Microplastic Treatment in the Great Lakes

A summary of industrial and domestic methods for removing microplastics from freshwater.

Queen's University TEAM Group 8
BlueGreen Innovations Group

TEAM

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Dedication

LAROCQUE Joseph Norman “Shaun”, B.Com.

This project is dedicated to Shaun Larocque, of Sarnia Ontario, who passed away on Thursday July 18th, 2019 at the tragically young age of 52.

Shaun was formally educated in accounting and economics at the University of Western Ontario. He had more than 20 years of business experience including as the Vice President of Finance at BlueGreen Innovation Group and as Credit Union board director with Mainstreet Credit Union (formally Lambton Financial).

Shaun had a longstanding career with the Canadian Coast Guard for over 26 years most recently as a Marine Communications supervisor. He was passionate about marine safety and the environment especially regarding pollution in the Great Lakes.

Shaun was also an entrepreneur/inventor and co-owner of Ayess Industries. He made valuable contributions to the science and engineering aspects of innovation as well as finance and administration.

He will be greatly missed by all especially his colleagues at BlueGreen Innovation Group.

DISCLAIMER

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Key Project Assumption: Toxicity of Microplastics

The analysis, prevention, and removal of microplastics (MP) pollution in water is identified as one major problem the world is currently facing [1]. Microplastics are classified as any plastics particle than in less than 5 mm in dimension. This report will use the term microplastics for particles that are no smaller than 20 µm and anything smaller than 20 µm is nanoplastic, which will not be addressed in this report. Significant progress has been made to understand where microplastics come from, and how they are transported through the environment and their fate. At this point there is evidence of occurrence and accumulation of microplastics in all aquatic environments, what remains to be determined is the effects that these particles have on human health [2]. Due to the recent finding of microplastics in drinking water, there is increasing concern over human exposure to microplastics. This has encouraged significant research on the effects of microplastics on human health. The Rochman Laboratory at the University of Toronto conducted a comprehensive review of laboratory studies investigating the effects of MPs on organisms. The review found that some studies reported detectable effects from microplastics while others reported no detectable effects [3]. The variability of the results is likely due to the variety in experimental methods, study duration, and the type, shape, size, and concentration of polymer used [3]. As such, a consensus has not yet been reached regarding the impacts of microplastics on human health [3].

Concern stems from the potential risk of microplastics and nanoplastics entering the blood stream and potentially the cells and impacting the DNA of the cell and potentially causing issues such as mutation and therefore increasing cancer risks. Presently research is geared towards whether microplastic particles are harmful on their own, how the different types of polymers impact toxicity and whether absorbents on the microplastic particles might be toxic as well.

The most recent and comprehensive research on the health impacts of microplastics presented at the 2019 Plastic Health Summit agrees with the results of the Rochman lab. According to presenters at the health summit the source and characteristics of human contact with microplastics may be the determining factor as to whether microplastics are harmful or not [4] . Researchers believe that microplastic inhalation, ingestion and exposure through the skin may achieve systemic circulation throughout the body. Once inside, microplastics may be responsible for tissue inflammation, cancer, birth defects, poor organ development, immune system issues, and/or serving as a vector for harmful microbes [4] [5] [6] [7] [8] [9] [10].

While the interest into microplastic health impacts grows, the scientific consensus suggests that current research efforts have not been enough to confirm whether microplastics alone are the sole culprit for these conditions. For instance, most researchers agree that particulate matter is one of the leading risk factors for global death but the role that microplastics play in particulate matter is still unknown [11].

Research into conditions such as Flock worker's lung suggests that acute exposure to high concentrations of short cut nylon fibres in the air may be responsible for causing respiratory issues, lung inflammation and scarring [12]. Similar tissue responses have been observed for people who are exposed to high levels of polyethylene and polypropylene. The majority of patients fully healed when removed from high concentration environments but low concentration environmental exposure may not be preventable. Since these conditions only happen at high concentrations, it is not certain whether any observed effect is due to microplastics or due to particulate matter [4].

Furthermore, ingestion of polystyrene by humans and mice have caused inflammation in the gastrointestinal tract. However, since the effects were only observed for high doses, the German Federal Institute of Risk Assessment has declared that microplastic ingestion is a low risk to intestinal health [4]. While there is a no scientific consensus on the toxic effects of microplastics, the presenting researchers at the health summit agreed that presence of microplastics alone cannot prove toxic effects. Instead, future studies will need to investigate all characteristics of microplastics, including size and shape distribution, composition, chemical and microbial concentration as well as the presence and magnitude of chemical leaching.

Despite the inconclusive research, this report will operate under the assumption that microplastics are harmful. Solutions for microplastic remediation and filtration will be proposed based on the assumption that eventually regulations will be implemented that require the removal of microplastics from wastewater.

Executive Summary

This report builds upon work that was performed by a previous Queen's TEAM group in the 2018/2019 school year. The 2018/2019 TEAM group concluded that there were significant concentrations of microplastics found within the Great Lakes waterways and that washing machine effluent was a main contributor. The focus of the information summarized in this report is on the methods of removal and/or treatment of microplastics from industrial/municipal and domestic wastewater streams. The report will also briefly discuss some information on potential sources of macroplastics and microplastics, and the economic impacts of the plastics industry. Municipal and industrial facilities can remove the largest quantity of microplastics, and their effluents are subject to regulations. Domestic solutions can remove large amounts of microplastics from washing machines, but consumers are not subject to regulatory oversight that would be readily enforceable. There are currently no standards for identification and quantification of microplastics in water or sludge.

The World Health Organization has not identified any adverse health effects in humans or the environment as a result of microplastics and currently, there is no limitation on the concentration of microplastics in wastewater effluents in Canada. As such, this report will operate under the assumption that microplastics are harmful. This report defines microplastics as plastic particles no smaller than 20 µm. Plastic particles smaller than 20 µm are considered nanoplastic and will not be addressed in this report.

The evaluation criteria that was used to evaluate industrial/municipal were: technology readiness level, efficiency/effectiveness, compatibility with current process, environment and safety, and simplicity of operation. The evaluation criteria for domestic solutions also included product availability and cost. Information regarding cost and energy consumption were included in individual sections for industrial solutions. Information regarding legal issues/regulatory approval was included in individual sections for both industrial and domestic solutions. Additional criteria were not used as an evaluation criterion. These criteria and their weightings were determined in conjunction with the members of BlueGreen Innovation Group Inc.

The industrial/municipal solutions were divided into existing and emerging solutions. The existing solutions evaluated were disc filter, dissolved air flotation, diatomaceous-earth filters, rapid sand filters, membrane bioreactor. The emerging solutions evaluated were electrocoagulation, centrifugal separation, functionalized, hybrid silica gels, Fenton's reagent, and separation by digestion of biological organic material. Additional solutions were included but not evaluated.

Domestic solutions evaluated were the Cora Ball, Filtrol 160, Lint LUV-R, Guppyfriend, and PlanetCare filters. For next steps in the project It is recommended that research be conducted into: sampling and testing methods to determine concentrations in streams, whether microplastics are harmful to human health or environment, proper disposal methods, and whether wastewater treatment plants are effective at removing microplastics and if so how to handle microplastics and nanoplastics within the sludge.

Meet the Team

Andrew Leung

Andrew Leung is a 4th year Chemical Engineering student at Queen's University with a focus in biochemical engineering. He has completed four summer co-op placements at Abbott Point of Care, a biomedical diagnostics manufacturer, in Research & Development, and New Product Introduction.

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Acknowledgements

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Client Stated Objectives

The primary objective of this project was to review emerging and existing technologies and methodologies to remove microplastics from effluent streams from municipalities and industries being released into the Great Lakes system. In addition, the project investigated removal techniques of microplastics that were already within the Great Lakes system. In the previous round of TEAM projects, microplastic buildup in the Great Lakes system was investigated with a significant source of microplastics found to be from washing clothing. Based on the previous project, BlueGreen Innovation Group sponsored this project to evaluate treatment or removal options. The project also included a feasibility analysis on potential solutions to determine which available options are the most feasible technically and economically.

Key Assumptions

The following assumptions were applied to the project:

Toxicity of Microplastics

Microplastics are harmful to the health of humans and the environment (as outlined in the introduction of the report). This assumption provides the justification for the purpose of the report and some reasoning behind the evaluation of the technologies.

Defined Size and Shapes of Microplastic

When the report references microplastics, it is referring to plastic particles that may come in the shape of spheres, fragments, films or fibres that are between 20 µm and 5mm in size. Any particle that is 20 µm or smaller is considered to fall under the category of nanoplastics. The removal of nanoplastics was not addressed in this report.

Assumption for Cost Evaluation

The technologies evaluated throughout the report that require construction are assumed to be required to be built new and facilities implementing the solution do not already contain any of the solution's equipment and all materials will be required to be procured.

Glossary

BOD	Biochemical Oxygen Demand	MP	Microplastic
BOM	Biological Organic Materials	PAX	Polyaluminium Chloride
CF	Cartridge filtration	PCDT	Poly-1, 4-cyclohexylene
COD	Chemical Oxygen Demand	PET	Polyethylene Terephthalate
CSTR	Continuous Stir Tank Reactor	PEZ	Pancreatic Enzyme
DAF	Dissolved Air Flotation	PP	Polypropylene
DE	Diatomaceous Earth	PVDF	Polyvinylidene fluoride
DF	Disc Filter	RO	Reverse osmosis
EC	Electrocoagulation	RSF	Rapid Sand Filter
FTIR	Fourier Transform Infrared Radiation	TRL	Technology Readiness Level
GAC	Granular Activated Carbon	TDS	Total Dissolved Solids
HDPE	High density polyethylene	TSS	Total Suspended Solids
KWS	Korono-Walzen-Schneider	WW	Wastewater
LDPE	Low density polyethylene	WWTP	Wastewater Treatment Plant
MBR	Membrane Bioreactor		

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1.0 Introduction

1.1 Project Description

1.1.1 Project Scope

Previous research was conducted on the plastic pollution in the Great Lakes by a Queen's TEAM group in the 2018/2019 school year. The research concluded that there was significant microplastic concentrations found within the Great Lakes with a common sources being the effluent streams of washing machines, microbeads from domestic products, fragments of plastics from litter, cigarette butts, foam from food packaging, film from plastic bags, wrappers, tire dust and production pellets from facilities [14]. Plastic pollution is becoming an increasing concern and investigations continue into the impact of MPs on human health and marine life. The focus of the information summarized in this document is on the methods of treatment for MP removal from wastewater streams. This document will also provide some information on potential sources of macroplastics and MPs.

As the goal of the project is to determine potential treatment methods on domestic and industrial/municipal scales this document will cover research and background information to date.

1.1.2 Project Objectives

The goal of the project is to research potential solutions that remove microplastics from freshwater streams on both a municipal/industrial and domestic scale. Industrial/municipal solutions will remove the largest quantity of microplastics from water due to the large capacity of water processed on a regular basis. Industrial/municipal microplastic removal may also have the ability to regulate the maximum permitted microplastic concentrations in a wastewater treatment plant (WWTP) and raw water treatment plants (WTP). Domestic solutions were included in the report as they offer a solution for the general consumer even though they will not be as effective at large-scale removal as industrial/municipal solutions. Although domestic solutions pose an opportunity to remove a significant amount of microfibres from the effluent of washing machines, it is not practical to regulate the filtering techniques of individual washing machines in individual's homes or businesses; therefore, it will not have as consistent results as industrial/municipal solutions.

The project explored industrial/municipal solutions that currently exist in WWTPs and/or WTPs, as well as promising emerging microplastic removal solutions that could be applied at an industrial/municipal level. Detailed literature research was conducted to determine the suitability of the solutions for MP removal using established weighted criteria which includes the solution's estimated technology readiness level (TRL), the efficiency of particle removal, the ability to integrate the solution into an existing plant, the environmental and safety impact and simplicity of operation. Supplemental information was also provided on the cost, legal restrictions and energy consumption, if available. Due to the preliminary state of these technologies for the purpose of MP removal, supplemental criteria were excluded from the evaluation to avoid inaccurate influence on the evaluation. Separate evaluations were conducted for existing and emerging technologies and solutions were ranked based on current research.

Domestic solutions were researched and evaluated for the most effective solution that could be applied to domestic washing machines. The criteria for domestic solutions included the efficiency/effectiveness, the simplicity of operation, the environmental impact, the technology readiness level and the product availability. The solutions were evaluated and ranked based on the weighted criteria.

The team provided recommendations based on the current state of research in MPs including the methods of testing and removing MPs from water on an industrial/municipal and domestic scale.

1.1.3 Population Demographic near the Great Lakes

The Great Lakes system accounts for 21% of the global freshwater volume and are responsible for sustaining life in the cities that surround them [15]. Approximately 8.5 million Canadians and 30.7 million Americans live near the Great Lakes and approximately 40 million people are supplied drinking water from the Great Lakes. Overall, 166 billion liters are being taken from the lakes daily for municipal, agricultural and industrial use [16]. Three of the Great Lakes, Ontario, Michigan, and Erie support several large cities with populations in excess of 100,000 people [17]. These higher populations likely correlate with greater plastic accumulation as industrial hubs located in these cities release plastics into the lakes during production and transportation of goods. Furthermore, the Great Lakes attract large numbers of tourists to beaches and harbours where litter can enter the water system. Even wastewater treatment facilities located on the shores of the Great Lakes do not filter 100% of all particles from their effluent, thereby providing a direct route into these bodies of water. Due to the potential for plastic buildup occurring in and around these cities, potential solutions will need to account for the large volume of people in these regions.

1.2 Definition of Microplastics

1.2.1 Source of Microplastics

The main microplastics found in WWTPs are polyester, polyethylene, polyamide and terephthalate [18]. A large source of microplastics in the Great Lakes were reported in the 2018/2019 TEAM report to be MP fibres and particles in effluent streams of washing machines. The government of Ontario has indicated that other sources include fragments of plastics from litter, cigarette butts, foam from food packaging, film from plastic bags, wrappers and production pellets from facilities that are along the Great Lake shorelines [19]. MP sources in the Great Lakes can be connected to the proximity of major Canadian cities to the location of sampling, as higher plastic levels were found on Toronto beaches [14].

1.2.2 Types of Microplastics Commonly Found in Water

There are many existing types of polymers. The polymers that were the most abundant in tested water throughout several research articles were polyester, polyethylene, polyamide and polyethylene terephthalate (PET) [18] [20]. These polymers are frequently used in common items such as clothing and food packaging. The common use, structure, general properties, and likely source at which they enter the water streams were analyzed for the identified polymers. More research into the properties of these polymers and how they influence the removal of these specific MPs from water will be required. Table 1 provides a summary from a study on the most common MPs found in water.

Table 1: As found in [21], the main kinds of microplastics found in different stages of the WWTP which were identified by micro-FTIR and micro-Raman.

Polymer	Description	Percentage of All MP Collected
Polyester	Fibres - Cross-section: Round, oval, flat - End: Cut, frayed, thickened - Appearance: Shiny or dull Particles - Shape: flat, angular fragment - Hardness: medium - Appearance: Shiny	79.1% *Mostly fibres
Polyethylene	Particles - Shape: uneven flakes and fragments, spherical - Hardness: medium to soft - Appearance: Dull or a bit shiny	11.4%
Polyamide, nylon	Fibres - Cross-section: Round, oval, flat - End: Cut - Appearance: Shiny	3.7%
Polypropylene	Particles - Shape: uneven fragments - Hardness: medium - Appearance: Dull	Negligible

1.2.2.1 Polyester

Polyester is a long chain polymer made from polyethylene terephthalate (PET) and poly-1, 4-cyclohexylene (PCDT) and is a petroleum-based polymer. The most common use of polyesters is for clothing, textiles, ropes, food packaging, and plastic beverage bottles [22]. The monomer structure of polyester can be seen in Figure 1.

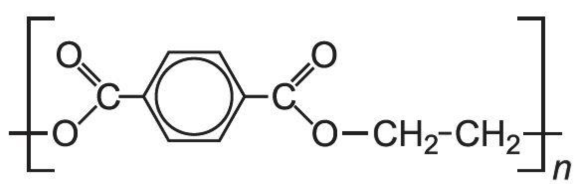


Figure 1: Monomer unit of polyester [23].

When manufactured for fibres, polyesters are formed in small granules, melted together and squeezed through a membrane to form a fibre structure [24]. Polyester may be released in the form of a MPs due to friction experienced in a washing machine causing the polymer's micro particles to break off and drain with the washing machine's effluent stream.

1.2.2.2 Polyethylene

Polyethylene is most commonly found in packaging for food, plastic bags, microbeads in hygiene products and toys [24] [25]. It can also be found in a variety of fabrics and textiles as it can be a component of polyesters [24] [25] [26]. The ethylene monomer that is polymerized to form polyethylene is produced from the cracking of ethane in natural gas [25]. Polyethylene is made of a long polymer chain comprised of the ethylene monomer shown in Figure 2.

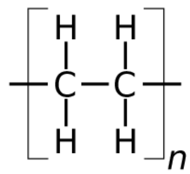


Figure 2: Monomer unit of polyethylene [27].

Polyethylene microbeads which are 1 to 5 millimeters in size are difficult to filter from wastewater and have been proven to pose a risk to aquatic life; These microbeads they have been identified in Great Lakes [26]. Measures to reduce the use of microbeads through the implementation of regulations began in Canada in 2017 [28].

1.2.2.3 Polyamide

Polyamides are commonly found in nylon fabrics used for clothing, carpets, rope, and brake hoses and are produced either in solid form or as fibres [29]. Polyamides are known for having high tensile strength, meaning that the polymer may undergo large amounts of force before breaking [30]. The most commonly found polyamide polymers are used are poly amide 6,6 and poly amide 6 [29]. Polyamides may have varying monomers present in the copolymer but are formed through the interlinking of the monomers by amide linkage, as shown in Figure 9 below.

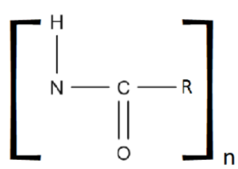


Figure 3: Linkage monomer consistent between polyamide polymers [29].

There are several likely sources of polyamides entering wastewater streams. The most likely is the washing of clothes resulting in small particles and fibres breaking off the materials and entering the wastewater stream.

1.2.2.4 Polyethylene Terephthalate (PET)

Polyethylene terephthalate (PET) is a synthetic polymer that is produced through the polymerization of ethylene glycol and terephthalic acid [31]. The monomer unit of the polymer can be seen in Figure 11 below.

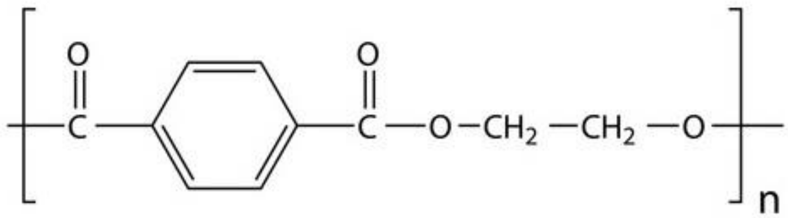


Figure 4: Monomer unit of polyethylene terephthalate [32]..

The polymer is known for its high strength and stiffness and is commonly found in beverage bottles and food containers. PET may also be used for permanent-press fabrics used in anti-wrinkle clothing. It is the most commonly recycled plastic and is a member of the polyester family of polymers [31]. PET likely enters water streams through litter in storm water sewers and through the effluent streams of domestic washing machines.

1.2.3 Shape and Dimension of Microplastics in Water

A MP is classified as a plastic particle that is less than 5 mm in diameter or length, with the most common MP particle size being between 20 to 100 micrometers [33]. The shape and dimension of the MP particle impacts the ability for the particle to be removed from water when treated.

Research from a WWTP in the Czech Republic studied the removal efficiency depending on size and shape of MP particles at three water treatment facilities. The study found that particles greater than 50 micrometers are almost completely removed during the skimming, sedimentation and tertiary filtration stages. Approximately 60% of particles between 10 and 50 micrometers in size can effectively be removed by traditional wastewater treatment processes. Testing the treated wastewater revealed that 95% of the remaining MP contamination was between the sizes of 1-10 micrometers. Minimal research was available on the removal of MPs under 10 micrometers in size. The ability to treat and remove plastics less than 50 micrometers is not thoroughly researched and many unknown hazards exist due to the lack of regulation for MPs in water [33]. A collection of international research on MP concentrations can be seen in Table 2. Please note that the testing methods and parameters of the studies were not given in the article and the concentrations may be influenced by exact areas, sample volumes, and method of detection and measurement.

Table 2: Reported microplastic particle concentration in final effluents of different WWTPs seen in [21].

Reference	MPs Concen-tration (MP particles/L)	Lower Size Limit for Fractionation (µm)	Type of WWTP	Country
Lares et al. (2018)	1.05	250	Primary and Secondary	Finland
Magnusson and Noren (2014)	0.00825	300	Mechanical, chemical and biological	Sweden
Dyachenko et al. (2017)	0.02	125	Primary, Secondary and Tertiary	USA
Mason et al. (2016)	0.05	125	17 WWTPs	USA
Murphy et al. (2016)	0.25	65	Primary and Secondary	UK
Carr et al. (2016)	0	45	Primary, Secondary and Tertiary	USA
Ziajahromi et al. (2017)	0.28	25	Primary, Secondary and Tertiary	Australia
Ziajahromi et al. (2017)	0.48	25	Primary and Secondary	Australia
Ziajahromi et al. (2017)	1.54	25	Primary	Australia
Michielseen et al. (2016)	0.5-5.9	20	2 WWTPs: Primary, Secondary and Tertiary	USA
Mintenig et al. (2017)	0.1-10.05	20	12 WWTPs: Mostly Secondary and Tertiary	Germany
Talvitie et al. (2015)	13.5	20	Primary, Secondary and Tertiary	Finland
Talvitie et al. (2017b)	0.005-0.3	20	4 Tertiary WWTPs	Finland
Leslie et al. (2017)	9-91	0.7	7 WWTPs	Netherlands
Brownie et al. (2011)	1	- (filtered)	Primary, Secondary and Tertiary	Australia

Microplastics can be found in a variety of shapes with the most common being fragments, spherical, or fibres. Fibres may be able to move through membrane filters more easily than spherical particles due to the variability of the shape and this should be considered when evaluating treatment methods. Studying three WWTPs showed that there was a large variety in terms of quantity and shape of micro-particles, but across the facilities fragments were the most commonly found shape [33]. Examples of various microplastic shapes can be seen in Figure 5.

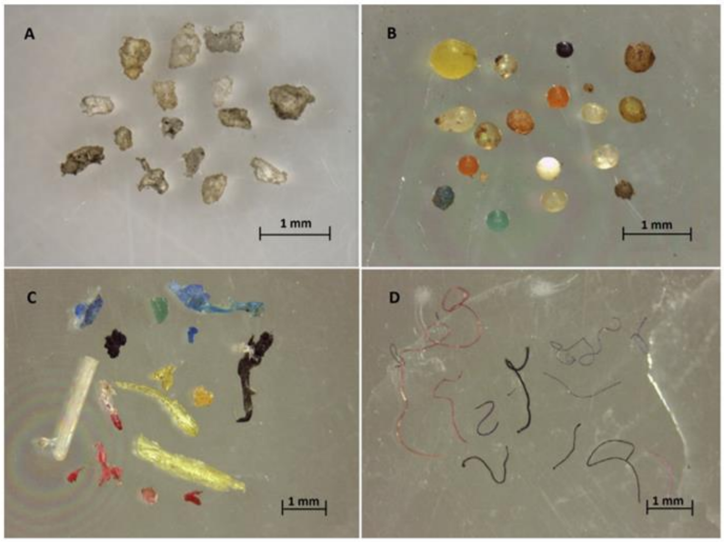


Figure 5: Example microplastic shapes: A and B are microbeads in the shape of fragments and spheres respectively and are derived from personal care products. C and D are in the shape of fragments and fibres, respectively and are from break-down of larger plastics and synthetic textile fibres. [20].

Research shows that wastewater and water treatment plants are expected to remove more than 90% of the MPs. The remaining 10% of particles fall under 100 µm in size. The majority of the 90% of MPs and fibres are removed in pre-treatment and secondary treatment [20].

It should be noted that the quantity and variety of microplastics, and the removal efficiency was dependent on the facility where the water was treated. The article used for the review of shape and dimension impact did not take data over a specific amount of time and used only three different treatment plants to perform experimentation. The location of the WWTP may also impact the level of microplastics in water due to the varying populations and industrial sites that surround the plant.

1.3 Measurement Methods for Microplastics

There are no existing standards on the identification and quantification of microplastics in water or sludge solutions; however, research labs often utilize similar techniques. Generally, the process will include the following steps:

1. Collect water sample containing microplastic particles.
2. Dry the sample.
3. Visual counting and classification by microscope or electron microscope.
4. Apply microplastic identification methods to identify the type of plastic.
5. Use statistical methods based on the sampling results to estimate a distribution of particle shape, size, and type.

The most common microplastic identification methods include Raman Spectroscopy, Fourier-transform infrared and focal plan array-based systems [34]. The microplastic measurement methods applied by the Rochman Laboratory, partnered with University of Toronto, were examined. Their identification process uses both Raman Spectroscopy and Non-Spectroscopy along with polymer-dye binding chemistry, density tests, surface morphology and fluorescence staining [34]. The rigorous method may successfully identify the type of microplastics which is important in understanding the plastic sources in the area. More information on the measurement method may be found in the Rochman Laboratory publication, "Identification of Microfibres in the Environment Using Multiple Lines of Evidence", from the Environmental Science & Technology journal [34].

The Rochman Laboratory collects their own samples from the surface water, water column, from sediments and organisms in the Toronto and surrounding areas. A fine strainer is used to isolate microplastics from the water and the measurement/identification method is then applied to the four sets of samples. A summary of various methods of detection have been outlined in Appendix A.

1.4 Regulations and Guidelines of Microplastics in Canada

The World Health Organization cannot identify any linked adverse health effects to humans or the environment for microplastics in water as the identification of microplastics as a pollutant in water is fairly recent and minimal studies have been conducted on the issue [19]. There are currently no regulations or guidelines in Canada for testing procedures or permitted levels of microplastics in drinking water, wastewater, or bodies of water. This lack of regulation permits variation in conducted studies' sampling requirements, testing methods and quantification requirements for particle size, shape and type of polymer. This variation in experimentation makes it difficult to compare results of the various studies and considered throughout the research.

As there is no defined limitation to the allowable concentration of microplastics in effluent wastewater streams, drinking water or bodies of water in Canada, this project will operate under a few assumptions.

Firstly, the project will assume that microplastics are harmful to the environment, human health, and aquatic life. This assumption comes from concern internationally that microplastics, nanoplastics and adsorbants found in water may be harmful. Currently research is being done on the subject, but no definitive results have been produced.

Secondly, the project will assume the federal, provincial and municipal governments within Canada will take action on the issue in the future. It is assumed that this will be done through the implementation of regulations, standards, and guidelines related to the testing requirements and allowable levels of microplastics being discharged to bodies of water including discharge to the Great Lakes system.

Third, the project will assume that the implementation of the regulations will result in the demand of treatment solutions for the removal of microplastics WWTPs and thus the methods suggested will be in demand and provide revenue in the future. Due to lack of research and regulation at the present time, the suggested treatment solutions made by the project are not predicted to be economical in the present time due to the current lack of demand.

1.5 Wastewater Treatment Plants

1.5.1 Stages of Treatment in Wastewater Treatment Plants

WWTPs are used to treat water collected from municipal sewers and discharge the treated water into a body of water. Raw wastewater is untreated water received as influent to a WWTP from sewers. This water can include human waste, litter from streets and litter found in lakes or rivers. There are three to four steps involved in wastewater treatment: preliminary, primary, secondary and tertiary treatment. At a minimum all plants in Canada are required to have primary and secondary treatment. The equipment used to meet requirements varies between WWTPs and selected equipment will vary with required capacities, age of the plant, and the location, as the size of the population directly influences the amount of water requiring treatment. Larger cities will have more stages of treatment such as primary, secondary and tertiary treatment whereas small towns will likely have minimal stages of treatment such as the minimum requirement of primary and secondary treatment.

Preliminary treatment in a WWTP involves the removal of larger items from the water that may cause operation issues with equipment in the plant. Primary treatment involves the removal of contaminants by physical such as primary settling basins, gross floatation/skimming DAF. Secondary treatment, also known as biological treatment, focuses on dissolved contaminants through bio-treating. Tertiary treatment is considered advanced treatment and is used to remove nutrients such as nitrogen and phosphorus from the water as well as disinfect the water. Most plants do not contain tertiary treatment, as it is not required to reach water requirements but may be required to meet any additional by-law restrictions or to serve larger populations.

The amount of required treatment is based on guidelines of water conditions set by the Ontario provincial government through O. Reg. 435/93: Water Works and Sewage Works under the Ontario Water Resources Act and the Environment Compliance Approval (ECA) process. The federal government regulates through the Wastewater Systems Effluent Regulations (SOR/2012-139) under the federal Fisheries Act. There are no guidelines set for microplastics in Canada and therefore it is not tested or regulated at WWTPs presently.

WWTPs use the water quality guidelines set by the government, typically municipal by-laws exist to enforce the guidelines as well. The WWTP will test effluent water to ensure the guidelines are met before discharge. Examples of parameters that are tested for include but are not limited to organic content and oxygen levels (BOD, COD), as well as total dissolved and suspended solids (TDS, TSS). WWTPs are typically upstream of WTPs which take in the water from a larger body and condition it for drinking and domestic purposes. Since intake WTP's are inevitably down stream of upstream communities and their WWTP's they will draw water containing contaminants released by those plants. Refractory contaminants, such as MP's will inevitably be included in that raw water.

For the configurations of WWTPs that sit along the shores of Lake Ontario in Toronto, Kingston and Sarnia, please see Appendix A.

1.5.2 Economics of Municipal Drinking and Wastewater Treatment Plants

The largest drinking water source in Canada is treated surface water which accounts for 88% of Canadian drinking water [35]. The remainder of the drinking water supply comes from groundwater and groundwater under the direct influence of surface water (GUDI). GUDI sources use surface water to replenish aquifers that would otherwise take years to refill [36]. Microplastics entering these drinking water sources through various possible entry points could pose risk to human health if microplastics are harmful to human health.

Drinking water treatment centers are responsible for treating water for drinking, as well as supplying water for commercial, industrial and residential uses [35].

In 2007, Stats Canada determined that 86% of households received water from their municipal water source, and that over 5.6 billion cubic meters of potable water was supplied [35]. This translated to drinkable water access for 24 million Canadians [35]. That same year, Stats Canada conducted a nationwide study to assess the operating and maintenance costs of WWTPs. It found that in 2007, $807 million was spent on operating and maintenance costs [35]. The largest component was labour costs at $302 million, followed by energy costs at $199 million, material costs at $198 million and other miscellaneous costs totaling $108 million [35]. In that year, the average conventional plant produced 5,706 ML of drinking water for 26,000 people [35].

While costs vary depending on the treatment type, conventional treatment is composed of coagulation, flocculation, sedimentation, granular media filtration, and disinfection [35]. In 2007, more than half of the water treated at drinking water plants was treated using the conventional treatment method [35].

Figure 6 below shows a plot that estimates the cost based on treatment volume. At the low end, the average annual operating and maintenance costs for a plant producing 100 ML of water is $123,000, while a plant that produces 50,000 ML of water is $3.79 million.

