Microplastics removal techniques: challenges and opportunities of *in situ* field trials and a review of contemporary microplastics removal technologies

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Dalhousie University is located in Mi'kma'ki, the ancestral and unceded territory of the Mi'kmaq. Field work took place at the IISD Experimental Lakes Area, on the ancestral and unceded territory of the Anishinaabe Nation.

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Abstract

Plastic pollution is a growing environmental concern, especially when understanding how polymers interact within ecosystems. Thanks to their low density, durability, and low cost, plastics are used around the world and have become an unavoidable source of pollution. Microplastics (MPs) are difficult to analyze in nature due to variety in polymer, size (MPs are smaller than 0.5 cm but can include nanoplastics with sizes below 1μm), and ecosystem interactions. MPs have been found in almost every ecosystem on the globe, from the deep-sea floor to arctic snow. Particles can float and persist in aquatic environments due to their low density and durable characteristics. Common MP removal techniques have been identified, but there has been no strategy identified as "best," and little to no implementation on a global scale. This proof-of-concept study first explored the deployment of an aquatic MP filtration system at the IISD Experimental Lakes Area (ELA) in Northern Ontario. Results counted 89,800 MPs from brush samples taken over six weeks, most of which were polyethylene (PE). Time constraints limited the ability to analyse efficacy and retainment rate of the filter brushes, suggesting the need for further field experimentation. The second part of this study identified existing and emerging aquatic MP removal technologies using predetermined criteria. Entries were collected from Duke University's Plastic Pollution Prevention and Collection Inventory, managed by Duke University's Nicholas Institute and found through searches on Google, in peer-reviewed publications, and in patent databases. The results delivered 38 technologies, which were discussed in relation to larger industry trends like ideal aquatic medium, collection method, and use status. The findings suggest the need for monitoring existing removal systems, encouraging creators to move beyond initial invention, funding technological scalability, and further testing collection techniques.

List of Abbreviations

ALDFG	Abandoned, lost, or otherwise discarded fishing gear
BACI	Before-After-Control-Impact
BPA	bisphenol A
BFR	brominated flame retardants
H_2O_2	hydrogen peroxide
IISD-ELA	IISD Experimental Lakes Area
L373	Lake #373 at IISD-ELA
L378	Lake #378 at IISD-ELA
L379	Lake #379 at IISD-ELA
MaP(s)	macroplastic(s)
MegP(s)	megaplastic(s)
MP(s)	microplastic(s)
NP(s)	nanoplastic(s)
PE	polyethylene
PG	PolyGone Systems
PPE	personal protective equipment
PS	polystyrene
PET	polyethylene terephthalate
SUPs	single-use plastics
WWTP(s)	waste water treatment plant(s)

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Chapter 1: Introduction

Plastic pollution is a growing environmental concern, spreading among ecosystems and organisms in all corners of the world. Between 2016 and 2040, an estimated 710 million metric tons of plastic waste will enter aquatic and terrestrial environments, despite global action and policy to manage production, consumption, and disposal/recycling (Lau et al., 2020). The low density, durability, and low cost of plastics make them a ubiquitous material used around the world, and as a result, they have become an unavoidable source of pollution (Lv et al., 2021). Plastic pollution is difficult to analyse in nature due to a wide variety in polymer, particle size, degradation, and ecosystem interactions (Schnurr et al., 2018). Debris, ranging in size, have been found in almost every ecosystem on the globe (Galloway & Lewis, 2016) and can persist in aquatic environments for significant periods of time (Lv at al., 2021).

Plastic debris is a side effect of mass plastic production, over consumption, and improper disposal that began in the 1950s (Ritchie & Roser, 2018). In 2022, an estimated 400 million tons of plastic were produced globally, up significantly from 1.5 million tons in 1950 (Boyle & Örmeci, 2020; Plastics Europe, 2023). While plastic's imperviousness to water and versatility makes it a highly convenient material, a lack of degradation and a high demand for single-use products, especially in the aftermath of the COVID-19 pandemic, have led to high rates of environmental pollution (Boyle & Örmeci, 2020**)**. During this time, the use of personal protective equipment (PPE) was necessary to prevent virus transmission; Prata et al. (2020b) estimated the monthly PPE use at 129 billion face masks and 65 million gloves. Incorrect disposal of these items, along with others, like single use plastics (SUPs) from the food industry, were commonly littered and further contributed to global plastic pollution (Patrício Silva et al., 2021)

Plastic particles are divided into five categories by size: megaplastic (MegP; >50 cm), macroplastic (MaP; 5-50 cm), mesoplastic (0.5-5 cm), microplastic (MP; <0.5 cm) (Malankowska et al., 2021), and nanoplastic (NP). The exact size range of NPs is widely debated in the literature (Hartmann et al., 2019), although they often measure under 0.1 µm (Boyle & Örmeci, 2020). Sporadic scientific reports of small plastic particles in the ocean occurred as early as the 1970s, but notable research into their distribution and impacts is often cited to a 2004 study led by Richard Thompson (Thompson et al., 2004), which first coined the term "MP" (Rochman, 2018). While MegP and MaP remain a significant focus within pollution and waste research, many efforts have recently turned to MPs, which are far more difficult to identify, monitor, and collect.

1.1. MP pollution in freshwater systems

1.1.1. Imbalance of aquatic MP research

Most plastic pollution studies focus on marine ecosystems (Akdogan & Guven, 2019; Bellasi et al., 2020), largely due to how long research in this field has been ongoing for (Allen et al., 2022). Similarly, studies have long prioritized MegP and MaP, with recent shifts to focus on MPs; annual MP publications have increased from less than 50 annually in 2013 to more than 2000 in 2021 (Allen et al., 2022). A similar transition has occurred with recent studies expanding into freshwater and terrestrial environments (Rochman, 2018; Allen et al., 2022). Between 2006 and 2018, 54% of MP publications were focused on marine ecosystems (Akdogan & Guven, 2019), with significant increases in publication since 2014/2015 (Allen et al., 2022). This recognition is important as research suggests that freshwater and marine systems may share countless similarities in their "transport [MPs] (e.g., surface currents); [their prevalence] (e.g., numerically abundant and ubiquitous); the approaches used for detection, identification and quantification (e.g., density separation, filtration, sieving and infrared spectroscopy); and the potential impacts (e.g., physical damage to organisms that ingest them, chemical transfer of toxicants)" (Eerkes-Medrano et al., 2015). Additionally, freshwater systems are a source and critical pathway for pollutants to enter the oceans (Dris et al., 2015), with an estimated 80% of marine MP pollution originating on land (Jambeck et al., 2015). Freshwater matrices are close to MP point sources and can be tracked alongside areas of high population and urbanisation (Szymańska & Obolewski, 2020). Notably, an estimated 1.15 to 2.41 million tons of plastic debris deposits into the ocean via rivers annually (Lebreton et al., 2017). Despite this, global understanding of freshwater MP pollution remains limited.

1.1.2. Freshwater resources

Like marine ecosystems, MPs are common in freshwater bodies at a global scale (Free et al., 2014). The small particles were first reported in freshwater lakes in 2013 (Eriksen et al., 2013), but an increasing number of studies over the past several years have shown MPs to be ubiquitous in global freshwater systems, including lakes, rivers, estuaries, and wetlands (Lu et al., 2021). As cited from various sources in Boyle and Örmeci (2020), plastic contamination is often concentrated near urban centers, like the Great Lakes and the Rhine River, but MPs have also been found in remote surface waters with minimal anthropogenic contact. And like marine fauna and flora, living organisms in these other ecosystems are also impacted; MPs have reported in freshwater insects, worms, clams, fish, and birds (Rochman, 2018).

1.2. Microplastic technology

While research continues to identify, monitor, and characterize MPs and their interactions within the environment, some scientists recommend reducing pollution by developing collection technologies (Schmaltz et al., 2020; Wu et al., 2016; Boyle & Örmeci, 2020; to name a few). Common MP removal techniques have been identified in select studies (Dey et al., 2021), but none have been identified as “best,” and there has been little to no implementation on a global scale (Beladi-Mousavi et al., 2021). Additionally, many techniques identify biological, chemical, or physical processes to remove MPs from milieu, but this does not reflect available devices that can be deployed successfully in the field. Of the existing systematic MP removal studies, many focus on wastewater or storm water treatment, as seen in Dey et al. (2021) and Stang et al. (2022), respectively, as opposed to freshwater ecosystems. While current efforts are notable, their capacity and lack of widespread implementation present a limitation when compared to the vastness of MP pollution (Schmaltz et al., 2020).

1.3. Research objectives

This thesis aims to test and assess The Plastic Hunter, a novel MP removal system designed by PolyGone (PG) Systems, in a freshwater lake in the context of existing aquatic MP removal technologies. More specifically:

a. Test the ability of PG’s system to collect MPs from a lake that has been previously dosed with plastics;
b. Determine the efficacy of PG’s filtration system in terms of design and brush placement;
c. Identify the MP polymers collected by the Plastic Hunter;

d. Identify existing aquatic MP removal technologies using pre-determined criteria; and,
e. Discuss existing devices based on various characteristics, like ideal particle size, collection method, intended ecosystem and current status/use.

