals are listed in Table 1, along with their characteristics:

Table 1. Chemicals of Mutual Concern.

Chemical name	**Primary use**	**Known presence in leachate**	**Toxicity**
Hexabromocyclododecane (HBCD)	Flame retardant	Limited data; presence in leachate may be limited due to low water solubility (Binational.net, 2017)	May be harmful to the environment or biological diversity (ECCC, 2023c).
PFAS: Long-chain perfluorinated carboxylic acids (LC-PFCAs)	Repellent	PFAS are generally observed in high concentrations in landfill leachate (Gewurtz et al., 2023; O'Connor, 2022).	May have a harmful effect on the environment or biological diversity, and may have health impacts (ECCC, 2023b).
PFAS: Perfluorooctanoic acid (PFOA)	Repellent	PFAS are generally observed in high concentrations in landfill leachate (Gewurtz et al., 2023; O'Connor et al., 2022).	May have a harmful effect on the environment or biological diversity. May cause developmental effects in children, as well as cancer, liver, immune and thyroid effects (Government of Canada, 2023b).
PFAS: Perfluorooctane sulfonate (PFOS)	Repellent	PFAS are generally observed in high concentrations in landfill leachate (Gewurtz et al., 2023; O'Connor et al., 2022).	May have a harmful effect on the environment or biological diversity. May cause developmental effects in children, as well as cancer, liver, immune and thyroid effects (Government of Canada, 2023b).
Mercury	Industrial applications	Present in landfill leachate (D. MacLennan, personal communication, March 4, 2024)	Varying human health impacts; Canadians not at risk of mercury poisoning, with the exception of those who consume large amounts of fish, marine mammals and wild game (Health Canada, 2021).
Polybrominated Diphenyl Ethers (PBDEs)	Flame retardant	Present in landfill leachate (Li et al., 2012)	Varying human health impacts, including neurodevelopmental toxicity, weight loss, and

			endocrine disruption (Binational.net, 2019).
Polychlorinated Biphenyls (PCBs)	Industrial applications	Present in landfill leachate (Arp et al., 2020)	Health impacts on aquatic ecosystems and in species that eat primarily aquatic organisms. Human health impact not known, but classified as probable human carcinogen (Health Canada, 2010).
Short-Chain Chlorinated Paraffins (SCCPs)	Lubricant, coolant plasticizer, fire retardant	Presence in landfill leachate may be negligible due to the strong binding capacity to soils (Binational.net, 2021). ECCC data sources have determined a presence in landfill leachate (D. MacLennan, personal communication, March 4, 2024)	Potential concern to the environment. Human endocrine disruptors, considered possibly carcinogenic (Health Canada, 2009).

As shown in Table 1, three of the CMCs, LC-PFCAs, PFOA, and PFOS, are categorized within the group called per- and polyfluoroalkyl substances (PFAS) that encompasses over 4,700 human-made substances (Health Canada, 2023). Several CMCs are present in a wide range of concentrations in landfill leachate, with studies indicating that PFAS compounds have notably higher concentrations than other contaminants (thousands of ng/L) (Gewurtz et al., 2023; O'Connor et al., 2022). HBCD is theorized to present negligible concentrations in landfill leachate due to its chemical characteristics.

Assessment conducted under the Canadian Environmental Protection Act (CEPA) has determined that some CMCs may have harmful effects on the environment or biological diversity, while all CMCs may have or have known harmful human health effects, for example, acting as possible carcinogens or endocrine disruptors. In consideration of these environmental and human health risks, numerous researchers, municipalities and companies in Canada and worldwide are looking at treatment options for the removal of CMCs from landfill leachate and wastewater, before entering waterways. This paper focuses on treatment opportunities of CMCs in landfill leachate. As current research and technologies focus on PFAS treatment, this study highlights PFAS treatment options and profiles other select CMC treatment technologies.

3.3 Green chemistry lens on treatment technologies to address CMCs

While there are technologies that exist which can be effective at removing CMCs, the environmental impacts of some of the processes, including the use of toxic chemicals, single use materials, concentrated waste disposal impacts and other waste issues can introduce additional problems that need to be mitigated. For these reasons, green chemistry principles can be used to guide decision-making around which technologies appropriately balance effectiveness with minimal environmental impact.

The U.S. EPA (2023) defines green chemistry as "the design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances. Green chemistry applies across the life cycle of a chemical product, including its design, manufacture, use, and ultimate disposal." Green chemistry aims to reduce pollution at the source by addressing potential hazards of chemical products and ensure that there are no residuals of persistent chemicals.

Green chemistry includes the following twelve principles (EPA, 2023):

1. Prevent waste by designing chemical processes that prevent waste production and the need for treatment or remediation.
2. Maximize atom economy, which means that the final product contains no more than the equivalent proportion of the starting materials.
3. Design less hazardous chemical processes that use and generate substances with minimal toxicity to human or environmental health.
4. Design safer chemicals and products that have minimal toxicity.
5. Use safer solvents and reaction conditions.
6. Increase energy efficiency.
7. Use starting materials that are renewable, rather than depletable.
8. Avoid chemical derivatives, which use additional reagents and generate waste.
9. Use catalysts instead of stoichiometric reagents to minimize waste.
10. Design chemical products that degrade so that they do not accumulate in the environment.
11. Analyze and monitor chemical processes in real-time to prevent pollution.
12. Minimize the potential for accidents (explosions, fires, releases to the environment).

Green chemistry principles can bring several benefits to leachate treatment processes, including reducing human exposure to toxic chemicals, increasing water quality, reducing disruptions to ecosystems, and reducing demand for landfill space (EPA, 2023). While green chemistry principles present several important considerations for selecting green technologies, the reality is that many of the emerging technologies that treat landfill leachate of CMCs and other contaminants do not address all of the principles. In consideration of environmental principles beyond green chemistry, this project reviews opportunities for technologies to address green engineering principles as well.

Building from green chemistry principles is the concept of green engineering. Green engineering focuses on reducing waste and hazards during the entire life cycle of a material, product, process or system (Centre for Green Chemistry and Green Engineering at Yale University, 2017). Green engineering includes the following principles (EPA, 2023):

1. Holistically using systems analysis and integrated environmental impact assessment tools.
2. Conserving and improving natural ecosystems while protecting human health and well-being.
3. Apply life-cycling analyses.
4. Ensuring that materials and energy inputs and outputs are as safe and benign as possible.
5. Minimizing depletion of natural resources.
6. Preventing waste.
7. Considering local geography, aspirations and cultures.
8. Innovating beyond current technologies.
9. Actively engage communities and stakeholders in the development of engineering solutions.

This study considered both the green chemistry and green engineering principles as a lens in assessing technologies which address CMCs in landfill leachate, as an additional layer of assessment. For the purpose of this review, these principles were further streamlined into 7 green technology standards, which are outlined in Section 6.

4. Project methodology

The generation of this white paper and associated technology database comprised of two primary research tasks:

1. Communication with academic experts and municipal members of CWN's Municipal Consortium
2. Literature scan

4.1 Communication with experts in the field

The CWN team connected with experts and practitioners from the following sectors:

1. Canadian municipalities and water utilities
2. Canadian academia
3. Canadian and U.S.-based technology companies

Key insights from this work are highlighted throughout, and a compiled summary of practice insights is presented in Appendix 1.

4.1.2 Canadian municipalities and water utilities

Through CWN's Canadian Municipal Consortium network, CWN emailed twenty municipalities and water utilities, requesting responses to survey questions. The objective of the survey was to understand the general trends around leachate management across Canada, the level of interest by municipalities to adopt leachate treatment technologies, and current efforts to treat CMCs in leachate or wastewater.

The survey questions were:

1. How is the landfill leachate from the local area landfill handled?
2. What are your main concerns with respect to landfill leachate?
3. Who are the contacts to follow up with on this topic?

Of the twenty municipalities and utilities contacted, fourteen responded to the survey questions. CWN scheduled follow-up virtual calls with six of the respondents, with the objective of gaining more in-depth insights. Follow-up virtual call questions included:

1. What would drive your organization to explore opportunities to pre-treat landfill leachate?
2. What are key considerations for landfill leachate treatment if you were to implement it?
3. What considerations would you have for monitoring landfill leachate for CMCs?
4. Are there municipal or private landfills that you are aware of that are exploring leachate treatment, in particular technologies featuring green chemistry.

4.1.3 Canadian academia

CWN included academia as part of its communication strategy to experts, with the goal of understanding the current focus of research on leachate and CMC-targeted treatment, as well as receiving direction on research institutes of interest. One university researcher from the University of Waterloo whose expertise lies in PFAS provided insights over a virtual call, discussing the difficulty of treating PFAS due to their chemical properties, including their hydrophilic nature. The researcher shared knowledge on potential technologies for treating PFAS in leachate and general thoughts on the effectiveness of landfill leachate treatment in reducing overall PFAS concentrations in effluent.

4.1.4 Canadian and U.S.-based technology companies

CWN arranged virtual calls with three technology companies that treat landfill leachate to gain insight into the benefits and challenges associated with the treatment systems, effectiveness at treating CMCs in leachate, and opportunities to apply green chemistry principles to the technologies. The following questions were discussed with the company representatives:

1. How is the system operated?
2. Which contaminants does the system treat for?
3. Why are you targeting certain chemicals?
4. How is residuals management handled?
5. What are the operational complexities?
6. What has been the general uptake of the technology?
7. How does your system apply green chemistry principles?

4.2 Literature scan

CWN undertook a comprehensive literature scan, drawing from Canadian and international scientific research studies that focus on:

- Landfill leachate treatment
- Technologies to remove CMCs
- Technologies that apply green chemistry principles to remove CMCs

The literature was also sourced from government agencies, non-profit agencies, and technology companies. In general, the research field of the effectiveness of leachate treatment technologies is not as commonly investigated as the effectiveness of wastewater treatment. Further, the literature scan found that there is very limited research that focuses specifically on technologies that follow green chemistry principles for removing CMCs from landfill leachate. By and large, PFAS are the most researched contaminant group of CMCs in landfill leachate treatment and wastewater treatment.

5. Current approaches to landfill leachate treatment

5.1 Characterization of landfill leachate

Landfill leachate is produced by water moving through a landfill, usually from rainfall or snowmelt. When this water escapes from the landfill, it brings with it contaminants that fall within four categories (Mojiri et al., 2021):

1. Organic contaminants and substrates
2. Inorganic compounds
3. Heavy metals
4. Total dissolved solids and colour

Age (years)	Young 0–5	Intermediate 5–10	Old >10
pH	<6.5	6.5–7.5	>7.5
COD (mg/L)	>10,000	5,000–10,000	<5,000
BOD_5/COD	0.5–1.0	0.1–0.5	>0.1
NH_3–N (mg/L)	<400	–	>400
H.M	Medium to low	Low	Low
VFA/HFA	VFA (80%)	VFA (5–30%) + HFA	HFA (80%)
Biodegradability	High	Medium	Low

H.M, heavy metals; VFH, volatile fatty acids; HFA, humic and fluvic acids.
(Sources: Aziz 2012; Yadav & Dikshit 2017; Tejera *et al.* 2019).

Figure 1. Leachate characteristics and treatability based on the landfill age (Mojiri et al., 2021).

As highlighted in Figure 1, the specific characteristics, including contaminant prevalence and concentrations of different parameters found in landfill leachate can vary depending on the age of the landfill. Refuse composition, moisture content, and seasonal factors such as temperature and precipitation can additionally impact these parameters (Teng, 2021). Table 1 in Section 3.2 highlights the potential presence of CMCs in landfill leachate. However, due to the high variability of leachate composition, individual landfill leachate monitoring is necessary to make this determination.