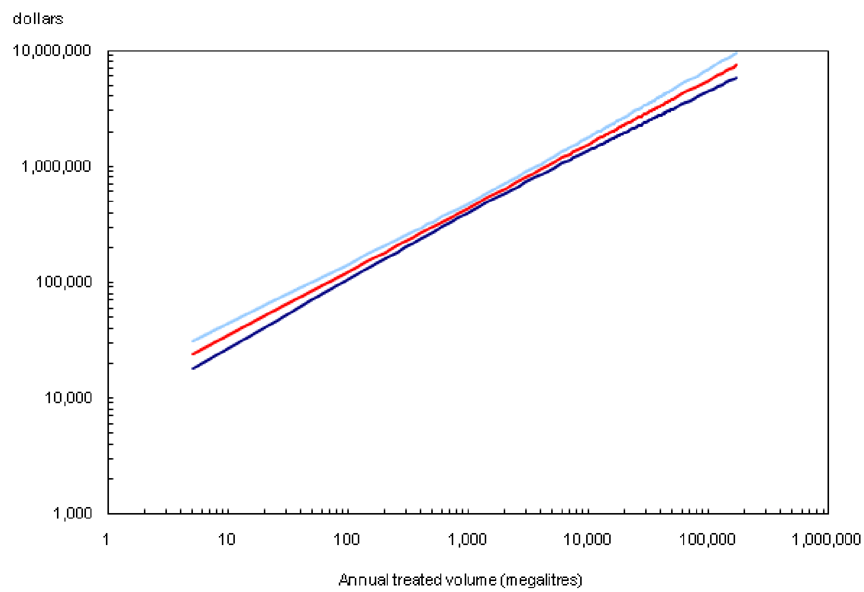


Figure 6: Plot of annual operating and maintenance costs as a function of annual treated volume. [35]

WW is considered to be any liquid waste that is discharged into drains and sewers, received by wastewater treatment centers or discharged waters that return to the environment. [37] WW can be divided into two categories: the first being sanitary sewage from housing, businesses, industries and institutions, and the second category being stormwater from rain or melting snow that enters the sewage system. In most cases, these waters must be treated before they are released to the environment.

According to a Stats Canada report, 82% of households were connected to municipal sewer systems and on average 668 L of WW per person were served by WWTPs. Overall, 65% of municipal influent comes from residential sources. After this, the next highest sources are the industrial/commercial sector, stormwater flow, and groundwater infiltration at 18%, 9%, and 8% respectively. To handle this demand, municipalities across Canada spent approximately $3.9 billion for sewage collection and disposal in 2006. [37]

1.6 Economic Perspective on Plastics and Microplastics

Microplastics are found in the form of microbeads and microplastics from the gradual degradation of macroplastics [38]. The impact of microplastics on the Great Lakes system and other water bodies is currently unknown. However, to develop an understanding, the overall global impact of plastic is a factor that must be understood. Plastic is one of the most readily used materials globally and its production volume continues to climb year after year. From 2014-2019, global flexible food packaging industry grew 5.72% [39]. Plastic is widely used to provide low cost materials that contribute to a higher standard of living. The production and consumption of plastic based materials has continued to increase over the years due to their simple and versatile applications. The overuse and disposal of plastic has been identified as an unsustainable habit that needs to be addressed. As the largest supply of fresh water in the world, the Great Lakes system plays a crucial role in supporting human and wildlife in North America. Therefore, the investigation into the impact of microplastic levels and removal techniques should be considered a top priority. Since the largest source of microplastics comes from the degradation of macroplastics, mitigation and prevention of overall plastic waste is one of several viable solutions [38]. The growing demand for solutions to this plastic waste issue has significant impacts both domestically and globally.

1.6.1 Economics of Plastic Use

Plastic use in society has been commonplace in consumer goods, both directly and indirectly since its rapid expansion starting in the 1950s and is still growing and a popular material choice today [40]. During this time period, its annual and cumulative production has grown steadily, the exception being the global financial crisis of 2008 as shown in Figure 7 and Figure 8.

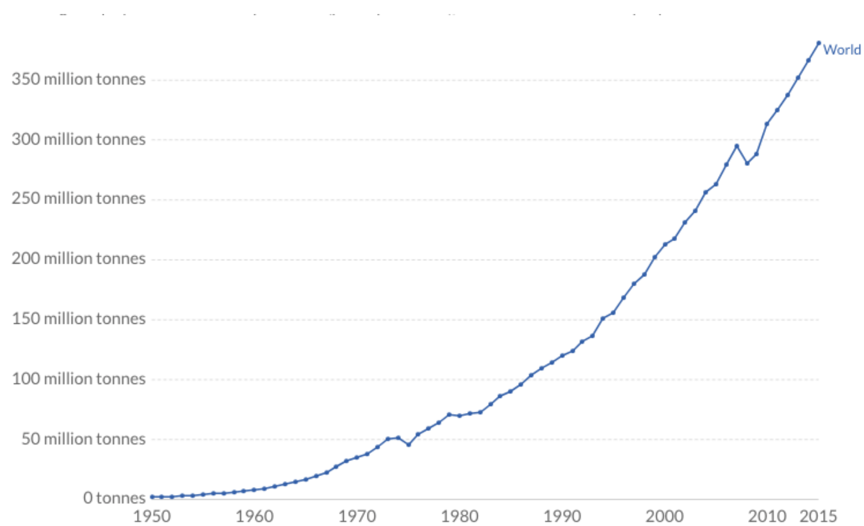


Figure 7: Annual production of plastics since 1950. [40]

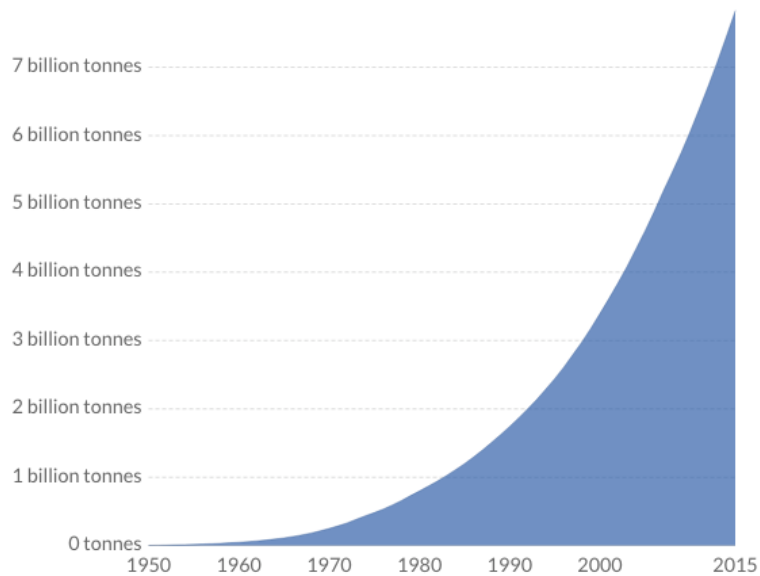


Figure 8: Cumulative production of plastics since 1950. [40]

In 2017, 348 million tonnes of plastic were produced globally, up from 335 million tonnes in 2016 [41]. The biggest market segment in the plastics industry is the plastics packaging materials and non-laminated film and sheet manufacturing, which is approximately 20% of the total industry as seen in Figure 9 [42].

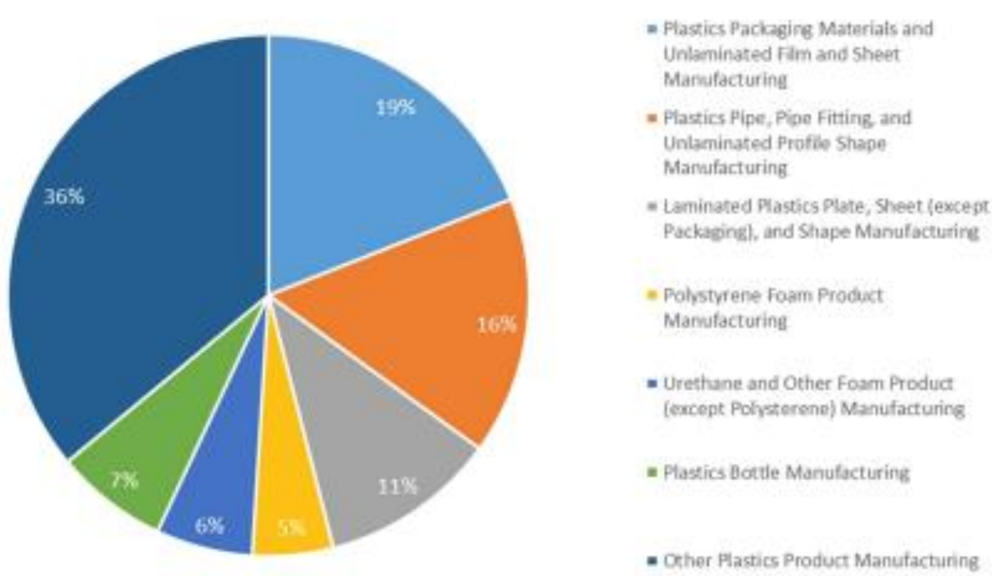


Figure 9: Plastics industry market segmentation 2016, in $ Billion. [42]

Due to its low production costs, plastics are commonly used to replace products that were previously made from paper, glass and metal [43]. In 2013, the American Society of Mechanical Engineers claimed that companies could achieve overall cost savings of up to 50% by utilizing plastic instead of metal for some automotive parts. [43] Reasons why plastic is more inexpensive than other materials include costs associated with part assembly, welding, and colouring the part [43]. As well, plastics offer lightweight durability, drastically reducing the weight of the part [43].

There are many vendors internationally within the plastic production industry [44]. The United States is the top producer of plastics in the global market, followed by the China, India and Brazil [42]. However, the production of plastics in the rest of the world are expected to exceed that of the United States in the near future, as the United States contends with the demand for sustainable business practices [42].

Plastic waste can enter the environment at any point in the linear economy model proposed by Eriksen et al such as during production, transportation, litter and wastewater effluent as seen in Figure 10 [45].

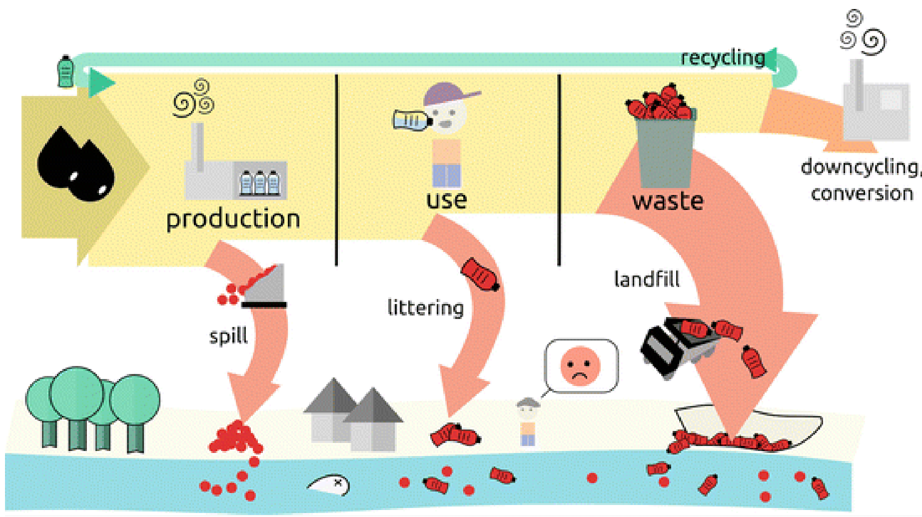


Figure 10: Linear economy model for plastic leaks proposed by Eriksen et al. [45]

1.6.2 Cost of Microbeads in Cosmetics and Cleaning Materials

Apart from degradation of plastic, microbeads found in personal care items are the other main source of microplastics. This includes toothpastes, face and body washes, body scrubs, makeup products and sunscreen [46] [47]. Products as small as a 150-mL tube of face wash can contain up to 2.8 million beads, and each time products like these are used, 94,000 microbeads can be flushed down the drain. Researchers in England believe that this could equate to 80,000 tonnes of microbeads entering the ocean annually [48].

A report from Reuters, estimates that the global cosmetics market in 2018 was worth $532.43 billion, and expected to rise to $805.61 billion by 2023 [49]. According the US Department of Environment and Energy, 80% of all companies surveyed identified as supplying products with microbeads [46]. Countries such as the United States, Canada, Australia, and New Zealand have already banned microbeads in products and other nations such as Sweden, the Netherlands, and Belgium are expected to ban the products in the near future [50]. In countries where they are not yet banned, companies such as L'Oreal, Unilever, Proctor & Gamble, Palmolive and Johnson & Johnson have voluntarily phased out microbeads from their products [50].

1.6.3 Financial Barriers to Effective Recycling

Recycling is commonly misperceived as the best way to mitigate the risks of harm to the environment. Due to inefficient processes and the low-cost benefit of recycling plastic, it can no longer be considered a long-term solution for plastic pollution. Plastic that is not recycled will either be incinerated or disposed of into landfills or the environment. In 2015, approximately 20% of all global plastic was sent to be recycled, 25% was incinerated, and 55% was discarded as shown in Figure 11 [40]. Canada has a recycling rate of 11% but has a predicted 8,000 tonnes of plastic into bodies of water [51]. The United States rate of recycling is near the global average of 9% but the it is still the largest producer of plastic pollution in the world resulting in approximately 26 million tonnes of plastic waste being produced in 2015 [52].

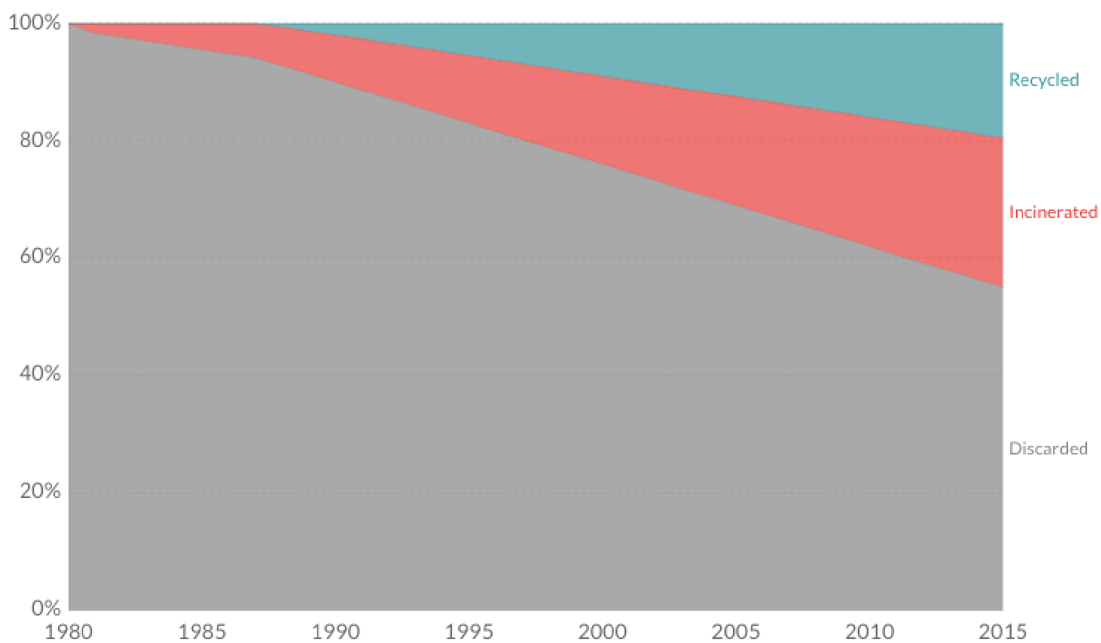


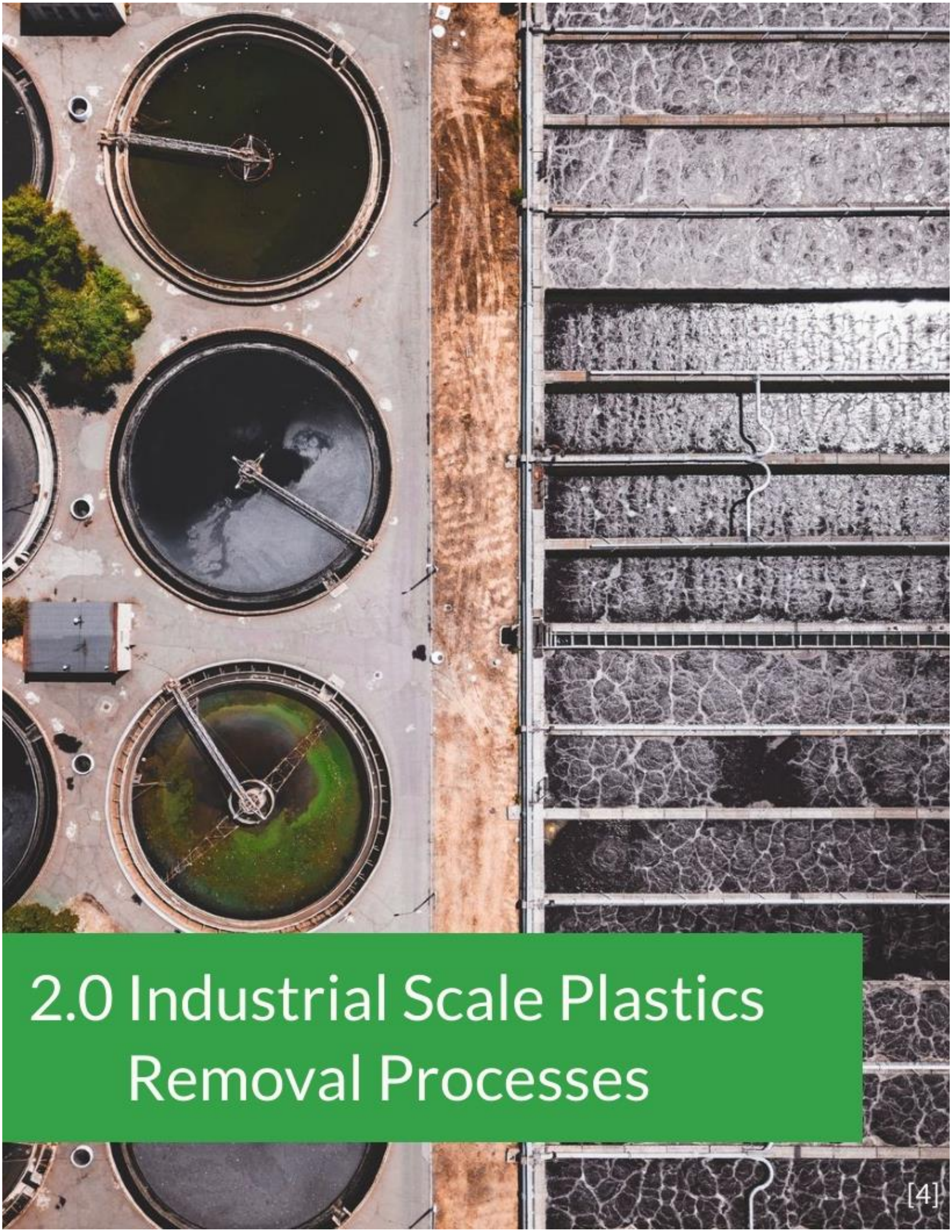
Figure 11: Global plastic waste by disposal method. [42]

Recycling is a $200 billion a year industry and is impacted by the changes in the global economy and operating costs [53]. Materials with food or biohazard waste, blended materials and cheap plastics are often not worth the cost of recycling and are discarded as plastic waste. This results in only 20% of plastic being sent to recycling centers globally [54]. In addition, each time a plastic material is recycled the polymer chain is shortened reducing the quality and tensile strength of the plastic [55]. For this reason, recycled plastics can only be recycled seven to nine times before it no longer fits the functional requirements, or it becomes too expensive to continue [55].

Since plastic is a petroleum-based product, when the cost of oil is low, it is cheaper to manufacture new plastic rather than recycle [56] [57]. This is especially true for thin plastics such as the ones used in grocery bags [57]. Conversely, higher quality and thicker plastics are more valuable and are prioritized over lower quality materials [56]. In the past, China and other Asian countries imported waste produced by G7 nations to the point where it contributed to an economic deficit. In response, China passed restrictive regulations on recycling imports. As a result, G7 nations that relied on China in the past were unprepared for the increase in their domestic waste. [53]

1.7 Sustainable Business Opportunities

While plastic use has increased exponentially over the last 70 years, recent social change has pressured businesses to adopt new strategies to mitigate their plastic use. The reasoning for this shift is to appeal to consumers who rank sustainability as a key criterion when choosing products [58]. Clothing and apparel companies such as Nike have all started to prioritize sustainability by selling products made out of recycled materials [59]. Other companies such as Allbirds and Patagonia have generated large revenue streams off of products made from cotton instead of non-synthetic materials [60]. However, this is not without its own drawbacks as growing cotton requires extensive pesticide and water use [59]. Social pressures in the food and beverage industry have also caused companies to transition to sustainability. Beer manufacturer Carlsberg has developed an adhesive that can be printed on cans to hold them together instead of traditional plastic handles. [61] As well, various restaurants have committed to elimination of plastic straws by 2020 and have rolled out straw less lids in North America [62].



2.0 Industrial Scale Plastics Removal Processes

[4]

2.1 Evaluation Criteria for Industrial/Municipal Technologies

To provide a focused scope of research, criteria for the industrial/municipal removal of plastic from aqueous systems were developed in discussion with Blue Green Innovation Group Inc. Five evaluation criteria were selected to assess the viability of industrial/municipal technologies in a weighted evaluation matrix, with three additional metrics to be considered, but not formally assessed. The five evaluation criteria for industrial/municipal technologies are detailed in the following section.

2.1.1 Technology Readiness Level

Technology Readiness Level (TRL) is a type of measurement system to determine the maturity of technologies. The levels outlined in Table 3 are based on information from Innovation Canada [63]. The levels given to the technologies being evaluated will be given based on the technologies' readiness for microplastic treatment.

2.1.2 Efficiency/Effectiveness

To determine the efficiency/effectiveness of a system, the percentage of microplastic removed, the size of microplastic removed, and the method of removal must be considered.

2.1.3 Compatibility with Current Process

To determine the likelihood and ease with which a new technology can be integrated into an existing WWTP, the compatibility with the current process must be assessed. Considerations when determining compatibility include installation time, footprint, capacity, and robustness.

2.1.4 Environment and Safety

Implementation of a new technology should not significantly increase the safety risks or environmental impact of the facility. Considerations include the exposure to additional chemical hazards, the production of dangerous waste products, increased mechanical hazards, and adherence to environmental regulatory guidelines.

2.1.5 Simplicity of Operation

The new technology should not be significantly different from the existing WWTP in terms of complexity of operation. The maintenance requirements, materials required, and number of unit operations required should be assessed.

Table 3: Description of TRL.

TRL	Description
Level 1	**Basic principles of concept are observed and reported:** Scientific research begins to be translated into applied research and development. Activities might include paper studies of a technology's basic properties.
Level 2	**Technology concept and/or application formulated:** Invention begins. Once basic principles are observed, practical applications can be invented. Activities are limited to analytic studies.
Level 3	**Analytical and experimental critical function and/or proof of concept:** Active research and development are initiated. This includes analytical studies and/or laboratory studies. Activities might include components that are not yet integrated or representative.
Level 4	**Component and/or validation in a laboratory environment:** Basic technological components are integrated to establish that they will work together. Activities include integration of "ad hoc" hardware in the laboratory.
Level 5	**Component and/or validation in a simulated environment:** The basic technological components are integrated for testing in a simulated environment. Activities include laboratory integration of components.
Level 6	**System/subsystem model or prototype demonstration in a simulated environment:** A model or prototype that represents a near desired configuration. Activities include testing in a simulated operational environment or laboratory.
Level 7	**Prototype ready for demonstration in an appropriate operational environment:** Prototype at planned operational level and is ready for demonstration in an operational environment. Activities include prototype field testing.
Level 8	**Actual technology completed and qualified through tests and demonstrations:** Technology has been proven to work in its final form and under expected conditions. Activities include developmental testing and evaluation of whether it will meet operational requirements.
Level 9	**Actual technology proven through successful deployment in an operational setting:** Actual application of the technology in its final form and under real-life conditions, such as those encountered in operational tests and evaluations. Activities include using the innovation under operational conditions.

2.1.6 Additional Metrics

The following section details metrics that were deemed important to the potential use of a technology but were not included in the evaluation matrix at this time due to lack of available information.

2.1.6.1 Legal Issues/Regulatory Approval

Before implementation of a new technology, legal issues must be assessed, and regulatory approval obtained. Considerations include whether the technology is patented, copyrighted, or trademarked, whether the materials for construction and operation, as well as technicians and operators will be available within the region.

2.1.6.2 Cost

Although cost is an extremely important, and often determining factor due to the novelty of these technologies, no reliable costing information could be obtained. However, where possible an estimate of capital cost, operating cost, and any associated legal costs will be provided.

2.1.6.3 Energy Consumption

Due to the novelty of the technology, it is not possible to obtain reliable values for energy consumption. Qualitatively energy consumption will be assessed in terms of anticipated additional energy required. The need for backup power in the event of a power outage will also be considered.

2.2 Existing Industrial Scale Microplastics Removal Processes

Five main existing industrial/municipal solutions were examined for the purpose of removing microplastic particles from WWTP effluent streams in the Great Lakes system. These solutions were assessed based on the five main evaluation criteria which includes the technology readiness, efficiency/effectiveness, compatibility with current processes, environment and safety, and simplicity of operation. The additional metrics were also researched but in most cases this information was not available. Three additional existing solutions are also described. It was evident that these filtration methods were less viable solutions for microplastic removal in the Great Lakes system WWTPs; therefore, they were not evaluated to the same extent.

2.2.1 Disc Filter

2.2.1.1 Technology Description

Disc filters (DF) are comprised of a series of 24 round meshed panels in an enclosed tank. The mesh filters are polypropylene, polyester or polyamide mesh which range from 10 - 40 µm in pore size [64] [65]. As the filter physically traps particles; a sludge cake forms. The layer of sludge decelerates the filtration process, causing the water levels to rise inside the entrance cylinder. The backwash is eventually triggered by a level sensor in the incoming cylinder [66]. The backwash system utilizes high pressure (approximately 800 kPa) to rinse the sludge off the filter [66]. The schematic of the DF filtration process which utilizes backflush is shown in Figure 12.

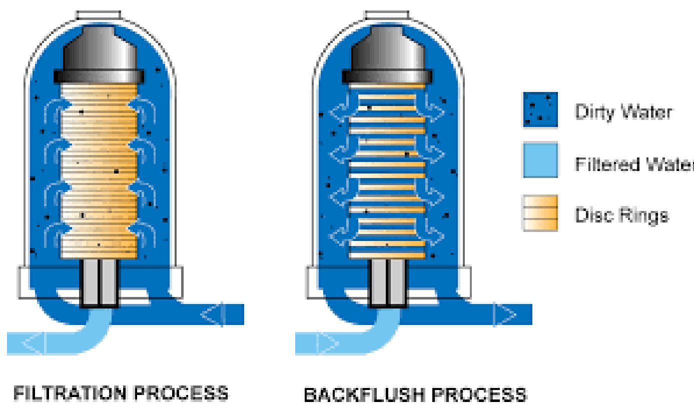


Figure 12: Schematic of the DF vessel during both the filtration and backflush process [67].

A rotating DF incorporates centripetal forces to clear the effluent sludge from the DF. The sludge is pushed to the perimeter of the filter drum and collected. The schematic for the rotating DF drum is shown in Figure 13.

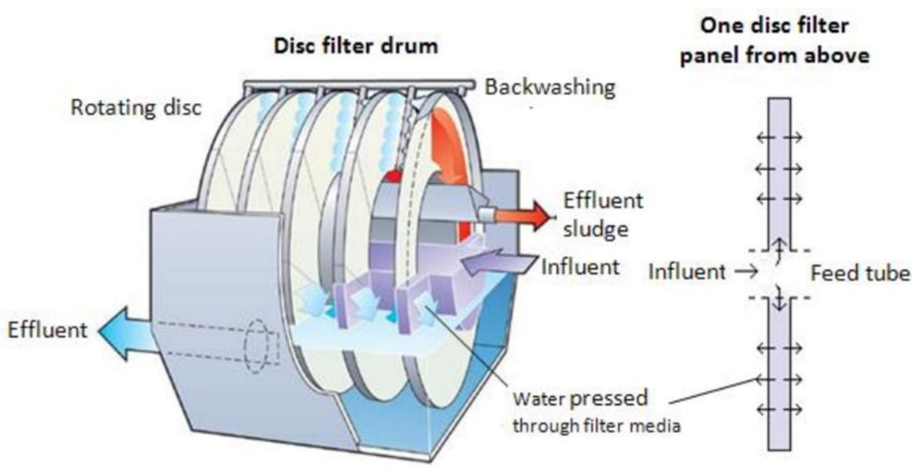


Figure 13: Diagram of high capacity rotating DF system [65].

2.2.1.2 Current State of Technology

DFs are currently used at select wastewater treatment plants as a final polishing step to remove fine particles. The use of DFs for microplastic removal has been tested in several pilot-scale studies; therefore, it is Technology Readiness Level 6 based on Innovation Canada’s technology readiness scale.

A study conducted by Aalborg University in Denmark examined a DF’s effectiveness at removing plastic particles greater than 10 µm in size in a WWTP following the primary sedimentation, activated sludge process and secondary clarification. The study evaluated a Hydrotech HF2220 DF with an operating capacity of 1200 m^3/h which consists of 13 discs, each with a pore size of 18 µm. Samples were collected before and after the DF using a strainer with a pore size of 10 µm. [68]

An alternative study assessed the removal of microplastics using the pilot-scale Hydrotech HSF 1702-1F system which consists of two-disc filters, both containing 24 filter panels. The study examined the system with filter pore sizes of 10 and 20 µm. Samples were collected in the study before and after the DF system using a mesh with a pore size of 20 µm before the filter accumulated a cake of collected particles. [20]

2.2.1.3 Evaluation of Technology

The Disc Filter method for use of microplastic removal in WWTPs surrounding the Great Lakes system was assessed based on the criteria outlined in Table 4 .

Table 4: Evaluation of the DFs and comparison of technology to project specific outlined criteria

Criteria	Notes
Technology Readiness Level	Level 6: System/subsystem model or prototype demonstration in a simulated environment. Although the DF is currently incorporated in WWTP processes, it is not yet incorporated for the main purpose of removing microplastics. Further testing is still being performed to assess the precise effectiveness of the filter for removal of microplastics. The testing of microplastic removal by this method of treatment is still emerging and is in the research phase. Properties and fate of the resulting sludge needs to be studied.
Efficiency/Effectiveness	The study performed at the Aalborg University in Denmark concluded that the Hydrotech HF2220 DF was capable of removing 89.7% of the total number of microplastic particles larger than 10 µm [64]. Another study assessed the removal of microplastic particles using the Hydrotech HSF 1702-1F DF system [20]. The study found that the system could remove up to 98.5% of microplastics larger than 20 µm [20].
Compatibility with Current Process	A DF is a filtration method with a relatively small footprint and minimal head loss; therefore, it can be an adequate addition to current WWTP processes [69]. The method is most successful as a tertiary filter as the majority of particles will already be removed; therefore, the filter will experience less blockages.
Environment and Safety	As the filter is purely mechanical, there are no environmental of safety concerns. If the sludge produced from the system cannot be used for agricultural use or repurposed in any way, the sludge will have to be incinerated or sent to landfill. This could result in emissions to the environment through incineration or additional required landfill capacity.
Simplicity of Operation	Controls for the DF are located at ground level to increase ease of operation and maintenance; however, the system is primarily automatic [70]. The frequency of maintenance is dependent on the flow rate, filter pore size and effluent flowing through the system.