1.4. Methodology overview

This thesis research falls under an international project titled, “pELAstic: Whole-lake experiment to determine the fate and ecological impacts of microplastics in freshwater systems.” The collaboration aims to measure the fate, transport, and ecological impacts of MP in an aquatic ecosystem and across multiple levels of biological organization (Rochman, 2022). The project experimentally manipulates a lake at the IISD Experimental Lakes Area (IISD-ELA) by adding an environmentally relevant amount and mixture of MPs to test the direct and indirect impacts (Rochman, 2022). The project employs a Before-After-Control-Impact (BACI) design to monitor the impacted late (L378) in comparison with the reference lake (L373). Of pELAstic’s objectives, the fourth and final provides the guidance for this thesis: “the recovery of a microplastic-contaminated ecosystem, including microplastic degradation and transformation” (Rochman, 2022).

For objectives a-c of this thesis, PG altered their existing filtration system design to fit the environment and sampling needs of the research site, which was chosen as part of the pELAstic project (see Chapter 3 for further detail). The device was deployed for six weeks near the outlet of L378, during which select brushes were sampled; daily samples were taken for the first six days, and then collection switched to weekly for the remaining five weeks. Each sampled brush was rinsed into a glass jar with distilled water, and the sample was filtered onto 20 µm filters. Samples from the first week moved directly to microscope identification, where analysis by eye was able to identify the number and colour of MP particles, in coordination with pELAstic project guidelines. Brushes collected by the second week (and onwards) were too heavy with biofilm to filter immediately; they were processed with 30% H_2O_2 to remove organics and subsampled with a 10% Alcojet solution (to prevent particles from sticking to each other) to make counting by eye possible. MPs were then identified under the microscope by the same methods and calculations were made to account for subsampling. Laboratory blank samples were collected onsite at ELA to mimic the brush cleaning and filtering, and the analysis processes were imitated at Dalhousie using Milli-Q® water. Protective equipment, multiple rinsings, and glass containers in the field minimized contamination throughout.

To complete objective d, a review of literature and existing aquatic MP removal technologies was conducted, modelled off Schmaltz et al. (2020). As many technologies, especially those in the developmental phase, are not covered in academic literature, other sources, like press releases, research briefs, tech catalogues, and trade publications, were considered. Similarly, focused was maintained on systems that target the removal of specifically MPs, avoiding those that collect the more common MaP debris. A catalogue of existing and active technologies was assembled, each distinguished by different features and characteristics.

1.5. Thesis outline

This thesis comprises five chapters. This chapter serves as the introduction, giving a brief overview of the issue and outlining the remainder of the study. Chapter 2 presents a background and review of MP impacts, presence in freshwater systems, and the need for further removal technology development. The third chapter covers context, methodology, results, and discussion for the testing of a pilot MP removal technology designed by PG in a formerly pristine lake that has been subjected to controlled MP pollution. Chapter 4 identifies existing aquatic MP technologies, discusses trends in design and use, and contextualizes the findings of the Plastic Hunter. The final and fifth chapter presents thesis conclusions and recommendations for further research and development into MP removal technology.

Chapter 2: Background on aquatic MPs and removal systems

2.1. Plastic consumption

2.1.1. History of mass plastic use

Plastic pollution is an issue that's grown significantly over the more than a century since the first entirely synthetic resin was produced in 1907 (Chalmin, 2019). As the materials to make plastic became cheaper and more accessible post-World War II (WWII), consumption—and therefore, disposal—increased exponentially (Chalmin, 2019; Geyer et al., 2017). The popularization of plastic use can be historically aligned with other societal trends; during WWII, naturally occurring polymers like latex, wool, and silk became hard to obtain, and production turned towards synthetic materials (Science History Institute Museum & Library, 2024). After the war, a renewed wave of consumerism took off, partly motivated by the deprivation of the Great Depression and wartime and increased access to radio and television, which widened advertising field (Higgs, 2021). This leap in consumption helped plastics secure their place in popularity as versatile, cheap, and convenient materials—just what a growing, goods-motivated society wanted on the tail end of economic downturn and war.

2.1.2. Single-use plastics and COVID-19

Plastic production and consumption have increased steadily as a staple of a consumer-based society, even as policy to curb habits has grown in recent years. A sharp uptick in plastic use can be attributed to the COVID-19 pandemic as the world turned to personal protective equipment (PPE) and plastic packaging as a sterile option. PPE like medical masks and gloves became essential not only to healthcare workers, but to many ordinary citizens, as well (Prata et al., 2020b). Monthly global use was estimated at 129 billion masks and 65 billion gloves, releasing additional plastic debris into the environment (Prata et al., 2020b; Tursi et al., 2022). Face masks, for example, are made of plastics like polypropylene, polyurethan, or polyacrylonitrile; the N95 mask, which became a highly recommended option as research into COVID-19 transmission expanded, are made of polypropylene and polyethylene terephthalate (PET; Prata et al., 2020b).

Concerns over virus transmission on contaminated surfaces also led to a dependency in single-use plastics (SUP) for food consumption and transport, with both consumers and producers preferring plastic containers, bags, and utensils (Patrício Silva et al., 2021). Plastic-focused policy also shifted away from sustainable progress. In the United States (U.S.) several states including New York, Massachusetts, New Hampshire, and Maine paused or reversed plastic bag bans amidst COVID-19 concerns (Prata et al., 2020b). Some states paused recycling programs to avoid transmission (Zambrano-Monserrate et al., 2020), instead prioritizing incineration and landfilling, ultimately contributing to plastic pollution (Patrício Silva et al., 2021). Similar actions were seen in Canada, Italy, and Australia, requiring or encouraging the use of SUPs in place of sustainable options (Prata et al., 2020b). Increased plastic production and consumption, along with improper disposal of PPE and SUPs, led to substantial littering (Patrício Silva et al., 2021), and in turn, global plastic pollution.

2.1.3. Plastics as an environmental contaminant

Through over production, consumption, and improper disposal, plastics have become a global pollutant. Most plastic is not reused or recycled, with more than half becoming waste in less than a year after production (Tursi et al., 2022). A study by Geyer et al. (2017) showed that only 9-10% of plastic is recycled, with 10-11% incinerated, and about 30% reused; the remaining

50% is disposed of in landfills or dispersed into the environment. This study occurred a few years before COVID-19; it can be presumed in the immediate aftermath of the pandemic that less plastic has been reused and more is improperly disposed of. While plastic in any form is an environmental contaminant, it can begin to fragment from waves, currents, high temperatures, pH, and radiation, increasing dispersion (Tursi et al., 2022) and the impacts of pollution.

2.2. Defining characteristics of plastic debris

Plastics are ubiquitous as a solid form in the environment, with varying dimensions, structures, densities, colors, and polymer types (Dey et al., 2021). Polymers are divided into five size categories (Figure 2.1.): megaplastic (MegP; >50 cm), macroplastic (MaP; 5-50 cm), mesoplastic (0.5-5 cm), microplastic (MP; <0.5 cm) (Malankowska et al., 2021) and nanoplastic (NP). The exact size range of NPs is widely debated (Hartmann et al., 2019), although they are often to measure under 0.1 μm (Boyle & Örmeci, 2020). While MegP and MaP remain a significant focus within pollution and waste research, many efforts have recently turned to MPs, which are far more difficult to identify, monitor, and collect. Common forms of MPs are fibers and fiber bundles, pellets, spheres, fragments, rubber, foam and film (Markley et al., 2024).

MPs can be further defined by their intended production, as primary or secondary plastics. Primary sources of MPs are purposefully engineered in microscope size; for example, microbeads in personal care products were first patented in the 1970s (Wu et al., 2016). These plastics are also found in industrial abrasives (Boyle & Örmeci, 2020**)**, as drug vectors in medicine (Patel et al., 2009), or as resin pellets to produce other plastic products (Wagner et al., 2014). Additional origins for primary source plastics include the fishing and clothing industry, shipping line, airblasting, and wastewater treatment plants (WWTPs; Dey et al., 2021).

Secondary MPs, however, come from the breakdown and fragmentation of larger plastics that already exist in the environment due to improper disposal or accidental release (Boyle & Örmeci, 2020). The degradation of secondary plastics is caused by biodegradation, photo degradation (usually from UV radiation), thermo-oxidative degradation (Gani et al., 2024), hydrolysis (Andrady, 2011), and fragmentation by mechanical friction or waves (Dey et al., 2021). Primary plastics are also subjected to further breakdown, changing their size, morphology, crystallinity, color, densities and surface functional groups (Guo & Wang, 2019). This dynamic variation in MPs results in increasingly diverse characteristics like abundance, density, and appearance, which impedes source identification (Zhang et al., 2017).

2.2.1. Polymer composition

Synthetic polymers are manufactured using raw materials such as coal, oil and natural gas and are classified as plastic (da Costa et al., 2017). This includes PET, high-density polyethylene, polyvinyl chloride, low-density polyethylene, polypropylene, polystyrene (PS) and polyurethane, which make up 90% of the total world plastic production (Phuong et al., 2016). PS, PET, and polyethylene (PE) are particularly important for this study and the analysis in the following chapter. PS is used primarily in food packaging, building insulation, electrical and electronic equipment, eyeglasses frames (Gani et al., 2024; Tursi et al., 2022). PET is used for drink bottles, including water, juice, and soda (Tursi et al., 2022), and in food packaging and fabrics due to it being durable, lightweight, and transparent (Boyle & Örmeci, 2020; Gani et al., 2024). PE is used for reusable bags and containers, in agricultural and food packaging, toys, shampoo bottles, and houseware (Tursi et al., 2022).