The practice insights and literature review indicated that the driving force for treatment comes from a facility's permit, provincial regulations, or requirements imposed by the wastewater treatment plant that accepts the waste. The contaminants that tend to be the most regulated in terms of treatment requirements include organic contaminants (indicated by chemical oxygen demand (COD)), ammonia nitrogen (NH_3-N), phosphorus, suspended solids, hydrogen sulfide, heavy metals, total suspended solids, dissolved oxygen, E.coli, and colour. Refer to the Glossary for additional information.

Municipal, utility and academic contacts have also shared that some landfills are observing emerging complexities to leachate handling. For example, in recent years black sludge has become present in some leachate collection and pump systems, causing issues with the equipment. The sludge is made of a polymer that may be derived from meat packaging, feminine hygiene products, and incontinence garments (Yilmaz et al., 2023). If further investigation finds that the sludge is comprised of contaminants of concern, this may drive additional pressures to seek treatment options for the contaminants.

5.2 Landfill leachate treatment

Based on the practice insights gathered for this report, drivers for leachate treatment include complying with the local municipal sewer use bylaw and/or the provincial landfill permit. Sewer-use bylaws address concerns related to leachate impacting the sanitary network (e.g. corrosion, biofouling, odours), and flow rates and contaminant loadings that might impact the wastewater treatment plant performance, including treatment processes, regulatory effluent limits, and biosolids quality. Currently, some CMCs may be monitored in landfill leachate or in municipal wastewater treatment plant effluent, but limits are not enforced in municipal by-laws.

As highlighted in Figure 2, a range of treatment processes are available to treat leachate at public or privately owned landfills before its transfer to municipal wastewater treatment facilities or for discharge to natural waterways (note the focus of this paper is on treatment prior to discharge to municipal wastewater treatment plants). These processes vary in cost, operational considerations, and their effectiveness at treating different contaminants, and are often found in combination as part of a treatment train to optimize removals.

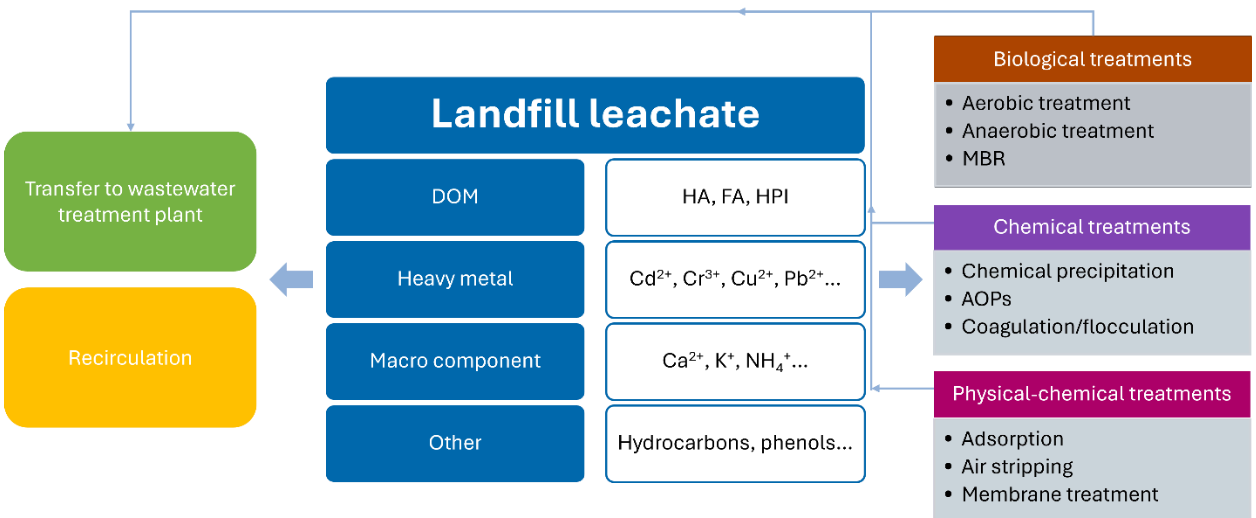

Figure 2. Common landfill leachate treatment methods (Teng, 2021).

Some considerations for landfill leachate treatment:

- Because of the drivers in place in the Canadian context and the cost-effectiveness, the most common approach to managing leachate is to not treat leachate prior to co-treatment at the local municipal wastewater treatment plant. Leachate is either conveyed from the landfill to the local wastewater treatment plant through the sanitary sewer system or hauled by truck.
- Generally, a higher level of leachate treatment occurs when leachate is discharged to natural waterways versus to a wastewater treatment plant for co-treatment. There is the potential that discharge limits of leachate to municipal wastewater systems may increase in light of growing environmental and health concerns regarding the trace amounts of persistent, bioaccumulative and toxic contaminants that leachate contributes to treated effluents (D. MacLennan, personal communication, March 4, 2024).
- As highlighted in the previous section, landfill leachate varies depending on the landfill age, composition, and other site-specific factors, and the appropriate treatment will depend on the characteristics and regulatory requirements.
- Aerated biological treatment is the most common approach for leachate treatment, based on communication with the utilities that are discharging to wastewater treatment plants for co-treatment.
    - The City of Montreal sends leachate from one of their landfills to an offsite leachate treatment plant for treatment prior to discharging to the sanitary sewer network for combined at a wastewater treatment plant. The treatment process is biological treatment technology called moving bed bio-reactor (MBBR) process to treat ammonia

    - nitrogen and hydrogen sulfide (proprietary treatment technology referred to as suspended media bioreactor (G. Szaraz, personal communication, January 25, 2024).
    - The City of Ottawa has an aeration pond prior to tanker haulage to wastewater treatment plant, to reduce hydrogen sulfide and some volatiles.
- Of the municipalities that responded to the survey, the City of Toronto is the only one that employs complete leachate treatment onsite (Green Landfill) prior to discharge to a local waterway instead of a wastewater treatment plant. Landfill leachate treatment employs a combination of physiochemical removal processes followed by biological treatment, ozone oxidation and filtration and a polishing engineered wetland (S. Little, personal communication, January 19, 2024).

Where treatment of landfill leachate is employed in comparable jurisdictions around the world, Appendix 2 provides an overview of common landfill leachate treatment methods, the contaminants they target, and advantages and disadvantages including their potential to address recalcitrant pollutants such as CMCs.

5.3 Removal of CMCs in landfill leachate

Based on the practice insights from municipal, research and technology experts in Canada and the U.S., the general consensus around CMCs is that they are by nature notoriously difficult to remove, degrade and destroy from waste streams when conventional technologies are employed. This is in large part due to the high degree of variability in the characteristics and composition of each contaminant. For example, the PFAS family alone is comprised of 4,700 different chemicals that have varying molecular structures (Government of Canada, 2023). Therefore, it is unlikely that a single treatment process or technology will address all the CMCs present in leachate, and a combination of treatment approaches would likely be required.

As presented in Table 1, HBCD is expected to be present in limited concentrations in landfill leachate and can be considered to not be priorities to treat. SCCPS, mercury, PBCDEs and PCBs are known to be present in leachate. Though the manufacturing of PCBs and PBDEs have been banned in Canada since 1977 and 2008 respectively, these chemicals are still found in leachate today due to their persistent nature and the continued use of materials containing these chemicals (McWatters et al., 2020; ECCC, 2017; ECCC, 2023d).

Removing PCBs from sediments and wastewater has been a priority in the past, driving certain companies to create technologies capable of removing PCBs from these sources (Regulated Materials Management, n.d.). PFAS (including LC-PFCAs, PFOA, and PFOS) have emerged as the primary contaminant of interest due to their persistent natures and tendencies to accumulate in water resources (Appleman et al., 2013).

Given the persistent nature of PFAS, in addition to the Canadian federal and provincial levels of government focusing on monitoring PFAS and the current development of PFAS drinking water objectives that will be included in updated national drinking water guidelines, studies on treatment technologies to remove CMCs in Canada is largely focused on PFAS. In addition, south of the border, there is also a significant focus of PFAS treatment in the U.S. and regulatory changes, which are driving research and technology development for on-site landfill leachate treatment technologies (N. Ganzon, personal communication, January 16, 2024).

5.3.1 PFAS monitoring activity in Canada

The Canadian federal government conducts various PFAS monitoring programs to advance knowledge on the presence of PFAS in ecosystems and wildlife across the country (ECCC, 2023a). These programs monitor ambient air, freshwater sites, and wastewater and biosolids. Leachate samples from thirteen large municipal solid waste landfills across Canada were collected between 2008 and 2014 to assess the presence of certain substances of concern. At least one PFAS was detected in all samples (J. Tessier, personal communication, March 15, 2024). Monitoring results also indicate that the concentration of certain PFAS generally increased following on-site leachate treatment (ECCC, 2023a). The increased concentrations may be attributed to the transformation of unmeasured precursors during treatment processes (ECCC, 2023a). In 2019 to 2020, the federal government analyzed six leachate samples from operational landfills and found that many of the 29 PFAS analytes were detected often (ECCC, 2023a).

More recently, as part of the Initiative to Protect and Recover Endangered Whale Populations, the Government of Canada sampled leachate from 10 operational municipal solid waste landfills in Canada over a four-year period (2019 to 2022) to determine the presence and concentration of specific substances, including certain PFAS, in landfill leachate (J. Tessier, personal communication, March 15, 2024; ECCC, 2023a). Currently, the Ontario Ministry of the Environment, Conservation and Parks is studying municipal landfills across Ontario, sampling PFAS from twenty landfills in the province. The study will provide insights into the presence and prevalence of PFAS in landfills of varying site conditions and landfill types, and will inform the provincial government's response to PFAS (Ontario Ministry of the Environment, Conservation and Parks, 2023).

In addition to provincial and federal programs, some Canadian municipalities have undertaken monitoring of PFAS in wastewater. For example, York Region recently collaborated with the Ontario Ministry of Environment, Conservation and Parks to investigate the presence of PFAS in various industrial processes and products (Payne et al., 2024); however, this monitoring is not routine and laboratory testing can be costly and complex. Therefore, it can be difficult to justify ongoing monitoring programs, and they are typically time-limited to particular research projects.

5.3.2 PFAS treatment technologies: opportunities and challenges

PFAS is a large family of thousands of diverse chemicals that exhibit a range of properties and characteristics, making it a challenge to predict their fate and behaviour (UKWIR, 2022), and to find a single technology that treats all of them. Further, some PFAS can biotransform into compounds that do not degrade in the environment, which complicates treatment approaches (UKWIR, 2022). PFAS possess a strong carbon-fluorine bond, which makes complete destruction a challenge. Incomplete destruction can result in the formation of new PFAS (EPA, 2020).

In general, applying conventional treatment techniques to PFAS is a challenge due to their persistence in the natural environment and tendency to accumulate in water resources (Appleman et al., 2013).

PFAS can be divided into two types of molecules: long-chains or short-chains. Long-chain PFAS have hydrophobic tendencies and higher sorption potentials than short-chain PFAS. Because short-chain PFAS have hydrophilic tendencies, low hydrophobicity, high solubility, and decreased sorption potential, removing these molecules can be a challenge (Chyi En We et al., 2024). Long-chain PFAS, including PFOS and PFOA, are being phased out of the industry and replaced by short-chain PFAS, which may make it an even greater challenge to treat PFAS from landfill leachate in the future (UKWIR, 2022).

According to the Solid Waste Association of North America (SWANA), the most common on-site landfill leachate treatment technologies to remove PFAS in North America include:

1. **Adsorption and ion exchange.** Ionic forces are used to bind the PFAS molecule to the surface areas of adsorption materials, such as iron and aluminum (SWANA, n.d.).
2. **Granular Activated Carbon (GAC).** PFAS is transferred from the liquid phase into solid media, similar to adsorption but without chemical degradation or transformation (SWANA, n.d.). Landfill leachate passes through a bed of GAC, resulting in the PFAS molecules adsorbing to the carbon surface (Aclarity, 2023).
3. **Reverse osmosis.** Removes most contaminants, including PFAS, by forcing the liquid under pressure through a semi-permeable membrane (SWANA, n.d.).