Additional Information Criteria	
Legal/Regulatory Applications	The application of the technology must adhere to the guidelines of Drinking-Water Systems regulation (*O.Reg. 435/93*) under the *Ontario Water Resources Act, 1990*. Use and storage of any reagents must be in accordance with *Regulation 860* under the *Occupational Health and Safety Act,* as well as Building Code (*O.Reg. 350/06*) under the *Building Code Act, 1992* and the Fire Code (*O.Reg. 388/97*) under the *Fire Protection and Prevention Act, 1997*. Depending on the site of implementation, local by-laws may also apply. [71]
Cost	The Kitchener Wastewater Treatment Plant in the Region of Waterloo, Ontario integrated a DF during an upgrade to the facility. The DF was added in the new tertiary stage in order to remove finer particles from the effluent stream. The DF was selected as it has a low capital, operating and life cycle costs in comparison to similar filtration alternatives. [69] If the sludge produced from the system cannot be used for agricultural use or repurposed in any way, the sludge will have to be incinerated or sent to landfill. This could result in lower income for the facility if the sludge is typically sold as fertilizer.
Energy Consumption	Energy is required to operate the pumps which move the effluent through the system and also facilitates back flushing. The amount of energy required is dependent on the size of the filter, flow rate, as well as the frequency of cleaning.

2.2.2 Dissolved Air Flotation

2.2.2.1 Technology Description

Dissolved Air Flotation (DAF), is a useful tool for the removal of both small and large particles from water and can commonly be found in WWTPs. There are several key stages to DAF which includes gas transfer across the air-water interface in a saturator tank, gas precipitation to form gas bubbles, transport of gas bubbles to solid particles to achieve adhesion of the particles to the bubbles and then flotation of the bubble-particle agglomerate in a flotation chamber which will be removed and sent to waste. The creation of fine bubbles allows very small particles to adhere to the bubbles via Van de Waals forces and floated to the surface which can then be collected. [72]

In DAF, wastewater is fed into a float tank containing a coagulant. The most commonly used coagulants in DAF systems are ferric chloride and aluminum sulfate. Research suggests that aluminum salts were more effective than iron-based salts in microplastic coagulation but both resulted in low microplastic removal with a maximum removal of 40% at the maximum dosage of coagulant [73]. More research is required into coagulants that are effective on microplastic particles. It should also be researched whether in partial flow pressure flotation with recycling flotation whether different oils could capture the microplastics and DAF can be used to remove the oil from the water. Note that the coagulant can be added to the water in a separate tank before the water is sent to the float tank or added directly to the float tank. [72]

The water leaves the tank and a small amount of DAF effluent water is routed to a small pressure vessel where compressed air is introduced to the water causing the water to become saturated with air at the pressure in the pressure vessel. The saturated air-water stream is then recycled into the float tank which is at atmospheric pressure. Under the float tank conditions, the water/air stream is supersaturated and with properly designed distributors and nozzles, releases a stream of very small bubbles. Suspended particles will adhere to the bubble and the bubbles will carry the particles to the surface where a scrapper will remove the film that has form at the top of the tank. Once the film has been removed the treated effluent leaves the system and small amount are recycled to be used for the bubble process. [72] An example of the process can be seen in Figure 14.

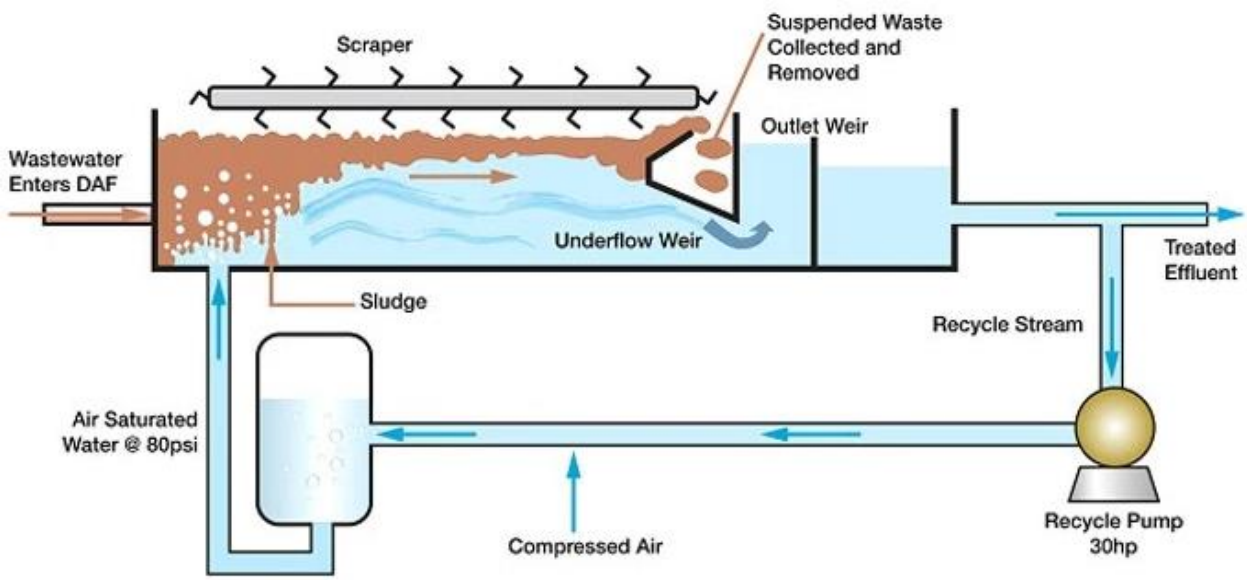


Figure 14: Dissolve air floatation general process flow diagram [74].

There are two main types of DAF systems, circular which is more efficient and rectangular which has more residence time. The circular system involves a circular tank in which a skimmer spins in circular motion removing the film. The rectangular system involves the skims moving from one end to another to remove the froth. Examples of both a circular and rectangular DAF system can be seen in Figure 15.

Figure 15: Circular DAF example (left) and rectangular DAF example (right) [75] [76].

2.2.2.2 Current State of Technology

DAF is currently used in industrial/municipal wastewater treatment and drinking water treatment. DAF is effective at the removal of suspended particles and is used for water supplies that are vulnerable to unicellular algae booms, are high in colour and have low turbidity. DAF systems for microplastic removal is still in the research phase to test the effectiveness of particle removal in pilot sized systems. An article published by Finnish researchers tested DAF where secondary effluent was pumped through a pilot scale DAF system with the flocculation chemical Polyaluminium Chloride (PAX) added to the wastewater (dosage of 40 mg/L) [20]. Samples of water were taken at the inlet and effluent of the system and examined using a stereo microscope to determine the count of microplastics in the water and were categorized by size and shape. The test results for the effectiveness of the DAF pilot can be seen in Figure 16.

The researchers noted that sample volume size varied for different methods of filtration and as a result small samples were more likely to give low microplastic concentrations, and airborne contamination may also result in false zeros [20].

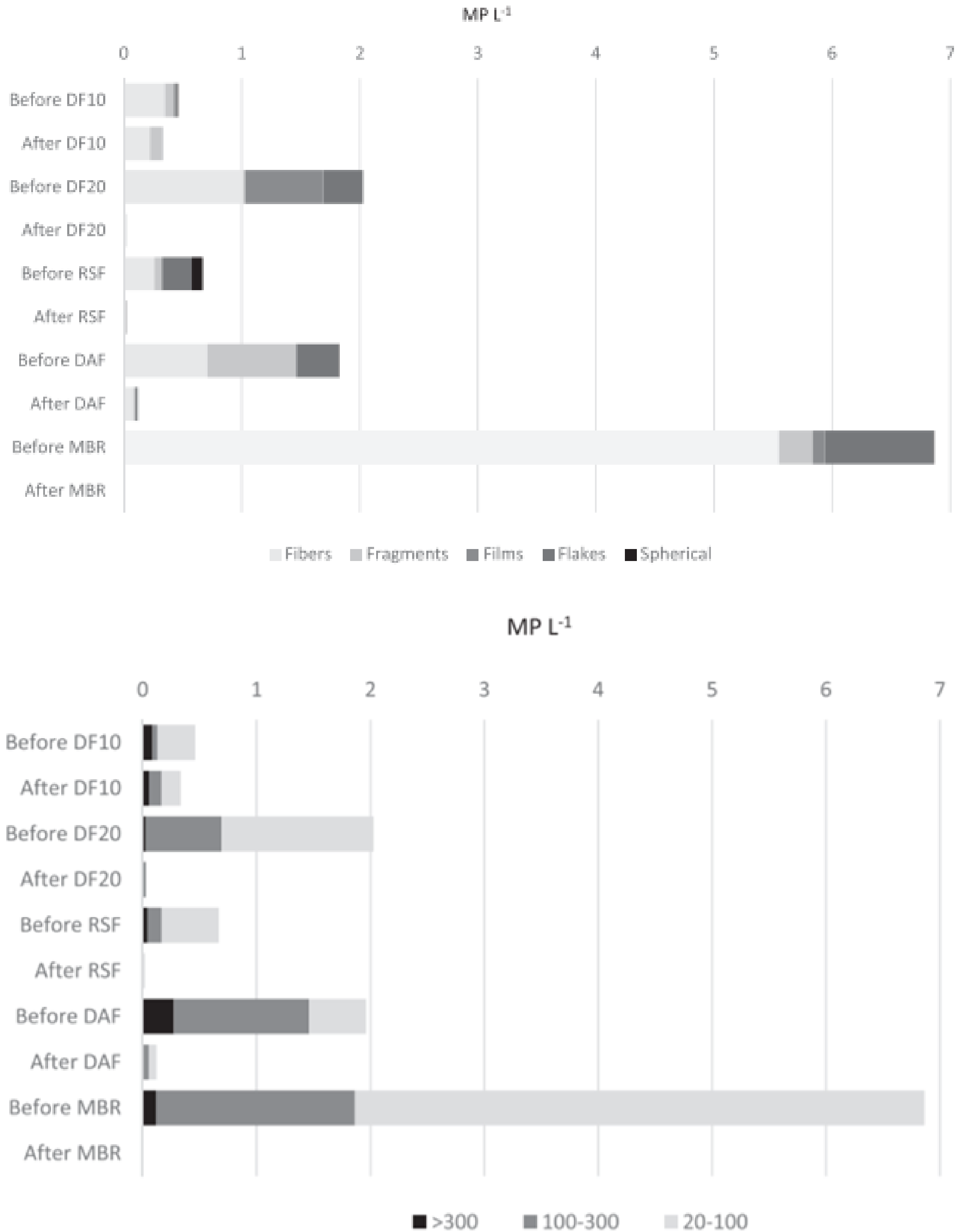


Figure 16: Results from [20], showing the effectiveness of DFs, RSFs, dissolved air floatation and membrane bioreactors in Finnish WWTPs based on the different shape categories and size fraction (20 to 100 µm, 100-300 µm, >300 µm) DF10=disc filter with pore size 10 µm, DF20= disc filter with pore size 20 µm.

2.2.2.3 Evaluation of Technology

The DAF system was evaluated based on the criteria outlined in Table 5. The DAF system was evaluated based on the criteria outlined in Table 5. The evaluation of the technology shown below was specifically related to its use for microplastic removal and was not based on the current state/use of the technology in other industries.

Table 5: Evaluation of DAF and comparison of technology to project specific outlined criteria.

Criteria	Notes
Technology Readiness Level	Level 5: Component and/or validation in a simulated environment The testing of microplastic removal by this method of treatment is still emerging and is in the research phase. The testing for research of this technology is preliminary but is done with pilot sized DAF systems as the pilot systems are readily available due to the maturity of the technology. Tests can be completed in controlled conditions using the pilot plant and can be completed using the water of actual WWTPs. However, due to the testing being preliminary the pilot plants are being used only for research purposes and not for commercial purposes. Due to minimal available research for this technology in microplastic removal specifically, the results are biased due to minimal sample locations internationally, minimal varying sample sizes and minimal number of studies conducted. The testing and results of the system may be influenced by the testing equipment used to quantify the microplastics removed.
Efficiency/Effectiveness	Figure 16 showed that there was approximately 95% removal of microplastic particles larger than 20 µm in size with all particles greater than 300 µm in size being removed. microplastics entering the system were fibres, fragments and flakes, following filtration the majority of remaining microplastics were fibres with minimal amounts of fragments and flakes also remaining.
Compatibility with Current Process	The use of DAF is common in water treatment and is used in industrial applications and can also be found in WWTPs [77]. The testing of microplastic removal by this method of treatment is still emerging and is in the research phase. The implementation of the process would require additional footprint, but the amount of footprint would vary with the filtration requirements of the WWTP and most existing WWTP have very little spare space.

Criteria	Notes
Compatibility with Current Process	The system is a mechanical and chemical separation process. For the mechanical perspective, the system could be installed in secondary treatment following the removal of large particles from the water. As the coagulant most ideally used for microplastics is not known, it should be noted that the water may need additional treatment depending on selected coagulant. Common coagulants used for DAF such as ferric chloride and aluminum sulfate would be used in water treatment and therefore no novel treatment methods would be required. However, research conducted thus far shows that they are not effective at coagulating microplastics. This may be due to the fact that most plastics are hydrophilic, therefore chemical additions would be required to make the plastic particles hydrophobic.
Environment and Safety	As the coagulant most ideally used for microplastics in not known it should be noted that the water may need additional treatment depending on selected coagulant. The addition of a new coagulant in the process would provide exposure to a new chemical to both employees and possibly the environment. If the WWTP currently does not use ferric chloride or aluminum sulfate and these are the chosen coagulants this would result in additional chemical exposure. Ferric chloride is corrosive and toxic and requires chemical googles, gloves, safety footwear, overalls, a PVC apron and a half face respirator when handling the chemical directly. Ferric chloride is relatively toxic to the environment with an LC50 of 8mg/L for fish. This means additional precautions would be required to handle and store the chemical at the WWTP. The chemical is not labelled as a marine pollutant but may not be allowed to be discharged to normal sewer systems and may require additional treatment for handling. [78] Aluminum sulfate is corrosive and toxic; it is also suspected of causing genetic defects. The PPE required includes chemical googles, gloves, safety footwear, overalls, a PVC apron and a half face respirator when handling the chemical directly. The chemical is toxic to the environment with an LC50 of >0.42 mg/L for fish. The chemical is not labelled as a marine pollutant but cannot be discharged to normal sewer systems and requires additional treatment for handling. [78] If the sludge produced from the system cannot be used for agricultural use or repurposed in any way, the sludge will have to be incinerated or sent to landfill. This could result in emissions to the environment through incineration or additional required landfill capacity.

Criteria	Notes
Simplicity of Operation	The DAF system at commercial scale would require a trained operator to use the equipment. Specialized maintenance training would also be required. The system involves more than one tank, a skimming system, bubbling system, additional pumps, lines and any required control systems. The size of the equipment would vary depending on the requirements of the WWTP. The system would require manual or automated addition of coagulant and would require full custom design by an engineering firm for each individual WWTP.
Additional Information Criteria	
Legal/Regulatory Applications	The application of the technology must adhere to the guidelines of Drinking-Water Systems regulation (*O.Reg. 435/93*) under the *Ontario Water Resources Act, 1990*. Use and storage of any reagents must be in accordance with *Regulation 860* under the *Occupational Health and Safety Act,* as well as Building Code (*O.Reg. 350/06*) under the *Building Code Act, 1992* and the Fire Code (*O.Reg. 388/97*) under the *Fire Protection and Prevention Act, 1997*. Depending on the site of implementation, local by-laws may also apply. [71]
Cost	Implementation of a DAF system would not require major engineering design since the technology is not novel. Additional cost could come from the chemical addition regimen for the particular microplastic load at a specific WWTP. There would be a regular operating cost associated with the system as power would be required for the additional pumps, control systems and skimming system. In addition, labour costs would increase due to increased maintenance and system complexity. If the sludge produced from the system cannot be used for agricultural use or repurposed in any way, the sludge will have to be incinerated or sent to landfill. This could result in lower income for the facility if the sludge is typically sold as fertilizer.
Energy Consumption	Power would be required for the additional pumps, control systems and skimming system. Energy consumption of the DAF system is approximately 0.05–0.075 kWh/m^3 of water treated [79].

2.2.3 Diatomaceous-Earth Filters

2.2.3.1 Technology Description

Diatomaceous-Earth Filters are membrane filter units that contain numerous flat membranes that are coated with Diatomaceous-Earth (DE) media. The membranes contain pores that vary in size and are set up in series within a tank. The water enters the feed and flows through the series of membranes where the membranes and the coating of the DE media acts as a filter that captures particles in the water. When used in treatment of large volumes of water, the DE filters are usually operated under vacuum conditions which allows for higher flow rates and increased surface area. The vacuum is created by the water passing through the filter septa holding the DE on the filter. [80] The filters have been used in water treatment since the second world war and have also been used as the primary source of water filtration in small communities [81]. A photo of how the membranes filter particles can be seen in Figure 17.

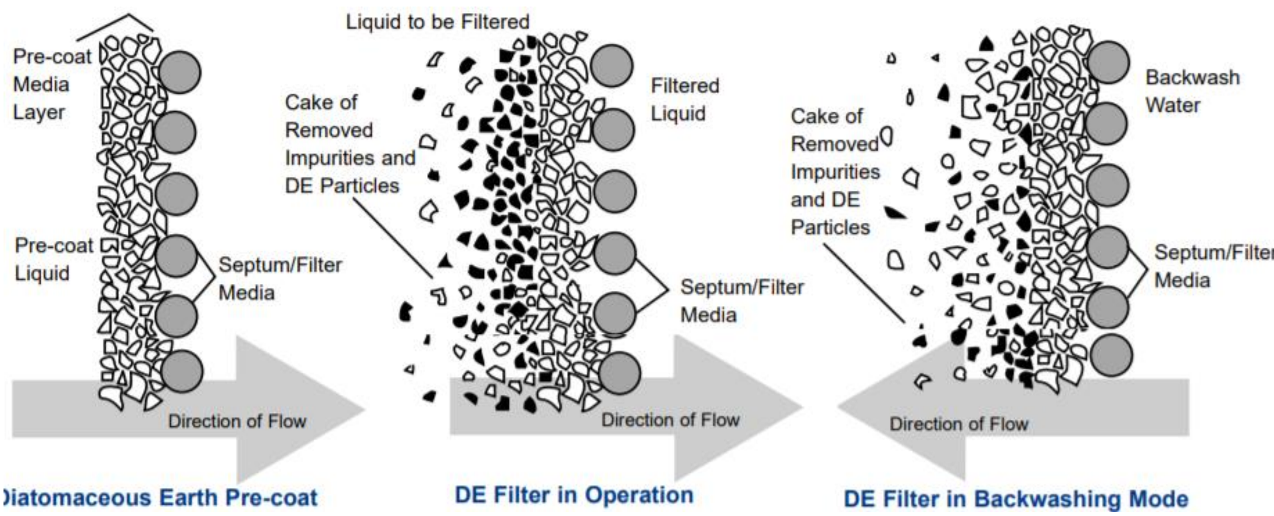


Figure 17: DE membrane example of the removal of particles from flowing water [81].

DE media contains pure silica manufactured from diatoms, which are the fossilized skeletons (frustules) of fresh water, unicellular algae. It should be noted that DE filters are most suitable to treat waters with low bacterial counts and low turbidities, which means that the filter would only be able to be used following bacterial treatment of water so the DE filter system may be required to be installed following tertiary treatment and disinfection of water or at a WTP. In addition, for microplastic removal would be increased with increase water quality in the feed. [80]

The process of DE filtration takes place in three steps as outlined in Figure 17; the precoat of the membranes with the initial cake, small amounts of DE are fed through the filter to maintain the porosity of the pre-coat that was applied and lastly the removal of the filter cake following filtration of particles through backwash of the system. The DE used in each filter run is sent to waste. If regulations are implemented pertaining to microplastic particle concentration in discharge, the waste streams would need to be characterized before disposal. In a WWTP plant the backwash water would need to be recycled back through the system. [80]

The exact amount of microplastic particles that can be removed through DE filters is not available due to the lack of research available on the subject. However, research has indicated that the filters have the ability to filter particles as small as 1 µm [82]. Filtration ability will vary with the required flowrates and membrane pore sizes. More testing with various pore sizes and a different number of membranes is required to determine the effectiveness of DE filters for microplastics.

2.2.3.2 Current State of Technology

DE filters are an established technology which means that the filter requires less engineering to manufacture relative to newer filtration systems. DE filters require less space than conventional filters and are simple to operate. However, operation is labor intensive compared to conventional filters and require high quality influent water to properly remove small particles.

In terms of microplastic removal, DE filters are not currently being researched. It is recommended that research be done to determine the current effectiveness of the filter to determine whether the technology has the capability to remove microplastics.

2.2.3.3 Evaluation of Technology

The DE filter system was evaluated based on the criteria outlined Table 6. The evaluation of the technology shown below was specifically related to its use for microplastic removal and was not based on the current state/use of the technology in other industries.

Table 6: Evaluation of DE filter and comparison of technology to project specific outlined criteria.

Criteria	Notes
Technology Readiness Level	Level 3: Analytical and experimental critical function and/or proof of concept The technology has existed for decades in water filtration. However, there is presently no research into the impact that this filter type has on microplastic removal.
Efficiency/Effectiveness	There is currently no research into the use of DE filters for microplastics. Research has showed that DE filters can remove particles as small as 1 µm. The particle filtration would vary with mesh size.
Compatibility with Current Process	DE filters have been used for water filtration for a long time and can be used as primary water filtration. DE filters are not common in Ontario WWTPs but do not add any chemical hazards as they operate as a mechanical filtration system and could be incorporated in the secondary treatment process at most WWTPs. The system would require additional footprint at a facility and would require the tanks and filter systems, additional pumps, piping, valves and controls.
Environment and Safety	DE media suitable for pre-coat is low in toxicity, not flammable and not harmful when humans come in contact. When handling the material directly the person should be using chemical gloves and a half face respirator for prolonged exposure, and always be wearing safety googles with side shields and overalls for minimal handling. Fresh DE is not toxic to the environment. [78] Spent DE will contain microplastic particles, biomass and other contaminants. Spent DE should be assessed for potential impact on the environment. If the sludge produced from the system cannot be used for agricultural use or repurposed in any way, the sludge will have to be incinerated or sent to landfill. This could result in emissions to the environment through incineration or additional required landfill capacity.

Criteria	Notes
Simplicity of Operation	The DE filters at commercial scale would require trained operators and maintenance staff to operate and maintain the equipment. The system involves more than one tank, filtration system, additional pumps, valves, lines and any required control systems. The size of the equipment would vary depending on the requirements of the WWTP. The system would require manual or automated addition of pre-coat for the filters and filter system as a whole would require design by an engineering firm for each individual WWTP.
Additional Information Criteria	
Legal/Regulatory Applications	The application of the technology must adhere to the guidelines of Drinking-Water Systems regulation (*O.Reg. 435/93*) under the *Ontario Water Resources Act, 1990*. Use and storage of any reagents must be in accordance with *Regulation 860* under the *Occupational Health and Safety Act,* as well as Building Code (*O.Reg. 350/06*) under the *Building Code Act, 1992* and the Fire Code (*O.Reg. 388/97*) under the *Fire Protection and Prevention Act, 1997*. Depending on the site of implementation, local by-laws may also apply. [71]
Cost	The cost of installation would be high due to required additional footprint, engineering design required, and a construction period required to install the equipment. There would be a regular operating cost associated with the system as power would be required for the additional pumps, automation of valves and control systems. In addition, labour costs would increase due to increased maintenance and system complexity. If the sludge produced from the system cannot be used for agricultural use or repurposed in any way, the sludge will have to be incinerated or sent to landfill. This could result in lower income for the facility if the sludge is typically sold as fertilizer.
Energy Consumption	Power would be required for the additional pumps, control systems and automated valve systems. Exact energy consumption would be dependent on the size of the system and the operating parameters of the system based on the individual WWTP's needs.

2.2.4 Rapid Sand Filters

2.2.4.1 Technology Description

Rapid Sand Filtration (RSF) utilizes layers of sand with various grain sizes to filter the particles from water. Typically, it is comprised of 1 m of gravel with a 3-5 mm grain size in addition to a 0.5 m layer of quartz with a 0.1-0.5 mm grain size [66]. A backwash system is routinely used to flush out the collected particles. The filtration chamber may either be an open tank or a closed tank. The open tank relies on gravity to drive the filtration process while a close tank utilizes pressure forces [83]. An example of the process can be seen in Figure 18.

The open system uses gravitational force to push water through the filter process and includes a backwash process to allow the sand to be reused and backwashed water is sent to a settlement pond where the water is drained off and injected into an earlier stage, while the backwash material is sent to landfill.

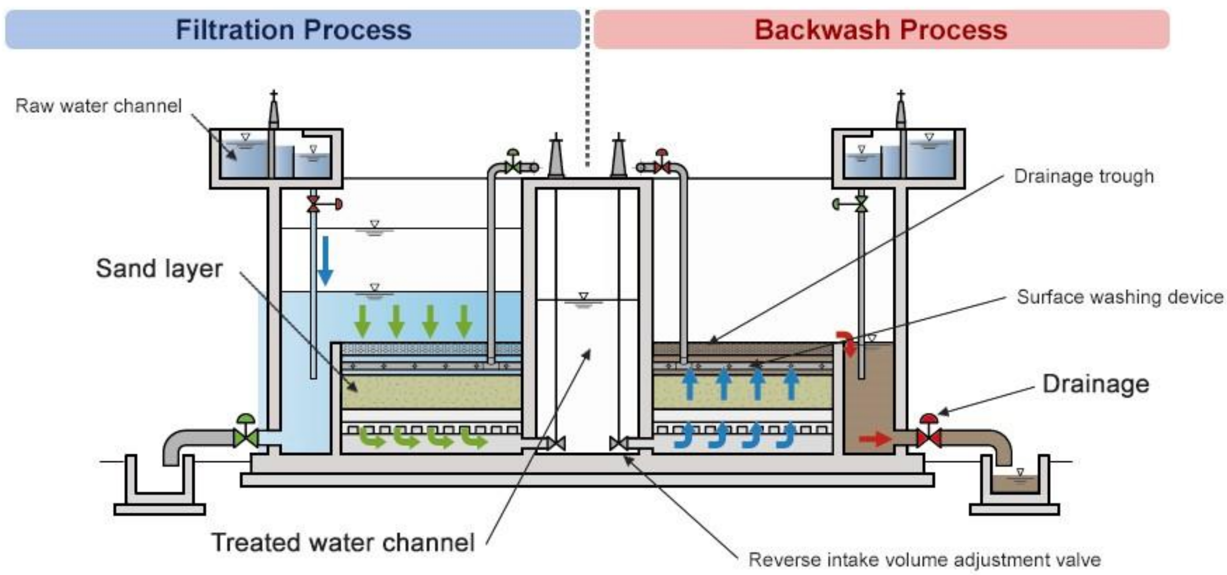


Figure 18: Diagram representing an open gravity RSF [84].

The diagram of a closed rapid sand pressure filter can be seen in Figure 19. The closed system of an RSF uses the pressure differential of the water above and below the sand and gravel to pull the water through the filter for treatment. The closed system also uses a backwash process to clean the sand and gravel so it can be reused for filtration.

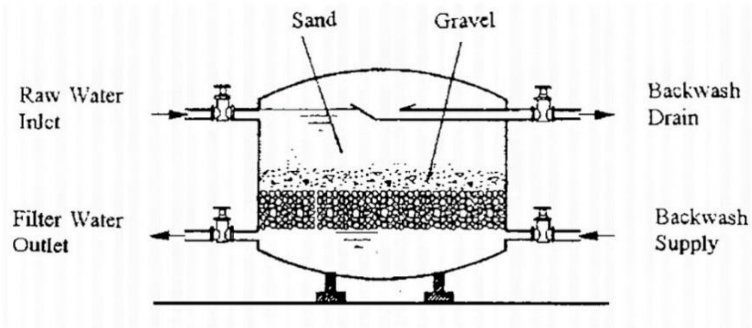


Figure 19: Diagram depicting a closed rapid sand pressure filter [83].

The filtration system traps particles through two possible methods. The first is by mechanically straining the particles which are not small enough to pass through the gaps between the sand grains and the second method is governed by the effect of van de Waals forces, which causes the smaller particles to adhere to the surface of the sand grains [85]. The diagram of the methods can be seen in Figure 20.

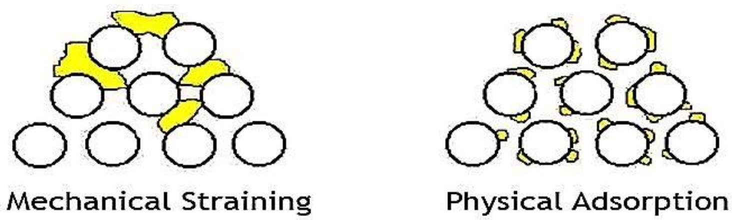


Figure 20: The two methods of particle filtration in the sand filter [85].

The system is cleaned using a backwash system which interrupts the process for 5 to 10 minutes. Generally, parallel units are constructed in order to support a constant water supply. Backwashing is required approximately every 24-72 hours. The backwashed water, in addition to the collected sludge must cycle through the treatment process again. Part-time supervision is required for this system in order to monitor the flow rate and input the correct dosage of disinfectant. Infrequent maintenance such as repacking the filter bed is sometimes required. RSF requires power-operated pumps to facilitate frequent backwashing and to control the flow through the system. The system has high capital and operational cost due to the extensive construction and power required to facilitate backwash. [83]

2.2.4.2 Current State of Technology

Utilizing RSF is a common tertiary filtration method in WWTPs within developed countries. There are also minimal land requirements for this method in comparison to other similar filtration methods. The main reason why RSF is not a more common system in wastewater treatment plants is due to its inability to filter bacteria, organic matter or odors from the effluent stream [5]. In order to produce safe drinking water, a RSF requires a pre-treatment of coagulation and flocculation as well as a post-treatment involving disinfection with chlorine [83]. The system is optimal for the filtration of dilute suspensions, less than 500 mg/L, and for particles ranging from 0.1 µm to 50 µm in size [86].

2.2.4.3 Evaluation of Technology

The RSF was evaluated based on the criteria outlined in Table 7. The evaluation of the technology shown below was specifically related to its use for microplastic removal and was not based on the current state/use of the technology in other industries.