2.3. How do plastics enter the environment?

Aquatic MP pollution starts primarily on land for both primary and secondary plastics (Andrady, 2011; Jambeck et al., 2015), notably through improper recycling or waste disposal (Dris et al., 2015). Daily activities like tire abrasion, wear and tear of microfiber materials, or the use of domestic cleaning and cosmetic products can also produce MPs (Y. Zhang et al., 2021; Ogunola et al., 2018). The small particles may be released into the air, waste or stormwater systems, or be carried by surface runoff (Dris et al., 2015), emptying into rivers, estuaries, and the ocean (Y. Zhang et al., 2021). The understanding that MPs undergo atmospheric transport is key in identifying their global pathways, which are not limited to aquatic systems (Dris et al., 2016). A recent study in the Northwest Atlantic showed that hurricanes can disperse and deposit significant quantities of MPs, sometimes travelling enormous distances (Ryan et al., 2023). If suspended in the atmosphere, MPs can settle back on land or the surface of rivers, lakes, and oceans through wet or dry deposition (Klein & Fischer, 2019). Additional contributions to MP pollution include agricultural processes that infiltrate soil and marine activities like ship painting (which chips) and fishing (Y. Zhang et al., 2021). Debris that is transported by surface runoff exacerbates pollution through land erosion (Xia et al., 2020) and has the potential to seep into the ground and harm groundwater reserves (Gani et al., 2024). Dispersion is further difficult to trace as differences in salinity, temperature, and water currents between marine and freshwater systems affect the transport of MPs (Eerkes-Medrano et al., 2015). While the dispersal of MPs is hard to track, they’ve traversed the globe, with recent findings in freshwater, groundwater, snow, ice, soil, sediment, terrestrial and aquatic biota, air, and even ocean spray (Allen et al., 2022).

Some plastic pollution begins in aquatic ecosystems in the form of abandoned, lost, or otherwise discarded fishing gear (ALDFG), such as netting, mono/multifilament lines, hooks, ropes, floats, buoys, sinkers, anchors, metallic materials and fish aggregating devices (MEPC 2020; FAO ISSCFG 2013). These items can directly impact marine organisms and break down further to contribute to MP pollution (United Nations Environmental Programme [UNEP], 2021). However, despite increasing research into ALDFG, it remains a challenge to determine waste contributions from fisheries and aquaculture (GESAMP, 2021).

2.3.1. MPs in freshwater sources

Freshwater ecosystems receive less attention for plastic pollution than oceans, despite contamination being just as severe (Dris et al., 2015). Additionally, most litter—almost 80%—is introduced from inland sources and transported to marine environments (GESAMP, 2021). It was previously thought that oceans were the primary sinks for MPs, with freshwater bodies serving as the source and transportation (Dris et al., 2015), but recent research by van Emmerik et al. (2022) suggest that rivers can also act as (long-term) sinks for MPs. Lakes and fluvial networks play a key role in pollution, as runoff occurs from nearby urban and rural landscapes, WWTPs, stormwater drainage, supply lakes, and other tributaries (Boyle & Örmeci, 2020). They distribute contaminants to larger freshwater bodies and to the ocean (Boyle & Örmeci, 2020). Currents and fluxes in water levels (due to precipitation, droughts, and floods) can further transport MPs, depositing particles on banks and shorelines far from the original site of contamination (Boyle & Örmeci, 2020). During dry seasons, MPs can have longer residence times in freshwater systems, further degrading before travelling to another ecosystem (Li et al., 2020). Recent research trends identified by Allen et al. (2022) reflect the growing understanding of the importance of freshwater systems in MP pollution, with the number of related publications increasing significantly over a decade—from around 0 in 2011 to over 800 in 2021.

2.4. Impacts of MPs on living organisms

MPs have been found not only in almost every ecosystem, but also within the tissues and gastrointestinal tracts of thousands of species, including humans (Allen et al., 2022). They pose a unique level of severity compared to larger plastics as their small size lends well to transfer through the food chain (Tursi et al., 2022). In addition, they act as vectors for toxins; their high surface area and distinctly hydrophobic character aids the absorption of substances from the surrounding environment (Tursi et al., 2022). Toxins leaching into organisms can also occur from production; there are more than 16,000 chemicals used or present in plastic materials, with less than 6% subject to global regulation (Wagner et al., 2024). More than 4200 of those chemicals are of concern because they are persistent, mobile, and/or toxic; over a quarter lack basic information on their identity and over half have ambiguous or missing details, highlighting a dangerous gap in the widespread impacts of plastics (Wagner et al., 2024).

2.4.1. Aquatic wildlife

Plastics have been found in animals at all levels of the food web, across trophic levels, and at all depths of the ocean (Bucci et al. 2020; Lau et al., 2020). One study by Sequeira et al. (2020) found MPs in the organs of 60% of fish belonging to 198 species captured in 24 countries. In another, 67% of shark samples contained at least one MP in the stomach or digestive tract (Parton et al., 2020). MPs are often ingested, whether unknowingly or mistaken as food, by a range of aquatic organisms. In crabs, ingested MPs were found in the hepatopancreas followed by the guts, gills and muscles (Wang et al., 2021). Scallops can take up billions of MPs, spreading to the intestine and distributed across kidneys, gills and muscles (Al-Sid-Cheikh et al., 2018).

Health impacts on aquatic biota are widespread. Larger plastics can cause wounds, strangulation, or suffocation and prevent mobility and feeding ability (Allen et al., 2012; Andrades et al., 2021). Plastic ingestion can also lead to false satiation, hunger, or complications from absorbed toxins, in turn spreading through the food chain (Watkins et al., 2019). Beyond the physical implications of MP ingestion, there are significant chemical effects. Once in the gastrointestinal tract, MPs can leach plastic additives, as well as any toxins absorbed at its origin, from the environment, or while in contact with other plastics (Boyle & Örmeci, 2020). Many of these contaminants are toxic to biota and can cause health defects, abnormalities (da Costa et al., 2017), or even death (Boyle & Örmeci, 2020).

The complete impacts of MPs on aquatic animals are unknown, with debates of how different factors, like life stage, could increase the potency of MPs. Fish embryos may be more sensitive to plastics and attached toxins than those that are juvenile or adult (Eerkes-Medrano et al., 2015). Added exposure of embryos in the riverbed to sediment-based plastics could further affect growth rates or survival (Eerkes-Medrano et al., 2015).

2.4.2. Humans

The risks of MP exposure for human health are difficult to assess, as the varied number, size and shape of polymers doesn’t translate well in terms of dose or mass (Tursi et al., 2022). There are three main routes for plastics to impact the human system—through ingestion, inhalation, and dermal contact.

Sitting atop the food chain, humans consume various fish and crustacean, ingesting any plastics that those species may have taken in (Dey et al., 2021). Annually, it is estimated that humans ingest anywhere from 11,845 to 193,2000 MPs, most of them from drinking water consumption (A. Rahman et al., 2021). This quantity likely varies between tap and bottled water; the former can range from 0-61 particles per liter, while bottled water has more uncertainty, ranging 0-10,000 particles per liter (Kannan & Vimalkumar, 2021). The presence of MPs has been highlighted in other beverages, like energy drinks, bottled tea, wine and beer (Shruti et al., 2021). In one study, Italian white wine contained 2563-5857 particles per liter, with most polymers coming from the synthetic PE stoppers; in Germany, 10-256 particles per liter were found in beer (Shruti et al., 2021). High quantities of MPs are also found in food; seafood is ranked as the third largest source of MP ingestion after bottler water and alcohol (Cox et al., 2019); this includes crustaceans, commercial fish, and bivalves (Tursi et al., 2022). Particles smaller than 150 mm can easily cross the gastrointestinal epithelium, those with dimensions of the order of 10 mm can pass through placenta and the blood-brain barrier, and MPs smaller than 2.5 mm can reach the systemic circulation by endocytosis (Kannan & Vimalkumar, 2021). Impacts include the disruption of immune function, translocation to distant tissues, alteration of metabolism and energy balance, oxidative stress and cytotoxicity, neurotoxicity, reproductive toxicity, carcinogenicity, and indirect effects as vectors of toxins (Tursi et al., 2022). Most recently, a study by Hu et al. (2024) found 12 types of MPs in 47 canine and 32 human testes.

Due to their low density and microscopic size, MP suspended in the air can accumulate in the atmosphere and be inhaled by humans (Prata et al., 2020a). MP inhalation can occur from clothing, building materials, waste incineration, landfills, and abrasions, and is more common than digestion (Ahmed et al., 2022). A recent study by I. Rahman et al. (2021) notes that inhalation is expected to increase MP contamination of about 35,000-69,000 particles per person per year. Atmospheric concentrations can also be difficult to assess, with significant fluctuations depending on the season, overall air quality, and characteristics of the particles (Prata et al., 2020a). Inhaled plastics accumulate predominantly in the lungs; the pulmonary alveoli have a very thin tissue barrier and large surface area, making them an optional adsorption site (Tursi et al., 2022) and entry point to the rest of the body. Prolonged exposure to the lungs can lead to a variety of diseases, including asthma, pneumoconiosis and extrinsic allergic alveolitis (Kannan & Vimalkumar, 2021; Prata et al., 2018; A. Rahman et al., 2021; Turcotte et al., 2013).