These technologies may be more effective when used as part of treatment trains and are discussed in greater detail in Section 7.

5.3.3 Environmental and health impacts of PFAS treatment technologies

Adsorption and GAC technologies use separation approaches to remove contaminants, rather than degrade or destroy them; residual management of treatment by-products and waste streams becomes an issue that landfill operators must address. Technologies such as GAC require consumable materials that must be replaced, further compounding the issue of waste disposal. Aclarity (2023) also notes that GAC materials, once used, must be properly disposed of to avoid the potential re-release of PFAS into the environment. PFAS possess a strong carbon-fluorine bond, which makes complete destruction a challenge. Incomplete destruction can result in the formation of new PFAS (EPA, 2020).

Current methods of contaminated residuals disposal include:

- **Underground injection**, where PFAS in liquids are stored underground. Limitations of this approach can be attributed to costs associated with the location and transportation. In the U.S., PFAS are injected into Class 1 wells with geologic formations below the lowermost underground sources of drinking water (EPA, 2020). The fate and transport of PFAS in the injection zones are not well understood, and can vary depending on the PFAS chemical properties, interactions with co-contaminants, and the properties of the injection zone (EPA, 2020).

- **Thermal treatment**, where PFAS are incinerated at high temperatures (greater than 1000°C (Government of Canada, 2023)). Incinerator options include hazardous waste combustors, carbon reactivation units, non-hazardous waste combustion, and thermal oxidizers (EPA, 2020). To effectively break the strong carbon-fluorine bond in PFAS, these systems must provide high concentrations of hydrogen radicals, or flames, to ensure the complete degradation of PFAS molecules to carbon dioxide and hydrogen fluoride. If the concentration of hydrogen radicals is too low, the carbon-fluorine fragments may recombine (EPA, 2020). In Canada, municipal solid waste incinerators reach sufficient temperatures to break down fluorinated compounds, including PFAS, though further investigation is required to determine what residence time is required to completely destroy PFAS compounds (Government of Canada, 2023). It is estimated that approximately 4% of all the PFAS in Canada is sent to and destroyed in incinerators while the remaining 96% ends up in landfills (Government of Canada, 2023). Like underground injection, there is limited information about how effective high-temperature treatment is at completely destroying PFAS. In addition, thermal treatment systems may result in the creation of byproducts of concern, such as fly ash.

- **Landfill PFAS waste streams**. After treatment to remove PFAS from leachate, the contaminated waste or wastewater may be returned to the same landfill or another hazardous waste site. One technology company stated in an interview that while landfilling is not be ideal, the reality is that landfills are inexpensive and effective at keeping PFAS trapped until new technologies for destruction emerge.

Considerations must also be made of the health risks that these sites can have on vulnerable populations in adjacent communities and those who work on or near the sites. Vulnerable populations can include low-income, minority and Indigenous groups, and children (EPA, 2020).

6. Application of a green chemistry lens on treatment technologies to address PFAS and other CMCs

While there are technologies that can be effective at removing PFAS and other target contaminants from leachate, concerns remain about the environmental impacts of some of the processes, including the use of toxic chemicals, single use materials, concentrated PFAS disposal impacts and other waste issues. For these reasons, green chemistry principles can be used to guide decision-making around which technologies appropriately balance effectiveness with minimal environmental impact.

In reviewing the potential effectiveness of conventional technologies in treating landfill leachate, CWN applied a green chemistry and green engineering lens. Many technologies offer promising qualities that support green chemistry and green engineering. For example, one technology company interviewed identified key environmental sustainability priorities that are the focus of their business. These priorities include preventing waste, increasing energy efficiency, using catalysts that carry out a reaction more than once (instead of stoichiometric reagents), conducting analysis in real-time, and minimizing the potential for accidents. Still, all these technologies have used processes that to some degree have environmental and human health impacts, for example, requiring the use of single-use or consumable materials, are energy-intensive, and produce large volumes of waste. As discussed in this paper, most existing and emerging technologies do not destroy, and instead remove contaminants, which raises the question of how to dispose of and completely destroy the contaminants of interest. All these environmental impacts, positive and negative, must be considered when weighing the application of treatment technologies. As such, CWN streamlined the 24 principles of green chemistry and green engineering into seven standards. Each standard encapsulates one or several green chemistry or green engineering principles, and this was done to simplify the process of analysis of each technology. No one technology can meet every principle, and some principles overlapped in practice. These standards are as follows:

1. A treatment technology will qualify for this standard if the treated effluent/waste streams from the process has low to no targeted CMCs present.
2. A treatment technology will qualify for this standard if CMCs are still present in the effluent/waste streams after the treatment process but are concentrated to improve the efficiency of their further management.
3. Treatment technologies which consider the full life cycle of any outputs, including re-use and proper disposal, would qualify for this standard.
4. A treatment technology will qualify for this standard if, in the case that a treatment technology requires any additives (in the form of solution, raw materials, reagents, or others), those

additives must be renewable, non-toxic, non-hazardous and not persist in the environment after the treatment. Additionally, a treatment technology can qualify for this standard if any inputs or additives are locally sourced or have the possibility of local sourcing.

5. Treatment technologies that have relatively low energy requirements would meet this standard. Technologies which maximize energy efficiency would also meet this standard.
6. Treatment technologies that opt for a catalytic reaction (which occurs when a substance is added to a chemical reaction that increases the rate of reaction without being chemically changed) when there is the option of using stoichiometric reaction would qualify for this principle.
7. Treatment technologies that can be monitored in real-time will qualify for this principle. Technologies which are scaled appropriately to account for changes during treatment would also qualify for this principle. It should be noted that this principle has more to do with the design of the process from the municipality / company that is piloting the technology, as it is not integral to the technology itself.

The breakdown of how each treatment technology meets different standards as well as the different green chemistry and green engineering principles that apply to each standard can be found in Appendix 3.

7. Treatment technology opportunities

Following outreach with municipalities, academia and technology companies, as well as an extensive literature scan, CWN has identified nine conventional technologies that are currently used to remove or destroy PFAS from landfill leachate (or demonstrate promise), that support some green technology standards. These technologies may be most suitable when used as part of treatment train system, while others may be effective when used as standalone treatment options.

CWN has drawn from available literature and expert insights to provide some detail of each technology, however, further investigations are needed to fully comprehend their functionalities and characteristics. The focus of the following assessment of technologies is based on the individual process identified (e.g. adsorption, foam fractionation, etc.), not based on the full treatment train, although pre-treatment requirements are noted as part of the broader set of considerations. However, for this study green chemistry and green engineering assessments are made primarily on the technology outlined, not considering the full treatment train.

As mentioned earlier in this paper, there are very few studies that review the potential for landfill leachate treatment technologies to remove or destroy CMCs other than PFAS. The first seven technologies listed below are considered the most promising at treating PFAS and other CMCs, and the final two technologies demonstrate some potential to treat landfill leachate of CMCs but are not used for that purpose in practice or have undergone limited research on their removal effectiveness. All the technologies listed below offer sustainable features that support green technology standards. All the technologies listed below offer sustainable features that support green technology standards.

Detailed information about all nine technologies is listed in the technology database, Appendix 3: Technology database. The database provides the following detail for each technology:

1. Known CMCs (and other chemical constituents) addressed
2. Known companies that are using the technology
3. Green chemistry or green engineering qualifications

4. Additional considerations, including pre-treatment requirements, relative costs, operational complexity, co-benefits, and lifespan

As the database drew on limited available literature and insights, there are knowledge gaps that made it difficult to provide a more complete picture of the technologies. In particular, the availability of information on green chemistry and green engineering qualifications is sparse. CWN has used its discretion based on the available resources to fill these gaps.

7.1 Adsorption, ion exchange and anion exchange

Adsorption and ion exchange are some of the most common landfill leachate treatment options for removing PFAS (SWANA, n.d.). Adsorption is the transfer of pollutants from the liquid phase onto the surface of a solid phase. Ion exchange is the exchange of ions between a liquid and solid phase, causing pollutants to bond to the adsorbent for the removal of various contaminants (Jorgensen, 1989). Anion exchange combines principles of adsorption and ion exchange, whereby the resins are adsorbents with ion exchange functionality.

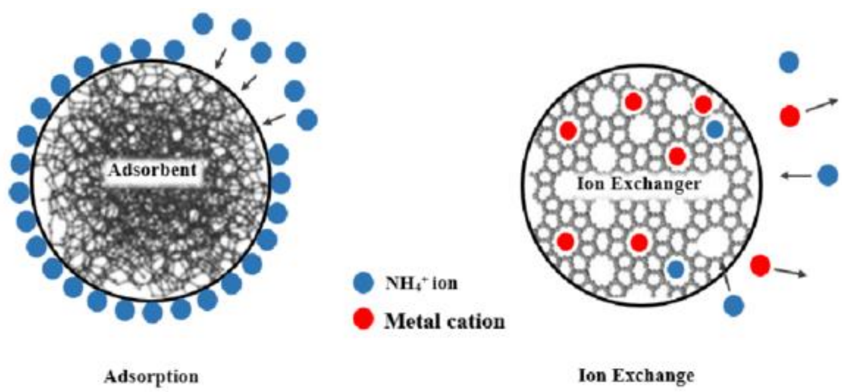

Figure 3. Adsorption and ion exchange for treating ammonium (Al Fami et al., 2022).

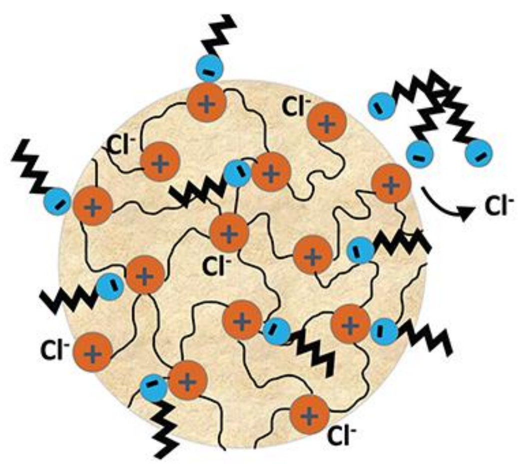

Figure 4. Anion exchange resin loaded with chloride designed to remove PFAS (Mayer, B., 2022).

Adsorption and ion exchange may require filtration prior to treatment or can be used in series with other technologies to increase effectiveness. Due to the complex nature of leachate, resins may face biofouling issues – the growth of biological organisms - reducing their ability to remove PFAS (LEEF, 2023).

Adsorption, ion exchange and anion exchange are considered to feature low operational complexities. When it comes to water treatment, these processes are quick to install, require less maintenance than other technologies (such as reverse osmosis) and have a relatively low initial investment (Atlas Scientific, 2022); given these characteristics in water treatment, there may be good reason to study the application of adsorption, ion exchange and anion exchange in leachate treatment.

Adsorption, ion exchange and anion exchange technologies rely on pumping, which supports the green technology standards of increasing energy efficiency (as compared to more energy-intensive technologies) and designing less hazardous chemicals processes that use and generate substances with minimal toxicity to human or environmental health. The specificity of a process is important in the realm of green chemistry and green engineering, with the preference being for processes to avoid derivatives or adding any potentially wasteful or unnecessary steps (EPA, 2023). Notably, ion exchange is a fast, specific reaction process compared to adsorption and requires a much shorter contact time between the resin and the contaminants. This short contact time means that a smaller system is needed, supporting green technology standards of preventing waste (Lenntech, n.d.). Resin regeneration is possible; however, in other cases resins and materials that collect the PFAS from the leachate must be disposed of, leaving the question of how the PFAS-concentrated resins can be disposed of in an environmentally-friendly manner (LEEF, 2023).