Table 7: Evaluation of RSF and comparison of technology to project specific outlined criteria

Criteria	Notes
Technology Readiness Level	Level 7: Prototype ready for demonstration in an appropriate operational environment to be utilized for microplastic removal purposes. Although RSFs are included in some WWTPs, it is not yet incorporated for the main purpose of removing microplastics. The testing of microplastic removal by this method of treatment is still emerging and is in the research phase.
Efficiency/Effectiveness	A study concluded that RSFs are capable of removing 97.1% of microplastics larger than 20 µm [5]. The study evaluated both the mass of the microplastics removed, as well as the number of microplastic particles [20]. Secondary effluent was examined which had a concentration of 0.7 microplastic particles per liter. This method also has a high potential rate of filtration as it may filter 4,000 to 12,000 liters per hour per square meter of surface area [83].
Compatibility with Current Process	RSFs perform optimally as a secondary or tertiary filter as it will reduce the amount of clogging and backwash required.
Environment and Safety	Some RSFs utilize coagulants; further safety precautions must be taken when including coagulants in the filtration process. Sludge is not directly produced in the filtration system due to the backwashing system.
Simplicity of Operation	Skilled operators are required to monitor the system during the backwash process as the rate of flow must be controlled to limit filter bed erosion. The backwash process lasts approximately 5 to 10 minutes and the frequency is dependent on the effluent conditions. Repacking of the filter bed is also necessary; this requires skilled workers. [83]

Additional Information Criteria	
Legal/Regulatory Applications	The application of the technology must adhere to the guidelines of Drinking-Water Systems regulation (*O.Reg. 435/93*) under the *Ontario Water Resources Act, 1990*. Use and storage of any reagents must be in accordance with *Regulation 860* under the *Occupational Health and Safety Act,* as well as Building Code (*O.Reg. 350/06*) under the *Building Code Act, 1992* and the Fire Code (*O.Reg. 388/97*) under the *Fire Protection and Prevention Act, 1997*. Depending on the site of implementation, local by-laws may also apply. [71]
Cost	Pricing of RSFs depends on the size of the system, flow rate of effluent and rate of cleaning. The system will have a substantial operating cost as power is required to operate the pumps which facilitate the back washing; however, a full-time operator is not required to manage the system.
Energy Consumption	Energy is required to operate the pumps which facilitates back flushing to clean the system. The amount of energy required is dependent on the frequency of cleaning.

2.2.5 Membrane Bioreactor

2.2.5.1 Technology Description

A membrane bioreactor (MBR) consists of an anaerobic and aerobic environment with microorganisms in suspension that consume biological organic materials (BOM) followed by a mechanical filter which would be responsible for the removal of the microplastics. The water is introduced to microorganisms in suspension which consumes BOM and then the water is pushed through a series of membrane filters using negative pressure using pumps where small particle will be captured and begin to cake which can be seen in Figure 21.

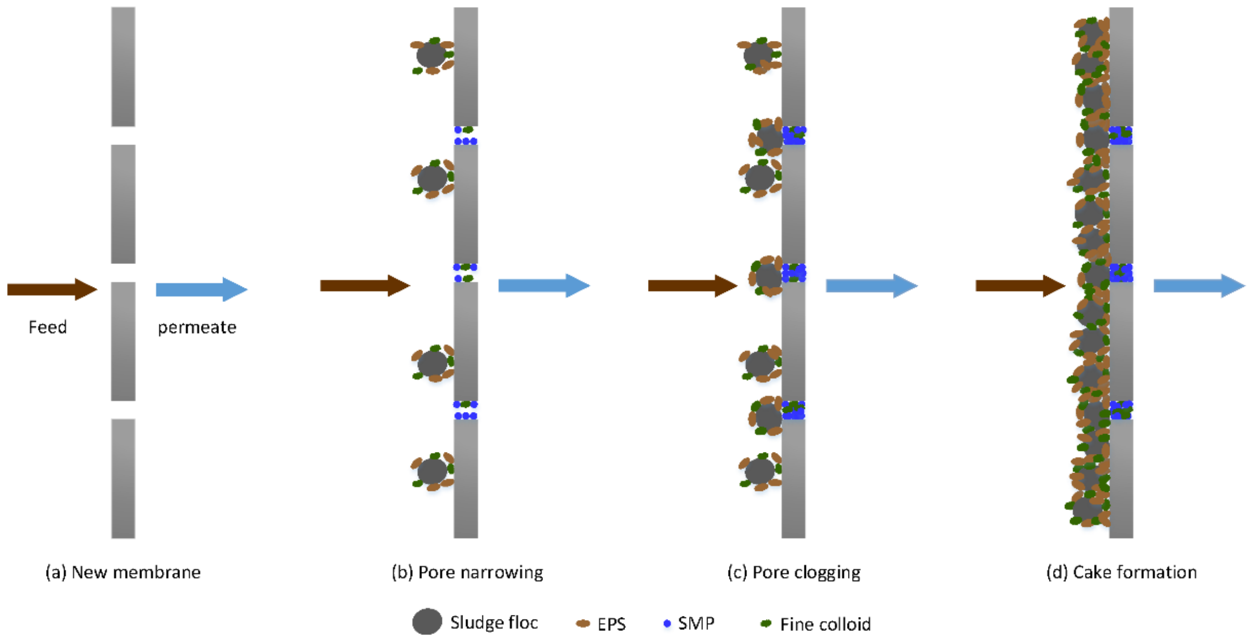


Figure 21: Flow through the membrane in an MBR unit [87].

The number of membranes and pore size varies with unit and required capacity. MBR is becoming increasingly popular in water treatment in European countries such as Sweden [88]. Membrane bioreactors are MBRs are limited in capacity which varies with pore size of the membrane and the ability to pump water through. MBRs can be set up where the membranes are submerged in the bioreactor itself or are a secondary unit that the bioreactor effluent feeds into, as seen in Figure 22.

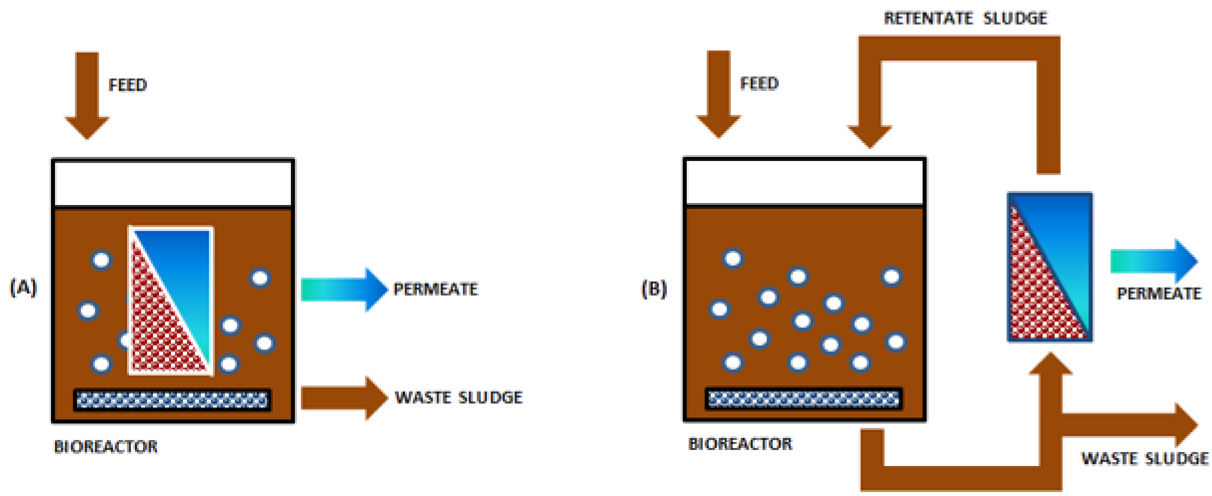


Figure 22: Example of MBRs with submerged membrane in the reactor (right) and separate membrane unit (left) [89].

Due to large amounts of water requiring treatment and a large variety of capacities required internationally at WWTPs, scale up research would be required where the flow of water is tested to see if water levels could ever be achieved. Although initial pilot and commercial scale MBRs are available, they are limited in their daily capacities, meaning only a certain amount of water can be treated a day. The filters are also able to filter all microparticles so depending on the quality of the inlet water the required filter maintenance will vary.

2.2.5.2 Current State of Technology

Currently the MBR is being used at pilot size for research only. The MBR is not commonly used in municipal WWTP in North America for microplastic treatment. Pilot-scale plants of the MBR for commercial applications do exist in European in countries such as Sweden. In terms of research, one article showed that a pilot sized MBR unit with 20 flat sheet membrane cartridges, a flow rate tested at 90 L per hour through, and a membrane pore size of 0.4 mm had a removal ability of 99.9%. The results were based on the count of microplastic per liter and accounted for microplastics that were 20 µm or larger. The pilot unit had a membrane area of 8 m^2 [20]. Another pilot-scale project in Turkey is able to handle 3000 liters of water a day with as much as 99.4% of the microplastics in the stream being removed. The Turkish MBR pilot plant was made up of an anaerobic tank, an aerobic tank and a membrane filtration tank with a submerged MBR unit with pore size on the membranes of 0.4 mm.

The MBR is usually designed to treat primary clarified wastewater. From [20], the test results of a study for the effectiveness of the MBR pilot can be seen in Figure 16 [20].

A company known as Alfa Laval is partnered with Plastic Change, Aarhus University, Roskilde University and EnviDan to measure the amount of microplastics released into one of Denmark's WWTPs after a membrane bioreactor pilot plant was implemented [90]. The pilot plant was capable of filtering particles down to a size of 0.2 µm and the technology can be implemented for the treatment of municipal and industrial wastewater. The technology is modeled after nature's natural filtration processes which aids in developing solutions with low energy consumption, minimal maintenance, and high-quality water output. The membranes used are made of chlorine resistant polyvinylidene fluoride (PVDF) and provide a barrier to bacteria, microplastics and other pollutants. The membrane technology can be altered to be implemented at existing plants or new plants.

A final example of a commercial pilot MBR was in Sweden, where the system consisted of a primary clarifier, biological reactor with a volume of 29 000 L and ultra-filtration. The pore size of the internal membrane was 0.2 µm and consisted of 44 membranes which had a total area of 79.64 m^2 of membranes per system [88]. Energy consumption required to pump the water through the unit was not reported but should be considered in further research. At commercial scale, MBR systems are starting to be used in Sweden to replace the existing conventional activated sludge process (CAS). The predicted capacity of the new MBR facility is predicted to be 1.6 million liters of water per year by 2040. The replacement is to improve the effluent water in terms of quality significantly [88].

2.2.5.3 Evaluation of Technology

The MBR was evaluated based on the outlined criteria. The evaluation of the technology shown below was specifically related to its use for microplastic removal and was not based on the current state/use of the technology in other industries.

Table 8: Evaluation of MBR and comparison of technology to project specific outlined criteria.

Criteria	Notes
Technology Readiness Level	Level 5: Component and/or validation in a simulated environment Although MBR is an established technology for other applications, its use in the context of microplastic removal is still being researched. The technology has been used at several WWTPs in Europe including Finland and Sweden to test microplastic removal using pilot scale equipment. The removal technique is not in commercial development at this stage as microplastic research is still in a preliminary state. One pilot plant facility exists in Sweden for MBR technology which is being used commercially in water treatment but is not microplastic specific.
Efficiency/Effectiveness	A membrane pore size of 0.4 mm reported a removal ability of 99.9% for microplastics that were 20 µm or larger. The shape of microplastics in was primarily fibres followed by flakes, fragments then films. The size of the microplastics into the MBR consisted primarily of 20-100 µm microplastics. Results seen in Figure 16 show that MBR had a large count of microplastics in and approximately no microplastics larger than 20 µm out.
Compatibility with Current Process	The MBR would be a combination of secondary and tertiary treatment but would require a large number of units due to low flow rate capability of technology in its current state of research. This means the technology would require a large footprint and would require tertiary treatment. This technology is not currently used in WWTPs in North America due to the restrictive operating parameters and may be better suited for smaller scale businesses or industrial plants.
Environment and Safety	The technology involves the use of biological organisms and a mechanical filter. The biological organism can vary in MBR systems but is unlikely to be harmful to humans or the environment through disease if the organism is approved for water treatment. If the sludge produced from the system cannot be used for agricultural use or repurposed in any way, the sludge will have to be incinerated or sent to landfill. This could result in emissions to the environment through incineration or additional required landfill capacity.

Criteria	Notes
Simplicity of Operation	The MBR at commercial scale would require trained professionals to operate and maintain the equipment. The system involves a bioreactor, filtration system, additional pumps, valves, lines and any required control systems. The size of the equipment would vary depending on the requirements of the WWTP. The system would require manual or automated addition of biological material and the MBR as a whole would require design by an engineering firm for each individual WWTP.
Additional Information Criteria	
Legal/Regulatory Applications	Regulations pertaining to the use of MBR to remove microplastics do not currently exist in Canada. The application of the technology must adhere to the guidelines of Drinking-Water Systems regulation (*O.Reg. 435/93*) under the *Ontario Water Resources Act, 1990*. Use and storage of any reagents must be in accordance with *Regulation 860* under the *Occupational Health and Safety Act,* as well as Building Code (*O.Reg. 350/06*) under the *Building Code Act, 1992* and the Fire Code (*O.Reg. 388/97*) under the *Fire Protection and Prevention Act, 1997*. Depending on the site of implementation, local by-laws may also apply. [71]
Cost	The cost of installation would be high due to required additional footprint, major engineering design required, and a construction period required to install the equipment. The technology would also require significant investment into the scaling up of technology and commercial testing in order to achieve more feasible operating conditions. There would be a regular operating cost associated with the system as power would be required for the additional pumps, automation of valves and control systems. In addition, labour costs would increase due to increased maintenance and system complexity. The technology's low capacities make it ideal in situations where high removal of microplastics in required but would not be the most economically feasible option in its current development stage. If the sludge produced from the system cannot be used for agricultural use or repurposed in any way, the sludge will have to be incinerated or sent to landfill. This could result in lower income for the facility if the sludge is typically sold as fertilizer.
Energy Consumption	Power would be required for the additional pumps, control systems and automated valve systems. Exact energy consumption would be dependent on the size of the system and the operating parameters of the system based on the individual WWTP's needs.

2.3 Additional Existing Solutions

2.3.1 Reverse Osmosis

2.3.1.1 Technology Description

Reverse osmosis (RO) technology utilizes high pressure to push liquid through a semi-permeable membrane, causing contaminants to be trapped in the membrane resulting in a purified output stream. The membrane is capable of filtering nitrates, pesticides, sulfates, fluoride, bacteria and microplastics from the water stream. It is estimated that the method can filter particles smaller than 0.0001 µm. A pre-treatment is generally incorporated into the system which remove larger sediments to reduce membrane fouling and maintain flux rates. Common pre-treatment systems utilize coagulants, disinfectants or oxidizing agents. Membrane fouling is also avoided through other strategies including surface modification and cleaning. [91]

The membrane does not remove any remaining odors and is therefore often paired with a post-filter as a polishing step [91]. A basic diagram of the Reverse Osmosis system is shown in Figure 23 below.

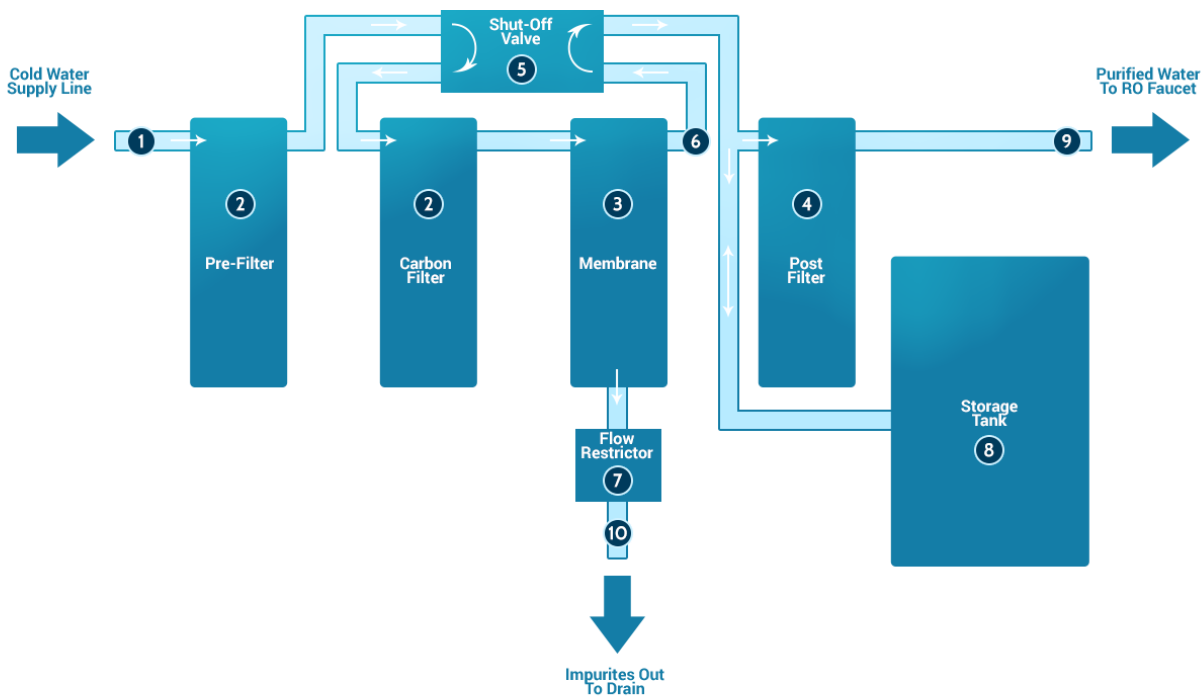


Figure 23: Basic Diagram of Reverse Osmosis Filter [92].

2.3.1.2 Current State of Technology

RO is utilized in many industrial applications such as desalination, the production of high-quality boiler feed water, and in some tertiary levels of WWTPs [91]. A study assessed the effectiveness of RO at removing wastewater-based microplastics following tertiary treatment [93]. The study found that RO could remove 92% of polystyrene microplastic particles larger than 20 µm in their laboratory tests [93].

Other studies identified significant levels of microplastic following the RO filter such as fibres as well as irregular shaped particles such as alkyd resin, a modified polyester [94]. The microplastic detection following the filter method was determined to be a result of membrane defects [94].

2.3.2 Cartridge Filtration

2.3.2.1 Technology Description

A cartridge filter is a polishing filtration system that utilizes both mechanical and chemical filtration. There are disposable cartridges available in addition to reusable, which are typically cleansed or backwashed periodically. Disposable cartridges may be comprised of woven, nonwoven, or pleated materials [95]. Once the pores of the fibres become saturated, the product is no longer operational and may be either replaced or cleaned and reused.

High-capacity cartridges have a large filter area and incorporate flow channels and chambers [95]. Water enters through a main pipe, passes through the meshed grids, and exits through the main standpipe, as shown in Figure 24. When utilized in chemical process industries, they may accommodate flow rates up to 1000 m^3/h but this is dependent on pore size and suspension concentration [95]. A strong core casing is required for high capacity cartridge filters as they may endure large forces due to the pressure differential induced during operation as particles accumulate [95]. Pressure drop data is collected, and the filter is replaced, cleaned, or backwashed once the pressure drop value nears the upper limit. Typically, a relief valve is incorporated in the design to prevent excessive pressure in the vessel. In non-fixed pore cartridges high differential pressure may result in media migration within the vessel, decreasing performance [95]. A skilled worker is required to monitor the system's pressure in addition to the flow rates at the system inlet and outlet [95].

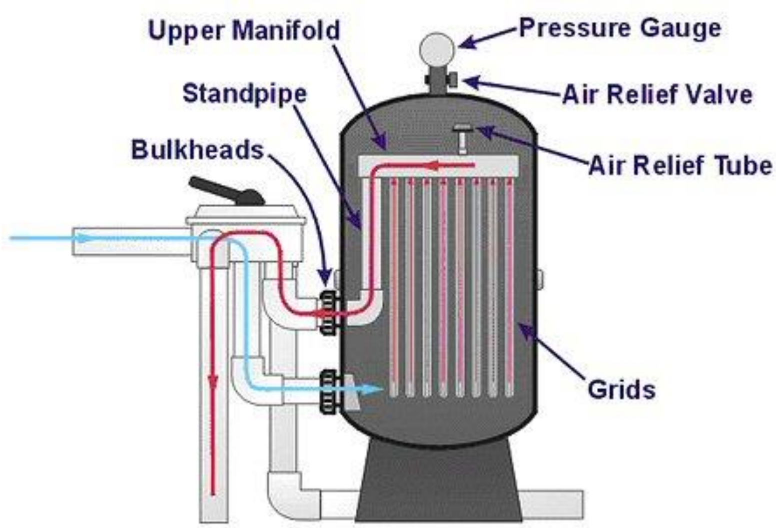


Figure 24: Diagram of the cartridge filter [96].

Cartridge filters are separated into two main categories: depth filtration and surface filtration. A depth filter will trap contaminants inside its pores [97]. As the filters become blocked, the flow rate will decrease. Eventually the filter will require cleaning applying a reverse flow, or the filter will be replaced. A surface filter does not permit the contaminants to enter the filter media [97]. This surface of the filter develops film of growing film of particles. As the particles accumulate, the flow rate continually decreases. The filter is routinely cleaned and reused to restore higher flow rates through the system. Figure 25 shows the flow of particles through both depth and surface filtration.

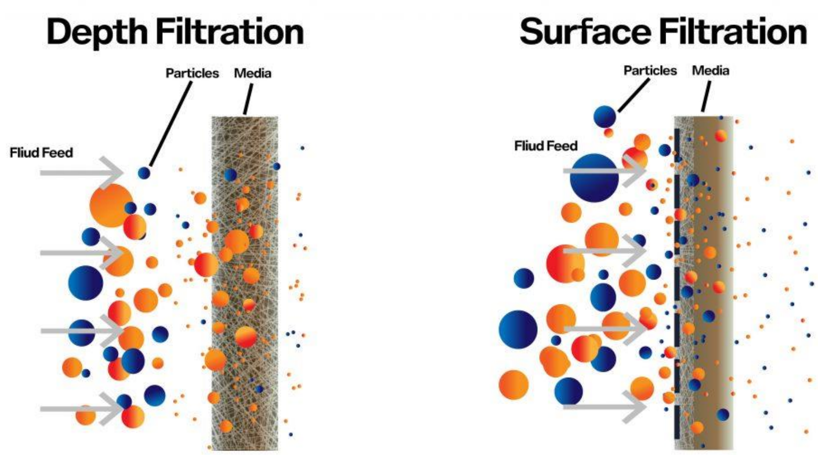


Figure 25: Cartridge filters; depth and surface filtration [97].

A variety of materials are available for filter cartridges including wound, melt-blown, stainless steel, pleated, activated carbon and oil-block cartridge filters, each device has varying applications and performance options [98]. The cartridge filter is advantageous as it is easy to install and occupies little space [99]. A disadvantage is that there is extensive maintenance involved to continually clean the filters. If there is a high concentration of suspended particles, the filters will require frequent replacement, causing an increased amount of system downtime.

2.3.2.2 Current State of Technology

High capacity cartridge filters are utilized in a wide variety of industries including refineries, pipelines, pharmaceuticals, power generation, biotechnology, food and beverage, microelectronics and WWTPs.

Filter cartridges are classified by their pore sizes and the effectiveness of the cartridge filter will depend on the pore size. A small pored filter would be more effective at removing microplastics than a larger pored filter; however, the small pored filter will require more frequent replacement. For microplastic removal applications, cartridge filters have been primarily tested for small scale purposes. Currently, disposal of cartridges is difficult and expensive. Disposal practices and costs of spent cartridges will need to be determined as a result.

2.3.3 Granular Activated Carbon

2.3.3.1 Technology Description

Granular activated carbon (GAC) works by the activated carbon absorbing the passing chemical in the filter. GAC can be found in some WWTPs as a method of removing colour from the effluent. GAC is effective as it is a highly porous material and has a large surface area. GAC can also commonly be found in domestic water filters with common name brands such as Brita. GAC is effective at capturing small particles if there is a system that removes the larger particles before and therefore is ideally place at the end of secondary treatment within a facility or located at the water treatment plant prior to dispensing drinking water [88]. A simplistic model of how activated carbon works can be seen in Figure 26. [100]

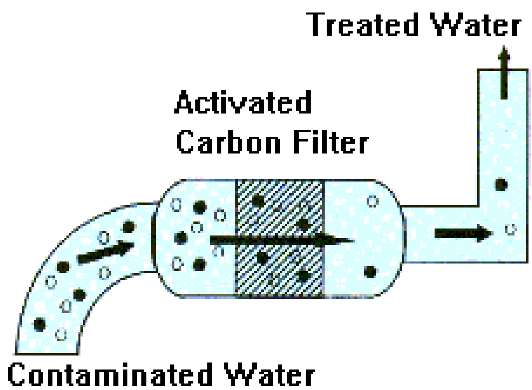


Figure 26: Basic flow diagram of how activated carbon filters remove particles from water [101].

Since the use of a GAC filter will require addition methods of treatment in series to be effective in removing microplastics future research will be required in the size of GAC filter required and which method combinations will maximize microplastic removal. The size of filter will vary with required design flowrate, the breakthrough time (time until filter needs to be replaced) and the empty bed contact time (EBCT). The surface loading rates for GAC filters typically range between 80 to 400 liters per minute per square meter. [100] GAC in one case was found to remove around 59% of small sized microplastics meaning it could be more ideal as secondary treatment to already filtered water [102] [103].

GAC is made from organic materials that are high in carbon such as wood, lignite and coal. GAC is made up of particles that range from 1.2 to 1.6 mm in diameter and a varying density that depends on the manufacturer and the size of the filter. Typically, GAC filters have a large uniformity coefficient to allow for proper backwashing in treatment plants. There are two common options for GAC treatment in WWTPs which are post-filtration adsorption and filtration-adsorption. Post filtration adsorption is where the unit is located after the conventional filtration process whereas filtration adsorption is where some to all of the filter media in a filter is GAC. These configurations can be seen in Figure 27. [100]

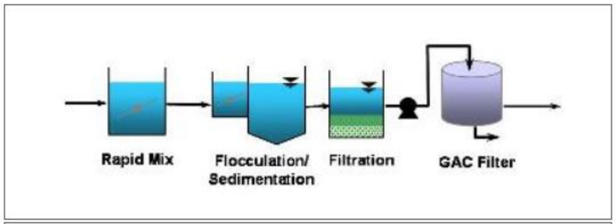


Figure 1: Post-filtration adsorption.

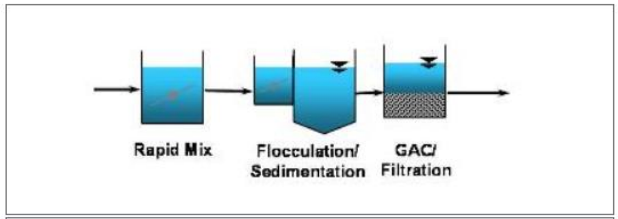


Figure 2: Filtration/adsorption.

Figure 27: GAC post filtration adsorption and Filtration-adsorption process setup examples [100].

In the case of microplastic removal, more research would need to be done to see the impact on concentration levels in the two set ups. The assumption would be that post-filtration adsorption would be the most ideal for particle removal as the GAC filter would receive water where the majority of the microplastics have been removed and only the smallest microplastics remain. This would allow the surface area of the GAC to capture the smallest particles whereas if the water contained large and small particles it would be more likely the small particles pass the filter as the large one would be captured first. [100]

The reactors themselves can be configured in three possible ways: downflow fixed beds, up flow fixed beds or pulsed beds and can operated in series or parallel. For microplastic removal, the units operating in series would be the most ideal to maximize the exposure of the contaminated water to GAC. [100]

Increased amount of carbon in a filter will generally increase the amount of contaminant removed due to the increased exposure time to the activated carbon. However, this could increase capital and operating cost related to the filter in a treatment plant. More research and tests are required from a surface chemistry perspective to determine the optimal operating parameters in the GAC system and filter size for various capacities of water and their respective concentrations of microplastics. This is due to the fact that GAC works through weak surface forces such as van der Waals forces. The use of GAC may also be linked to environmental and economic issues as facilities that wish to reuse the GAC will required regeneration systems or could opt to send the used GAC to waste. This could increase the amount of waste produced by a facility and the capital cost of the regeneration system would need to be compared to the operating cost of new GAC. GAC is most commonly regenerated using steam, thermal regeneration or chemical regeneration. [100]

2.3.3.2 Current State of Technology

The technology is commonly used in commercial scale water treatment both domestically and industrial/municipal applications. The technologies filtration abilities for microplastics is currently in research stages and is commonly tested with other forms of filtration such as a pilot plant MBR [88]. The article produced by Christian Baresel of the IVL Swedish Environmental Research Institute, stated that the main advantage of using activated carbon is that it has a broad and effective ability to remove microparticles such as microplastics and there are no by-products are generated as a result of the adsorption of the particles [88]. The filter that followed the MBR unit in the article consisted of a 10 cm thick sand bed on the bottom and a 1 m layer of commercial granulated carbon. Through the testing of the MBR and GAC combined filtration showed a removal efficiency of 100% for particles that were 20 µm or larger. More individual studies are required for the effectiveness of GAC for microplastic filtration to determine whether GAC provides enough microplastic removal to be economically feasible.

2.3.4 Purifics

2.3.4.1 Technology Description

Purifics is a Canadian company based in London, Ontario that has developed a comprehensive water purification process. The process is composed of three individual treatments that can be used in tandem and can be tailored to individual treatment needs. Purifics' Ceramic Ultrafiltration (Cuf) treatment uses a silicon-carbon hydrophilic membrane process that can filter contaminants and reduces concentrations of chemicals in solution. In the Cuf process, raw water is screened for large organic and inorganic materials in a cross-flow arrangement. The transmembrane pressure (TMP) is set to maintain constant flux and experiences regular dynamic shock to self-clean the membranes to prevent fouling. As a result, the automated process can be operated almost continuously. The Cuf process is not TMP limited nor is it dependent on fluid temperature so it can run at constant flux. The Cuf process is only limited by the TMP pump's capability and thus can respond to viscosity, load, and demand fluctuations of the incoming stream. The Cuf process comes in 11 different volume options that can be tailored to specific capacity needs [104].

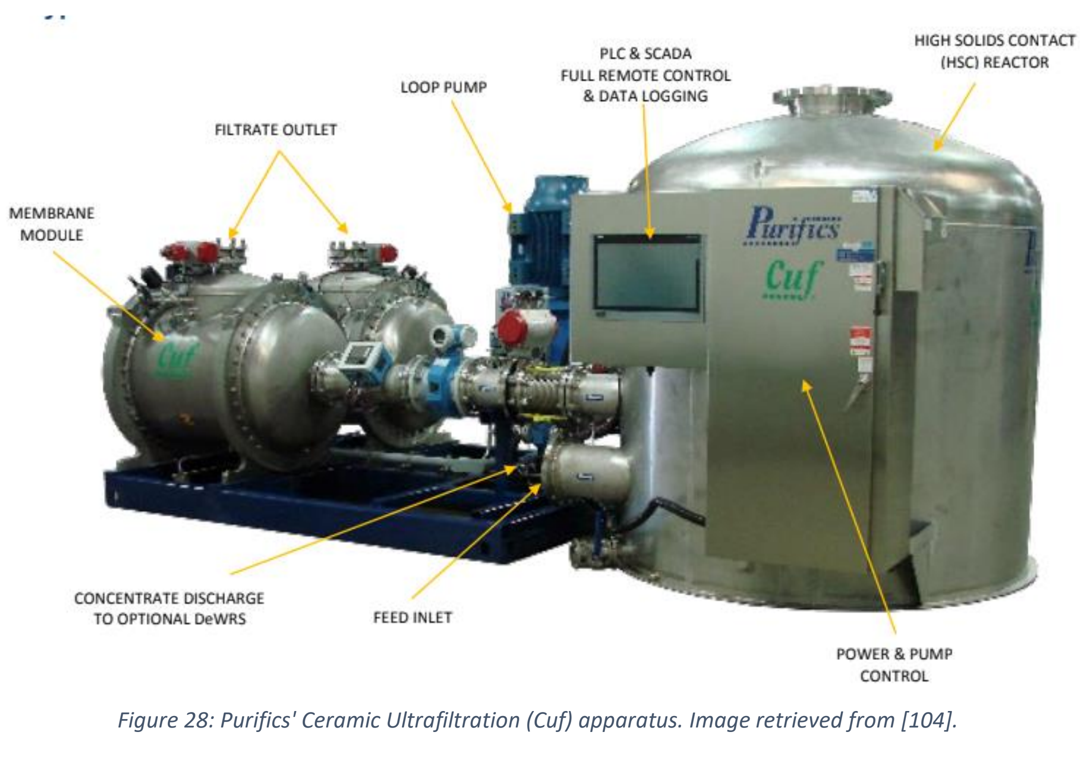


Figure 28: Purifics' Ceramic Ultrafiltration (Cuf) apparatus. Image retrieved from [104].