MP absorption through the skin is not possible; only NPs, measuring less than 100 nm, are able to cross the dermal barrier (Revel et al., 2018). This can happen through direct contact with textiles, indoor dust, or personal care products (Revel et al., 2018). However, personal care products that contain MPs, like facemasks, facewashes, hand cleansers, and toothpastes, can cause skin damage due to inflammation and cytotoxicity (Sharma & Chatterjee, 2017).

Of the additives in plastic production, the most widely used are bisphenol A (BPA), brominated flame retardants (BFR), phthalates, triclosan, nonylphenol, and organotin compounds (Dey et al., 2021). Exposure to BFA, often through food containers, can lead to thyroid inhibition, liver malfunction, lowering insulin resistance, altering the reproductive system, brain malfunction, and complications in the wombs of pregnant women (Dey et al., 2021). Phthalates are responsible for health issues involving sexual abnormalities, birth problems, and carcinogens (Gómez & Gallart-Ayala 2018).

2.5. Existing action on MP pollution

Plastic pollution has seen a consistent uptick in annual publications since 2011, increasing from around 200 papers per year to more than 2000 per year in 2021 (Allen et al., 2022). Publications specifically on MPs have seen a similar rise from less than 50 papers per year in 2013 to more than 2000 in 2021 (Allen et al., 2022). While research into freshwater MPs has increased, more information is needed to understand the extent of impact compared to what is already known about marine plastics (Boyle & Örmeci, 2020). In the United States and Canada, the Great Lakes have been a common site of MP surveys, with significant variability in abundance and types of plastics (Boyle & Örmeci, 2020). This can be attributed partially to the varying population densities along the Lakes, the proximity of various industrial sectors, and differing hydraulic conditions (Boyle & Örmeci, 2020). However, this does not define MPs in the Great Lakes, nor does it explain the range of pollution in North America, let alone the rest of the world.

As research into plastic pollution has grown, so have policy efforts to curb the problem. Some interventions focus on post-consumption management, which requires additional funding, awareness campaigns, and improving waste collection and infrastructure (UNEP, 2021). Policy implementation, whether at the local or national level, can support the implementation of the waste hierarchy, which prioritizes prevention, minimization, reuse, recycle, recovery, and then final disposal (UNEP, 2021). Other researchers and policymakers push biodegradable materials or bioplastics as a solution to reduce pollution (UNEP, 2021). Individual countries and states/provinces have established bans or restrictions on certain products, including single-use plastics (bags, utensils, straws) and microbeads (Dauvergne, 2018; Schnurr et al., 2018), although much of this fluctuated during the COVID-19 pandemic (Prata et al., 2020b). Other solutions involve removing plastics from the environment, which, while effective, requires significantly more research, funding, and testing in the future.

2.5.1. MP removal from the ecosystem

Plastic pollution removal is a difficult task due to the pervasiveness of debris and variability in size and material, and this grows increasingly more challenging as the particles degrade into smaller sizes (Y. Zhang et al., 2021). Two paths are considered ideal for the development and mobilization of plastic removal technologies, according to Schmaltz et al. (2020): 1) those that prevent debris from entering waterways or 2) those that collect aquatic pollution in the field. Schmaltz et al. (2020) also points out that to date, few reports have focused on such technologies and existing developments are scattered. Research on MP removal technology is in its preliminary stages, with many limitations on details like the type and size of target particles (Gao et al., 2022). Additionally, many removal devices are designed for MaPs—sensibly so, as they are larger to see and easier to collect—meanwhile neglecting MPs, which continue to travel from ecosystem to ecosystem. Technological innovation, while currently effective on a small scale, will grow in benefit when coupled with private industry action to match the global nature of the problem and stakeholders involved (Schmaltz et al., 2020).

An important distinction in the conversation of MP removal development needs to be made between technologies and techniques. Many papers (Y. Zhang et al., 2021; Dey et al., 2021, Ahmed et al., 2022) discuss what they call “technologies” to remove MPs from aquatic medium; these, however, can be better understood as techniques, as they represent different ways to collect particles that can then be implemented into devices. For the purposes of this thesis, removal “technologies” will refer to inventions or systems that can collect MPs, whereas “techniques” will reference the implementable and proven methods, as further described below. The terms “device” and “system” will also be used interchangeably with “technology.”

2.5.2. MP removal techniques

Various techniques have been developed and identified to separate MPs from aquatic systems, with the hopes of being integrated into scalable and effective removal technologies (Y. Zhang et al., 2021). A comprehensive list, including benefits and drawbacks, was compiled by Dey et al. (2021), featuring the following methods: adsorption, biofiltration, magnetic extraction, coagulation, electrocoagulation, membrane filtration, conventional activated sludge, biological degradation, and photocatalytic degradation. Other techniques, as further identified by Ahmed et al. (2022), Karimi Estahbanati et al. (2021), Wang et al. (2023), and Y. Zhang (2021), include fungal pelletization, separation by oil film or density and froth flotation. Each performs in the following manners:

- Filtration methods, whether membrane or plant-based, prevent particles from passing through the holes or spaces left by media (Dey et al., 2021; Y. Zhang et al., 2021).
- Adsorption, including biosorption or electro-sorption, induces the attraction of particles, either to adsorbents or to charged electrodes (Mrvčić et al., 2012).
- Conventional activated sludge occurs when materials soluble organics, ammonium and phosphate are removed mainly via microbial assimilation and dissimilation, including aerobic biological oxidation and nitrification–denitrification (Jenkins & Wanner, 2014). The process can also be used to separate MPs (Dey et al., 2021).
- Chemical coagulation employs coagulants to “capture dissolved solids in wastewater by forming flocculants and to settle them” at the bottom of a tank (Dey et al., 2021). Similarly, in electrocoagulation, cations are formed by metal electrodes, which in turn creates coagulants (Dey et al., 2021).

- Magnetic extraction utilizes magnetic fields to separate MPs grafting with seed particles (Y. Zhang et al., 2021).
- Biodegradation breaks down the particle using microorganisms, which decompose plastic waste into biomass, methane, carbon dioxide, water, and various inorganic compounds (Dey et al., 2021). This process is highly dependent on polymer types and their physical/chemical characteristics (Dey et al., 2021).
- Photocatalytic degradation, which is a form of advanced oxidation, uses light-mediated radicals to break down plastics (Y. Zhang et al., 2021). Advanced oxidation processes in general are notable for their capability to mineralize persistent organic pollutants (Qin et al., 2020; C. Zhang et al., 2021).
- Fungal pelletization spurs MP assimilation, with easy removal of the fungus biomass (H. Wang et al., 2023).
- Density separation isolates MPs from sediments; the lighter MPs float to the upper layer of suspension and can be easily removed (Y. Zhang et al., 2021).
- Oil film separation, while similar, is a hydrophobicity-based method that separates MPs from aquatic samples using oil extraction (Crichton et al., 2017).
- Froth flotation utilizes bubbles on target materials; those with a hydrophobic surface float as bubbles aggregate, while hydrophilic counterparts flow below (Bayo et al., 2020; Shu et al., 2020; Zhang et al., 2020).

Despite numerous effective techniques, significant research and innovation is needed to identify best methods for MP removal technology and to scale deployment to match the scope of pollution.

Chapter 3: Proof of concept microplastic removal filter technology and characterization in the Experimental Lakes Area (IISD-ELA), Canada

3.1. Abstract

Plastic pollution is a growing environmental concern, especially when understanding how polymers interact within ecosystems. Microplastics (MPs) are difficult to analyse in nature due to variety in polymer, size, and ecosystem interactions. MPs have been found in almost every ecosystem on the globe, from the deep-sea floor to arctic snow, becoming an unavoidable source of pollution. Particles can persist in aquatic environments, although research is lacking on freshwater ecosystems, with oceans initially receiving the bulk of scientific focus. Common MP removal techniques have been identified, but there has been no strategy identified as "best," and little to no implementation on a global scale. This proof-of-concept study explored the deployment of an aquatic MP filtration system at the IISD Experimental Lakes Area (IISD-ELA) in Northern Ontario. The research was conducted as part of the pELAstic project, which dosed a lake with three polymers throughout the field season—polyethylene (PE; yellow), polystyrene, (PS; pink), and polyethylene terephthalate (PET; blue). Sampling occurred daily for the first five days, and then switched to weekly. Three to four filter brushes were collected at each sampling and cleaned in the laboratory, to be reused. Analysis used a hydrogen peroxide (H_2O_2) digestion and 10% Alcojet subsampling procedure on the concentrated brushes, followed by tally counting for all. Particle identification was completed by eye under a microscope. Results counted 89,800 MPs from brush samples taken over six weeks, most of which were yellow (PE). Time constraints limited the ability to analyse efficacy and retainment rate of the filter brushes, suggesting the need for further field experimentation in various freshwater environments.

3.2. Introduction

Between 2016 and 2040, an estimated 710 million metric tons of plastic waste will enter aquatic and terrestrial environments, despite global action and policy to manage production, consumption, and disposal/recycling (Lau et al., 2020). Plastics have become a chosen material around the world and an unavoidable source of pollution due to their low density, durability, and low cost (Lv et al., 2021). This dependence on plastic products, many of which are single-use, was only exacerbated by the COVID-19 pandemic (Boyle & Örmeci, 2020**)**. Plastic pollution is difficult to analyse in nature due to variety in polymer, particle size, degradation, and ecosystem interactions (Schnurr et al., 2018).