Given existing knowledge of the effectiveness of PFAS removal through adsorption, ion exchange and anion exchange, CWN suggests that these technologies may be effective at removing other CMCs, though further research would need to be explored to determine the effectiveness. Other contaminants, such as UV-absorbing substances and organic nitrogen, can be removed (Pathak, 2013). As discussed earlier in this section, SWANA states that adsorption and ion exchange are options for removing PFAS in leachate in North America, however, specific companies that use the technologies have not been identified through this review.

Anion exchange resins are more expensive than GAC but can exhibit faster adsorption of PFAS and a higher capacity for PFAS removal (LEEF, 2023). The reason for the increased effectiveness of PFAS removal through anion exchange versus GAC is that short-chain PFAS are hydrophilic. Ion exchange resins may have a longer life for PFAS removal (6-18 months) as compared to GAC (9-12 months) (Lenntech, n.d.).

7.2 Granular activated carbon

Granular activated carbon (GAC) is another technology that can be used to treat landfill leachate for PFAS (SWANA, n.d.). GAC applies principles of adsorption, whereby leachate passes through GAC filters and PFAS molecules adsorb to the carbon surface (Aclarity, 2023). GAC filters are made from an activated carbon source, typically charred wood, coal, or coconut shells (Minnesota Department of Health, 2022). The filters can effectively remove varying levels of PFAS concentrations (Aclarity, 2023) and various contaminants (COD, trace metals) (Mohammad-pajooh et al., 2018).

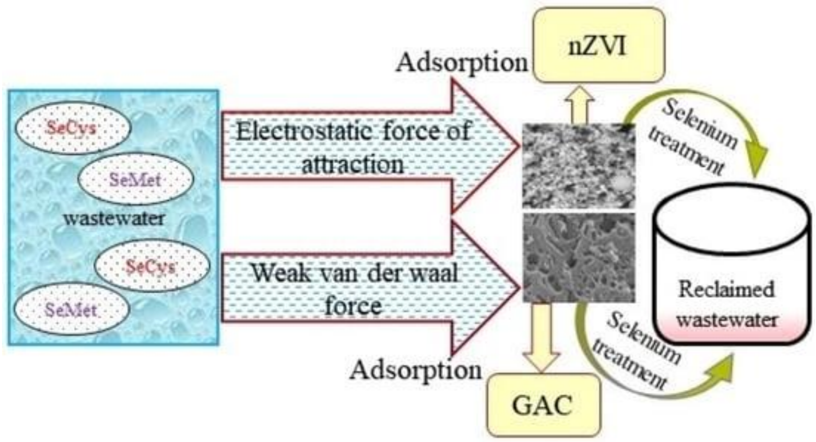

Figure 5. Adsorption by GAC and non zerovalent iron from wastewater (Okonji et al., 2020).

GAC materials are hydrophobic in nature (Lenntech, n.d.) and have less affinity to short-chain PFAS. While studies on the use of GACs to treat CMCs is limited, this technology is effective at removing mercury from simulated landfill leachate (Budihardjo et al., 2021) and has demonstrated success at removing PCBs from aqueous solutions (Jaradat, A.Q. et al., 2010). Further, ATLRA|Sanexen, a Montreal-based company, has a treatment technology for removing PCBs from solution that the company promotes as being highly effective when combined with GAC (Altra Sanexen, n.d.). The U.S.-based company, Calgon Carbon, states in its promotional material that GAC, when combined with biological treatment, is highly effective for odour removal and the treatment of soluble organic chemicals, pesticides, endocrine disruptors, and other contaminants of emerging concern (Calgon Carbon, 2024).

Activated carbon adsorption processes are understood to have simplistic designs and operating mechanisms, while having the ability to remove a wide variety of contaminants. It should be noted that there is a high production cost associated with activated carbon, due to a long processing time and high energy consumption (Foo et al., 2013). GAC performs well on long-chain PFAS and less well with short-chain PFAS – when used to treat short-chain PFAS, the filters must be replaced more frequently, increasing costs and waste (EPA, 2019). Like adsorption, fouling can be an issue. Once they reach the end of life, filters must either be disposed of (incineration, landfilling) or regenerated. Regeneration is a process that cleans GACs to be recycled and reused, reducing waste and supporting the green chemistry principle of using starting materials that are renewable. If filters are disposed of, the waste production from this process remains a significant consideration when applying a green chemistry or green engineering lens.

As with adsorption, ion exchange and anion exchange, SWANA states that GAC is commonly used to treat PFAS in leachate in North America. One company, Calgon Carbon, is based in the U.S. and promotes the use of its GAC technology to treat landfill leachate, water, and other sources of contaminants (Calgon Carbon, 2024).

7.3 Foam fractionation

PFAS chemicals, when introduced to water, reduce surface tension. Taking advantage of the surfactant properties of PFAS, foam fractionation removes PFAS from leachate and can be used following basic filtration. An elongated cylindrical column that contains the liquid is sparged of air from the bottom of the column to create bubbles. The bubbles result in an air-liquid interface that is used to adsorb PFAS. Following this process, foam that contains PFAS forms at the top of a foam fractionator, and the foam is harvested out of the column (Chyi En We et al., 2024).

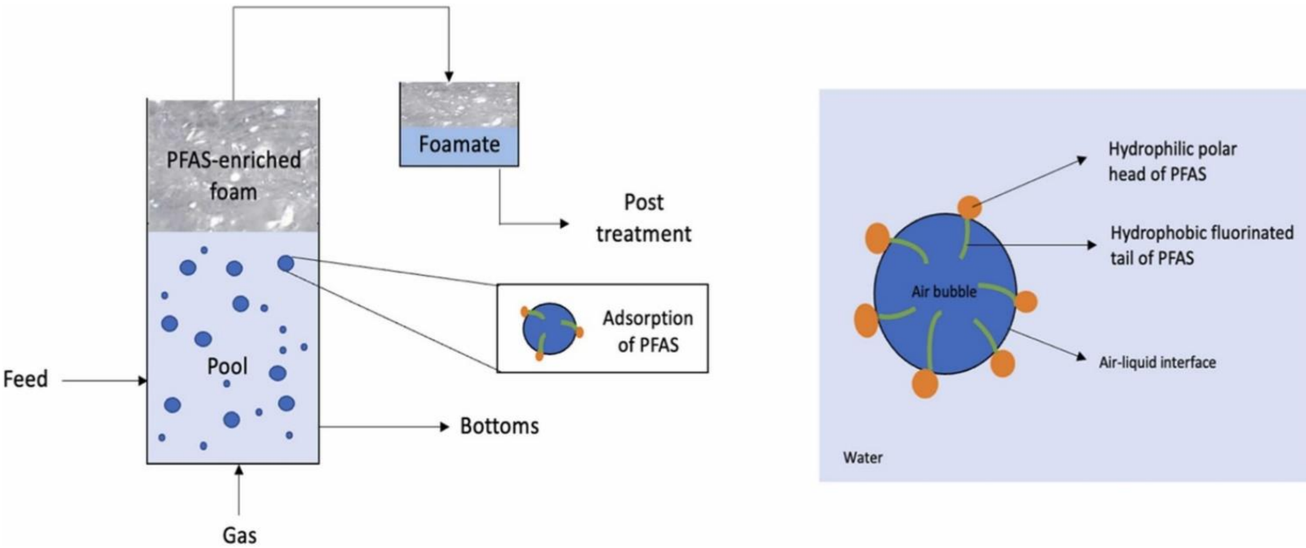

Figure 6. Foam fractionation process for PFAS removal (Chyi En We et al., 2024).

Foam fractionation is more effective at removing long-chain PFAS over short-chain PFAS. The removal of short-chain PFAS is challenged by their low hydrophobicity, high solubility and mobility in water (Chyi En We et al., 2024). Recent research has found that the addition of co-surfactants may increase the removal of short-chain PFAS. The foam fractionation technology developed by one technology company, Altra|Sanexen, is promoted as being capable of removing PCBs, hydrocarbon, chlorinated solvents (e.g. PCEs), ammonia and metals.

Some companies, including Altra|Sanexen, boast the ease of deployment and operation of their foam fractionation technologies through the use of mobile units. The plug and play concept is scalable (Altra Sanexen, 2023). Other technology companies have confirmed that there are no significant operational issues, noting that minerals do need to be cleaned and scaled on occasion.

From a green chemistry and green engineering perspective, foam fractionation boasts several positive features. According to the company LEEF (2023), the process requires minimal energy, does not use consumables, and produces a minimal waste stream in the form of foam concentrate. This treatment output is typically more concentrated than the waste streams of many other removal processes, including reverse osmosis, and the high concentration of the foam can improve the outcome of post-treatment destruction methods (Aclarity, 2023; The Water and Carbon Group, 2023). This process supports green technology standards of increasing energy efficiency, preventing waste, and designing less hazardous chemical processes. Still, the foam concentrate does need to be destroyed using natural evaporation or injection at the landfill (N. Ganzon, personal communication, January 16, 2024; M. Bureau, personal communication, January 23, 2024). Further, if co-surfactants must be used to increase the effectiveness of PFAS removal, there may be concerns about the environmental impacts of the chemicals used as co-surfactants. Waste is still produced by the treatment process and the risks associated with the disposal or destruction of residuals should be taken into consideration. Finally, one technology company noted that the foam fractionation process can exhaust gas out of the building, raising concerns about the potential PFAS volatility and air contamination.

Foam fractionation is currently being applied by technology companies in Canada and the U.S. to specifically target PFAS in landfill leachate; as part of this project, CWN interviewed Altra|Sanexen (Canada) and The Water & Carbon Group (Australia, with a U.S. office).

7.4 Electrochemical oxidation

Electrochemical oxidation functions by applying an electric current through a solution to oxidize pollutants (EPA, 2021). Oxidation can occur via direct or indirect mechanisms, depending on the specific PFAS. Direct oxidation occurs from the transfer of electrons from the PFAS molecules to the anode; indirect oxidation occurs when powerful oxidants, such as hydrogen radicals, are used. Unlike the previously mentioned technologies, electrochemical oxidation strives to completely degrade PFAS by oxidizing the carbon-fluorine bonds in PFAS at the molecular level. However, the complete PFAS destruction via electrochemical oxidation has not been confirmed (EPA, 2021).

Electrochemical oxidation can be applied without treatment and can eliminate other contaminants, including ammonium nitrogen (Mandal et al., 2017), organic contaminants, and colour (Deng and Englehardt, 2007). One study found that electrochemical oxidation was more effective at removing organic compounds from leachate than coagulation/flocculation, ozonation, Fenton process, and other physical/chemical processes (Deng and Englehardt, 2007). Electrochemical oxidation is effective when used at the beginning or end of a treatment train (Mandal et al., 2017).

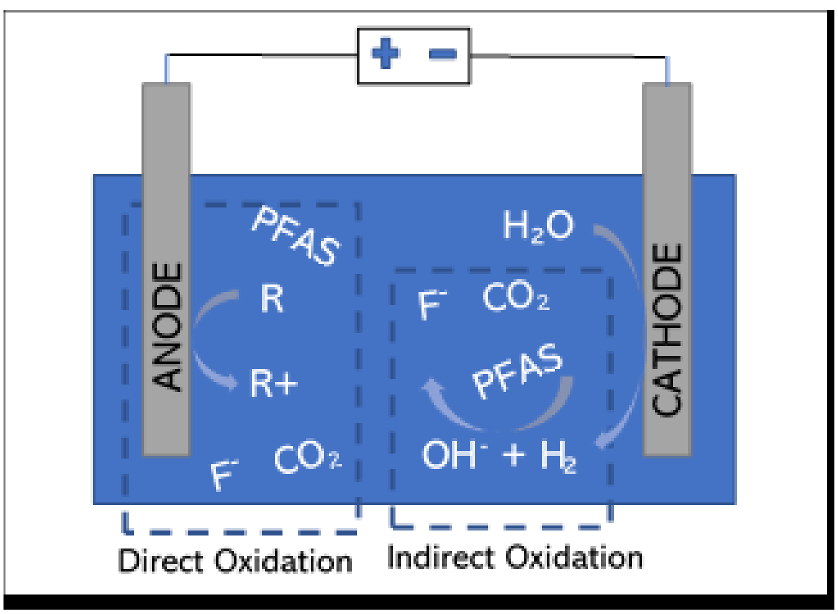

Figure 7. Mechanisms of electrochemical oxidation (EPA, 2021).