Eventually concentrated filtered material may begin to impact the transmembrane pressure of the system. At this point, the concentrate must be either removed manually, or directed to Purific's Dewatering Recovery System (DeWRS). Waste products generated from Cuf can be recovered by their Dewatering Recovery System (DeWRS) with no liquid discharge. DeWRS recovers waste product in sludge that can be recycled for mineral re-use or for landfill disposal. It is a fully automated, chemical free ceramic membrane process that can de-water solids such as Dissolved Organic Carbon (DOC), biomass, bacteria, and metals. The recovered water can be used for drinking water or any other purpose. Purifics' claims that their residual waste is recovered at 20% solids and non-aqueous phase liquids and oil can be recovered to neat product [104].

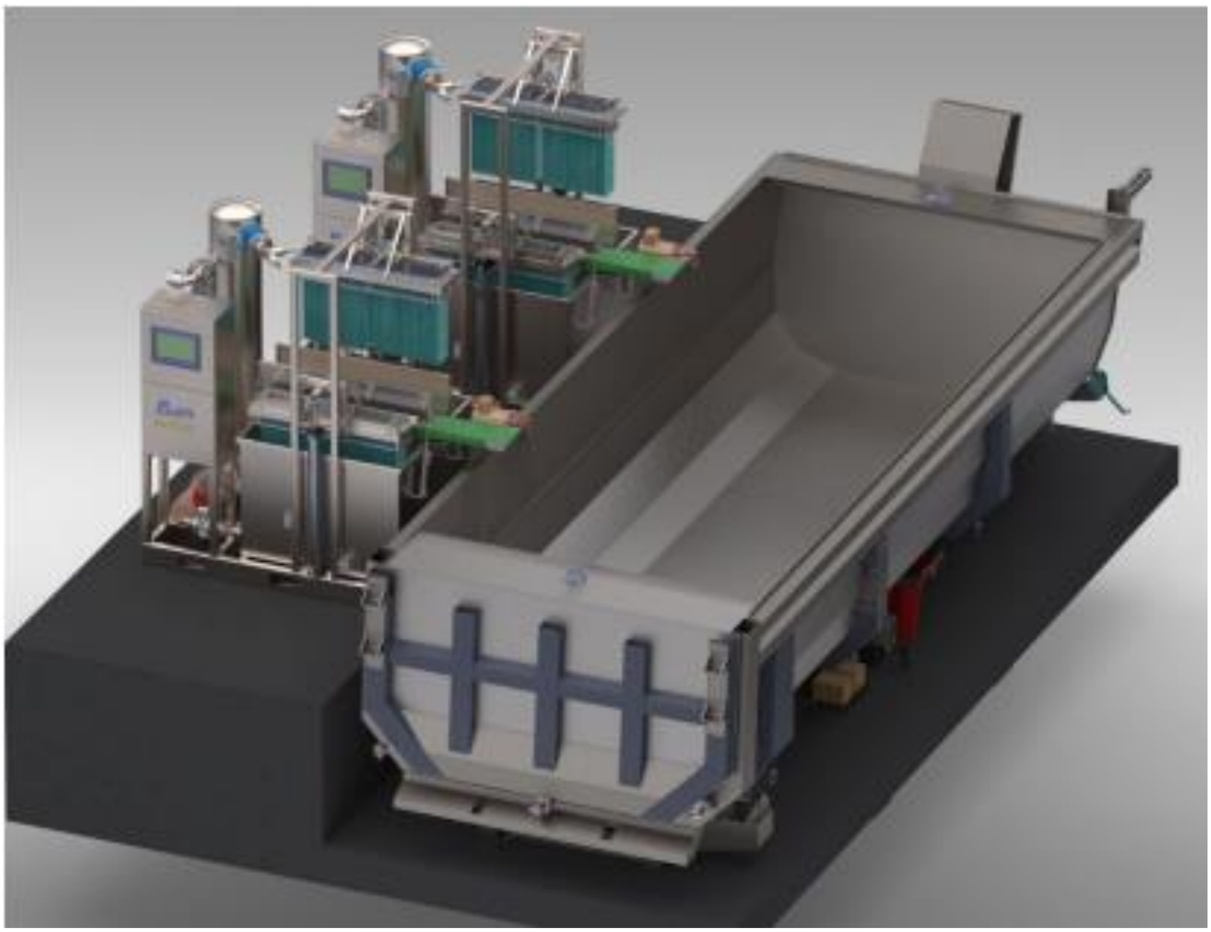


Figure 29: Purifics Dewatering Recovery System (DeWRS) apparatus. Image retrieved from [104].

For organic components that cannot be filtered by Cuf, Purifics' Photocatalytic (Photo-Cat) advanced oxidation process can destroy chemicals and pathogens using its photocatalytic membrane without the use of added chemicals. The process uses a TiO_2 slurry-based photocatalytic process to detoxify water sources. It's oxidation potential is rated between 3.18 – 4.8 eV, which is greater than conventional oxidation process such as UV/ozone (2.8 eV), UV/peroxide (2.8 eV), cavitation (2.8 eV), and chemical treatments (1.77-3.05 eV). The process is a fully automated, solid-state device that can operate for greater than 20,000 hours before maintenance is required [104].

Figure 30: Purifics' Photocatalytic (Photo-Cat) apparatus. Image retrieved from [104].

2.3.4.2 Current State of Technology

Although they do not specifically deploy their technology for microplastics, Purifics' claims that its Cuf and DeWRS membrane technology can remove DOC as low as 0.1 µm and 100% at the 10 µm level. Below this size, a portion of any particulate matter will be removed by either agglomeration or aggregation processes. As well, the company claims that its combined Cuf and DeWRS technology can remove anywhere from 90-100% of TSS and its operating capacity is as high as 200 ML per day. While their Photo-Cat process is not designed to degrade plastics, it may be able to remove any accompanying pathogens, pharmaceuticals or thalates attached to the microplastics. Purifics' has operated pilot and process plants with this technology for over 25 years in both Canada and USA. They offer various technology for drinking water plants, groundwater remediation, wastewater treatment plants and industrial facilities [105].

2.4 Emerging Industrial Scale Microplastics Removal Processes

2.4.1 Electrocoagulation

2.4.1.1 Technology Description

Electrocoagulation uses metal electrodes to produce coagulant electrically and does not rely on chemicals or microorganisms such as in chemical coagulation or activated sludge processes. The process of electrocoagulation functions by liberating metal ions from sacrificial electrodes into the water stream via electrolysis. The ions then form coagulants which destabilize the surface charges of the suspended solids, breaking up the colloids which allows them to approach each other close enough for van der Waals forces to take effect. The coagulant forms a sludge blanket which traps the suspended particles. The hydrogen gas liberated in the electrolysis process then lifts the resultant sludge containing the microplastic particles to the water surface. A diagram of the process is shown in Figure 31. Lab-scale testing showed removal efficiencies of 99.24% for PE microbeads of size 300-350 µm. These results suggest that electrocoagulation has the potential to be an effective method for removal of microplastic contaminants. However, significant further testing is required using different types of plastic, smaller particle sizes, and larger flow rates to better predict its capability at an industrial scale with an environmental sample of water.

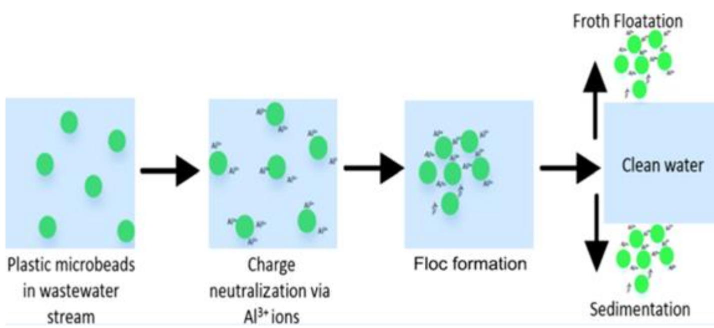


Figure 31: Diagram of electrocoagulation process [106].

To evaluate the potential for this technology to be successfully implemented at a WWTP the results of the lab-scale experiment will be evaluated based on the criteria. Testing was carried out using spherical PE beads of size 300-350 µm and density 0.997 g/cm3 [106]. The robustness of the technology is evident as it can be used with a wide range of pH values representative of the fluctuations of pH in wastewater. A removal efficiency of 89% successfully achieved for all samples in pH range from 3-10. Typical domestic/municipal wastewater has a controlled pH range of 7.5-8.5. Wide pH range indicates that EC is suitable for removing microplastics from wastewater streams with a wide range of pH values and would not require the addition of further chemicals to adjust the pH. The optimal pH for production of coagulant was determined to be 7.5 [106]. At this pH value the maximum removal efficiency of 99.24% was observed for the PE microbeads for a 60-minute residency time [106].

The impact of conductivity was investigated by adjusting the concentration of sodium hydroxide (NaCl) which showed that NaCl concentration had no significant effect on removal efficiency [106]. Previous studies found that the presence of chloride ions and formations of hypochlorous acid (HOCl) resulted in beneficial side reactions that aided in decomposition of the pollutants/dyes and aided adsorption onto the formed flocs. It is suspected that the time taken for HOCl to cause degradation in the microbeads exceeds the optimal 60-minute residence time [106]. Future research into increasing the residence time could be considered to determine if it is worthwhile to allow the microplastics to degrade through exposure to HOCl [106].

In the study, an evaluation of cost and energy consumption was used to determine optimal operating conditions. Operating cost is a function of energy required, sodium chloride required, and electrode consumption. It was determined that the two most important parameters in determining cost are energy and sodium chloride concentration. Although as the concentration of sodium chloride increases, energy requirements decrease, the cost of chemicals increases more sharply than the decrease in utilities. Therefore, for the lab-scale process minimum cost occurred at the lowest concentration of sodium chloride which was 2 g/L [106]. In most electrolysis processes, electrical energy consumption is very high and a major portion of the operating costs. However, optimum operating cost may be subject to change as the process is scaled up.

2.4.1.2 Current State of Technology

Testing has been conducted in a 1 L bench-scale stirred-tank batch reactor with seven metal electrodes. Wastewater was added, and electrodes were placed in parallel along the reactor connected to a DC power supply which controls the voltage and current density [106].

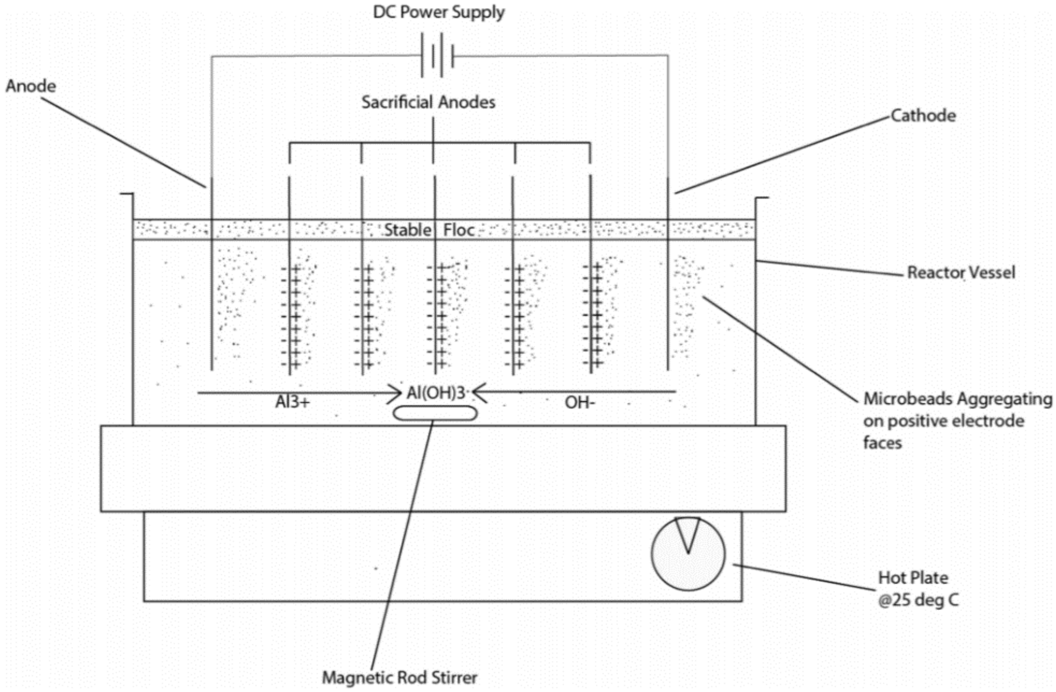


Figure 32: Experimental set-up of electrochemical reactor [106].

2.4.1.3 Evaluation of Technology

The electrocoagulation process was evaluated based on the outlined criteria, a summary of the results is shown in Table 9. The evaluation shown below was specifically related to its use for microplastic removal.

Table 9: Evaluation of electrocoagulation and comparison of technology to project specific outlined criteria [106].

Criteria	Notes
Technology Readiness Level	Level 4: Component and/or validation in a laboratory environment Electrocoagulation has been tested in a 1 L bench scale environment with water particles emulating environmental wastewater samples. Pilot plant testing and significant scale-up redesign would be required before implementation at a WWTP.
Efficiency/Effectiveness	The removal efficiency at the optimal pH of 7.5 is 99.24% for the 300-350 µm PE microbeads tested [106].
Compatibility with Current Process	Implementation of electrocoagulation processes requires significant installation and construction. Materials that are not currently purchased by WWTP such as electrodes will be required. As the technology has only been tested at a 1 L scale to date, it is unknown how large of a footprint the technology will required if it is to be scaled to meet the flow requirement of a WWTP.
Environment and Safety	The technology does not rely on chemicals or microorganisms to form coagulants. The use of electrodes produces a current density through the water which poses the risk of electrocution.
Simplicity of Operation	The current electrocoagulation process must be manned almost full time. The process is not yet automated. Scale-up to WWTP requirements would require full design by a professional engineer. Trained operation and maintenance personnel would be required for operation of this process.
Additional Information Criteria	
Legal/Regulatory Applications	The application of the technology must adhere to the guidelines of Drinking-Water Systems regulation (*O.Reg. 435/93*) under the *Ontario Water Resources Act, 1990*. Use and storage of any reagents must be in accordance with *Regulation 860* under the *Occupational Health and Safety Act,* as well as Building Code (*O.Reg. 350/06*) under the *Building Code Act, 1992* and the Fire Code (*O.Reg. 388/97*) under the *Fire Protection and Prevention Act, 1997*. Depending on the site of implementation, local by-laws may also apply. [71]

Addition Information Criteria	
Cost	It is expected that the cost of implementation would be high. This is due to the significant investment required for the scale-up and pilot plant testing before it is approved for installation at a WWTP. Costs related to the additional footprint, major engineering design and a construction period required to install the equipment would also be incurred. There would be a regular operating cost associated with the system as power would be required for the additional pumps, automation of valves and control systems. Raw material supplies such as the electrodes would also be expensive.
Energy Consumption	In most electrolysis processes, electrical energy consumption is very high and a major portion of the operating costs. Exact energy consumption would be dependent on the size of the system and the operating parameters of the system based on the individual WWTP's needs.

2.4.2 Centrifugal Separation

2.4.2.1 Technology Description

Hydrocyclones are commonly used in the process industries for sand, aggregates, coal, industrial minerals and hard rock mining as a physical separation technique [107]. Ecofario is a German start-up that has developed a process based on hydrocyclone technology to be implemented in municipal and industrial WWTPs. The goal is to reduce the amount of microplastic particles and pollutants in the effluent stream from the WWTPs that is sent to the lakes [108].

Hydrocyclones achieve separation of feed materials with varying density based on rotating fluid flow generating centrifugal force. Feed material enters the feed inlet at a designated pressure and volume specific to the application. In the case of microplastic filtration, the feed material is wastewater that has undergone primary and secondary treatment. An upward air forces the fluid to follow a rotating path. As a result of the rotation, centrifugal forces send the heavier density particles out the bottom and the low-density particles out the top. For testing, both streams are collected to determine the composition and load of microplastic particles. A schematic of a typical hydrocyclone is shown in Figure 33.

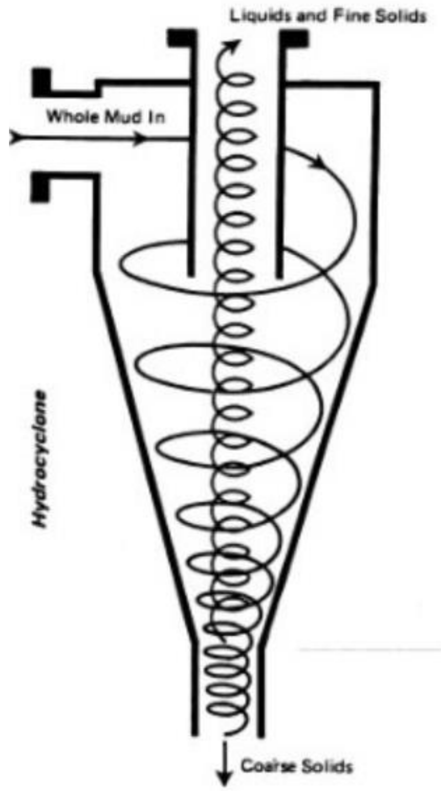


Figure 33: Schematic of hydrocyclone separation process [107].

The separation process is based on hydrocyclone technology that will be installed as the final mechanical stage of treatment in WWTPs. The core component is a high G-separator which uses centrifugal force to generate a vortex that separates microparticles from water based on density differences. Most traditional hydrocyclone technologies do not have the capacity to separate microplastics from water because the difference in density is so minimal, however Ecofario claims that their patented technology can increase separation efficiency by a factor of 50 when compared to traditional hydrocyclone technologies which allows for separation of particles very close in density. The technology does not yet exist on the market, but lab testing has been completed and the company is working with a mobile pilot plant to be implemented at WWTP facilities in Germany. The company has a patent for the technology [109].

Based on their patent, Ecofario specifies that for the purposes of their technology, a microplastic is any polymeric plastic particle less than 5 mm in size and the technology is specifically targeted at particles less than 1 mm in size [109]. Currently, the company is focused on microplastic removal, but testing should be conducted using nanoplastic size particles before the technology is implemented as a solution at an industrial scale WWTP. The hydrocyclone developed by Ecofario has a conical body with 3 inlets and outlets. The feed flow of water and microplastics enters the cone tangentially via the inlet at the top of the cone and is forced into a rotational flow. The flow is driven in a spiral down to the tapered end of the separator. The flow path causes a free flow reversal, which leads to an upward movement of a light flow in the center spiral of the fluid vortex.

The light stream is mainly composed of low density microparticles with a small number of high-density particles. The light stream is discharged in the upper part of the centrifugal separator. The higher density, heavier impurities are driven down and discharged through the tapered bottom of the cone. Separation based on density occurs due to the centrifugal force induced by rotation. As centrifugal force increases so does the selectivity of the separation. Important design factors that affect separation are volume flows, inlet-acceptance reject ratios, pressure differences, viscosity of the medium, and degree of soiling [109].

2.4.2.2 Current State of Technology

A prototype was produced using selective laser sintering (SLS) 3D printing technology. The prototype was constructed from fibre reinforced polyamide. The prototype was operated and evaluated at lab-scale. The microplastic used was an HDPE powder from Pallmann with a density of 0.96 g/cm^3 and an average size particle size less than 500 µm [110]. Running the prototype at 250 kPa with a flow rate of 30 L/min the microplastic separation efficiency was evaluated gravimetrically to be approximately 30%. Using these results and simulation software it was determined that if pressure is increased to 700 kPa, 50% separation can likely be achieved [110]. Although the separation efficiency is relatively low, further research of the technology should be pursued because until regulations are established it is unknown whether this removal efficiency will be sufficient. Despite the low efficiency, it is expected that the technology will be able to handle a high flow capacity if multiple hydrocyclones are arranged in series. Arrangement in series will also likely increase overall removal efficiency. Ecofario is moving forward with construction of a mobile pilot-scale plant. A schematic of the pilot plant is shown in Figure 34.

Figure 34: Mobile pilot plant developed by Ecofario [83].

2.4.2.3 Evaluation of Technology

The use of centrifugal separation for filtration was evaluated based on the criteria outlined in Table 10. The evaluation of the technology was related to microplastic removal over just the state of the technology to meet project requirements.

Table 10: Evaluation the use of centrifugation for filtration and comparison of technology to project specific outlined criteria.

Criteria	Notes
Technology Readiness Level	Level 6: System/subsystem model or prototype demonstration in a simulated environment A model or prototype that represents a near desired configuration. Activities include testing in a simulated operational environment or laboratory. Lab-scale testing on prototype has been completed by the company who designed the process. Development of a pilot plant is in progress to be used at WWTP but will require considerable scale-up to meet required flow rate for a WWTP.
Efficiency/Effectiveness	Prototype showed filtration efficiency of only 30% for HDPE powder particles of average size less than 500 µm. Simulations show that an increase in operating pressure and scale-up will increase filtration efficiency to 50%. Until regulations for microplastic removal efficiency are established it is unknown whether this removal efficiency is sufficient. Despite the low efficiency, it is expected that the technology will be able to handle a high flow capacity if multiple hydrocyclones are arranged in series. Arrangement in series will also likely increase overall removal efficiency. Construction of a pilot plant for further testing is being built.
Compatibility with Current Process	Implementation of a hydrocyclone would not require significant land space. Could easily be implemented in existing facility. Mechanical separation only, therefore only room required for centrifuge and associated pumps. No chemical storage area required.
Environment and Safety	Does not require the introduction of additional chemicals to the process. Some mechanical hazard, but not significant in comparison to existing WWTP unit operation.
Simplicity of Operation	The process is fully automated, however rotating equipment typically needs regular maintenance by specialized technicians.

Additional Information Criteria	
Legal/Regulatory Applications	The application of the technology must adhere to the guidelines of Drinking-Water Systems regulation (*O.Reg. 435/93*) under the *Ontario Water Resources Act, 1990*. Use and storage of any reagents must be in accordance with *Regulation 860* under the *Occupational Health and Safety Act,* as well as Building Code (*O.Reg. 350/06*) under the *Building Code Act, 1992* and the Fire Code (*O.Reg. 388/97*) under the *Fire Protection and Prevention Act, 1997*. Depending on the site of implementation, local by-laws may also apply. [71]
Cost	Information on the expected cost of implementation was not detailed by the researchers. Since it is just an additional unit operation and not an entire additional system, it is not anticipated to incur significant capital costs.
Energy Consumption	Energy will be required to pump water through the system at sufficient flow that separation will occur. May increase energy requirement of facility depending on flow rate and number of centrifuges required.

2.4.3 Functionalized Hybrid Silica Gels

2.4.3.1 Technology Description

The use of functionalized hybrid silica gels for industrial/municipal wastewater treatment is adapted from the conceptual idea introduced in the journal article *A concept for the removal of microplastics from the marine environment with innovative host-guest relationships* published in 2016 by Adam Frank Herbort and Katrin Schuhen [111]. The concept makes use of an agglomeration-fixation reaction of the sol-gel process wherein a highly cross-linked solid inorganic-organic macromolecule is formed by a series of hydrolysis and condensation reactions [112].

This process is applicable to the removal of microplastics from wastewater as organosilanes have an affinity for the surface of the microplastics due to van der Waals interactions. The reaction mechanism of alkyltrichlorosilanes in water with microplastic particles used to create agglomerates is shown in Figure 35. The first step of the process is a hydrolysis reaction. Leaving groups of the organosilanes are hydrolyzed to highly reactive silanol groups. The second step of the process is a condensation reaction. The highly reactive silanol groups formed during hydrolysis then connect the microplastics to each other by forming siloxane bonds. Colliding microplastic particles attach to each other and collect in large agglomerates that are chemically bound to each other. This results in the formation of large agglomerates which can then be more easily removed by filtration [112]. Proper disposal methods for the 3D hybrid silica-microplastic complex must be developed to comply with Canadian Environmental regulations.

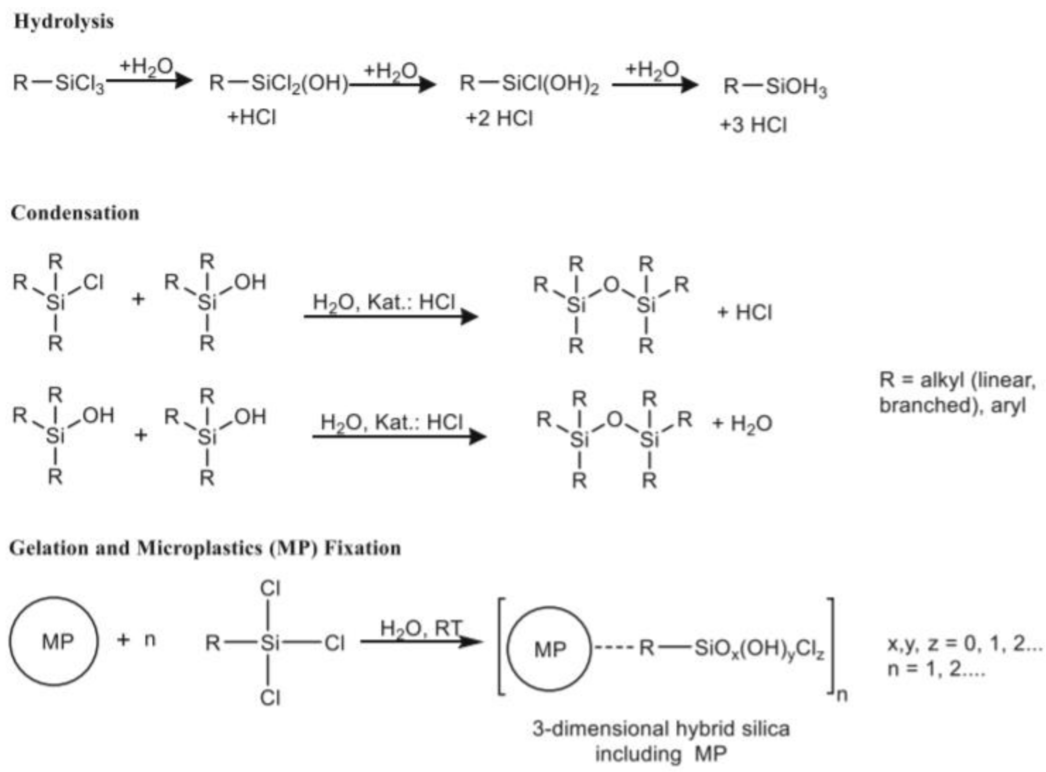


Figure 35: Reaction mechanism of alkyltrichlorosilanes in water with microplastic particles [112].

Parameters that can be adjusted to optimize the process are the proportion of water, the solvent, the temperature, the pH, the addition of catalysts, and the precursor to solvent ratio [112]. The introduction of new chemicals into a WWTP would require the facility to obtain new MSDS and SOP for use depending on the selected chemical. Until a particular chemical is specified the actual environmental and safety risk cannot be properly assessed. However, the risks associated with the introduction of a new chemical to the process can be mitigated with appropriate PPE, SOPs, and training.

2.4.3.2 Current State of Technology

Lab testing was conducted in Germany to determine whether the use of functionalized hybrid silica gels would be successful at removing microplastics. The type of polymer used for the testing were LDPE, HDPE, and PP which ranged in size of 1 µm to 1 mm, but the shapes of the particles were not specified for testing. Alkyltrichlorosilanes with 1 to 18 carbon atoms were used to determine the most effective organosilane [112]. A schematic of the set-up to determine removal efficiency of the technology is shown in Figure 36. All removal efficiencies were determined gravimetrically.

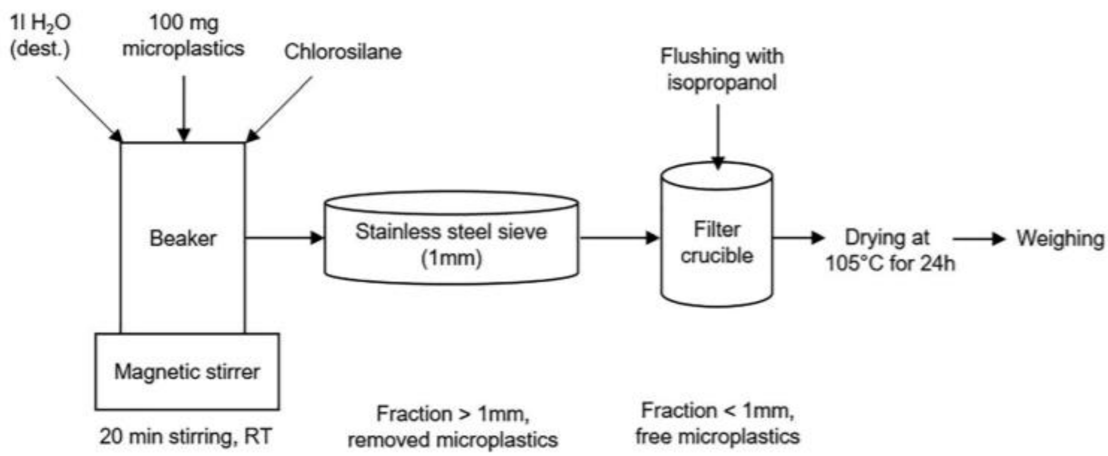


Figure 36: Laboratory-scale testing to determine removal efficiency [112].

It was determined that the highest removal efficiencies were observed for n-propyltrichlorosilane, n-butyltrichlorosilane, isobutyltrichlorosilane, and pentyltrichlorosilane isomers. Efficiencies greater than 95% were recorded for these compounds at varying concentration and results were reproduced across multiple tests of randomly shaped LDPE, HDPE, and PP microplastic particles in the size range of 1 µm to 1 mm at various concentrations. The greatest removal efficiency achieved was 99.1% using n-butyltrichlorosilane [112]. A summary table of the removal efficiencies for all chemicals tested is shown in Table 11.

Table 11: Removal efficiency by various alkyltrichlorosilanes at a concentration of 300 µL/L [112].