Plastic pollution is often defined by particle size, with microplastics (MPs) measuring smaller than 0.5 cm (Boyle & Örmeci, 2020). They can be further defined by their intended production, identified as primary or secondary plastics. Primary sources of MPs are purposefully engineered in microscope size; microbeads, a common source, were first patented in personal care products in the 1970s (Wu et al., 2016). Secondary MPs, however, come from the breakdown and fragmentation of larger plastics that already exist in the environment due to improper disposal or accidental release (Boyle & Örmeci, 2020). MPs may be released into the air, waste or stormwater systems, or be carried by surface runoff (Dris et al., 2015; Xia et al., 2020). The understanding that MPs undergo atmospheric transport is key in identifying their global pathways, which are not limited to aquatic systems (Dris et al., 2016). If suspended in the atmosphere, MPs can settle back on land or the surface of rivers, lakes, and oceans through wet or dry deposition (Klein & Fischer, 2019; Ryan et al., 2023).

Most MP research focuses on pollution in oceans and amongst marine species (Akdogan & Guven, 2019; Bellasi et al., 2020), with only recent studies expanding into freshwater and terrestrial environments (Rochman, 2018). Between 2006 and 2018, 54% of MP publications were focused on marine ecosystems (Akdogan & Guven, 2019); however, over the past several years, an increasing number of studies have shown MPs to be ubiquitous in global freshwater systems, including lakes, rivers, estuaries, and wetlands (Lu et al., 2021). This holds significance as oceans were once considered primary sinks for MPs; terrestrial and freshwater ecosystems can function as sinks and are the primary source of plastic particles (Dey et al., 2021). Some freshwater matrices, like rivers, are close to MP pollution point sources and can be tracked alongside areas of high population and urbanization (Szymańska & Obolewski, 2020). Notably, an estimated 1.15 to 2.41 million tons of plastic debris deposits into the ocean via rivers annually (Lebreton et al., 2017).

Although the harmful effects of MPs on organisms are not consistently demonstrated, according to Lau et al. (2020), "ingestion has been documented across trophic levels and at all depths of the ocean" and at all levels of the food web (Bucci et al., 2020). MPs pose a unique level of severity compared to larger plastics as their small size lends well to movement through the food chain (Tursi et al., 2022). In addition, they act as vectors for toxins; their high surface area and distinctly hydrophobic character aids the absorption of substances from the surrounding environment (Tursi et al., 2022). Plastic ingestion can lead to false satiation, hunger, or complications from absorbed toxins (Watkins et al., 2019), and many contaminants can cause health defects, abnormalities (da Costa et al., 2017), or even death (Boyle & Örmeci, 2020). Humans face health complications from plastic pollution, as well; particles can infiltrate the body through ingestion (Dey et al., 2021), inhalation (Ahmed et al., 2022), and direct contact with the skin (Revel et al., 2018). Impacts include disruption of immune function, translocation to distant tissues, alteration of metabolism and energy balance, oxidative stress and cytotoxicity, neurotoxicity, reproductive toxicity, carcinogenicity, and indirect effects as vectors of toxins (Tursi et al., 2022).

While research continues to identify, monitor, and characterize MPs and their interactions within the environment, some scientists recommend reducing pollution by developing collection technologies (Schmaltz et al., 2020; Wu et al., 2016; Boyle & Örmeci, 2020; to name a few). However, MP removal from the environment is difficult due to the pervasiveness of debris and variability in size and material (Y. Zhang et al., 2021). Common MP removal techniques, such as filtration, biological and photocatalytic degradation, and magnetic extraction, have been identified in select studies (Dey et al., 2021), but none have been identified as "best," and there has been little to no implementation on a global scale (Beladi-Mousavi et al., 2021). While current removal technology efforts are notable, their capacity and lack of widespread implementation present a limitation when compared to the vastness of MP pollution (Schmaltz et al., 2020).

This proof-of-concept study aimed primarily to test and assess a novel MP removal system designed by PolyGone (PG) Systems in a freshwater lake. The first goal tested the ability of the device to collect MPs from a contaminated lake. Secondly, the collected particles were quantified and identified by polymer, as guided by the pELAstic project (see below). Lastly, this research identified any trends that could influence filter efficacy, like brush orientation and placement.

3.3. Background on project coordination

3.3.1. The pELAstic Project

The pELAstic project is an international collaboration across several Canadian and American universities, operating in the field at IISD-ELA. IISD-ELA's "natural laboratory" consists of 58 small lakes and their watersheds in a sparsely populated area of Northern Ontario, allowing scientists to observe the impacts of environmental threats like climate change, agricultural runoff, and contaminants on all components of an ecosystem (IISD Experimental Lakes Area, 2024). Research done at the site has been influential in environmental policies, regulation, and management (IISD Experimental Lakes Area, 2024). The boreal ecosystem represented at IISD-ELA not only reflects the global impacts of MPs in freshwater environments, but within Canada specifically. Twenty eight percent of the world's boreal forests are in Canada and serve as critical cultural, economic, recreational, and environmental resources (Government of Canada, 2024).

The project aims broadly to understand the transport, impact, and fate of MP pollution in a freshwater lake ecosystem. More specifically, there are four identified objectives, the last of which provides direction for this thesis: to realize not only the fate of MPs, but also the remediation techniques and technologies (Rochman, 2022). The project employs a Before-After-Control-Impact (BACI) design that monitors a reference and a manipulated lake, L373 and L378, respectively. Both are small, dimictic, oligotrophic headwater lakes; L373 measures 27.4 ha with 21.2 m maximum depth and L378 measures 24.3 ha and 18.2 m maximum depth (McIlwraith et al., 2024). The reference lake has been monitored for hydrology, water chemistry, phytoplankton, zooplankton, and fish for more than 30 years, and L378 has been assessed for the same parameters since the 2019 season (Rochman, 2022).

After a few years of baseline assessments and mesocosm and limnocorral research, which use self-contained enclosures within the lake, experimental manipulation began in the summer of 2023, simulating municipal stormwater runoff based on natural meteorological patterns (Rochman, 2022). Biweekly additions during the 2023 ice-off season totaled 330 billion particles (Rochman, 2022). Fragments of three polymers, polyethylene (PE), polystyrene (PS), and polyethylene terephthalate (PET), were used for manipulation and ranged in size from 37-1408 μm (Rochman et al., 2024). PE, PS, and PET were chosen a) for being among the most mass-produced and consumed plastics and b) for having positive, neutral, and negative buoyancies, respectively (Rochman, 2022). The particles were specifically ordered in three distinct colors (yellow/PE, pink/PS, and blue/PET) and added to the lake in a slurry, released from a boat along transects bi-weekly. Analysis of field samples look to identify only these three polymers as opposed to others that enter the ecosystem, whether from independent pollution processes or anthropogenic contamination (such as clothing or laboratory/sampling supplies). Guidelines to quantify the three plastics were set by the pELAstic project and first consisted of training to identify each polymer by eye under a microscope. A petri dish with a small amount of the three plastics was used to familiarize each researcher with the variety in size, shape, and color, and to practice using tweezers to collect the fine particles. The collected MPs during training weres moved to another petri dish to confirm correct selection. This process was overseen by a team member who had already undergone the training and was on standby to ensure correct quantification. Support was further given by the team member for the first few environmental samples, answering questions and checking the picked particles to confirm their physical characteristics matched those used by the pELAstic project.

3.3.2. PG technology development

To assess MP removal technologies in field, a collaboration was formed with PG, a startup based out of Princeton University, that desgined the Plastic Hunter, a biomimetic filtration system for aquatic medium. PG had existing innovations prior to this research, but a dedicated system was designed for the needs of the pELAstic project.

The PG base brush design, seen in Figure 3.1., uses hydrophobic silicone bristles that act as an adhesive for particles and debris in water (PolyGone, "Technology: The Plastic Hunter"). The central stem is made of a stainless-steel coil, guaranteeing both brush stability and flexibility under varying water currents. Each brush measures about one foot long. Small metal carabiners attach the brush to the bars of the pontoon, the main flotation system, for easy removal and replacement, and a drop weight holds the brush vertical in the water column to maximize adhesion. Further detail about PG's brush design can be seen in Appendix A.

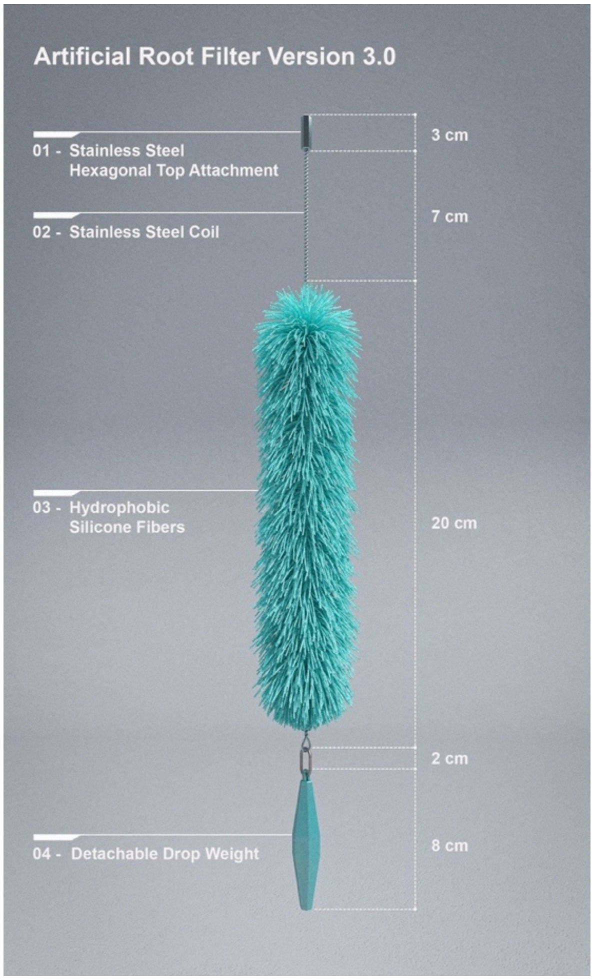

Figure 3.1. An individual brush as designed by PG and used in their filtration system (PolyGone Systems, Artificial Root Filter Version 3.0).