Electrochemical oxidation faces a significant barrier when it comes to full scale implementation, owing to high energy demands (and in turn, high costs). To offset the high energy consumption, electrochemical oxidation processes can be combined with other biological or physicochemical treatment processes (Mandal et al., 2017).

Despite relatively higher energy inputs, electrochemical oxidation supports the green chemistry principle of increasing energy efficiency, as the energy demands are lower than incineration, another PFAS destruction approach (EPA, 2021). Since this process does not rely on chemical oxidants, it also supports the green engineering principle of ensuring that materials are as safe and benign as possible. Further, this process does not produce any residuals, such as sludge, which supports the green chemistry principle of preventing waste (Mandal et al., 2017). That said, there are risks associated with the potential generation of toxic byproducts (including organo-chlorinated compounds) (Mandal et al., 2017), incomplete destruction of some PFAS, and potential volatilization of contaminants (EPA, 2021). As discussed earlier, there is a high operational cost associated with high electricity demands (Mandal et al., 2017).

Electrochemical oxidation is currently practiced in the U.S., notably by a company called Alcarity. In operation since 2017, this company recently piloted the use of its electrochemical technology at a Michigan-based centralized waste treatment facility to treat PFAS, with future plans for a full-scale installation. Results from the pilot will be published in the future (Alcarity, 2023), which can provide further insights into the potential for applying electrochemical oxidation in the treatment of CMCs.

7.5 Ozonation

Ozone is an agent that has oxidizing properties, with the potential to degrade or remove complex molecules that do not easily break down. Ozonation is a process by which gas stream that contains ozone is fed into the aqueous solution, producing hydrogen radicals. These hydrogen radicals have the potential to degrade and break down pollutants. Zakaria (2019) states that ozonation alone yields poor results when it comes to the percentage removal of COD, colour and ammonia-nitrogen in comparison to combining ozonation with other processes. Similarly, it is generally understood that ozonation alone is not strong enough to break down the carbon-fluorine bond in PFAS and requires a catalyst or oxidizing agents to be successful (Lenntech, n.d.). However, a recent study found that ozonation may be effective at removing long-chain PFAS but is much less effective at removing short-chain PFAS. The study also acknowledged that it was unclear if the PFAS were broken down completely or if the process may have resulted in the creation of potentially toxic byproducts (Malovanyy et al., 2023).

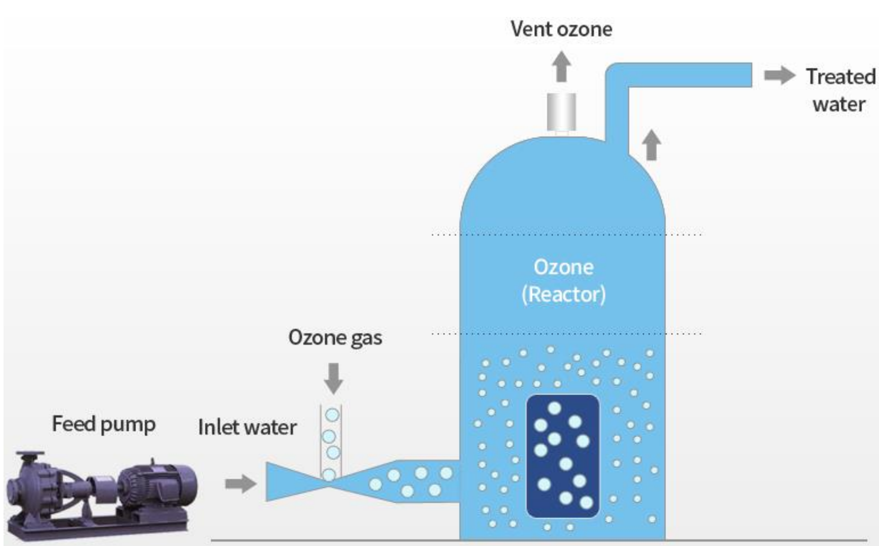

Figure 8. Ozonation in water treatment (PAOR, 2020).

Due to the high energy demand for ozonation, scaling up may be a challenge and barrier. A study that focused on the removal of colour, DOC and COD determined that using ozonation following coagulation may significantly reduce costs (due to lower concentrations of ozone required to treat the leachate) (Gomes et al., 2021).

Compared to most other treatment technologies, ozonation offers a great benefit of not producing any waste, supporting the green chemistry principle of preventing waste. Using ozone as a precursor for hydroxyl radical formation supports the green chemistry principle of using starting materials that are renewable. However, ozonation has a high demand for energy, which varies depending on the dosage requirements of ozonation to break down contaminants of interest (Ortiz, 2006). As noted above, combining ozonation with other treatments such as coagulation may help reduce energy demand and costs, but coagulation requires disposal of the sludge. As well, ozonation implies a risk of eventual release of the toxic gas (Ortiz, 2006).

The City of Toronto uses ozonation as part of a landfill leachate treatment train (combination of physiochemical removal processes, biological treatment, ozonation and filtration, and a polishing engineered wetland) to target parameters that include total suspended solids, total ammonia nitrogen, total phosphorus, dissolved oxygen, and colour. Removing colour is the driver for ozonation, and presently CMCs are not targeted.

7.6 Advanced oxidation processes (AOPs)

Advanced oxidation processes (AOPs) involve the conversion of large organic molecules into smaller molecular organic matter, or the large molecules are directly mineralized to water and carbon dioxide (Teng, 2021). AOPs include processes that are Fenton-based, ozone-based, and UV-based. AOPs can be used following biological treatment to remove refractory organic substances (Teng, 2021). Like ozonation, AOPs degrade pollutants.

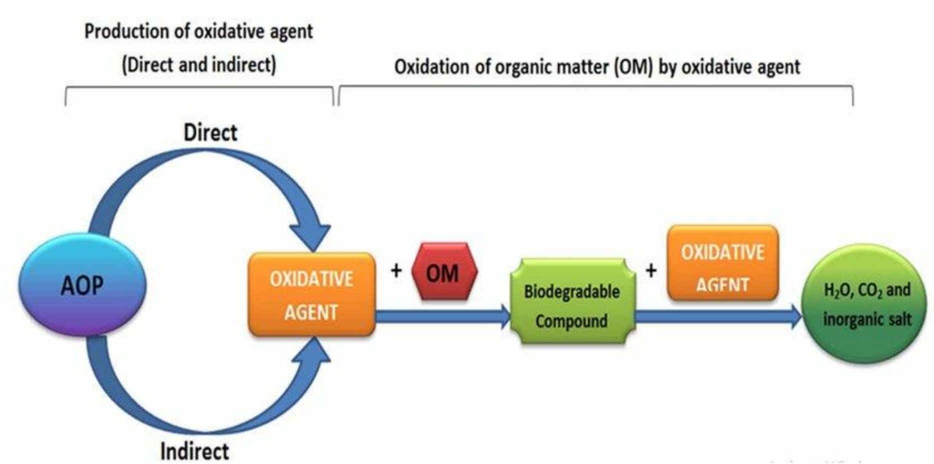

Figure 9. General mechanism of AOPs to treat wastewater (Zakaria, 2019).

While AOPs have been researched on their effectiveness at reducing TOC and degrading contaminants such as heavy metals, salts, and phenols (including BPA) in landfill leachate (Han et al., 2020), there is limited research on the effectiveness of this treatment process on CMCs. That said, it is believed that AOPs, for example, ozone-based processes, may be effective at degrading PFAS (Lenntech, n.d.). One study found that ozone-based AOPs preferentially degraded hydrophobic substances in leachate (Feng et al., 2021), which could indicate that long-chain, hydrophobic PFAS may be more effectively destroyed than short-chain, hydrophilic PFAS.

AOPs are generally known to have high energy demands and high capital costs. In particular, ozone-based AOPs are energy-intensive (Pob et al., 2016). Further, the lamps used in UV-based AOPs may be subject to fouling and require maintenance (D. MacLennan, personal communication, March 5, 2024). However, when used in combination with a biological treatment system, ozone-based AOPs can be cost-effective (Feng et al., 2021). According Ultraaqua (n.d.), a UV disinfection system company, UV-based AOPS can be more cost-effective in the long-term as they require lower operational and maintenance requirements than other technologies. One study that compared the landfill leachate treatment costs based on electrical consumption from various AOPS, including Fenton, ozone, and hydrogen peroxide, found that Fenton was the cheapest option (Joshi and Gogate, 2019).

The degree to which AOPs support green technology standards varies depending on the process being used. For example, ozone-based AOPs use a clean and renewable reagent, supporting the green technology standards of preventing waste and using starting materials that are renewable. However, ozone-based processes can be energy-intensive and implies an eventual release of toxic gas (Ortiz, 2006). UV-based processes use lamps that once fouled, create waste (D. MacLennan, personal communication, March 5, 2024). Fenton-based processes that use iron salts and hydrogen peroxide will produce waste. It should be noted that iron salts are considered innocuous and hydrogen peroxide is not toxic in its diluted form, which supports the green technology standards of using safer solvents and auxiliaries, designing safer chemicals and products that have minimal toxicity, and minimizing the potential for accidents (Ortiz, 2006). UV-based AOPs avoid the use of chemicals and can be powered by renewable energy sources (Ultraaqua, n.d.), supporting the green chemistry principle of preventing waste, increasing energy efficiency, and designing less hazardous processes. UV-based AOPs also support the green engineering principle of ensuring that materials are as safe and benign as possible. UV-AOPs may be piloted full-scale, supporting the green chemistry principle of analyzing and monitoring processes in real time (Ultraaqua, n.d.).

AOPs are available worldwide for advanced treatment of contaminants in landfill leachate. For example, the company Bi Pure Water, is a Canadian company states on its webpage that it offers a new AOP technology as part of a treatment train (including coagulation/flocculation, moving bed biofilm reactor, filtration and disinfection) to destroy phenols, BPAs, creosotes, naphthenic acids, and other contaminants that cannot be effectively treated using biological treatment (Bi Pure Water, n.d.). Bi Pure Water’s technology has been used at the pilot and production level for the remediation of municipal landfill leachates contaminated with refractory organics (phenols, PFOAs, and other contaminants); the participating municipalities have not been identified. Ultra Aqua is a company based in Denmark that uses a UV-based AOP to destroy complex chemical compounds (Ultraaqua, n.d.).

7.7 Reverse osmosis (RO)

Reverse osmosis (RO) is performed by applying high pressure to the aqueous solution, such as pre-treated leachate (D. MacLennan, personal communication, March 8, 2024), causing the water to diffuse through a semi-permeable membrane (PCI Membranes, 2019). The membrane stops large molecules, such as CMCs, from passing through.