Name	Formula	Branched	PE [%]	S.D. PE [%]	PP [%]	S.D. PP [%]
Blank	–	–	0.68	0.46	0.58	0.39
Methyltrichlorosilane	$(C_1H_3)SiCl_3$	–	20.6	15.0	7.7	7.6
n-Propyltrichlorosilane	$(C_3H_7)SiCl_3$	–	**95.2**	3.2	**99.0**	0.2
n-Butyltrichlorosilane	$(C_4H_9)SiCl_3$	–	**99.1**	0.3	**98.0**	1.1
Pentyltrichlorosilane (Isomere)	$(C_5H_{11})SiCl_3$	(+)	**98.0**	1.1	**96.6**	0.1
n-Hexyltrichlorosilane	$(C_6H_{13})SiCl_3$	–	64.0	13.7	78.3	19.5
n-Octyltrichlorosilane	$(C_8H_{17})SiCl_3$	–	29.2	1.8	49.5	9.5
n-Decyltrichlorosilane	$(C_{10}H_{21})SiCl_3$	–	68.5	7.8	63.7	12.5
n-Undecyltrichlorosilane	$(C_{11}H_{23})SiCl_3$	–	39.6	16.4		
n-Dodecyltrichlorosilane	$(C_{12}H_{25})SiCl_3$	–	73.2	4.5		
n-Hexadecyltrichlorosilane	$(C_{16}H_{33})SiCl_3$	–	75.0	7.8		
n-Octadecyltrichlorosilane (5–10% Isomere)	$(C_{18}H_{37})SiCl_3$	(–)	58.0	17.5		
Isobutyltrichlorosilane	$(C_4H_9)SiCl_3$	+	**98.7**	0.04	**98.9**	0.5
t-Butyltrichlorosilane	$(C_4H_9)SiCl_3$	+	13.3	5.0	7.0	6.1
Thexyltrichlorosilane	$(C_6H_{13})SiCl_3$	+	96.3	0.5	94.1	0.8
(3,3-Dimethylbutyl)trichlorosilane	$(C_6H_{13})SiCl_3$	(+)	84.1	6.7	84.8	8.2

Based on the results of this study, a pilot plant was built at a WWTP in Germany. This allows the researchers to run the technology using environmental samples with unknown concentration and composition of microplastics to determine the robustness of the organosilanes and work towards optimizing the process for large-scale applications. Pilot plant testing began in June 2019, but testing is on-going, and the results have not yet been published [113]. Since pilot plant testing is still underway and scale-up of the technology has not been finalized detailed and reliable costing information is not yet available.

2.4.3.3 Evaluation of Technology

The hybridized silica gel process was evaluated based on results from the laboratory-scale experiments, with the knowledge that pilot plant testing is currently occurring. A summary of the evaluation criteria can be found in Table 12.

Table 12: Evaluation of the hybridized silica gel process and comparison of technology to project specific outlined criteria.

Criteria	Notes
Technology Readiness Level	Level 5: Component and/or validation in a simulated environment Laboratory-scale testing has been completed with successful results. Pilot plant testing began in June 2019 at a WWTP in Germany, but the results have not yet been published.
Efficiency/ Effectiveness	The company Wasser 3.0 performed laboratory-scale testing which revealed that n-propyltrichlorosilane, n-butyltrichlorosilane, isobutyl trichlorosilane, and pentyltrichlorosilane (isomers) consistenyl achieve greater than 95% removal efficiency of PE and PP. The ability to achieve greater than 95% removal of LDPE, HDPE, and PP microplastic particles in the size range of 1 µm to 1 mm with a number of different chemicals demonstrates the robustness of the process.
Compatibility with Current Process	The current pilot plant testing is set-up in a mobile container on-site at a WWTP. Implementation of this processing step would require additional land footprint. Since the process uses chemical coagulants, land storage area would be required to store the material.
Environment and Safety	The discharged agglomerate will be a 3D hybrid silica-microplastic complex. Proper disposal methods must be developed in accordance with the Canadian Environmental Act. The introduction of new chemicals into a WWTP would require the facility to obtain new MSDS and SOP for use depending on the selected chemical. Until a particular chemical is specified the actual environmental and safety risk cannot be properly assessed. However, the risks associated with the introduction of a new chemical to the process can be mitigated with appropriate PPE, SOPs, and training.
Simplicity of Operation	The operating procedure used at the WWTP where pilot plant testing is occurring has not been published. Based on the laboratory-scale testing the procedure is not very operator intensive. It is unknown to what extent the process will be automated if it is implemented at the industrial scale.

Additional Information Criteria	
Legal/Regulatory Applications	Regulations may have to be implemented to characterize the waste stream if it contains alkyltrichlorosilanes to ensure that it meets environmental regulations before discharge. The application of the technology must adhere to the guidelines of Drinking-Water Systems regulation (*O.Reg. 435/93*) under the *Ontario Water Resources Act, 1990*. Use and storage of any reagents must be in accordance with *Regulation 860* under the *Occupational Health and Safety Act,* as well as Building Code (*O.Reg. 350/06*) under the *Building Code Act, 1992* and the Fire Code (*O.Reg. 388/97*) under the *Fire Protection and Prevention Act, 1997*. Depending on the site of implementation, local by-laws may also apply. [71]
Cost	Information on the expected cost of implementation was not detailed by the researchers. Cost will be dependent upon footprint, materials of construction, energy consumption, purchasing chemicals, as well as any associated legal or training costs.
Energy Consumption	Energy is required to provide agitation to encourage mixing in the system. It is assumed that pumps will be required to move the water from the system. The amount of energy required is dependent on the size of the filter, flow rate, as well as the frequency of cleaning.

2.4.4 Fenton's Reagent Degradation

2.4.4.1 Technology Description

Fenton's reagent (also referred to as Fenton's reaction or Fenton's chemistry) is the name of a chemical treatment that combines hydrogen peroxide and an iron catalyst to generate a biological oxidant [114]. Typically, ferrous iron sulfate (Fe^{2+}) is used as the iron source but ferric (Fe^{3+}) iron sources may be used as well. Fenton's reagent requires a relatively short preparation time compared to methods involving chemical or enzyme catalysis. Since the reagent only digests biological organic material (BOM), microplastics of any size present in a wastewater stream can be separated. Once the BOM is digested, the microplastic residue can be discarded or incinerated.

Fenton's reagent is prepared under acidic conditions by the oxidation of iron (II) ions in the presence of hydrogen peroxide. During the course of three sequential reactions, iron (III), hydroxyl, and hydroperoxyl ions are produced according to the reaction mechanism shown below:

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + 2OH^-$$

$$Fe^{3+} + H_2O_2 \rightarrow Fe^{2+} + OOH^- + H^+$$

$$2H_2O_2 \rightarrow OH^- + OOH^- + H_2O$$

The hydroxyl and hydroperoxyl ions produced in these reactions can act as free radicals that can further decompose BOM and can degrade microbial cells, thereby freeing microplastics for separation.

The hydroxyl and perhydroxyl radicals are some of the most reactive chemical species based on relative oxidation power and thus provides effective digestion of BOM. A list of reactive species and their relative oxidation power is shown below in Table 13.

Table 13: Oxidative species and their relative oxidation power [115].

Reactive Species	Relative Oxidation Power
Fluorine	2.23
Hydroxyl radical	2.06
Atomic oxygen (singlet)	1.78
Hydrogen peroxide	1.31
Perhydroxyl radical	1.25
Permanganate	1.24
Hypobromous acid	1.17
Chlorine dioxide	1.15

Due to the oxidative nature of these species, Fenton’s reagent is used commonly to treat industrial/municipal wastewater effluents with high concentrations of difficult to remove or toxic organic compounds [115]. When applied to wastewater effluents, the process can be used to improve organic pollutant destruction, toxicity reduction, biodegradability, BOD/COD removal and odour and colour removal.

Fenton’s reagent is used for treating organic solvents that are resistant to common forms of biological treatment or carbon adsorption. Specific organic compounds that are commonly treated with Fenton’s reagent include phenols, formaldehyde, methylene chloride, and chlorinated solvents [115]. Fenton’s reagent has also been widely used for treatment of complex wastes from pesticide, petroleum, refining, wood preservative, plastic additive and rubber chemical industries.

Fenton’s reagent is reliant on the presence of its iron catalyst. Without it, there is no hydroxyl radical formation and no oxidative digestion. On its own, the addition of hydrogen peroxide does not reduce the level of a phenolic (most general) wastewater effluent. When the incoming concentration of iron is increased, phenol removal increases until a plateau is met, and no more phenol removal can be achieved by adding more iron. This means that an optimal dose range exists for the concentration of the iron catalyst in any wastewater effluent. It is recommended that this dose range be first characterized in a lab setting and confirmed in a pilot-scale testing prior to large-scale implementation.

Previous characterization studies indicate that a minimum iron concentration of 15-30 mg/L will allow for an adequate reaction time that is independent of the concentration of the organic matter in the stream. While this accommodates a range of different organic matter concentrations, further optimization is required. The concentration of hydrogen peroxide is often described as a ratio of the iron dose used. Ratios of iron to hydrogen peroxide range from 1:5 to 1:25 [115].

Both ferric and ferrous iron sources can be used for most reactions. Usually hydrogen peroxide is supplied in excess. However, in cases where a low concentration of hydrogen peroxide is used (< 10-25 mg/L) it may be beneficial to use a ferrous iron source. To be safe, a ferrous iron source is recommended.

For an automated process, the dosage of hydrogen peroxide is determined by monitoring the Oxidation-Reduction Potential (ORP) of the stream. The higher this reading is, the more oxidizing power the stream has, while a negative potential indicates that the stream has reducing potential. A typical ORP value for a Fenton's reagent process is +500 mV [115]. Fenton's reagent reaction is an exothermic reaction; thus, the rate of the reaction can be increased by increasing the temperature.

Previous characterization studies indicate that temperatures above 20°C have a more substantial impact on rate. Conversely, temperatures in the range of 40-50°C, hydrogen peroxide use becomes more inefficient. It is important to note that at hydrogen peroxide doses greater than 20 g/L, the reaction will proceed at higher rates. As the rate increases, the reaction temperature will increase as well, thereby necessitating addition of more hydrogen peroxide to account for the reduced efficiency. The reaction is also pH sensitive. In general, an optimal pH range occurs between a pH of 3.5 to 4.5 but process optimization is required. Considerable operating cost would likely be required to bring large volumes of wastewater to be treated down to a pH between 3.5 and 4.5, and then readjust the pH to approximately 7 to allow for discharge.

The overall reaction time is dependent on aforementioned variables described in this section, chiefly the catalyst dose and the concentration of the organic material in the wastewater stream. In simple cases such as phenol oxidation with phenol concentration lower 250 mg/L, a typical time frame is 30-60 minutes. Difficult cases where heavily concentrated wastes are present, may be as high as several hours. For such cases, sequential loading of iron and hydrogen peroxide may be more effective and safer. The level of completion of the reaction can be assessed standard bench testing for BOM or by colour changes. Wastewaters charged with hydrogen peroxide are dark and will clear up when the reaction is complete. The general procedure for treating wastewater with Fenton's reagent as described by Wilson Environmental is as seen in Table 14.

Table 14: Outline of Fenton's Reagent Degradation process. [115]

Step	Description
1. pH Adjustment	Wastewater is drawn from an equalization tank to the reactor tank where the pH is adjusted from 3.0 to 4.0. This is done by the addition of sulfuric acid (H_2SO_4). The lower pH will cause the iron to dissolve into the wastewater. At neutral or higher pH levels (<7 pH units) the iron granules of ferrous sulfate will not dissolve. Lowering the pH also brings the oxidation strength of the Fenton reagent into the optimum range. Dosage is typically less than 5 gallons for 1,000 gallons of wastewater. Note: Sulfuric acid can be purchased at 93% but it can be dangerous at the concentration. A lower concentration is recommended. Commercially available concentrations vary. May be purchased in 55-gallon drums or in 290-gallon totes.
2. Iron Catalyst	Adding the iron catalyst, ferrous sulfate as dry granules or as a premixed solution in water and mixing for 2 to 4 hours. The amount required is determined by jar testing. Typical iron requirement is 8 to 10 pounds per 1000 gallons of wastewater. Ferrous sulfate is purchased in 50-pound bags.
3. Hydrogen Peroxide Addition	The hydrogen peroxide is added slowly. The pH is monitored continuously to maintain a pH of 3 to 5 during the oxidation step. Hydrogen peroxide is added until an ORP reading of +500 mV is maintained. The temperature is also monitored to prevent overheating. 10 gallons per 1000 gallons of wastewater is typical usage for wastewater. Hydrogen peroxide is the cost driver for operational costs. Current cost is around $3.00/gallon. Purchased in 55-gallon drums or 290-gallon totes.
4. Lime Flocculation and pH Adjustment	The pH is now adjusted back to neutral (7 pH) using lime. If metals are present and metals removal is being conducted the pH will be adjusted in this step to optimal pH for the removal of the metal. The presence of iron in the reaction mixture makes it particularly suited to lime flocculation. 8 pounds is typical for 1000 gallons. Purchased in 50-pound bags. Note: Metals removal is a separate subject but can be accomplished at this time in the process. Further pH adjustment is accomplished by using lime.
5. Polymer Addition	A small amount of polymer is added to create a floc (flakes of precipitate material visible to the eye). Typical dosage of polymer is 2 oz. per 1000 gallons. Purchased in 5-gallon containers.
6. Settling	The reactor tank is allowed to settle for 4 hours or more, no mixing.
7. Decant	The clear water is now removed by decanting from the reactor vessel.
8. Solids Removal	The settled solids are removed and sent to a filter press to remove excess water. The filter press will produce what is called filter cake. The solid residues, like a cake, can usually be sent to a landfill for disposal.

2.4.4.2 Current State of Technology

Domestically, it has been widely used for the last 50 years as a well-established oxidative agent used in WWTP today. It has been used in various industry facilities and wastewater treatment plants in the United States but is new to microplastic treatment. A list of a few of these facilities and their removal levels are shown in Table 15.

Table 15: Fenton's reagent performance in domestic facilities [116].

Chemical Process	Parameter	Effectiveness (%)
Specialty Chemical Manufacturer with Chemical Waste Enriched with Phenols	Phenols Removal	90
Wood Treating Facility with Chemical Waste Enriched with Phenols, Napthols, and Cresols	Combined Phenol, Napthol, and Cresol Removal	95
Aircraft Painting and Stripping Facility with Stream Containing Toxic Organic Compounds	Toxic Organic Removal	95
Emergency Treatment of Phenol Contaminated Wastewater from Chemical Plant	Phenols Removal	99

Globally, it has been used as disinfectant in wastewater and industrial/municipal waste treatment facilities outside of North America. A list of a few of these facilities and their removal levels are shown in Table 16.

Table 16: Fenton's reagent performance in facilities outside of North America.

Chemical Process	Parameter	Effectiveness (%)
Semi-Aerobic Landfill Leachate **[117]**	COD Removal	58
	Colour Removal	78
Coking Wastewater **[118]**	Oxygen Uptake Rate	65
Drinking Water Contaminated with CFVP **[119]**	Degradation of CFVP	100
Organic Pollutants in Textile Effluent **[120]**	COD Removal with Mesophorous Activated Carbon (MAC)	90
	COD Removal without MAC	70
	BOD Removal with MAC	90
	BOD Removal without MAC	60
Agro-Industrial Waters **[121]**	TOC_7 Removal	58
Polluted Pharmaceutical Waters **[122]**	COD Removal	90
Oil Recovery Wastewater **[123]**	COD Removal	86
	COD Removal with UV Treatment	81
Petroleum Hydrocarbons in Oily Sludge **[124]**	Total Petroleum Hydrocarbon Removal	73

As shown in Table 15 and Table 16, there are several uses for Fenton's reagent, each with varying levels of effectiveness. Due to its ability to treat many different types of industrial/municipal effluent streams, many researchers have begun to test its ability to filter microplastics from sludge, sediment or wastewaters containing large amounts of BOM. So far, most studies that have investigated the use of Fenton's reagent have used it as a method for separating only small volume samples [125]. Currently, the best study conducted indicates an organic removal rating of 86.9% while several studies have found lower removal rates closer to 25% (no size range noted) [126] [127].

Many of these studies require Fenton's reagent to isolate their microplastic samples and thus are not recording its use as a digestion solution. As well, some of these studies are using other chemical or physical separation techniques to purify their samples, which may suggest that Fenton's reagent alone may not be a suitable solution for separating microplastics [126].

Another limitation that may be holding back Fenton's reagent as a separation technique is the unknown influence that it might have on the polymer structure and composition. Although some studies have shown that Fenton's reagent does not impact the chemical nature of popular plastics, other studies have successfully demonstrated that Fenton's reagent can digest PVC [128]. Further testing is required to determine whether Fenton's reagent can effectively degrade BOM while leaving plastics untouched.

2.4.4.3 Evaluation of Technology

The use of Fenton's reagent was evaluated based on the evaluation criteria. The evaluation of the technology was based on results from the lab-scale experiments. The summary can be found in Table 17.

Table 17: Evaluation of Fenton's reagent and comparison of technology to project specific outlined criteria [106].

Criteria	Notes
Technology Readiness Level	Level 3: Analytical and experimental critical function and/or proof of concept. The testing of microplastic removal by this method of treatment is still emerging and is in the research phase. Although Fenton's reagent has been used in various large-scale applications including WW treatment, it has yet to be demonstrated as an effective treatment technique for separating microplastics from BOM at a reliable sample size. Preliminary testing in the laboratory has been used to separate digest small BOM samples containing microplastics. These volumes are too small to be considered effective representation of the technology's efficiency at this point in time. Pilot-scale testing must be completed with larger sample volumes to confirm that this solution could be viable at a WWTP.
Efficiency/ Effectiveness	Independent of microplastic removal, Fenton's reagent has varying degrees of digestion effectiveness in many different types of BOM. Several different large-scale processes and their associated COD/BOD removal can be found in Table 15 and Table 16. Specific studies investigating microplastic removal shows a range of removal rates. Since no physical separation is required, this treatment could conceivably separate microplastics. However, since microplastics account for a very small portion of the mass in a waste stream, digesting the entire mass of the entire BOM in the waste stream is likely not a practical use of resources. To improve the efficiency, it is recommended to combine use of this process with a physical separation process to remove as much BOM as possible prior to digestion.

Criteria	Notes
Compatibility with Current Process	Since Fenton's reagent has already been used in WWTP and other treatment processes its application is compatible with the physical infrastructure of most plants. If a plant does not already use Fenton's reagent, several holding tanks for hydrogen peroxide and iron sulfate as well as pH additives will be required. Additional equalization tanks may be required to facilitate the interaction between the WW and Fenton's reagent. Depending on the operation of the process, a manual or automatic control system will be required to be set up for the process and integrated into the existing electrical equipment. These changes do not necessarily require the addition of new infrastructure if existing equipment is present at the facility. However, in the event they do not, introduction of this equipment may be a substantial financial cost.
Environment and Safety	Due to the low concentrations used in the reaction, hydrogen peroxide and iron sulfate are not considered hazardous to the local community. However, the reaction can be vigorous and can result in release of oxygen, steam, carbon dioxide and halides (if present in WW) and the facility must take precautions to safely vent these gases. There are no additional safety concerns associated with transport or storage. Iron sulfate is classified as a skin and eye irritant, as it may form combustible dust concentrations in the air and is harmful if swallowed. Face and eye protection should be worn as well as protective gloves and clothing. Iron sulfate has an LD50 of 319 mg/kg (rat) and no LC50 listed. It is safe in the environment in low concentrations. [129] Hydrogen peroxide is classified as a skin and eye irritant, a corrosive material and is a strong oxidizing material. It may it cause fire or explosion; it is hazardous to inhale and can cause severe skin burns and eye damage upon contact. It should be stored away from heat/sparks. Face and eye protection should be worn as well as protective gloves and clothing. A 35% solution has an LD50 of 1232 mg/kg (rat) and an LC50 of 42g/m^3. [130]

Criteria	Notes
Simplicity of Operation	At a commercial level, the process would require trained professionals to operate and maintain the equipment. The number of equalization tanks is proportional to the size of the incoming WW stream. The system will require manual or automated (suggested) addition of reactants and adjustments/supervision to ensure optimal conditions are achieved and would require full design by an engineering firm. Compared to other forms of BOM digestion, preparation of Fenton's reagent is much quicker and requires a lower degree of sample preparation.
Additional Information Criteria	
Legal/Regulatory Applications	The application of the technology must adhere to the guidelines of Drinking-Water Systems regulation (*O.Reg. 435/93*) under the *Ontario Water Resources Act, 1990*. Use and storage of any reagents must be in accordance with *Regulation 860* under the *Occupational Health and Safety Act,* as well as Building Code (*O.Reg. 350/06*) under the *Building Code Act, 1992* and the Fire Code (*O.Reg. 388/97*) under the *Fire Protection and Prevention Act, 1997*. Depending on the site of implementation, local by-laws may also apply [131]. No current patent exists for the use of Fenton's reagent on a reaction basis. Patents exist for specific remediation apparatus designs.
Cost	Initial capital cost would involve the addition of several holding tanks for chemicals, equalization tanks, and a manual or automatic control system which will be required to be set up for the process and integrated into the existing electrical equipment.
Energy Consumption	Depending on the starting phenol concentrations and the desired level of COD removal, energy consumption levels range from 11.41 to 458.5 kWh/kg. These energy values were reported in 2010 and may be subject to industry fluctuation. These estimates are based upon traditional WW treatment and not microplastic treatment protocols. [132]

2.4.5. Chemical and Enzymatic Digestion of Biological Material

2.4.5.1 Technology Description

Chemical degradation of BOM involves the digestion of BOM by treatment of chemical denaturants, oxidizing agents, and strongly acidic or alkaline chemicals to digest the material holding microplastics. Chemical treatments are designed to digest organic materials only and leave the chemically inert polymer behind untouched. Often several treatments are required in sequence to increase the effectiveness of separation. However, use of such strong chemicals can sometimes result in damage to the suspended polymers [133].

Enzymatic digestion of BOM is an alternate separation solution that is much gentler on polymers, although not as effective and usually requires a longer preparation time. Enzymatic degradation uses various enzymes to separate microplastics from fish or sources of residual BOM such as zooplankton and other benthic invertebrates. Many different aquatic organisms ingest microplastics that enter their ecosystems. Eutrophic or mesotrophic lakes such as Lake Ontario and Lake Erie have high levels of these organisms, that can enter into WW influent. These specimens can be degraded by using a variety of different enzymes that release microplastics, which would otherwise be unable to be separated.

Generally, chemical and enzymatic degradation treatments are paired together, and with other physical separation techniques such as density separation [134]. Density separation is typically used to extract microplastics from sediment samples by floating small microplastic particles in a solution with a greater density, while larger particles such as dirt or sediment sink to the bottom. Several density solutions such as sodium chloride, sodium iodide and sodium polytungstate are frequently used and have shown no impacts to the structural integrity of polymers [134]. However, these solutions may not be viable for denser polymers to create a large enough gradient for effective biological separation.

2.4.5.2 Current State of Technology

There have been several chemicals for degradation treatments described in the literature such as SDS, hydrogen peroxide, potassium hydroxide, sodium hydroxide, nitric acid, hydrochloric acid, perchloric acid, and sodium perchlorate. Although these treatments have been investigated, there is no standardized procedure, which means that different sources of BOM are being used along with different preparation methods. However, for the majority of these studies a digestion efficacy is measured. For these calculations, digestion efficacy is measured as:

$$Efficacy\ (\%) = 100 - \frac{Dry\ weight\ on\ filter\ paper\ (g) * 100}{Wet\ weight\ entire\ organism's\ tissue\ (g)} \tag{3}$$

A few of the treatments, their digestion efficacy and any notes of polymer damage are listed in Table 18.

Table 18: Chemical treatments and their respective digestive efficacies. No size range noted.

Chemical Treatment	Digestion Efficacy (%)	Noted Damage
1M HCl **[127]**	82.6	None observed
2M HCl **[127]**	72.1	None observed
35% (v/v) HNO_3 **[135]**	100	Fusing of HDPE, PET, and PA
1M NaOH **[135]**	90	None observed
1M NaOH **[127]**	100	None observed
2M NaOH **[127]**	85	None observed
10M NaOH **[127]**	91.3	Partial destruction of PA, some loss of PL, some fusion of PE, yellowing of PVC
10% (v/w) KOH at 60C for 24 hours **[136]**	99.6	Change in shape of PET
10% (v/w) KOH at 25, 40 & 50C for 96 hours **[137]**	97.1-98.9	Polymer yellowing at 50C
10% (v/w) KOH at 60C for 96 hours **[137]**	97.6	None observed

There have been a number of enzyme degradation studies conducted for separating microplastics from BOM. Once again, since there is no standardized procedure, different BOM sources are used as well as different preparation and digestion methods which prevents comparison of results. A few of the treatments, their digestion efficacy, and any notes of polymer damage are listed in Table 19.

Table 19: Enzymatic treatments and their respective digestive efficacies. No size range noted.

Enzymatic Treatment	Digestion Efficacy (%)	Noted Damage
Alcalase **[138]**	98	None observed
Collagenase **[139]**	78	None observed
Corolase 7089 **[135]**	100	None observed
Pancreatic Enzyme (Pez) **[140]**	97.7	None observed
Papain **[139]**	75	None observed
Protease with 1M NaOH and 35% (v/v) HNO_3	93	Severe damage to all polymers
Proteinase-K **[127]**	97.7	Damage to nylon fibres, fusing of PE, discoloration of PVC
Proteinase-K, Protease, Cellulase, and Chitinase with peroxide and SDS **[141]**	98.3	None observed
Trypsin (formaldehyde) **[139]**	78	None observed
Trypsin (fresh) **[139]**	86	None observed
Trypsin (frozen) **[139]**	88	None observed

2.4.5.3 Evaluation of Technology

The use of chemical and enzymatic digestion was evaluated based on the evaluation criteria. The evaluation of the technology was based on results from the laboratory-scale experiments. The summary can be found in Table 20.

Table 20: Evaluation of chemical and enzymatic digestion and comparison of technology to project specific outlined criteria.

Criteria	Notes
Technology Readiness Level	Level 1: Basic principles of concept are observed and reported. The testing of microplastic removal by this method treatment is still emerging and is in the research phase All of the research surrounding this topic is geared towards enzyme and solvent-based digestion of BOM in small volume samples. It has yet to be demonstrated as an effective treatment technique for separating microplastics from BOM at a reliable sample size. Preliminary testing in the laboratory has not produced a standardized method for digestion. Instead, a combination of different enzymatic and other chemical treatments is used sequentially to digest BOM. Despite the use of several of these treatments in tandem, only small samples of BOM have been tested thus far to separate out microplastics, and those that have are typically no more than a liter in volume. Further laboratory-scale testing is required before even pilot-scale testing can commence. This technology is not ready for large-scale use.
Efficiency/ Effectiveness	Due to the variety of different treatment types, there are varying levels of both chemical and enzymatic digestive effectiveness. Various chemical treatments have a range of effectiveness levels shown in Table 18Table 18. Several different digestion treatments and their digestion effectiveness are listed in Table 19.

Criteria	Notes
Compatibility with Current Process	Since there is no standardized procedure it is difficult to gauge the number of additional unit operations that may be added. However, the majority of cases involve anywhere from one to four enzyme treatments and several chemical treatments. Several holding tanks for the new chemicals and enzyme solutions will be required as well as several equalization tanks for the reaction to occur. Depending on the operation of the process, manual or automatic control systems will be required to be added for the additional unit operations and integrated into the existing plant electrical systems. These do not necessarily require the addition of new infrastructure if there is existing equipment available for use. If not, this additional infrastructure may constitute a large financial cost.
Environment and Safety	Only a few enzyme solutions present biohazardous hazards. However, they have the potential to have allergenicity, activity-related toxicity, and chemical toxicity. On their own enzymes are typically not toxic or mutagenic but enzyme preparations may contain harmful contaminants that are present from processing or preparation. Other chemical treatments used in BOM digestion include sodium dodecyl sulfate, hydrogen peroxide, potassium hydroxide, sodium hydroxide, nitric acid, hydrochloric acid, perchloric acid, and sodium perchlorate. Sodium dodecyl sulfate is classified as flammable, harmful or fatal if ingested, and harmful to the environment. It should be stored away from heat or hot surfaces. Any fumes should be avoided and vented safely. Face and eye protection should be worn as well as protective gloves and clothing. Precautions should be taken to avoid release to the environment. It has an LD50 of 1288 mg/kg (rat) and an LC50 of >3.9 g/m^3 (rat). [142] Although diluted hydrogen peroxide is available in pharmacies for use as an antiseptic, when used at industrial strength, hydrogen peroxide is classified as a skin and eye irritant, a corrosive material and is a strong oxidizing material and may cause fire or explosion. It is hazardous to inhale and can cause severe skin burns and eye damage upon contact. It should be stored away from heat/sparks. Face and eye protection should be worn as well as protective gloves and clothing. A 35% solution has an LD50 of 1232 mg/kg (rat) and an LC50 of 42g/m^3. [142] Potassium hydroxide is classified as harmful if ingested and corrosive to skin and metals. Face and eye protection should be worn as well as protective gloves and clothing. KOH has an LD50 of 284 mg/kg and an LC50 of 80 g/m^3 (rat). [142] [143]

Criteria	Notes
Environment and Safety	Sodium hydroxide is classified as harmful if ingested and corrosive to skin and metals. The fumes/dust particles are hazardous if inhaled. Face and eye protection should be worn as well as protective gloves and clothing. Use only in a well-ventilated space. It has an LD50 of 1350 mg/kg (rabbit) and an LC50 of 2.3 g/m^3 (rat). [142] Nitric acid is classified as harmful if ingested and corrosive to skin and metals. Face and eye protection should be worn as well as protective gloves and clothing. HNO_3 as an LD50 of >90,000 mg/kg and an LC50 of 2500 ppm. [143] [142] Perchloric acid is classified as flammable, harmful if ingested and corrosive to skin and metals. It should be stored away from heat/sparks. The fumes/dust particles are hazardous if inhaled. It has an LD50 of 1100 mg/kg (rat) and an LC50 of 11.4 g/m^3 (rat). [142] [144]
Simplicity of Operation	Since there is no standardized procedure it is impossible to evaluate all protocols. Qualitatively, chemical treatments tend to be quicker and easier to conduct than enzymatic digestion procedures. However, enzymatic digestion does not appear to have the same potential to damage polymers that chemical treatment has. At a commercial level, the process would require trained professionals to operate and maintain the equipment. The number of additional unit operations is dependent on the magnitude of the incoming stream as well as the digestion procedure that is being followed. The system will require manual or automated (suggested) addition of reactants and adjustments/supervision to ensure optimal conditions are achieved and would require full design by an engineering firm. Compared to other forms of BOM digestion, the chemical and enzymatic treatment preparation and procedure is much longer and more complex.

Additional Information Criteria	
Legal/Regulatory Applications	The application of the technology must adhere to the guidelines of Drinking-Water Systems regulation (*O.Reg. 435/93*) under the *Ontario Water Resources Act, 1990*. Use and storage of any reagents must be in accordance with *Regulation 860* under the *Occupational Health and Safety Act,* as well as Building Code (*O.Reg. 350/06*) under the *Building Code Act, 1992* and the Fire Code (*O.Reg. 388/97*) under the *Fire Protection and Prevention Act, 1997*. Depending on the site of implementation, local by-laws may also apply. [71] All of the enzymatic treatments for microplastic separation are in laboratory-scale development. At such a point where an enzymatic procedure is applicable, a patent may exist.
Cost	Due to the emerging nature of both the chemical and enzymatic treatments, cost information is not yet established. Depending on the procedure that is being followed, several unit operations may be required including mixers, heaters, coolers, pumps, holding tanks, reactors, and control systems. Labour costs would increase due to the increased maintenance and system complexity.
Energy Consumption	Due to the emerging nature of both the chemical and enzymatic treatments, energy consumption information is not yet established. Power would be required for the additional unit operations. Exact energy consumption would be dependent on the size of the system and the operating parameters of the system based on the individual WWTP's needs.