3.4. Methods

3.4.1. Deployment location and timing

The initial filter design aimed to remove any particles that may escape via the outflow of L378 into the neighboring L379 by suspending the brushes in the channel; however, further exploration led to the realization that the channel was too rocky and often dry to sample there. The new project design placed the filtration system in the outlet region of L378, on the outlet side of a floating boom (Figure 3.2.). For this study, our main focus was brush function, the feasibility of brush collection/cleaning, and brush absorption capacity based on placement and time in the water.

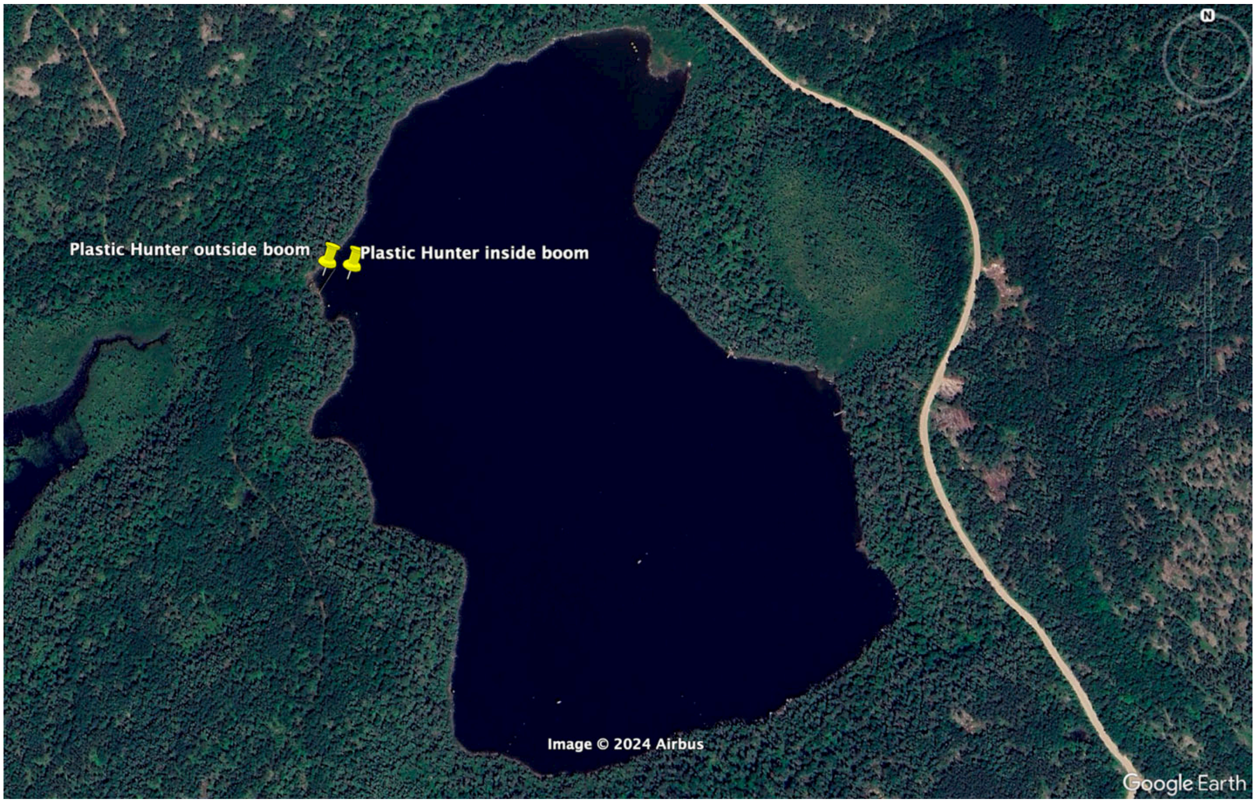

Figure 3.2. Diagram of the Plastic Hunter as deployed in the outflow region of L378. The pontoon was deployed initially on the lake side the boom, before being moved to the outflow side (Google Earth Pro, n.d.).

The device resembles a small pontoon, with two five-foot floating “arms,” and five bars bridging the two sides. When viewed from above, the pontoon rows were labeled top to bottom as A-E, with numbers assigned from left to right (Figure 3.3.).

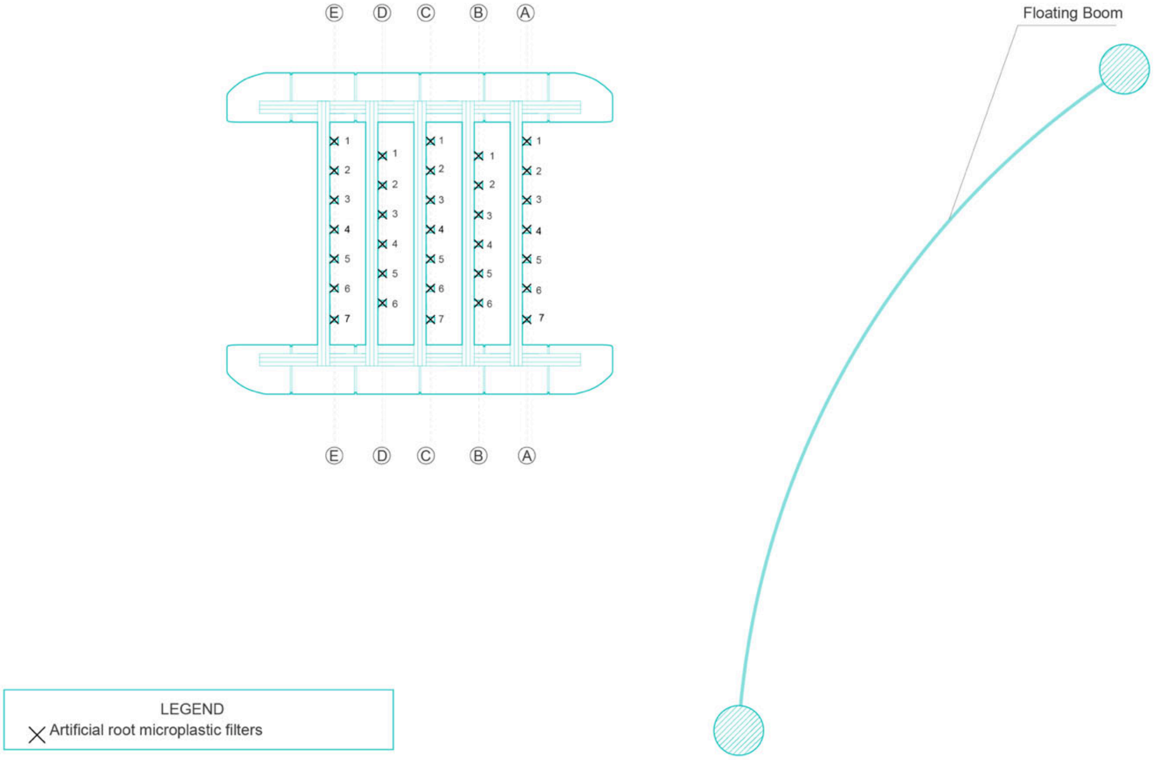

Figure 3.3. The pontoon rows were labeled A-E from right to left, and the brushes were numbered 1-6 or 1-7 from top to bottom. The floating boom is visible to the right; the pontoon was anchored in spot to the bottom of the lake. (PolyGone Systems, personal communication, June 14, 2024).

Each bar holds a row of six or seven brushes (alternating), which hang into the water, with the bottom eight inches submerged and the top four above the surface (see Figure 3.4.). The pontoon was anchored in place using several cement anchors on the lake floor, about two meters down, allowing a slight rotation with the wind/currents.

Figures 3.4. Two angles of the PG plastic filtration technology, showing the project-specific design.

The Plastic Hunter was deployed for the last six weeks of the 2023 season, starting on September 16 and ending on October 26. During the field season, a floating boom was installed near the outflow channel of L378 to minimize MP contamination to L379. For proof-of-concept, the PG pontoon was initially deployed on the lake side of the boom, where the plastics were added. After the first five days of sampling, the pontoon was moved to the outflow side of the boom to facilitate any necessary cleanup from particles that crossed the boom.

3.4.2. Sampling

Upon initial deployment, the brushes were sampled every day for the first five days, beginning September 16 and ending September 20; this aimed to keep an eye on the system and troubleshoot any issues. After that, the pontoon was moved to the outside of the boom, and sampling occurred once a week on Thursdays, to align with the MP additions (microplastics were added to the lake every other Wednesday, so Thursday sampling allowed the previous addition to be accounted for). Weekly sampling occurred September 21 and 28, and October 5, 12, 19, and 26. The pontoon was removed from the lake after the October 26 collection. Immediately before and during deployment, there were four MP additions—September 13, September 27, October 11, and October 25. The first two of the four included a double dose of PET to make up for a prior manufacturing issue.