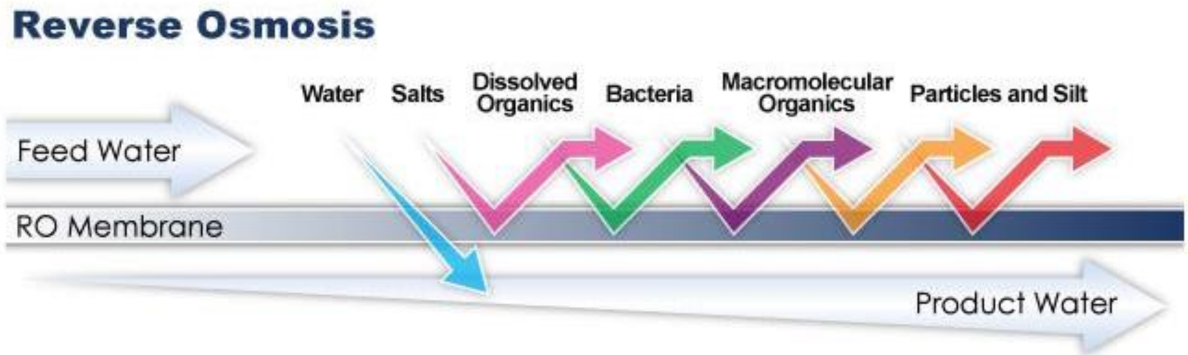

Figure 10. Overview of reverse osmosis in water treatment (Fresh Water Systems, 2019).

Overall, RO systems can have very high operating costs (Topal and Atasoy, 2022). RO creates two streams through the membrane: one stream contains the treated liquid, and the other creates the brine of concentrated contaminants and requires a storage tank and plan for disposal. RO is a complex system to install, with more connections and components needed for the systems to operate correctly. Because RO requires more components, such as storage tanks and pumps, costs are higher (Fresh Water Systems, 2019), in addition to pre-treatment.

RO offers some advantages from a sustainability perspective. RO does not require additional chemicals, resins, or ion exchange bed, however, pre-treatment processes require chemicals, resins, or ion exchange beds (D. MacLennan, personal communication, March 5, 2024). It should be noted that the membranes have a limited lifetime and are at risk of fouling which necessitates chemical cleaning of the membranes (Topal and Atasoy, 2022). RO systems may be at risk of corrosion of the equipment caused by hydrogen sulfide in leachate. Further, RO has high energy demands. Finally, the membrane brine, or concentrated waste stream, must be disposed of or further treated (Topal and Atasoy, 2022).

RO has gained some traction in Canada and worldwide as a mechanism to treat landfill leachate. Saltworks is one Canadian company that piloted landfill leachate treatment using RO in combination with biological treatment (Saltworks, 2019). A Germany-based company, Wehrle, shares on its company webpage that it offers an RO technology to treat landfill leachate through a standardized and containerized RO system (Wehrle, 2019).

7.8 Natural coagulants

Coagulation/flocculation involves the transfer of pollutants from liquid to solid phase. Conventional coagulants, such as iron salts or aluminum salts, are applied as coagulants to landfill leachate. The coagulants allow contaminants to form large masses of sludge that can be settled and removed (Teng, 2021). Coagulation can be effective as part of a treatment train for removing contaminants and can improve the treatment efficiency of other processes such as treatment prior to biological treatment, AOP, ozonation, RO, or as a final polish process to eliminate non-biodegradable matter. The process of settling out suspended solids and organic matter may also remove some refractory organic compounds (Agua Sigma, 2021). There is limited research on the effectiveness of coagulation in removing PFAS, however, a recent study investigated the potential for coagulation to remove PFAS from soil washing water. The study found that the effectiveness at treating long-chain or short-chain PFAS is highly variable depending on the coagulant and its properties (hydrophobic interactions, electrostatic interaction). The coagulants and flocculants selected in the study were more effective at removing long-chain PFAS (61-99% removal, depending on the coagulant) than short-chain PFAS (30-76% removal, depending on the coagulant) (Hubert et al., 2024).

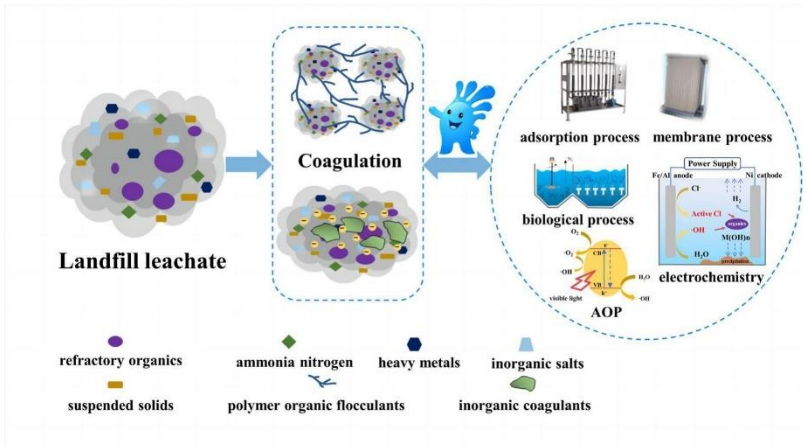

Figure 11. Coagulation as part of a landfill leachate treatment train (Chen et al., 2024).

However, coagulation produces a large volume of sludge, raising concerns from a waste perspective. As well, the conventional aluminum-based coagulants may exhibit toxic behaviour (Righetto et al., 2021). In recent years, plant-based materials have been studied as potential alternatives to conventional coagulants. In addition to exhibiting non-toxic, biodegradable behaviour, natural coagulants cost less compared to conventional coagulants (Ahmed et al., 2020). According to Ahmed et al. (2020), natural coagulants should exhibit the following properties:

1. Non-toxic,
2. Do not cause any detrimental physiological effects on human health
3. Available at a lower cost
4. Produce a lower volume of sludge

A number of studies have determined that various natural coagulants may be effective at treating landfill leachate of COD, colour, humic substances, total nitrogen, total phosphorus, ammonia, and other pollutants, including heavy metals (iron, lead, mercury, nickel, titanium, chromium, aluminum, vanadium, copper, arsenic) (Rhigetto et al., 2021; Nithya & Abirami, 2018). These natural coagulants include hibiscus rosa-sinensis leaf extract, psyllium husk, jackfruit seeds starch, and a tannin-based product called HTH. It should be noted that the studies have found effectiveness under very specific conditions (dosage, pH, in combination with conventional coagulants), and will vary considerably regarding the pollutants that are removed.

The complexities associated with coagulation include: natural characteristics of the coagulant of choice (e.g. molecular structure, molecular weight, and electric properties), dosage, pH of the leachate being treated, the mixing condition (rapid mixing, slow stirring) and settlement time, and leachate temperature. All these aspects can influence the effectiveness of the process (Chen et al., 2024). Additionally, to be viable as an alternative coagulant chemical, locally available sources or suppliers must be available.

The literature scan did not find any studies that investigated the potential effectiveness of natural coagulants to remove CMCs from landfill leachate. In addition, there are no existing companies that have been found to use natural coagulants to treat CMCs in landfill leachate. Still, there may be potential applications of natural coagulants to treat CMCs that can be investigated.

7.9 Constructed wetlands

A constructed (engineered) wetland system functions to increase water quality (Mojiri et al., 2021). The constructed wetland comprises permeable substrata, such as gravel, which is typically planted with emergent wetland plants (Mojiri et al., 2021). Studies have indicated that various contaminants can be efficiently removed from landfill leachate by constructed wetlands. These include degradable organic carbon, ammonia, and heavy metals. Constructed wetlands offer natural attenuation processes, meaning that the wetlands can remediate water and soil through physical, chemical, or biological processes without human intervention to reduce contamination (Water Research Foundation, 2014).

While they are mechanically simple and require less operations and maintenance than more conventional engineered technologies, constructed wetlands rely on complex designs to achieve the desired results. Further, constructed wetlands need time to allow for vegetation to establish and develop, and can take over one year. The delay in plant development can impact the plant root system, which affects initial plant uptake and transport of contaminants. It is therefore recommended that plants be developed before the start-up period for the constructed wetland system, to avoid possible delays (Nan et al., 2023). Additionally, there is the occasional need to remove contaminated soils from constructed wetlands to prevent the buildup of solids. These solids can impact the efficacy of constructed wetland treatment ability, and if not removed can lead to the re-contamination of treated leachate (D. MacLennan, personal communication). Further, the biological processes used in the treatment process of constructed wetlands can slow during winter months, which should be taken into consideration (D. MacLennan, personal communication).

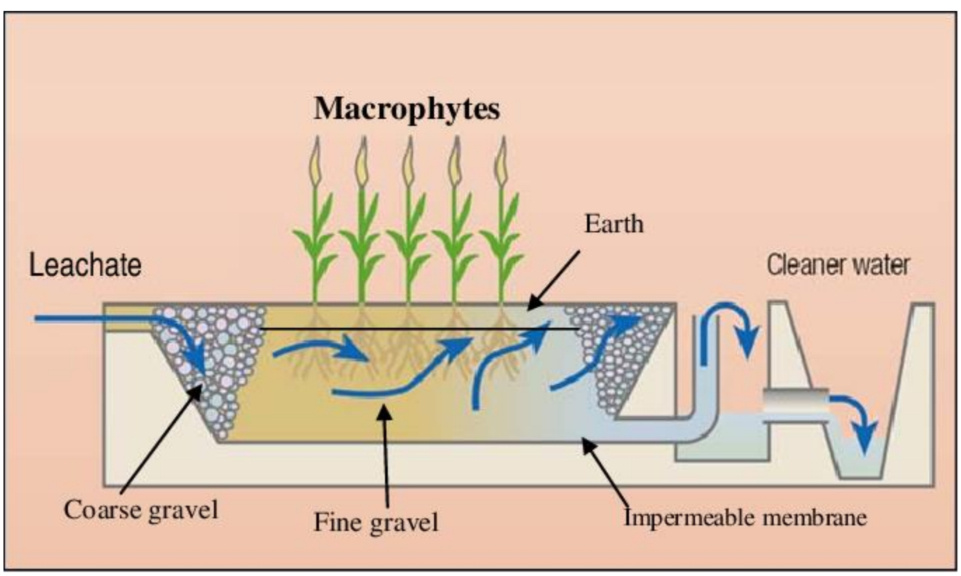

Figure 12. Main features of a sub-surface constructed wetland (Madera and Valencia, 2009).

A study that was jointly funded by Water Research Foundation, Water Environment Research Foundation, and the EPA investigated the potential benefits from constructed wetlands for treating surface water of contaminants of emerging concern. The study involved the use of laboratory-scale wetland microcosms, whereby seven organic CECs (17β-estradiol, testosterone, atrazine, carbamazepine, caffeine, primidone and parachlorobenzoic acid) and two engineered nanomaterials (functionalized nano-silver, aqueous fullerenes) were introduced into the wetland microcosms. The study found that design configuration impacts the CEC removal mechanisms. For example, wetlands with a greater area of an open water zone support photolysis, while wetlands with larger vegetated areas support greater sorption (Water Research Foundation, 2014). Steroidal organic compounds experience the greatest removal among all the CECs that were investigated, at 70-99%. While surface water was the focus of the project, the outcomes may be useful for informing future research of the effectiveness of constructed wetlands on pre-treating landfill leachate of CMCs.

While the City of Toronto uses an engineered wetland as the final step of a leachate treatment train, through CWN's research no existing constructed wetlands were identified as being actively used to treat landfill leachate of CMCs or other contaminants.

8. Opportunities and knowledge gaps

The topic of this white paper addresses emerging topics of research, including characterizing the prevalence and removal of CMCs and notably PFAS, treatment technologies that follow green technology standards, and applying that to landfill leachate. As a result, there are a number of areas for which there is active research or limited research. As discussed in section 5.3.1., The Government of Canada and the Government of Ontario have recently monitored PFAS in landfills. The Government of Canada sampled leachate from ten operational landfills under the Initiative to Protect and Recover Endangered Whale Populations, while the Ontario Ministry of Environment, Conservation and Parks is sampling PFAS in twenty landfills in Ontario. These monitoring programs will provide insights into the concentrations of PFAS in landfills before and after on-site leachate treatment. The programs may provide useful information about which CMCs are most prevalent in landfill leachate, helping decision-makers understand which contaminants are opportune to target for treatment. Building on these programs, additional research and monitoring — more specifically on landfill leachate treatment technologies and disposal and destruction methods — can help advance the action needed to protect the Great Lakes and other Canadian waterways from CMCs.