2.5 Additional Emerging Solution: Electrostatic Separation

2.5.1.1 Technology Description

Electrostatic separation relies on the conductive properties of plastic particles to separate it from other types of matter. A device known as a Korono-Walzen-Schneider (KWS) separator can be used to divide non-conductive material by using a dry separation process that is not limited by particle density. The dry separation mixture is carried by a vibrating conveyor belt into a rotating grounded metal drum. As this occurs, it passes by a corona electrode that can be electrostatically charged up to 35 kV. As the matter passes through the corona field, each material is electrostatically charged based on its substance specific properties.

A corona field discharge is the release of electricity that may occur when a fluid surrounding a conductor is ionized. [145] In a unipolar conduction coronas, the corona inducing voltage will be dependent on the space charge field (charge distribution) of the drifting ions. Current two-stage electrostatic precipitators used to clean air from dusts, smokes or fumes have a corona voltage of 9-13 kV [145]. While WW may require a different ionization voltage, the KWS separator is designed to only handle dry samples. The drum is grounded so the particles are discharged as they leave the corona field. The more conductive materials are discharged faster than non-conductive materials. Due to the rotational movement of the drum, the particles are separated into different sample collectors based on their discharge speed.

2.5.1.2 Current State of Technology

There are currently KWS devices sold in Europe as recycling separators for metals. [146] Preliminary research has been done to investigate the effectiveness of using these devices to separate microplastics from various environmental samples such as suspended particulate matter, freshwater sediment, quartz sand, and beach sand. This research has been performed at a bench-scale and currently there are no pilot-scale facilities utilizing this technology.

Based on the lone research conducted so far, the treatment appears to be an effective physical separation technique. It has been assigned a level 4 on the technology readiness scale since it is a component and/or validation in a laboratory environment. Testing of microplastic removal using a KWS separator is still emerging and only one study has been completed to date. In the study, seven common types of microplastics were spiked into samples, ranging from 63 – 5000 µm. Using the KWS separator, nearly all of the dry sample sediment mass was removed without any microplastic loss. The specific recoveries of different sizes of microplastics when run on a 900 rpm conveyor belt with a 20 kV corona field for 2-3 hours is nearly 100% for all four size ranges tested (63 – 200 um, 200 – 630 µm, 630 – 2000 µm, 2000 – 5000 µm) [147].

While certainly promising, preliminary testing volumes are also too small to be considered viable at this point of time (approximately 20 g of sediment in 100 mL of distilled water). More studies must also be conducted to validate the removal efficiency. As well, the sorted material must be dried before sorting, which presents an issue for a WWTP. Most Canadian WWTPs process incredibly large volumes (average of 5,706 ML in 2007) and so the heating costs required to dry the sediment would be very large [35]. Since the KWS separator is a purely physical separator, there are no chemical or biological hazards. However, due to the high voltages that may be used, operators will need training on its electrical hazards. Once implemented, the system functions on a conveyor system and thus would still require trained operator support although less than other processes since it is an automatic process.

3.0 Industrial Scale Plastics Removal Processes Evaluation

3.1 Criteria Weighting and Justification for Industrial/Municipal Solutions

The criteria for the industrial/municipal solutions were outlined in Section 2.1. To complete the evaluation of the technologies to compare them based on the criteria, scoring metrics were outlined and are shown in **Error! Not a valid bookmark self-reference.**.

Table 21: Industrial/municipal solutions ranking description and justification for outlined criteria.

Criteria	Weight	Low Rank (1)	Mid Rank (3)	High Rank (5)
Technology Readiness Level	30	Levels 1 through 4	Levels 5 and 6	Levels 7 through 9
Efficiency/Effectiveness	25	Size: 1 to 5 mm Percent removed by count or mass: less than 60%	Size: 200 µm to 1 mm Percent removed by count or mass: 60%-89%	Size: 20 to 200 µm (or smaller) Percent removed by count or mass: 90% or greater
Compatibility with Current Process • Can the new equipment or process be added into the current process easily? • Will the implementation of the equipment require significant installation time? • What amount of space is required for the technology? • If required, could the unit be installed outdoors? • Will the daily capacity change with this new equipment? • Requires tertiary treatment.	20	Requires significant installation and construction time with significant downtime to existing plant Requires major additions to the process and may be difficult to incorporate into a current WWTP Requires tertiary treatment at plant to operate or is dependent on other technologies at the WWTP	Requires large amount of installation and construction time with some down time to plant Requires some addition to the process, but still could be incorporated within an existing facility Benefits from tertiary treatment or is a form of tertiary treatment but does not require tertiary treatment to already exist within plant.	Requires minimal amount of installation and construction time with minimal down time to plant Requires addition to the process, but can be incorporated within an existing facility easily Does not require tertiary treatment to already exist within plant and can be easily added to the secondary treatment of a plant.

Criteria	Weight	Low Rank (1)	Mid Rank (3)	High Rank (5)
Simplicity of Operation • Maintenance requirements (materials that need to be stored, number of required labour hours, automatic vs manned, required downtime)	15	Requires a significant amount of operations effort (more than other elements in the WWTP). Process is not automatic and must be manned almost full time. Significant downtime and/or materials required.	Some operations effort required (somewhat similar to maintenance required for other processes in the WWTP). Process is not automatic and needs to be checked frequently. Short downtime and/or extra materials required.	Minimal operations effort is required (less maintenance than other processes at the WWTP). Process is fully automatic. Little to no downtime and/or extra materials required.
Environment and Safety • Exposure to chemical hazards • If there any dangerous waste produced? • Exposure to mechanical hazards	10	Significant additional mechanical and chemical hazards. Expert training required and additional unit operations for handling hazardous chemicals. Dangerous waste produced must be dealt with by third party/off-site.	Increased mechanical and chemical hazards. Risk can be mitigated with PPE and training. Dangerous waste produced can be dealt with on site.	Same level of risk of chemical and mechanical hazards as existing unit operations. No dangerous waste produced.

3.2 Evaluation Matrix for Industrial Scale Microplastics Removal Processes

Although based on the same criteria and weighting system, the existing and emerging industrial/municipal solutions were evaluated in separate matrices. Due to the high weighting of TRL it was determined that ranking existing and emerging solutions in the same matrix would show significant bias toward existing solutions. Separating the matrices eliminates TRL as the deciding factor by comparing solutions with similar TRL scores and allows the overall result to showcase the solutions effectiveness and potential to be implemented on an industrial/municipal scale. The weighted evaluation matrices for existing and emerging technologies can be seen in Table 22 and Table 23 respectively.

Table 22: Evaluation matrix for existing industrial scale microplastics removal processes including disc filters (DF), dissolve air flotation (DAF), diatomaceous earth filter (DE filter), rapid sand filters (RSF) and membrane bioreactor (MBR)..

Criteria	Weight	DF	DAF	DE Filter	RSF	MBR
Technology Readiness Level TRL	30	3	3	1	5	3
Efficiency/Effectiveness	25	3	5	1	5	5
Compatibility with Current Process	20	3	3	3	3	1
Simplicity of Operation	15	5	3	3	5	1
Environment and Safety	10	5	3	3	5	3
Total	**500**	**350**	**350**	**190**	**460**	**280**

The top existing technologies that were selected for evaluation were chosen based on what technologies are the most researched for microplastic treatment, and which are going to be available earlier for implementation and testing in a WWTP. Additional solutions were excluded for the evaluation but information pertaining to the functionality of the solutions can be found in their respective section. A summary of the evaluation of each solution can be found for disc filters (DF), dissolve air flotation (DAF), diatomaceous earth filter (DE filter), rapid sand filters (RSF) and membrane bioreactor (MBR) in Table 4, Table 5, Table 6, Table 7 and Table 8 respectively.

It should be noted that there may be bias in the results of the evaluation matrix due to the available amount of information available for each solution. Some of the solutions were further along in the research timeline than others in terms of microplastic removal and therefore may have had more information and overall better outcome as a result. A rating of 1, 3, or 5 was used to lower the bias of each criteria weight however some bias is still likely to exist.

The solution which ranked the top solution for microplastic removal was the use of a RSF. Although the solution involves high installation costs if it does not already exist at a facility, the use of a RSF is common in WWTPs, has been the focus of many studies for microplastic removal, and the results of those studies have proven it to be an effective method of treatment for microplastic removal. The solution poses minimal safety and environment risks and as it is common in WWTPs the training required for the use of the equipment would not be unique to an operator.

The next solutions were the DF and DAF both ranked high due to the fact they both commonly exist within WWTPs. DFs do not require the introduction of new chemicals and have less equipment involved to operate the processes meaning that they are generally simpler to operate than DAF. In addition, more research has been conducted into the use of DFs for microplastic research and pilot-scale plants have been built increasing the TRL of the solution compared to DAF. DFs and their removal capabilities may vary with the unit operation chosen as different filter pore sizes can be used in the unit. It should be noted that DAF has a higher removal efficiency than DFs but higher safety concerns as a coagulant is needed for microplastic coagulation, but the required chemical is unknown and therefore has unknown safety risks.

The lowest ranked solutions were DE filters and MBRs, both of which are novel technologies. MBRs did not rank last due to the technology's potential ability to treat microplastics effectively and its use for water treatment in facilities in Europe. It did not rank higher due to its low capacity meaning that many units would be required for any WWTP to be able to achieve treatment requirements. Due to the technology being novel in WW treatment and the large number of units that would be required to operate, the technology would not prove simple to operate and would not be compatible with current processes at WWTPS. However, MBRs were a staple in microplastic removal research and as more research is completed, and the technology is further developed for large-scale operations the technology could prove to be extremely promising in microplastic removal.

DE filters although effective at particle removal are not commonly found in WWTPs and no research existed for the removal of microplastics from water using this technology, so no data existed on the efficiency of the technology. This resulted in the technology ranking low in TRL in terms of microplastic removal and efficiency of removal which were the highest weighted criteria.

Table 23: Evaluation matrix for emerging industrial/municipal technologies.

Criteria	Weight	Electro-coagulation	Centrifugal Separation	Functionalize Hybrid Silica Gels	Fenton's Reagent	Digestion of Biological Material
Technology Readiness Level TRL	30	1	3	3	1	1
Efficiency/ Effectiveness	25	5	1	5	1	1
Compatibility with Current Process	20	1	3	3	3	1
Simplicity of Operation	15	1	5	1	5	1
Environment and Safety	10	1	5	3	3	3
Total	**500**	**200**	**300**	**320**	**220**	**120**

The top emerging technologies that were selected for evaluation were chosen based on what technologies are the most researched for microplastic treatment, which are going to be available for implementation and testing in a WWTP the quickest. An additional solution was excluded from evaluation but information pertaining to this technology can be found in its respective section. A summary of the evaluation of each solution can be found for electrocoagulation, centrifugation, functionalized, hybrid silica gels, Fenton's reagent, and digestion of biological material in Table 9, Table 10, Table 12, Table 17, and Table 20, respectively.

The scores for some of the solutions may be biased due to some being at more advanced stages of technology development, with more information available for evaluation. The rating system was chosen as 1, 3, and 5 to eliminate this bias, although some may still exist.

Functionalized hybrid silica gels, and centrifugal separation both scored 320 and 300 out of a possible 500 points, respectively. Functionalized hybrid silica gels scored high in technology readiness level and efficiency/effectiveness, which were the two criteria with the highest weightings. The technology is at level 5, meaning that component and/or validation can be simulated in a simulated environment. Already, laboratory-scale testing has produced successful results. Based on the strength of these results, pilot-scale testing has commenced as of June 2019 at a WWTP in Germany. As well, tests conducted by Wasser 3.0, n-propyltrichlorosilane, n-butyltrichlorosilane, isobutyltrichlorosilane, and pentyltrichlorosoline isomers have shown the ability to routinely remove 95% or more of PE and PP microplastics in test-work.

Centrifugal separation scored well in technology readiness level, simplicity of operation, and environment and safety it received a low score in efficiency/effectiveness. The company claims that a very high removal rate of microplastics is possible, but the only published data shows a much lower efficiency near 50%. The process is fully automated and would only require minor maintenance if a blockage occurs. Since it is purely a physical separation process, no additional chemicals are required, and any additional mechanical hazards would not be significant in a WWTP.

Fenton's reagent scored high in simplicity of operation and followed closely to centrifugal separation. Fenton's reagent has been used effectively for several decades to degrade BOM. Since it does not target the microplastics specifically, but rather the BOM, pairing this treatment with an additional filtration method may be applicable across a large size range. As well, Fenton's reagent degradation encompasses only one reaction that can be operated continuously, which reduces the preparation time. An automated process is suggested to ensure that optimal conditions are maintained throughout the course of the reaction.

Chemical and enzymatic digestion scored below the top three solutions. The solution scored low on the technology readiness level criteria. The solution does not have a standardized procedure and often requires long and arduous preparation procedures. Electrocoagulation scored the lowest of all five emerging solutions. It scored low in all five criteria. Currently, the removal efficiency recorded at optimal conditions is 99% of organic material but further testing will be needed to determine if such a high efficiency can contribute to effective filtration of microplastics when combined with another technology.

3.3 Recommendations for Industrial Scale Microplastics Removal Processes

It is recommended that once more research is available for the researched industrial/municipal solutions that the rating of the technologies be re-evaluated for a more accurate comparison. Currently certain technologies are promising in the field of microplastic removal however, as a result of the minimal research available, the technology was not ranked as high as technologies with more advanced testing.

It is recommended that of the technologies already existing at WWTPs, the influent and effluent of the unit operations be tested at the plant to determine the actual removal capabilities. Since it is suspected that the majority of microplastics are filtered into the sludge, it would be beneficial for facilities to study the microplastic loading of their sludge and waste chemicals. Information from multiple facilities will provide more realistic data and will give results based on types of equipment and their corresponding brands to see the effectiveness of equipment across the industry.

The results of research at full scale WWTP equipment will allow facilities to determine whether the equipment that exists at their facility is already capable of removing a certain amount of microplastic concentration or whether the facility will require more removal solutions and if so which will be the most effective and feasible for that individual plant. More research into the disposal methods of the sludge containing individual microplastics and separated individual microplastics is required to determine whether the microplastics must be disposed of through incineration, sent to landfill or whether the materials can still be repurposed or recycled in some manner.

4.0 Domestic Solutions

[4]

4.1 Evaluation Criteria for Domestic Technologies

It has been identified that washing machine effluent is a major source of microplastics as a result of synthetic fibres in clothing releasing microplastics due to friction and abrasion during the washing process. The goal of a domestic product would be to provide a simple, affordable solution to a consumer who is looking to reduce their microplastic output. The three main factors researched for these products includes the ability to remove microplastics for the water, the cost to the consumer and the simplicity of operation and maintenance.

There are several existing products available that are designed to collect and filter microplastics from washing machines and washing machine effluents. It should be noted that the data regarding the amount of microplastic removal was provided by the company selling the products. No data was provided from external sources on the efficiency of the product; therefore, company bias could be present.

The set criteria for the domestic technologies are efficiency/effectiveness, simplicity of operation, environmental impact, technology readiness level and product availability.

4.2 Commercially Available Domestic Solutions

4.2.1 Cora Ball

The Cora Ball is a product produced by Cora Ball company which can be seen in Figure 37. The Cora Ball is added to the washing machine and the hoops within the design are intended to catch and collect microfibres. After the washing cycle is complete, the Cora Ball is removed from the washing along with the clothes and can be reused for several years before needing to be replaced. The microfibres can be removed through the use of tweezers. Once the consumer is done with the product, the company offers recycling options for the ball to ensure the product does not end up in the landfill. The Vermont-based company is in the start-up phase; therefore, the product availability could be limited.

Figure 37: Image of the Cora Ball provided by the producing company [148].

The Cora Ball is estimated to catch 35% of microfibres per load by particle count, based on in-house testing. A study by the Marina Pollution Bulletin, the Rochman Laboratory at the University of Toronto and the Ocean Conservatory determined that the Cora Ball removed microfibres which were 1.2 mm (1200 µm) or larger and removed approximately 26% of microfibres by count per load [149].

The product is simple to use as the user simply places it in the washing machine basin with their load of washing. The unit can be hard to maintain as the user must remove the entangled fibre by hand. Reviews on the company's website suggest that the only way users can clean the product is through the use of fine tweezers, which is time consuming. This would be a deterrent to some consumers and as a result the product may not be used as frequently due to the labour required.

The cost of the product is $37.99 USD which is approximately $50 CAD before tax, shipping and duty. The product can be purchased online but is also sold at small retail locations throughout the world with the majority of retailers based in the USA, Australia and Canada. Cost of product in retail stores may vary and the product is not currently sold in any major retail stores.

The product is marketed to remove microfibres from the washing machine. However, based on the reviews on the website for the product, most users state using it for pet hair over the intention removing microplastics. The product should be tested further by testing microplastic concentrations, sizes and shapes from the effluent of a washing machine both with and without the product. The tests are recommended to be completed by an external party to determine the efficiency of the product in terms of quantity and size of microplastic removal without potential biases.

4.2.2 Filtrol 160

Filtrol 160 is a patented reusable filter by the company Wexco Environmental and is produced in Minnesota, USA. The device is attached to the discharge hose of a washing machine and fixed to the wall. The unit contains a filter bag that is permeable to water but is designed to catch fibres and particles from clothing. The Fitrol 160 system can be seen in Figure 38.

Figure 38: Filtrol 160 system installed on a domestic washing machine [150].

No information was found on the percent of microplastics removed from water streams. The manufacturer has not listed microplastic filtration as one of the product capabilities but a general filtration of small particles including fibres, hair, sand, fur and nylon. The product is primarily marketed as a solution to better preserve plumbing and septic systems by reducing clogging in pipes. The website does not contain any marketing focused on the reduction of pollution or minimizing microplastics.

The simplicity of the maintenance for the product varies based on the source. The installation and maintenance of the filter is quoted to be minimal and easy by the company producing the product. However, product reviews suggest that the installation is not difficult but must be done correctly in the first attempt to avoid damaging the washing machine hose. Tutorials and customer service support is available for the installation of the product. The filter is required to be emptied when visibly full and requires replacement every one to three years.

The purchased product includes a canister with an O-ring, a lid, a wall bracket, a filter bag and the required hosing and pieces needed for assembly. The initial system costs $139.99 USD which is approximately $185 CAD before tax, shipping or duty. Replacement filters can be purchased for $13 USD ($17 CAD) each and replacement parts can be purchased from the company website. The product cannot be purchased in store, only through the product website.

4.2.3 Lint LUV-R

Lint LUV-R is external filter system produced by Environmental Enhancements who are based in Nova Scotia, Canada. The setup of the product can be seen in Figure 39. The product is attached to the effluent stream of the washing machine. The product uses a metal mesh filter to capture small particles from the washing machine effluent stream.

Figure 39: Lint LUV-R installed on a domestic washing machine [151].

The product is not able to filter extremely small particle sizes from the effluent as the filter contains hole sizes of 0.0625 inches in diameter which is the equivalent of 1587.5 µm (1.59 mm). The product is made from stainless-steel filter and is designed to be reusable. Cleaning is required every three weeks depending on washing frequency and filters are reusable. A 45 cm clearance above the product is required to ensure the filter can be removed and cleaned efficiently. A study by the Marina Pollution Bulletin, the Rochman Laboratory at the University of Toronto and the Ocean Conservatory reported that 87% of microfibres were captured per load by particle count which were on average 0.4 mm (400 µm) or larger in length [149].

The marketing of the product is focused on protecting plumbing and septic systems from becoming clogged as well as the removal of microplastic fibres from entering the environment. The product comes with a five-year warranty and the company claims the installation process is simple. The installation requirements were not provided. However, for customers located Halifax, Nova Scotia the product can be installed by a professional. This may suggest that the product should be installed by a trained professional, which should be considered when purchasing.

The product does not require replacement filters meaning that the product will cost the consumer one payment of approximately $155 CAD before shipping and tax. The product can be purchased online directly from the production company or purchased in two retail locations: Home Hardware in Upper Tantallon, Nova Scotia or Ferguson Plumbing Supplies in the USA.

4.2.4 Guppyfriend

The Guppyfriend is a washing bag that is produced by a German company of the same name. The bag is 74 by 50 cm large and is filled with clothes, closed and placed in the washing machine. The website for the product claims that the bag can catch microparticles as small as 15 µm in size. The product can be seen in Figure 40.

Figure 40: Example of Guppyfriend bag with clothes in it [152].

The product is marketed to reduce microplastic pollution by reducing the fibre shredding from the clothes and catches the fibres that do break off. The product can be used several times before cleaning is required. The particles and fibre will collect in the corner of the bag and can be removed by hand and disposed of in the garbage. The product description claims that the bag itself will not shed due to the material it is comprised of which is untreated polyamide 6.6. The bag is designed to be recyclable if the zipper is removed. The bag is limited in size and might require more than one bag to wash all clothes in a load. The bag costs $30 USD or approximately $40 CAD before tax, duty or shipping. The bag can only be used at a maximum temperature of 40 °C for an hour and a half at a maximum speed of 800 rpm [153] [152]. The product can be purchased directly from the company's website or from the retailer Patagonia.

Guppyfriend contracted several external companies to test the effectiveness of the product at removing microplastics from the washing machine effluent stream. Guppyfriend hired German Textile Research Institute, Fraunhofer Institute, and University of California through the Patagonia research program. It should be noted that as the tests were procured by the company, biases may exist in the results. Exact results were only given by one of the institutes which stated that the use of the bag reduced the amount of breaking fibres for partly synthetic clothes by 79% and completely synthetic by 86%. It was also noted that nanoparticles could penetrate through the bag.

4.2.5 Planet Care

PlanetCare filters are an external filter that is mounted to the wall or washing machine. The company that produces it is PlanetCare and is based in Slovenia. The company produces filters for both domestic washing machines as well as industrial/municipal and commercial applications. The thickness and the length of the fibres from the clothes that are caught by the filter primarily depend on the structure and composition of the textile but also on washing and drying conditions (i.e. machine used, program, temperature, detergent, load etc.). The company reported that the filter will catch 90% of fibres that are 50 µm to 5 mm in size [154]. The filter has multiple international patents currently pending for the technology. An example of the domestic solution can be seen in Figure 41.

Figure 41: Example of PlanetCare filter attached to domestic washing machine [155].

The commercial solution designs are intended for use in hotels, hospitals, marinas and laundromats. The commercial solution is an external unit requires no energy and does not add significantly to the complexity and management system of the machine. The filter will require regular maintenance which should be considered when a business decides to implement the solution.

The filters contain cartridges that need to be replaced monthly or after every 20 washes which provides a regular cost to the consumer. The user orders a set of cartridges with the filter. After they have all been used, the user is to pack them up and ship them back and order new replacement filters. PlanetCare guarantees that all spent filters will be reused and disposed in the most environmentally sound way, hence why they request the filters be returned. The cartridges should not be cleaned by the user as the fibres cannot be separated by hand from the filtering media. PlanetCare takes the returned filters and disassembles them to remove the media containing the fibres. The company will then recycle as much of the used cartridge as possible and return to consumers while the fibre removed are sent to incineration for energy production.

PlanetCare offers a membership program that ships within the USA and EU. The membership comes with required cartridges and all filter components. The company's website does not mention shipping to Canada on the membership plan that was available. The filters may also be purchased outright with extra filters and extra filters can be ordered over time. The base filter can be initially ordered with cartridges. The breakdown of costs related to the membership program and the initial filter and cartridges purchased outright can be seen in Table 24.

Table 24: Summary of PlanetCare filter costs.

Item	Initial Cost (CAD)	Approximate Monthly Cost (CAD)	Notes
Filter with 7 cartridges	$192.07	$27.44	Does not include duty. Tax and shipping included. Confirmed that this order can be shipped to Canada.
Filter with 13 cartridges	$257.80	$21.48	Does not include duty. Tax and shipping included. Confirmed that this order can be shipped to Canada.
Refill pack of 6 cartridges	$126.34	$21.06	Does not include duty. Tax and shipping included. Confirmed that this order can be shipped to Canada. Assumes the filter has already been purchased.
Refill pack of 12 cartridges	$184.77	$15.40	Does not include duty. Tax and shipping included. Confirmed that this order can be shipped to Canada. Assumes the filter has already been purchased.
Membership Monthly Cost	$22.56	$22.56	Includes shipping cost to USA and tax. Assumed the shipping cost to USA would be approximately the same to Canada. Duty not included. Comes with filter in first month with 7 months' worth of cartridges.

4.3 Domestic Solutions Evaluation

4.3.1 Criteria Weighting and Justification for Domestic Solutions

Energy consumption and compatibility with process were not included in the matrix as none of the product consume energy and all products are designed to operate with any washing machine. Legal issues/regulatory approval is commented on but not included in the matrix. The justification of the ranking of the domestic solutions can be seen in Table 25: Justification of weighting and ranking of criteria for domestic solutions.

Table 25: Justification of weighting and ranking of criteria for domestic solutions.

Criteria	Weight	Rank 1	Rank 3	Rank 5
Efficiency/Effectiveness	15	Amount of fibres removed: 30% or less Size of fibre removed: 1-5 mm	Amount of fibres removed: 30- 80% Size of fibre removed: 200 µm to 1 mm	Amount of fibres removed: 80% or more Size of fibrfe removed: 20 to 200 µm
Simplicity of Operation	20	Installation: Difficult or requires professional installation. Maintenance of Filter: Filter difficult to maintain, requires significant maintenance time.	Installation: Somewhat difficult but does not require professional installation Maintenance of Filter: Filter somewhat difficult to maintain, requires some maintenance time.	Installation: Easy installation of the filter, can be easily installed by user. Maintenance of Filter: Filter is easy to maintain, requires little maintenance time.
Environmental Impact	20	Product must be thrown in the garbage. Fibres removed from device are intended for landfill.	Components of the product can be recycled. Fibres removed from device are intended for landfill. Options for recycling exist.	All components of the product can be recycled. Fibres removed from device are intended for recycling. Options for recycling exist and easy for consumer to utilize.
Technology Readiness Level	15	Levels 1-4	Levels 5-6	Level 7-9
Product Availability	10	The product is not available online. Product is only available in local retail stores.	The product is available online in limited countries. Product is available in small or local retail locations.	The product is available internationally online. Product can be purchased at major retailers.
Cost	20	Products will be ranked from 1 to 5 from high to low cost for the consumer.		

4.3.2 Summary of Domestic Solutions

Table 26: Summary of domestic solutions based on evaluation matrix criteria.

Criteria	Cora Ball	Filtrol 160	Lint LUV-R	Guppy Friend	Planet Care
Efficiency/ Effectiveness	26 to 35% of microfibres per captured per load of laundry. Microfibre count done by count. Fibre size captured was 1.2 mm or larger.	No quoted numbers. No studies conducted with this filter. Filter company does claim to remove particles as small as sand, concrete dust, fur and nylon. Dimensions unknown.	87% of microfibres per captured per load of laundry. Microfibre count done by count. Fibre size captured was 400 µm or larger.	90% of microfibres captured. Fibre size captured was 50 µm or larger. Results were not provided by independent study but by company producing product.	90% of fibres captured. Fibre size captured was 50 µm to 5 mm in size. Results were not provided by independent study but by company producing product.
Simplicity of Operation	The product is easy to use but has been reported by users to be difficult to maintain. The hair and fibres caught by the product must be removed by hand by the consumer. One review by a user quoted that small tweezers were required to properly clean product.	The product is stated to be easy to install and operates automatically once installed. The installation will include the connection of the effluent line of the washing machine to the filter which may be difficult in some situations. The filter bag needs to be emptied once visibly full and needs to be replaced every one to three years. Emptying of the filter bag involves the removal of the lid and dumping of the bag.	The product is stated to be easy to and operates automatically once installed. The installation will include the connection of the effluent line of the washing machine to the filter. The filter basket needs to be emptied once visibly full. Emptying of the filter bag involves the removal of the lid. There may be difficulty in the removal of fibres from the metal holes. Removal of the basket requires clearance above filter.	The product is simple to use but has been reported to be difficult to clean by reviewers of the product. The product involves adding clothes to the bag, sealing it, running the cycle and once done remove the clothes and collect the fibres in the corners of the bag. One reviewer noted that the fibre collects around the zipper which can be difficult to remove and may require tweezers.	The product is stated to be easy to install and operates automatically once installed. The installation will include the connection of the effluent line of the washing machine to the filter which may be difficult in some situations. Removal of the cartridge requires clearance above filter. The cartridges do not need to be cleaned by the user but shipped back to the company.

Criteria	Cora Ball	Filtrol 160	Lint LUV-R	Guppy Friend	Planet Care
Environmental Impact	Product can be recycled if shipped back to company following use. No recommendations on method of disposal of fibres once removed. Product shipped from USA.	No recommendations made on the disposal of filter once requiring disposal. Recommends throwing the collected fibres in the trash. Product shipped from USA.	No recommendations made on the disposal of filter once requiring disposal. No recommendations made on the disposal of fibres once removed. Product shipped from within Canada.	Product can be fully recycled by user or if returned to the company. Recommends throwing the collected fibres in the trash. Product shipped from USA.	Product can be fully recycled by the company, recycling of the returned cartridges is done by the company. Waste collected is sent to incineration for energy production (form of recycling in EU). Product must be shipped from Europe.
Technology Readiness Level	TRL 7 Product is being produced and sold internationally. Company is limited to selling product online and at small retail locations.	TRL 7 Product is being produced and sold internationally. Company is limited to selling product online and at small retail locations.	TRL 7 Product is being produced and sold internationally. Company is limited to selling product online and at small retail locations.	TRL 7 Product is being produced and sold in Canada and USA. Company is limited to selling product online and at Patagonia.	TRL 7 Product is being produced and sold internationally.
Legal Issues/ Regulatory Approval	There are currently patents pending for the product.	Technology is patented (USA and Canada).	No patents found for product.	Technology is patented (USA and Canada).	There are currently patents pending internationally.

Criteria	Cora Ball	Filtrol 160	Lint LUV-R	Guppy Friend	Planet Care
Product Availability	Available internationally for purchase online. Available for purchase in some small retail locations throughout USA, Canada and Australia.	Available internationally for purchase online.	Available in Canada and the USA for purchase online. Can be found in small retail stores located in Nova Scotia, Canada and the USA.	Available internationally for purchase online. Can be found in Patagonia retail stores located within North America.	Available internationally for outright purchase online. Membership available in EU, Canada and USA. Not available in retail locations.
Cost	$50 CAD before tax, shipping or duty $67.42 CAD before tax and duty for one Cora Ball (includes shipping to Canada) Tax will vary with region that item is being shipped to.	For initial purchase: $185 CAD before tax, shipping and duty $250.49 CAD after shipping (international) and US tax (does not include duty or Canadian tax) Tax will vary depending on the region that item is being shipped to.	$155 CAD before shipping and tax Product is shipped from Eastern Canada. Shipping costs can be found on their website and vary with region. Tax will vary depending on the region that item is being shipped to.	$40 CAD before shipping, tax and duty $52.83 CAD before tax and duty (includes international shipping) Tax will vary depending on the region that item is being shipped to.	Varies with time, cost per month varies from $21.48 to $22.56 CAD a month including shipping and tax (not including duty)

4.3.3 Evaluation Matrix for Domestic Solutions

The evaluation matrix for the domestic solutions can be seen in Table 27.