At each sampling, three or four brushes were removed and replaced with clean ones; the number of brushes sampled alternated each day/week. Over the first five days of collection, one row was sampled each day to assess any issues and confirm proof of concept. Once sampling switched to weekly on Thursdays, brushes were replaced in mirrored patterns to gain insight on collection variation between inside and outside brushes. Some brushes were sampled twice throughout the deployment, although this was not frequent, and any related takeaways should be confirmed with further research.

When collecting brushes from the field, a large IKEA jar with a hook lid (KORKEN model, 47 oz/1390 mL) was used to transfer the used brushes to the lab. This jar was selected for being affordable, durable, made of glass (limits plastic contamination) and fitting the requirements of being tall enough to hold a brush and having an attached lid. Sampling also required replacement brushes (the same number as those collected, plus one for safety), labelling tape, a sharpie, Milli-Q® water in a squeeze bottle, and a bucket (for carrying). Prior to heading into the field, the jars were labelled with the respective brush (A4, for example). In the field, brushes were unclipped from the bars one at a time and carefully lifted into the corresponding jar. The lid was closed, and the jar was placed in the bucket. The replacement brushes were rinsed with Milli-Q® water and clipped in place. The process repeated for all brushes sampled.

3.4.3. Laboratory procedure

Methodology after collecting the brushes varied slightly based on how concentrated the samples were, which was influenced by length of time in the water. Figure 3.5. displays a flowchart of the laboratory processes.

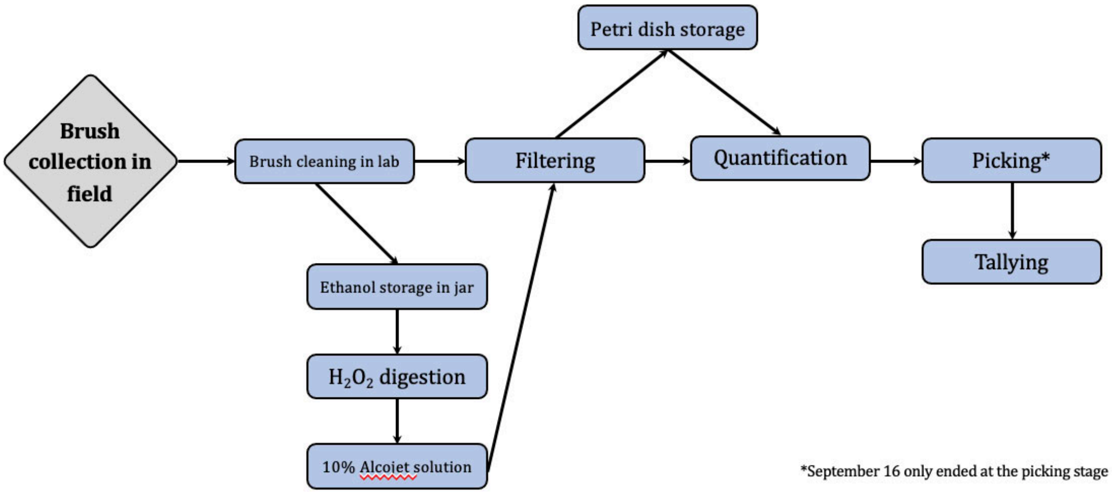

Figure 3.5. Flowchart of methods from field sampling through particle quantification.

All brushes were cleaned and filtered in the lab, but those that were highly concentrated could not be filtered immediately and had to undergo a digestion process, and a second subsampling procedure to make quantification feasible. All steps will be further detailed in the following sections.

3.4.3.1. Sample brush cleaning

In the lab, a petri dish was labeled with the corresponding date and brush code, and a fresh 20 μm filter was placed inside. The carabiner was removed from each brush, and each jar was filled with Milli-Q® water. The brush cleaning technique was developed beforehand by PG and employed for this project. A small squirt of Dawn dish soap was added to the jar, and the top of the stainless-steel brush stem was inserted into the head of a drill. Carefully, and on the lowest setting, the brush was spun inside the jar for three increments of 30 seconds, waiting a few seconds in between each round for the debris to settle. The brush was unhooked from the drill and lifted out of the jar while using Milli-Q® water to rinse any remaining debris on the bristles back into the sample. The brush was left to air dry and be reused at the next sampling.

3.4.3.2. Storing samples

Storage of samples occurred in two forms. Samples collected through October 5 were stored on filter papers in petri dishes. Those from September 28 and October 5 were noticeably more concentrated with both plastic particles and organic matter and had to be filtered onto multiple papers. By October 12, samples were stored in jars with ethanol for preservation to await organic material digestion later. Details about each of these methods are described below.

For the early samples that were stored in a petri dish, the filtration process came next, rinsing all parts of a vacuum filtration system before assembling. The receptacle was filled with Milli-Q® water and filtered once without any filter paper to ensure cleanliness. Next, the corresponding 20 μm polycarbonate membrane filter was placed on the frit. The jar of soapy, debris water was then poured into the vacuum filtration system. The jar was filled with fresh Milli-Q® water, shaken for 30 seconds, and filtered. This process occurred two more times to rinse the sides of the jar and ensure all debris deposited on the filter. Using tweezers, the filter was moved to its assigned petri dish. The jars and vacuum filters system were rinsed thoroughly with Milli-Q® water three times before moving on to the next sample. The jars air dried and were used again for the next field sampling.

For samples that were too concentrated with organics to be filtered immediately, the same laboratory procedure to clean the brushes was followed, but the soapy debris water was poured into a 20 µm sieve to remove excess liquid. The contents of the sieve were rinsed with Milli-Q® water into a smaller jar, to which a small amount of ethanol was added to preserve the sample. The jar was labelled with the date and brush code and set aside for organics digestion at a later point.

3.4.3.3. Organic digestion

Samples that were too concentrated underwent a 30% hydrogen peroxide (H_2O_2) digestion. Each storage jar (containing the collected debris in a mix of Milli-Q® water and ethanol) was poured into a 20 µm sieve to remove as much liquid as possible. The sample was rinsed into a 500 mL or larger beaker with H_2O_2. An additional 40 mL, or about three times the size of the sample, of H_2O_2 was added and the beaker was covered with aluminum foil and labeled with the sample date, brush code, and date/time that the digestion process began. A single hole was poked in the aluminum foil to let the sample breathe. The beaker was placed in a plastic tub in case the solution bubbled over. The tub was placed in an oven at 47°C for 24 hours, by which all organic material would be digested. Next, the sample was rinsed through the 20 µm sieve again, with the H_2O_2 caught in the sieve pan and disposed of accordingly.

To keep particles in these highly concentration samples from sticking to each other, a 10% Alcojet solution was used. To a two L beaker, 100g of Alcojet detergent and one L of Milli-Q® water were added. The beaker was placed on a stir plate and mixed until the Alcojet dissolved. The vacuum filtration pump was assembled and rinsed following the earlier procedure, and a 1 μm filter was placed on the frit. The Alcojet solution was filtered and stored in a clean jar.

3.4.3.4. Subsampling

Samples from later in the season that were highly concentration required subsampling by extracting 1.25% of the entire solution after using the 10% Alcojet. After the concentrated samples underwent H_2O_2 digestion, they were rinsed into a 500 mL beaker with Milli-Q® water, adding as much as needed to bring the total sample volume to 360 mL. Forty mL of the Alcojet solution was added, totaling 400 mL. At this point, a petri dish with a fresh 20 μm filter was labeled and the vacuum filter system was assembled and rinsed following previous protocol. Using a clean pipette, 5 mL of the 400 mL plastic-Alcojet solution was pipped into the vacuum filter. The pipette was moved up and down within the beaker, and from side to side, while piping to try to collect a representative sample of the solution. Milli-Q® water was used to rinse down the sides and bottom of the glass receptacle and pipette. This achieved a subsample of 1.25% of the original, allowing for more manageable counting. The remaining 395 mL of the solution was filtered through the 20um sieve to remove the Alcojet and rinsed with Milli-Q® water into a clean, labelled jar for storage.

3.4.3.5. Particle quantification

MPs were quantified by eye using the Omax Trinocular 20X-40X-80X 720p WiFi Stereo Microscope on Wide Table Stand with 56-LED Ring Light and a small, circular grid paper placed under the petri dish, provided by the pELAstic team, to structure counting. To set up the quantification process, a piece of clear projector paper was traced and cut to fit inside a 150 mm petri dish as a base. Strips of double-sided stick tape were placed across the paper circle. Each line was labelled with the corresponding date and brush code. The initial picking and counting protocol of the particles was consistent across all samples. Using a pair of fine tipped tweezers, the first 10 particles of each colour were picked from the sample paper and placed on the sticky tape. Using a sharpie, each particle was circled and numbered 1-10 to make them easier to see, and these counts were recorded on the data sheet. After the first 10 of each colour were counted, the tally procedure was started. Using the grid paper under the petri dish, plastics of each colour were counted using a clicker counter, moving from one grid box to the next. This total was tallied on a separate data sheet and added to the first. The tally was recounted twice more, for a total of three times, to ensure the correct number of particles was recorded. Samples that were extracted as 1.25% of the sample followed the same quantification steps, including picking the first 10 particles of each color and tallying the rest. The total was extrapolated up to represent the entire 400 mL solution and noted on a data sheet.