Presented below are potential opportunities that ECCC can support in three ways. The first is to investigate research and monitoring practices to address CMCs by advancing knowledge and understanding to inform decision-making. The second way is to explore areas of research that are currently understudied or underfunded. The third is to support monitoring and research in areas that are active and the knowledge base is expected to rapidly grow in the coming years.

1. Investigate research and monitoring practices to address CMCs by advancing knowledge and understanding to inform decision-making. The practice insights and scan of technologies has identified opportunities and gaps that may be of interest to ECCC:
    a. **Understanding treatment co-benefits:** Investigate the co-benefits associated with existing landfill leachate treatment technologies and understand whether there are opportunities to build on existing treatment technologies to target CMCs and other contaminants of concern. Due to the complexity and variety of parameters found in

landfill leachate, opportunities may include combining several treatment technologies as part of a larger treatment train to expand the list of contaminants that can be treated.

   b. **CMC point-source prioritization:** Because CMCs have different removal and destruction mechanisms, prioritizing which CMCs to target can help determine which treatment technologies should be applied. Additional monitoring of CMC point sources upstream of wastewater treatment plants, including landfills and industries, may help inform which CMCs to prioritize and at which point source.
   c. **Life cycle analysis of technologies:** To better determine the potential for technologies to support green chemistry and green engineering principles, there may be value in completing life cycle analyses of the technologies. As Ortiz (2006) states, reviewing the principles of green chemistry alone has limitations, namely, due to the lack of comprehensive evidence that confirms good environmental and economic performance of new technologies. Ortiz suggests that a life cycle approach is required to assess all environmental sustainability considerations, and the literature scan found limited life cycle analyses on the treatment technologies. Mandal et al. (2017) also suggest that the environmental footprint of a proposed technology should be evaluated prior to recommending its widespread application, with a life cycle assessment being a reliable and transparent method of identifying potential environmental impacts.
   d. **Characterizing opportunities for natural coagulants:** Natural coagulants represent a relatively easy opportunity to improve the sustainability of treatment processes that involve coagulation. There are significant knowledge gaps around the effectiveness of natural coagulants in removing CMCs from landfill leachate. The international research field of natural coagulation for landfill leachate treatment of common pollutants appears to be rapidly accelerating in recent years, and there may be opportunities to expand the research to include CMCs.

2. Explore areas of research that are currently understudied or underfunded. Two of the technologies listed in this paper are of interest and may have potential to treat CMCs, however, more research is needed to truly understand which contaminants they are capable of treating. Further, there could be an opportunity to extend a challenge or provide funding for the development of new treatment technologies:
   a. **Characterizing opportunities for AOP**: Advanced oxidation processes remain a promising approach to address emerging contaminants and yields potential when applied to landfill leachate and as a sustainable technology option. Given limited research on the applicability of this technology to treat CMCs in landfill leachate, additional research on the effectiveness of various AOPs in treating CMCs would address this knowledge gap when considering options for treatment.
   b. **Characterizing opportunities for constructed wetlands:** While studies have measured the effectiveness of constructed wetlands at treating conventional contaminants, and others have investigated how constructed wetlands can be designed to treat CECs in surface water, there remains a gap when it comes to understanding whether constructed wetlands may treat CMCs in landfill leachate.
   c. **Creating opportunity for developing new technologies:** Though this white paper outlines several promising technologies for treating landfill leachate, there remains the potential for new technologies which have not yet been developed. By offering a

challenge or presenting the opportunity for funding, this would grant space for future technology.

3. Monitor areas of research that are active, and the knowledge base is expected to grow rapidly in the coming years. As the topic of this study is at the leading edge of research and technology development, there are several areas that are actively being researched or for which very limited research is presently available. To stay apprised of the growing knowledge base, these are some areas to follow in the coming years:
    a. **Destruction methods for CMCs**: Currently, literature states that it is unclear as to whether or not destruction technologies like electrochemical oxidation and ozonation completely break down PFAS or other CMCs, or if they unintentionally create toxic byproducts. Further investigation into the mechanisms of CMC destruction.
    b. **Fate and transport of disposed CMCs:** As discussed in the report, the current methods for disposing of contaminants are via underground injection and thermal treatment. Further monitoring should be conducted to understand the fate and transport of PFAS and other CMCs in the injection zones, as well as how effective high-temperature treatment is at completely destroying PFAS. Further monitoring may lead to a better understanding of best practices which leads to new potential disposal methods that minimize environmental impacts.
    c. **New leachate management challenges:** In consideration of the fact that landfills are increasingly observing black sludge in their collection and pump systems, further monitoring and research would be useful for identifying the chemical compounds that make up the sludge, sources, and technologies that may effectively treat the sludge.

Overall, this report provides a starting point for understanding leachate management options in the Great Lakes Basin context and leading technologies to address CMCs, particularly PFAS that feature green chemistry and green engineering features. The list above highlights opportunities for more research and monitoring that are needed to better inform decision-making around reducing the release of CMCs in the environment through landfill leachate.

9. Conclusion

This project's review of landfill leachate treatment technologies has revealed a diverse array of methods currently in use or demonstrating potential for the removal or destruction of PFAS and other CMCs. These technologies — which include adsorption, ion exchange, and anion exchange, GAC, foam fractionation, electrochemical oxidation, ozonation, AOPs, reverse osmosis, natural coagulants, and constructed wetlands — each offer unique advantages and challenges.

While some technologies are more established and widely used, such as adsorption and ion exchange, others are still in the early stages of research or application. Each technology's effectiveness can vary significantly depending on specific conditions and the nature of the contaminants being treated. The ECCC landfill leachate working group states that no technology has yet been proven to effectively treat the entire class of PFAS or other CMCs; currently, a treatment train of technologies is needed (D. MacLennan, personal communication, March 6, 2024). Furthermore, the sustainability of these technologies, as evaluated through the lens of green chemistry and green engineering principles, also varies.

Despite the challenges, these technologies collectively represent a promising toolkit for addressing the complex issue of CMC contamination in landfill leachate. Continued research, development and collaboration among municipalities, academia and technology companies will be crucial in advancing these technologies and ensuring their effective and sustainable application in the future.

Monitoring data obtained through the sampling of landfill leachate by the Government of Canada's sampling of leachate from ten operational landfills in Canada under the Initiative to Protect and Recover Endangered Whale Populations and the Ontario Ministry of Environment, Conservation and Parks' sampling of PFAS in twenty landfills in Ontario are providing some valuable insights into the accumulation of CMCs in landfills and some baseline information to understand the contribution of landfill leachate to CMC loading in wastewater effluent. However, there are significant gaps in our understanding of technologies, the effectiveness of natural coagulants, the potential of constructed wetlands and the mechanisms of CMC destruction. Current disposal methods, such as underground injection and thermal treatment, also require further investigation to understand their environmental impacts and effectiveness in destroying PFAS. As the research field of natural coagulation for landfill leachate treatment accelerates, there are opportunities to expand the research to include CMCs. Ultimately, more research and monitoring are needed to better understand which CMCs to target and where, the effectiveness and sustainability of landfill leachate treatment processes to remove or destroy CMCs, the environmental impacts of current disposal methods of treatment residuals, and to explore future sustainable opportunities for destroying or disposing of CMCs captured through treatment.

Appendix 1: Summary of practice insights

This section provides an overview of the information that was shared by municipal, utility, academic and technology company contacts. CWN received survey responses from fourteen of twenty municipalities contacted. In addition, CWN held six follow-up interviews with municipalities, one interview with an academic researcher, and three interviews with technology companies.

The surveys and interviews drew the following insights:

- Waste management versus wastewater management priorities: There are varying degrees of interactions and collaboration between the departments. In some cases, there are strong siloes and competing priorities that make it a challenge to advance innovation in leachate treatment. Due to organizational structures, treatment is more likely to take place on-site, operated and funded by the waste management department or private landfill.
- Regulatory drivers for treatment: Leachate treatment to address CMCs or other contaminants would be driven by the municipal sewer use bylaw and/or the provincial landfill permit. Both requirements would need to be driven by provincial or federal regulations on CMCs. There is a growing awareness of contaminants of concern in landfill leachate, in particular, PFAS.
- Contaminant drivers for treatment: While most municipalities do not treat landfill leachate, those municipalities interviewed expressed concerns around certain contaminants, which would drive the need to treat leachate: nitrogen, ammonia, phosphorus, colour, microplastics, odours (including hydrogen sulfide), black sludge (see next point), total suspended solids, dissolved oxygen, and E.coli.
- Black sludge: Some landfills are observing black sludge picked up in the leachate collection and pump systems, causing issues with the equipment. Studies on the sludge have determined that the sludge is made of a polymer or rubber-like compound that may be derived from meat packaging, feminine hygiene products, and incontinence garments. Landfills are working to determine methods of degrading the sludge. This may impact on-site treatment systems.
- Other drivers for treatment: Municipalities shared other factors that would accelerate their interest and prioritization of treatment, including containment and prevention of impacts to surface water and groundwater, effluent toxicity from contaminants, and impacts of contaminants on disposal or containment processes.
- Monitoring needs and challenges: There is limited existing monitoring data on CMCs in landfill leachate and what their total contribution is to wastewater treatment plant discharges to the environment. Industrial sources are generally considered to have more significant contributions to discharges. To support the case for advanced treatment on-site of landfills, private and public landfills would need to carry out additional monitoring of target CMCs, which may be logistically difficult and expensive. Access to labs and affordable testing is a significant barrier.
- General trends around leachate management: Of the municipalities contacted, very few are pursuing or requiring landfill leachate treatment, unless required by an ECA/permit. Currently, treating for PFAS in leachate is on the radar of solid waste professionals and growing in conversations and investigations, but is not an urgent matter in Canada. In almost all cases,

discharge to the wastewater treatment plant is the approach taken in Canada, with no to very little treatment.

- Leachate management concerns: When responding to the survey question about main concerns related to landfill leachate management, municipalities highlighted a variety of concerns including the risk of spills, contamination of ground and surface waters, impacts on sanitary systems (corrosion, biofouling, odours), and compliance with provincial and municipal regulations, emerging contaminants (PFAS) which are not currently consistently monitored for in most places, potential impacts to wastewater treatment plant processes and byproducts (total nitrogen, toxicity to biological processes, metals in biosolids).

- Challenges for leachate treatment: Leachate is a challenge to treat and manage, in large part due to its variable composition of contaminants. Conventional treatment approaches to removing or destroying common contaminants in leachate, such as nutrients and odour, are already technically and operationally challenging, and are not known to treat CMCs. Advanced treatment technologies can be even more complex and involve a 'treatment train' (several treatments used in combination).

- CMCs have different removal mechanisms: every CMC exhibits different characteristics that result in varying removal mechanisms. One treatment technology that may be effective for one contaminant may not be effective for others.

- Awareness of green chemistry application to treatment technologies:

    - Research and technologies are limited when it comes to environmentally sustainable alternatives to treat CMCs from landfill leachate. There is considerably more research focus on PFAS.

    - Green chemical substitutes may open opportunities to advance the sustainable treatment of landfill leachate. One example includes the use of natural coagulants instead of conventional coagulants ((iron salts, aluminum salts) as part of treatment trains. While there are many studies on natural coagulants, their effectiveness at removing CMCs, including PFAS, has not been studied.

- Limited familiarity with green chemistry: Municipalities and some technology companies are not acutely aware of how green chemistry principles can be applied to treatment technologies. There is more familiarity of a select number of principles, namely, waste reduction, energy efficiency, and safety. There is a general reliance on using conventional treatment approaches over exploring new technologies that apply a green chemistry lens.

- Residuals management: Most treatment technologies are focused on contaminant removal – transferring the contaminants to a different media, as opposed to actual destruction of the CMC molecules. The concentration of contaminants in leachate and environmental impact of disposal options is a key consideration and knowledge gap.