Table 27: Weighted evaluation matrix for domestic solutions

Criteria	Weight	Cora Ball	Filtrol 160	Lint LUV-R	Guppy Friend	Planet Care
Efficiency/Effectiveness	15	1	1	3	5	5
Simplicity of Operation	20	3	3	3	3	3
Environmental Impact	20	3	3	3	3	5
Technology Readiness Level	15	5	5	5	5	5
Product Availability	10	3	4	3	5	3
Cost	20	4	2	3	5	1
Total	**100**	**320**	**290**	**330**	**420**	**360**

Based on the results, the Guppyfriend is the most ideal product based on the weighting of the criteria for household use. In terms of cost it was the cheapest and easiest to use. The cleaning of the product was not the easiest relative to the other products as outlined in Table 26. However, is easy to procure and can be easily implemented into everyday life of the consumer.

The second product was the PlanetCare filter which ranked above the other filters of similar style/function (Filtrol 160 and Lint LUV-R). The filters although of the same design, the PlanetCare version did not involve intense cleaning by the consumer and was available all across the world. It did rank the lowest in cost as it was the only product of all of them that required frequent reoccurring purchases in order to properly maintain. The product was also the only product that offered industrial solutions for laundry machines that may not be located in a domestic setting. For commercial industries PlanetCare would be the most ideal product as it was the only product with the option of commercial scale products.

4.4 Domestic Solutions Recommendations

It is recommended that further testing be conducted on the domestic solutions summarized in Table 26 to determine more accurate and comparable efficiencies for microplastic removal. Based on the microplastic loading, the implementation of regulations in regard to the amount of microplastics a household can discharge should be explored. Regulation and enforcement are likely a necessary step before the widespread use of domestic solutions will be accepted and appropriately implemented by the public.

Although the products are ranked, based on the research, a combination of products would provide the most effective solution and it is recommended that the products such as the Cora Ball, Guppy Friend and one of the fixed filters be combined to maximize the amount of microplastics removed for the washing machine. To reduce microplastics from laundry it is recommended that fabric softener be used, lower the rpm used and to reduce the amount of synthetic clothing worn.

4.5 Current Studies in Domestic Solutions

4.5.1 Washing Machine Discharge Filter – Rochman Laboratory

A study is being conducted on 100 households in Parry Sound, Ontario located on the shore of Lake Huron's Georgian Bay. The households installed filters on their washing machines designed to reduce the amount of microplastics from synthetic fabrics that enter the Great Lakes system from domestic washing machines [156]. The initiative is part of a joint research project with a research team from the Department of Ecology & Evolutionary Biology at the University of Toronto and the local environmental group Georgian Bay Fever.

This project aims to evaluate the effectiveness of the filters and will allow the team to gauge consumer compliance by studying how such filters will work in real people's homes to assess whether the filters will be used properly and be changed when required. The study will be conducted over a two-year period to ensure the effectiveness of the and test the water in the town's WWTP before and after the filters are installed to assess the level of microplastics filtered from the water over time.

The filters used in the project are sourced from a company in Minnesota and cost $150 per filter. They are reported to remove approximately 90% of microfibres [149]. A Canadian made alternative to these filters is available from the company Environmental Enhancements who produce the "Lint LUV-R" washing machine discharge filter [151].

5.0 Recommendations

[4]

5.1 Detection of Microplastics

5.1.1 Detection in Water

The next key step in microplastic research is the development and standardization of the sampling, analysis and classification for microplastics of various colours, shapes and sizes.

Based on the research conducted for this report, there are no standard methods of testing for microplastic detection, size or type. According to researchers at the Rochman Laboratory at the University of Toronto, it is common practice for laboratories to share methods in attempt to create some consistencies between results, but this is not a requirement. The methods used for sampling and analysis are not regulated and therefore any method can be chosen by a researcher, which results in an inability to compare results between studies that utilize different methods.

Lack of consistency in testing methods can cause studies using different methods for testing to have different standard error in equipment used, which could result in a larger variations in results making it difficult to compare different studies. To avoid inconsistencies related to methods, a standard model of the type of equipment used, methods of sampling, detection and measuring as well as the required sampling conditions should be developed and regulated between laboratories to ensure that any future inconsistencies in data cannot be attributed to how samples were collected or analyzed.

It should be noted that separate tests may be required for different sizes of microplastics. The detection of various particles sizes may differ as microplastics are classified as particles smaller than 5 mm but have been detected as small as 20 µm. It is believed that microplastics less than 20 µm exist but are not detectable using the methods used for 20 µm or greater. The Rochman Laboratory stated that the lowest size detectable at their laboratory was 100 µm. This indicates that different size ranges will require different sampling and analysis methods to be developed and microplastics under 100 µm in size will require specialized testing. In addition, plastic particles that are in the nanometer range measurements are classified as nanoplastics and are categorized differently and will require unique sampling and analysis.

Without standardization of sampling and analysis methods the study of microplastics will be limited as the results will be biased to the methods with the lowest error and more assumptions made during analysis.

5.1.2 Detection in Sludge

Several sources indicated throughout the report stated there was no concentration of microplastics in the effluent of WWTPs. This may provide indication that the microplastics were removed with the organic content that was treated and either sent for landfill or formed into sludge which was sent to be spread on agricultural fields as fertilizer.

It is recommended that sampling and testing to determine microplastic concentrations in the sludge be developed and standardized. This will provide insight into whether this sludge is acting as alternative entry for microplastics into natural water streams. Several options exist for the disposal of sludge including landfill, spreading onto fields and mine reclamation. The concern is that after the sludge is spread onto the field or used for an alternative purpose there is the risk of microplastics re-entering the environment and water supply. If the sludge is applied to land during the dry season, it will dry out and microplastic particles may be picked up and transported by the wind before being ultimately settling in lakes and rivers. Microplastics can also be released back into the water system if the area is exposed to a form of watering (i.e. rain or irrigation) and the flow of the water draining from the area will result in the microplastics draining into natural bodies of water.

5.2 Particle Size: Microplastics vs. Nanoplastics

More work needs to be done on the testing, capturing and removal of nanoplastics (less than 20 µm or anything measured in nano scale measurements). Due to the incredibly small size of particle, current methods of testing cannot effectively detect the presence of particles less than 20 µm in size. This means a test must be established for the testing of not only microplastics but nanoplastics.

An article reported that WWTPs generally remove 95% of microplastics and fibres that are larger than 50 µm [20]. Results in a study indicated that the majority of microplastics when washing clothing were assumed to be 5 to 15 µm in size. This indicates the remaining amount of microplastics entering the water course are likely to be under 50 µm or are to be sourced from sources such as fragments of plastics from litter, cigarette butts, film from plastic bags, tire dust and production pellets from facilities that are along the Great Lake shorelines. In addition, it should be noted that this cannot properly represent the Great Lakes system as this study was conducted in Finland.

This means that the remaining plastics in those streams would be nanoplastics. There are several reasons why these particles are not captured in the current processes. First, particles which are under 100 µm in size have increased cohesion of particles and as a result the particles cannot flow under gravity and will remain in suspension. This means that the particles will not settle and remain in the water column passing the secondary treatment methods. The particles are also difficult to flocculate. This is due to the varying chemical makeup of the plastics and the hundreds of kinds of plastics and possible absorbed material on the plastics that could possibly be found in the streams. There are a majority of plastics found that could be targeted but this may require a larger range of chemicals to be added.

Lastly, the current plants are not typically designed to handle items in suspension that are extremely small due to the high operating costs associated with their removal. At the Kingston Ravensview WWTP, the plant is indicated to have a 20 µm screen. The removal of very small particles would involve more pumps to operate at higher pressures as the screens/filters would be extremely small and capacities are very large. This would result in extremely high utility costs to run these pumps. Once the toxicity of the nanoplastics is determined and testing is standardized, an evaluation of the additional cost to remove the nanoplastics compared to the removal efficiencies is recommended.

5.3 Toxicity of Microplastics and Nanoplastics

Further studies are required to determine the impact of microplastics and nanoplastics on human health and the environment. There is significant variability in the types of the polymers which make up the microplastics and nanoplastics found in WWTP streams and bodies of water within Canada. There is also a significant number of additives such as pharmaceutical residues, cosmetic products and hygiene products in which the impact on human and environmental health is unknown. It should be investigated whether these additive chemicals can adhere to microplastics and if so whether the additives or the actual microplastic particle is what causes impact on ecology and human health.

According to the Rochman Laboratory, the large variability in microplastics regarding their types of polymers, colours, sizes, shapes and the potential additives that may adhere to the particles may be the result of the current inconclusive results related to whether microplastics are toxic. Research taking into account all the variabilities regarding microplastics needs to be completed and a number of studies from established health institutions must make a robust consensus on the toxicity of microplastics.

If the microplastics are shown to be harmful to human health or the environment, further research will be required into the concentration of microplastics present in water sources and bodies of water and classified based on developed standards. Investigation into the sources of the microplastics will also be required so methods to mitigate microplastic entry into water streams can be developed. Following determination of amounts of microplastic, feasible removal technologies for current water streams will need to be further investigated. This report provided preliminary investigation, but solutions may be better evaluated when the above information becomes available.

Further investigation will be required into the impact of nanoplastics on the human body. According to the Rochman Laboratory, there is presently concern that plastic particles are on a nano scale may be able to enter bloodstreams and cells and cause impact to human or animal health on the cellular level. Research will be required to determine whether nanoplastics are entering the bloodstream and are entering cells. If it is determined this is the case, it will be required that additional research be done to determine the impact of this on the health of the body and the cells both on short- and long-term timelines.

5.4 Recommendations for Regulation Follow Up

The Canadian federal and Ontario provincial governments have presently launched studies into microplastic pollution but should look to regulate the sampling and analyzing of microplastics in both fresh and saltwater to ensure the results of research being done are consistent.

If microplastics are found to be harmful and must be removed from water, the federal and provincial governments will be required to determine and regulate the acceptable amount of microplastic allowed in marine environment, agricultural water, WWTP effluents and drinking water. The government will also be required to establish sampling and testing methods that are required by regulated facilities (i.e. WTP, WWTPs). All water requirement guidelines will require updating to reflect changes made.

If microplastics are considered to be harmful, it is recommended that the federal and provincial governments launch formal research into the health impact and the actions that may be taken by the general public to counteract the impact of already consumed microplastics and methods of filtering and avoiding microplastic consumption at a domestic level. In addition, governing bodies should launch investigations into the main sources of the microplastics and regulate concentrations of microplastic at these sources. Controlling microplastics at the source by imposing regulations on manufacturers to find alternatives to plastics or find alternate production methods to significantly lower their microplastic loading concentration would likely be an unpopular but effective solution.

5.5 Industrial/Municipal Solutions

5.5.1 Water Treatment

Once a method is determined and approved by governing bodies, and it is confirmed by health authorities that microplastics are harmful, facilities responsible for the treatment of water at the WW or drinking water level should conduct testing of microplastics levels in the influent and effluent of drinking water streams, WW streams and bodies of water.

This will give insight into the distribution of microplastic in various areas of the plant and provide general information into the effectiveness of existing plants. If levels are acceptable, further research into removal technologies will not be required and research into the sludge leaving the plant should be conducted.

If levels are unacceptable further research will be needed to determine level of microplastics at various levels of treatment plants and determine which equipment is the most effective at microplastic removal as well as how different equipment may be modified to improve filtration. Testing should be done at the influent, following primary treatment, secondary treatment, if available at facility tertiary treatment and the effluent of the plant. This will help narrow the most effective removal location of the plant and the equipment in that section of the plant may be further investigated for effectiveness.

In addition, more research will be required into the most effective methods of microplastic removal or destruction for industrial/municipal plants once more information on concentrations of microplastics, types of microplastics and what about the microplastics is harmful are known. Outlined research in this report provides preliminary information on filtration solutions based on large assumptions. The results and effectiveness of filtration solutions may vary without the assumptions that are in place in this report. This means that once more information on microplastics is available more detailed research will be required to determine feasibility of the solutions, including from operational and economical standpoints.

5.5.2 Sludge Treatment

Sludge from WWTPs is sent to a landfill, mine reclamation or is spread on farmers’ fields to be used as fertilizer. The test on microplastic concentrations in sludge will provide indication of whether sludge being spread on farmers' fields is a source of microplastics and will provide regulatory bodies insight into whether this practice should be terminated to avoid the spreading of microplastics. More research is required into the impact of microplastic in sludge in landfills and whether this is another source of microplastics into water. The results of this research will be an indicator on whether treatment to removal microplastics from sludge is required prior to disposal.

If treatment is required, it is recommended that removal technologies be investigated to determine whether waste treatment plants will be able to effectively remove microplastics from the sludge. Proper disposal methods for microplastics in sludge and on their own once separated from sludge or water will need to be further investigated.

5.6 Domestic Solutions

It is recommended that further testing be done on domestic solutions summarized in Table 26 to determine more accurate and comparable efficiencies for microplastic removal. Currently removal efficiencies are primarily given by the company producing and selling the product. Third party studies are required to determine actual removal efficiencies of the technologies for microplastics based on particle size and shape. This will give consumers more accurate information in order to select product most ideal for their needs.

It is recommended that before the widespread implementation of domestic solutions, the health effects of microplastics and the average concentration of microplastics being discharged from households should be determined. Regulation and enforcement are likely a necessary step before the use of domestic solutions will be accepted and appropriately implemented by the public.

5.7 Next Recommended Steps in Project

It is recommended that the following be investigated to continue the project:

- Conduct research into sampling and testing methods.
- Conduct research to determine whether microplastics are harmful to human health or the environment.
- Investigate proper disposal methods and destruction in-situ or after removal of microplastics and microfibres to avoid re-entry into water streams.
- Investigate whether WWTP are effective in removing microplastics and if they are, how to deal with the microplastics within the sludge. Determine whether microplastics are leaching into water systems through the spreading of sludge of fields or through landfill systems.
- If sludge cannot be sent to agricultural use due to microplastic concentration the sludge will be required to be sent for incineration or to landfill. It is recommended that the impact of this change be further explored. Key areas required in the investigation would include exploring ways to remove microplastics from sludge, the impact to the farmers who utilize the sludge, the economics of the WWTPs who sell the sludge and the capacities of the landfills.

Appendix A – Description of Microplastic Testing Methods

The testing of microplastics is not currently standardized and each study may combine several various methods. Common methods used to detect and identify microplastics include Raman Spectroscopy, Light/ Scanning Electron Microscopy, Fourier Transform Infrared Spectroscopy, focal plan array-based systems and culture counters. These specific methods which are used within laboratories testing procedures are described below.

Raman Spectroscopy

The method is commonly used for microscopic inspection and has a spatial resolution in the order of 0.5-1 µm; however, this technique is typically used to identify microplastic particles greater than 20 µm in size [157] [158]. This non-destructive technique uses light-scattering to detect a particles vibrational, rotational and low-frequency modes of molecules [159]. Raman Spectroscopy can determine a particle's chemical structure and identify, phase and polymorphism, as well as contamination and impurity [158]. A Raman spectrum is produced, peaks in the generated plot correspond to specific molecular bonds [158]. The Raman Spectroscopy imaging system is shown in Figure 42.

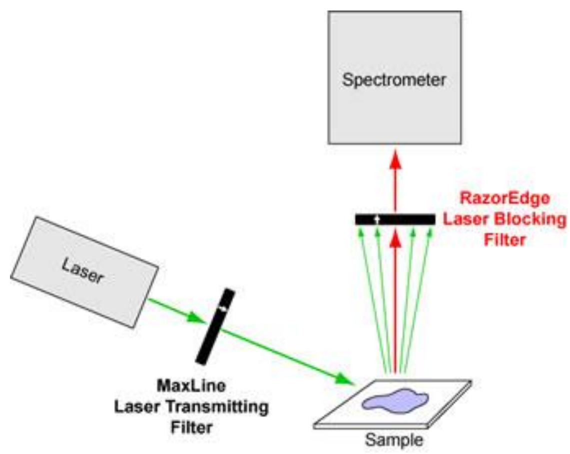


Figure 42: Standard Raman spectroscopy schematic [157].

Light Microscopy

Light microscope is a technology which augments the size of the sample in order to inspect small particles and fine details. A magnified image of the sample is seen through the eyepiece due to the arrangement of a series of convex lenses [160]. Microplastic identification within samples typically requires 4.5x magnification in order to accurately identify its type, shape and color [160]. This method has a high source of human error as contaminants such as cotton fibres, wool fibres and Styrofoam are often mistaken as microplastics [161]. This method also requires fine filters collect the miniscule particles from the water stream, if the water source contains a high concentration of suspended solids this technique may be difficult to isolate and identify the microplastics.

Scanning Electron Microscopy

Scanning Electron Microscopy is capable of assessing areas from 1 cm to 5 µm and can achieve a magnification ranging from 20X to 30,000 X. The microscope scans the surface of a sample with an electron gun which delivers a focused beam of high-energy electrons [162]. Signals are then produced which provide information on the particle's chemical composition, morphology, crystalline structure and material orientation [162]. This technology is also capable of producing a two-dimensional image which demonstrates the spatial variation of the particle's properties [162]. A diagram depicting a typical scanning electron microscope is displayed in Figure 43.

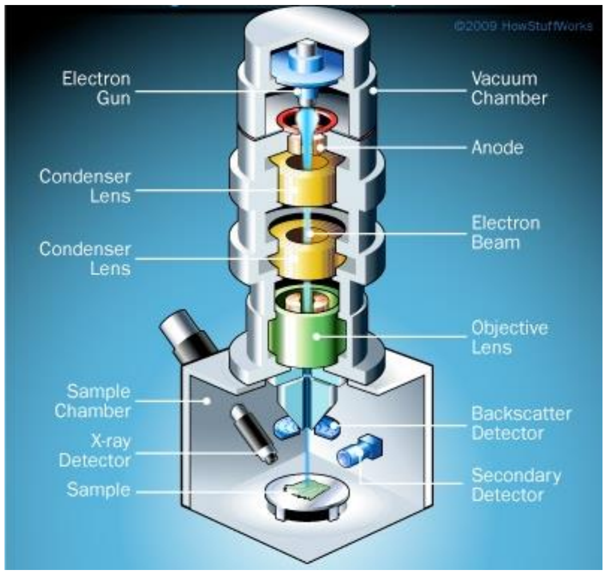


Figure 43: Schematic of scanning electron microscope [163].

Fourier Transform Infrared Spectroscopy

Fourier Transform Infrared Spectroscopy is commonly referred to as Fourier transform infrared (FTIR). This technique determines the infrared spectrum of absorption, emission, photoconductivity or Raman scattering of the sample based on the wavelengths absorbed [164]. The information regarding the infrared absorption bands may then be applied to determine the particle's molecular components and structures within the analyzed sample.

Coulter Counter

The Coulter Counter principle was originally developed to quickly count blood cells using a method which measures the change in electrical conductivity [165]. This system can measure any particulate material which may be suspended in an electrolyte solution, including particles as small as 0.4 µm [165]. The system measures the impedance between two electrodes, one is placed within an aperture tube and the other outside the tube. Particles in low concentration which are suspended within the electrolyte solution may be detected and counted as they are passed through the aperture as they alter the resistance and therefore the voltage readings.

Appendix B – Description of Toronto, Kingston and Sarnia Wastewater Treatment Plant Processes

Ravensview Wastewater Treatment Plant – Kingston

The Ravensview WWTP in Kingston was selected as it was toured by the team and used as a basis for the report. The Ravensview Plant is one of three WWTPs in Kingston and has the largest capacity of the three. It has a rate capacity of 95 000 m^3 per day with a peak capacity of 193 000 m^3 per day as of 2017. The city of Kingston has an approximate population of 136 685 as of 2017. A schematic of the plant can be found below in Figure 44 [166]. The process contains preliminary, primary and secondary treatment followed by tertiary treatment designed for nutrient removal (phosphorus) and disinfection. The raw WW is fed into three 12 mm mechanical bar screens and then pumped through two aerated grit tanks. The water is then sent to primary treatment which consists of seven rectangular settling tanks and is directed by gravity to the Intermediate Primary Effluent Pump Station. Settled sludge and floatable scum is sent to an anerobic digester while the primary treated effluent water is sent for secondary treatment. [166]

Secondary treatment consists of an 11-cell biological aerated filter/reactor system. The biological aerated tank has water pumped through filter media in cone structures that catch particles in the water with a media depth of 3.5 m. Aeration allows aerobic microbes to break down dissolved organic contaminants and settled waste to be removed. The biological aerated filters contain a backwash system which sends the backwash back through the process. Any collected waste is then sent back through the aerated grit tanks. Following the filters, the water is sent for disinfection using sodium hypochlorite for chlorination before being returned to Lake Ontario. The plant contains tertiary system containing phosphorus removal where the three chemical feed pumps add alum in two storage tanks. [166] The plant contains sludge digesters which utilize anaerobic digestion and it contains two primary digesters, a secondary digester and one temperature phased anaerobic digester. The digester is used with centrifuges to prepare the sludge for disposal. The facility sends sludge to landfill or for agricultural use.

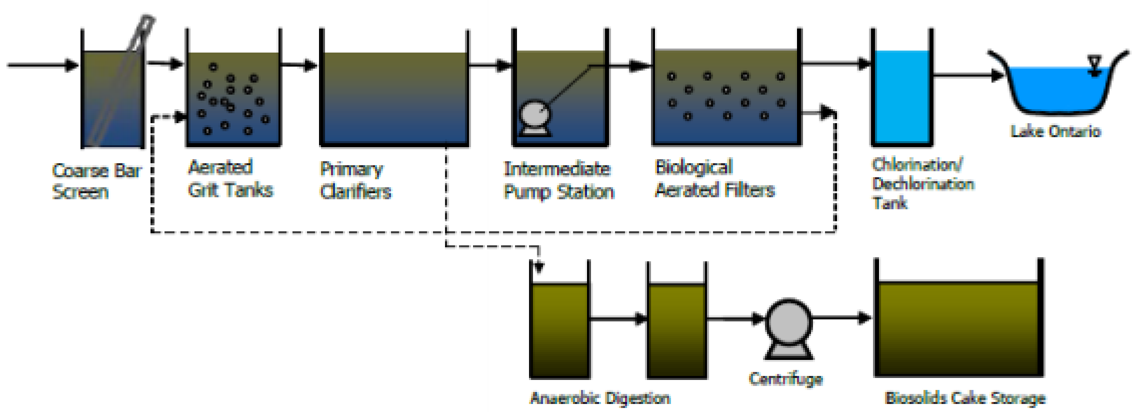


Figure 44: General schematic of the Ravensview WWTP [166].

Sarnia Sewage Treatment Plant

The Sarnia Sewage Treatment Plant has a daily capacity of 38 700 m^3 per day and services the domestic areas of Sarnia which has a population of approximately 72 000. The plant contains preliminary, primary, secondary and tertiary treatment along with sludge treatment processes. The primary and secondary treatment have capacities of 164 000 m^3 and 91 000 m^3 per day, respectively [167].

The preliminary treatment of the plant starts with two mechanical bar screens with 15 mm openings which each have a 164 000 m^3 per day capacity. Following the bar screens, the influent is sent for grit removal via two aerated grit tanks, two grit pumps, two grit conveyors and a grit classifier. In addition, the grit removal contains two air blowers which provide air supply to the grit and aeration systems. Following the grit aeration system there is primary treatment which consists of six clarifiers that contain sludge and scum collection equipment, four sludge pumps and two scum pumps. Primary treatment area also contains a flow splitting chamber which directs the primary effluent over a motorized weir gate to the aeration tanks in the secondary treatment areas. The peak time capacity of the splitting chamber is 91 000 m^3 per day and any storm water overflow is bypassed to the disinfection facility in the plant. [167]

The primary treated effluent water is pumped to secondary treatment where it undergoes biological treatment consisting of four CSTRs with recycle and fine bubble aeration, four air blowers each rate for capacities of 165 600 m^3 per day. The water is then sent to secondary sedimentation where it is treated in four secondary clarifiers that are equipped with sludge and scum collection equipment, and three sludge pumps. The plant uses sodium hypochlorite for disinfection and injects at the return activated sludge splitting chamber upstream of the aeration tanks. [167]

In addition, the plant contains tertiary treatment systems for phosphorus removal. The phosphorus removal treatment process involves the injection of alum or ferric chloride at the primary clarifier influent and the aeration tank effluent. In addition, phosphorus is treated through the injection of polymer at the primary clarifier influent. The disinfection system at the plant utilizes an Ultraviolet (UV) disinfection system consisting of two banks of lamps installed in a single channel. The treated effluent line from the UV system discharges to the Saint Clair River. [167]

The plant contains a sludge management system which consists of sludge dewatering through centrifugation, screw mixer, which is fed with the sludge and lime, a mechanical dryer and an odour control system. The treated sludge is stored onsite until it can be taken for disposal with a total plant capacity of 8 352 m^3 of storage. All sludge produced at the plant is sent for agricultural use and the existing process produces class A sludge through line stabilization meaning the sludge can be used for agricultural use on plants intended for human consumption. If sludge cannot be sent to agricultural use due to microplastic concentration in the future, the sludge will be required to be sent for incineration or to landfill. [167]

Ashbridges Bay Treatment Plant - Toronto

A Toronto WWTP was chosen since Toronto has the largest population in all of Canada and therefore WWTPs in the city will process a large amount of WW and will experience high volumes due to the large population of the city and the surrounding areas. The Ashbridges Bay Treatment Plant has the largest capacity of the four WWTPs in Toronto with an estimated capacity of 818 000 m^3 per day and services approximately 1.5 million people. The plant contains preliminary, primary, secondary, tertiary treatment and solids management. A schematic of the plant can be found below Figure 45.

In the preliminary treatment section of the plant there are ten aerated grit channels and eleven mechanical screens separated into two buildings. The plant, as of December 2018, was expected to add six mechanical screens and three aerated grit channels. The raw WW is sent through the screens which collect large materials that would otherwise impact plant operations. These are removed and sent to landfill. [168] Primary treatment occurs in primary clarification tanks where heavier solids are allowed to settle to the bottom of the tank and are removed by sludge sweepers. The floating solids in the tank are skimmed/scraped and pumped out. The plant contains 12 clarification tanks.

The effluent water of the process is sent to secondary treatment where it is first treated in aeration tanks through a biomass activated sludge process. The microorganisms naturally present in the WW breakdown organic material when in the presence of oxygen. Oxygen is supplied to 11 aeration tanks where the microbes will reduce the organic content of the water. The water is then sent to 11 large final clarification tanks where activated sludge settles out. Following the clarification tanks, the water is sent to 10 dissolved air flotation tanks where air and a thickening polymer (coagulant) are used to remove additional suspended solids in the water. The final effluent is treated with sodium hypochlorite to disinfect the effluent as required to meet environmental regulations. The final effluent is then discharged into Lake Ontario. [168]

Plant sludge is treated through anaerobic digestion to deactivate the sludge. The sludge is then conditioned and dewatered in 12 centrifuges in the plant. The sludge could be sent to landfill, mine reclamation, palettization, and third-party process stabilization of agricultural land application. As of 2018 no sludge was sent to landfill from the plant with all being repurposed. Sludge was identified by the Rochman Laboratory as a potential source of microplastics, because the microplastics may be removed from the water via current treatments and concentrated in the sludge. The repurposing of sludge may act as an entry point of microplastics into bodies of water.

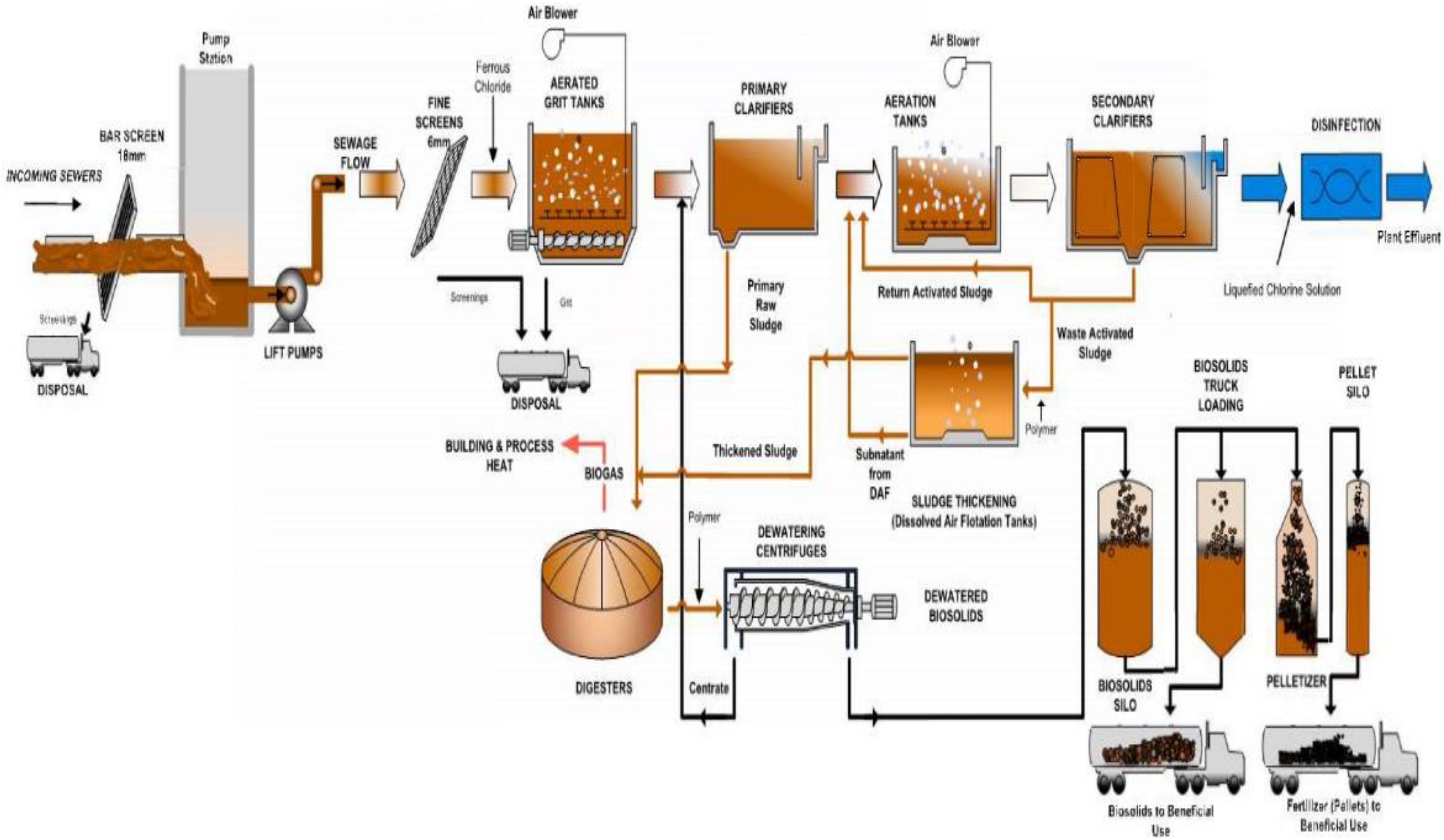


Figure 45: Schematic of the Toronto Ashbridges plant [168].

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