The following tables highlight insights from contacts who responded to CWN's communication efforts.

Table 2. Landfill leachate treatment approaches at municipalities and utilities (insights synthesized above).

Organization	Sector	Landfill leachate treatment approach
Capital Regional District	Municipal (regional)	No leachate treatment. Leachate is discharged to the municipal sewer system where it is treated at the wastewater treatment plant.
City of Calgary	Municipal	No leachate treatment. Leachate is discharged to the municipal sewer system where it is treated at the wastewater treatment plant.
City of Guelph	Municipal	There is no onsite leachate treatment, but dilution occurs due to precipitation infiltration. Leachate is discharged to the municipal sewer system where it is treated at the wastewater treatment plant.
City of Hamilton	Municipal	No leachate treatment. Leachate is pumped to the sanitary sewer system and is treated at the wastewater treatment plant.
City of Montreal	Municipal	Leachate is pumped from a single location to a local treatment plant to treat ammonia nitrogen and hydrogen sulfide. The leachate is then conveyed to the municipal wastewater treatment plant, where it is treated of ammonia nitrogen and hydrogen sulfide using Mabarex's suspended media bio-reactor (SMBR) technology).
City of Ottawa	Municipal	There exists some leachate treatment on-site through an aeration pond to reduce hydrogen sulfide and some volatiles, then hauled via a tanker to the wastewater treatment plant.
City of Saskatoon	Municipal	No leachate treatment of leachate. The leachate is pumped into a lift station that discharges to the wastewater treatment plant.
City of Toronto	Municipal	They have a leachate treatment system that uses a combination of physiochemical removal processes, followed by biological treatment, ozonation and filtration, and a polishing engineered wetland to target contaminants that include total suspended solids, total ammonia nitrogen, total phosphorus, dissolved oxygen, and colour. The treatment does not target CMCs.
Halton Region	Municipal (regional)	No leachate treatment. Leachate is only treated at the regional wastewater treatment plant.
Region of Durham	Municipal (regional)	No leachate treatment, other than some minor recirculation. All of the Region owned landfill sites rely on natural attenuation for leachate management. The Region does have one private site connected to the sanitary system with combined treatment at a WWTP.
Region of Waterloo	Municipal (regional)	No leachate treatment. Leachate is only treated at the regional wastewater treatment plant.
Town of Cobourg	Municipal	No leachate treatment. Leachate is only treated at the wastewater treatment plant.
Utilities Kingston	Utility	No leachate treatment. Leachate is only treated at the regional wastewater treatment plant. Leachate is conveyed through a trunk sewer to the wastewater treatment plant.
York Region	Municipal (regional)	No leachate treatment. Leachate is treated at the regional wastewater treatment plant. York Region recently participated in a study with the Ontario Ministry of Environment, Conservation and Parks investigating the concentrations of PFAS in industrial processes and products. Maximum concentrations for individual PFAS were seen in carpet cleaning wastewater (Payne et al.,2024).

Table 3. Insights from academia.

Research institution	Insights
University of Waterloo	Researchers have a better understanding of how to manage hydrophobic chemicals using technologies such as coagulation, flocculation and filtration; however, PFAS tend to be more hydrophilic and cannot be removed using conventional methods. The concentration of PFAS in leachate is high enough for concern but is much lower than hazardous waste sites and other sources, such as sewage and runoff.

	Landfill leachate is likely not the primary source of PFAS. Additional monitoring should be done to identify sources of PFAS in industrial wastewater and landfill leachate, to better understand the main source of PFAS concentration and where treatment should be targeted. More emphasis should be placed on reducing PFAS in products.

Table 4. Landfill leachate treatment approaches and other insights from technology companies.

Company	**Landfill leachate treatment approach**	**Other insights**
Altra|Sanexen (Canada)	Uses foam fractionation to treat PFAS and other contaminants in landfill leachate. Has proprietary technology for removing PCBs from wastewater called ULTRASORPTION.	Technology is energy-efficient and produces very little sludge. The technology uses a closed system, with no vents or emissions. The technology has been implemented in Canada (including Nunavut) and the U.S. McGill and the University of Montreal both have labs to analyze samples containing PFAS. Destruction options include natural evaporation (if there is a lot of sun), injection, and emerging destruction technologies (not specified).
Mabarex (Canada)	Uses suspended media bio-reactor (SMBR) to treat contaminants in landfill leachate, and a resin-based technology to remove PFAS from groundwater.	Bioreactor technology is commonly used for landfill leachate treatment in Quebec. It is unclear as to whether the resin PFAS technology applies green chemistry principles. There is potential to recycle the resin in the future, as well as replace chemicals with electrocoagulation.
The Water & Carbon Group (U.S.)	Uses foam fractionation to treat PFAS in landfill leachate.	PFAS is on the verge of becoming even more significant with federal push and public awareness. In the U.S., there has been interest in piloting programs, with recent interest in short-chain PFAS. The Water & Carbon Group currently does not have clients in Canada. PFAS treatment residuals – there is no good way of handling them. There are emerging technologies with promise – supercritical oxidation, high alkalinity, and electrochemical oxidation. Foam fractionation can achieve very high concentration ratios, which opens up to a variety of destruction methods. However, the reality is that landfills are cheap, and modern landfills are effective at keeping PFAS trapped (until new technologies become more available).

Appendix 2: Common landfill leachate treatment methods

Table 5. Common landfill leachate treatment methods (Table adapted from: Agua Simga, 2021 and Teng, 2021).

Treatment Method	Principle/ Description	Age (years) and treatment efficiency of leachate			Main objective	Advantages	Disadvantages	Ability to address CMCs
		Young (<5)	Intermediate (5-10)	Mature (>10)				
No onsite treatment								
Co-treatment at WWTP	Landfill leachate combined with municipal sewage for treatment at WWTP.	Good	Fair	Poor	Suspended solids	Convenient; the most inexpensive.	Excess nutrients; refractory organic matter/UV absorbing compounds may make disinfection less effective disinfection process ineffective. Potential impacts to collection system. Potential impacts on treatment performance and effluent and sludge quality due to nitrogen and trace contaminants and emerging pollutants.	Unlikely to address CMCs
Recirculation	Returning the collected landfill leachate to landfills. The landfill system serves as the biofilter.	Good	Fair	Poor	Improving the leachate quality.	Accelerate waste stabilization of landfills; increase the amount of garbage degraded; reduce the volume of landfill leachate.	Refractory dissolved organic matter is accumulated, which is more difficult to treat.	Will not address CMCs, because there is no treatment provided. Will increase their concentration in the leachate (D. MacLennan, personal communication, March 6, 2024)

Treatment Method	Principle/ Description	Age (years) and treatment efficiency of leachate			Main objective	Advantages	Disadvantages	Ability to address CMCs
		Young (<5)	Intermediate (5-10)	Mature (>10)				
Biological Treatment								
Biological treatment (aerobic treatment, anaerobic treatment)	Degradation of organic pollutants in leachate by aerobic or anaerobic reactions of microorganisms degrading organic compounds to carbon dioxide (aerobic and anaerobic) and methane (anaerobic). Most common are aerated lagoons, aerobic bioreactor as sequencing batch reactors (SBR).	Good	Fair	Poor	Suspended solids, biodegradable organics, nitrification of ammonia, hydrogen sulfide	Simplicity; reliability; highly cost-effective; widely used for young leachates with high COD; promising option of combined options of membrane bioreactors (MBR) and moving bed bioreactors (MMBR) to address refractory organic pollutants	Ineffective to non-biodegradable dissolved organic matte (hampered by refractory compounds). Requires long reaction times; very high concentrations of ammonia nitrogen is toxic to microorganisms, physical-chemical treatment would be required. Activated sludge processes typically ineffective at treating leachate based on its quality, although widely applied for co-treatment.	Potential to address CMCs combined with other treatment
Chemical treatments*								
Coagulation/ Flocculation	Generation of aggregates by the addition of coagulant, which destabilizes suspended solids, and aggregates group together, by the addition of a flocculant, that can be more readily separated by clarification/ sedimentation.	Poor	Fair	Fair	Heavy metals and suspended solids	Low cost; high efficiency. Usually used in combination with other treatment processes.	Generation of excessive sludge; secondary pollution with conventional coagulants; pH dependent	Potential to address CMCs
Chemical precipitation	Chemical reagents react with soluble substances to form precipitates.	Poor	Fair	Poor	Heavy metals and ammonia nitrogen	Strong capability; simplicity; low operational costs.	Low COD removal efficiency; pH dependent; high precipitant dosage; excessive sludge generation; Requires further treatment of the generated sludge.	Potential to address CMCs

Treatment Method	Principle/ Description	Age (years) and treatment efficiency of leachate			Main objective	Advantages	Disadvantages	Ability to address CMCs
		Young (<5)	Intermediate (5-10)	Mature (>10)				
Advanced oxidation Processes (chemical oxidation)	Free radicals destroy dissolved organic matter and degrade it into small molecules or directly mineralize it into CO2 and H2O	Poor	Fair	Fair	Organic compounds	Strong oxidation capability; high efficiency; mild operating conditions; ease of operation and low maintenance; fast reaction rate	Ozone, chlorine and other non-desired sub-products are generated; High chemical reagent dosage; high energy consumption; non-renewable elements.	Potential to address CMCs
Physical-Chemical treatments*								
Adsorption	Pollutants are transferred from the liquid phase to the surface of a solid through physical and/or chemical interactions.	Poor	Fair	Good	Organic compounds	Cost-effective; high efficiency.	Regeneration of adsorbents; High consumption of adsorbents. Adsorption is usually combined with other physicochemical methods as a treatment or post-treatment step.	Potential to address CMCs
Air Stripping	Air or water vapor passes through the leachate, transferring ammonia nitrogen from the liquid phase to the gas phase	Poor	Fair	Fair	Ammonia nitrogen	Simple process; stable; strong adaptability; low investment costs. Note, air stripping can be used for hydrogen sulfide too.	Leakage of ammonia; low efficiency for COD removal; calcium carbonate scaling of the stripping tower.	Unlikely to address CMCs
Ion exchange	Reversible ion exchange between the solid phase of a column and the liquid phase of the leachate in which there is no permanent change in the solid structure of the column.	Good	Good	Good	Dissolved compounds, cations and anions	This treatment removes traces of heavy metals and recalcitrant organic compounds. Not widely applied to leachates but growing interest.	Used as polishing after biological treatment. High operational cost	Potential to address CMCs
Membrane Treatment	Screening by size and electrostatic interactions between membranes and molecules. Microfiltration (MF), ultrafiltration (UF),	Poor - MF, UF Good - NF, RO	Good - NF, RO	Good - NF, RO	Suspended solids (MF); High molecular weight compounds (UF); Sulphate salts and alkalinity ions (NF); Organic and inorganic compounds (RO)	High effectiveness; low cost; simple equipment requirements; mild conditions.	Expensive, limited by membrane fouling and the production of membrane concentrated landfill leachate. RO requires treatment, usually UF.	Potential to address CMCs

Treatment Method	Principle/ Description	Age (years) and treatment efficiency of leachate			Main objective	Advantages	Disadvantages	Ability to address CMCs
		Young (<5)	Intermediate (5-10)	Mature (>10)				
	nanofiltration (NF) and reverse osmosis (RO)							

*The chemical and physical-chemical treatments of leachates consist of the reduction of total suspended solids, colloidal particles, floating material, color, odour, toxic compounds, heavy metals and refractory organic compounds (humic and fulvic acids). These processes are used within the leachate treatment train as pretreatment before biological treatments or as final polishing. Specific technologies can also be applied to eliminate a specific contaminant in a specific leachate.

Table adapted from: Agua Sigma, 2021 and Teng, 2021.

Appendix 3: Technology database

Please refer to the attached file, associated with this report: FINAL_CWN_Green Chemistry Technologies Database.xlsx

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