3.4.3.6. Quality assurance/quality control

To account for contamination, white cotton laboratory coats were worn during brush cleaning, filtering, and analysis to minimize microfiber shedding from everyday clothes. Although only certain plastics were being quantified in this experiment, reducing contamination is good practice and ensured samples would be less concentrated, and therefore easier to analyze. Additional protective equipment, such as goggles and gloves, were worn for safety and to prevent further human contamination. Glass storage jars were used to minimize MP degradation from plastic containers and to protect brushes while transporting from the lake to the laboratory. All sampling and analysis equipment was tripled rinsed with Milli-Q® water in between every use. The vacuum filtration system with run with Milli-Q® water before each sample to avoid contamination from others or the environment, especially in a shared laboratory space. Blank samples were collected at ELA, mimicking the procedures for brush cleaning and sampling filtering onto papers using Milli-Q® water. At Dalhousie, where the remaining processes (some filtering, H_2O_2 digestion, the 10% Alcojet solution, and subsampling) took place, Milli-Q® water was used to imitate these steps. No pELAstic particles were found in the blank samples. In picking the particles, I underwent several rounds of training on a practice sample, with positive results, and a lab mate looked over my first three days of environmental samples to ensure correct quantification and polymer identification. For most brushes, each round of counting a singular brush resulted in the same number, reducing error.

3.5. Results

Of the total 35 samples collected during deployment, 27 were processed, analyzed, and quantified using the above procedures. The remaining eight were given to PG prior to any analysis, so those samples may be noted throughout, but their particle concentrations will not contribute to analysis. The quantification procedure used by PG identified a total number of MPs in each sample, but this was across all potential polymers, as opposed to identifying only the three used by the pELAstic team. Figure 3.6. replicates the pontoon orientation and documents the date of each sample, as well as noting which brushes were double collected over the deployment and which samples were given straight to PG (meaning the concentration of pELAstic-specific particles in these is unknown). In the image, green-filled circles mark the brushes that were sampled twice, and blue bold text marks those sent to PG.

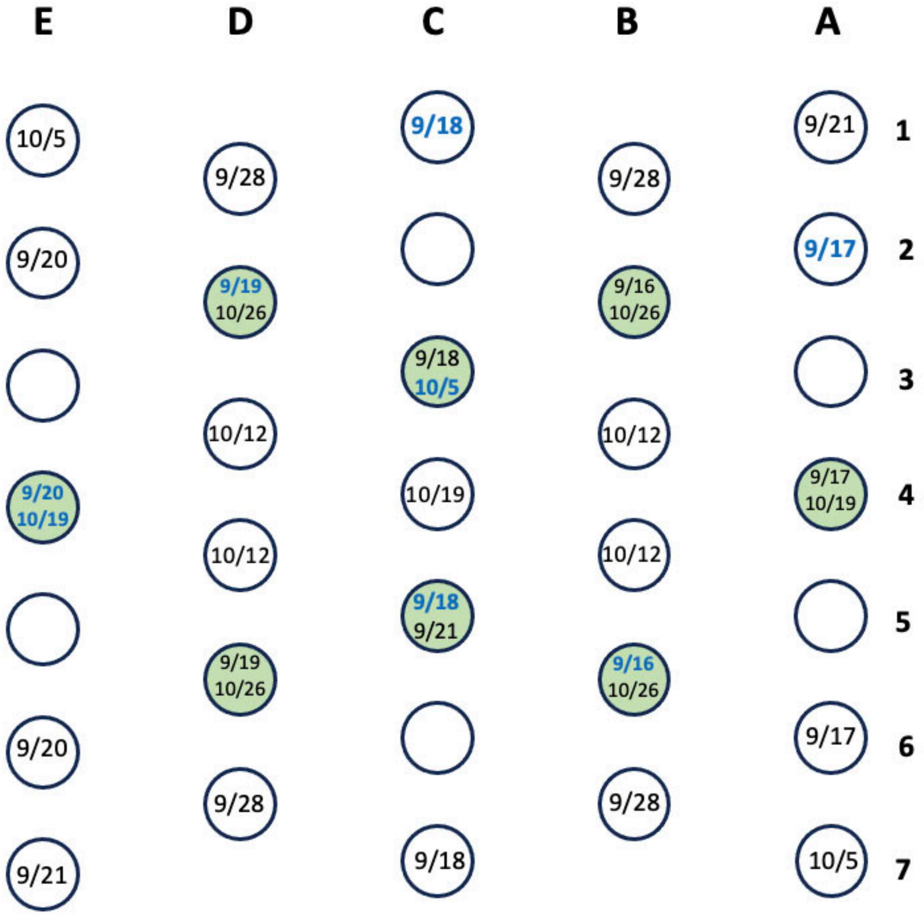

Figure 3.6. Diagram of brush orientation; rows labeled A-E and brushes numbered 1-6 (rows B and D) or 1-7 (rows A, C, and E). Designations are made for brushes that were sampled twice and those that were analyzed by PG using different methods.

In total, 89,800 particles from the pELAstic additions were collected by the sample brushes over the Plastic Hunter's six-week deployment. The smallest sample was 16 plastics on the first day taken from brush B2, and the largest was 7930 from B3 on October 12. Of these, most of the particles—89,775—were yellow (PE), with 21 pink (PS) polymers and four that were unidentifiable as one of the three colors, but that matched the shape, size, and material of the others. There were no blue (PET), despite the double doses on September 13 and 27. For the first week, during which samples were collected daily, concentrations sat below 500 particles per brush. After collecting brushes on September 20, the device was moved to the outside of the boom. Concentrations are not notably higher the next day, September 21, but after taking a week off and sampling on September 28, counts jumped into the thousands, where they stayed for the remainder of the deployment.

In Figure 3.7., the particle counts per brush are standardized by time, taking into account that each brush was deployed in the lake for a different amount of time before sampling. This assumes that the brush's retainment rate is consistent across its entire deployment, as opposed to collecting plastics at a steady rate before eventually plateauing. Samples analyzed by PG are not considered here.

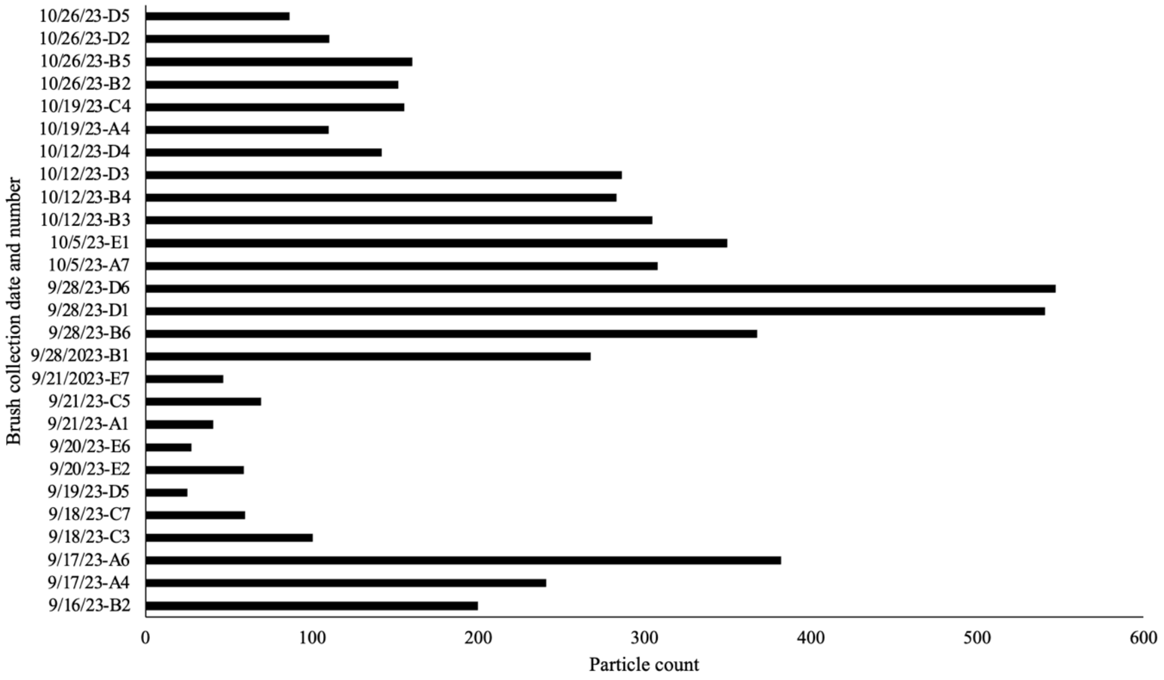

Figure 3.7. Number of MPs collected from each brush, divided by the numbers of days deployed.

Due to the wide range of polymer counts throughout the deployment, the following diagram (Figure 3.8.) serves as a "heat map" to identify plastic concentration per brush per numbers of days deployed. The map only accounts for weekly samples, which also began after the device was moved to the outflow side of the boom. Daily samples were disregarded as they served as an opportunity to troubleshoot and are not representative of a typical filtering schedule, which would see brush replacements on a weekly or longer basis. The colors correspond to concentration; light yellow represents under 100 particles, yellow is 100-200, orange is 200-300, bright red is 300-400, dark red 400-500, and black is more than 500 plastics per bush. White circles note brushes that were either not sampled at all, that were sampled during the daily collections, or that were analyzed by PG.

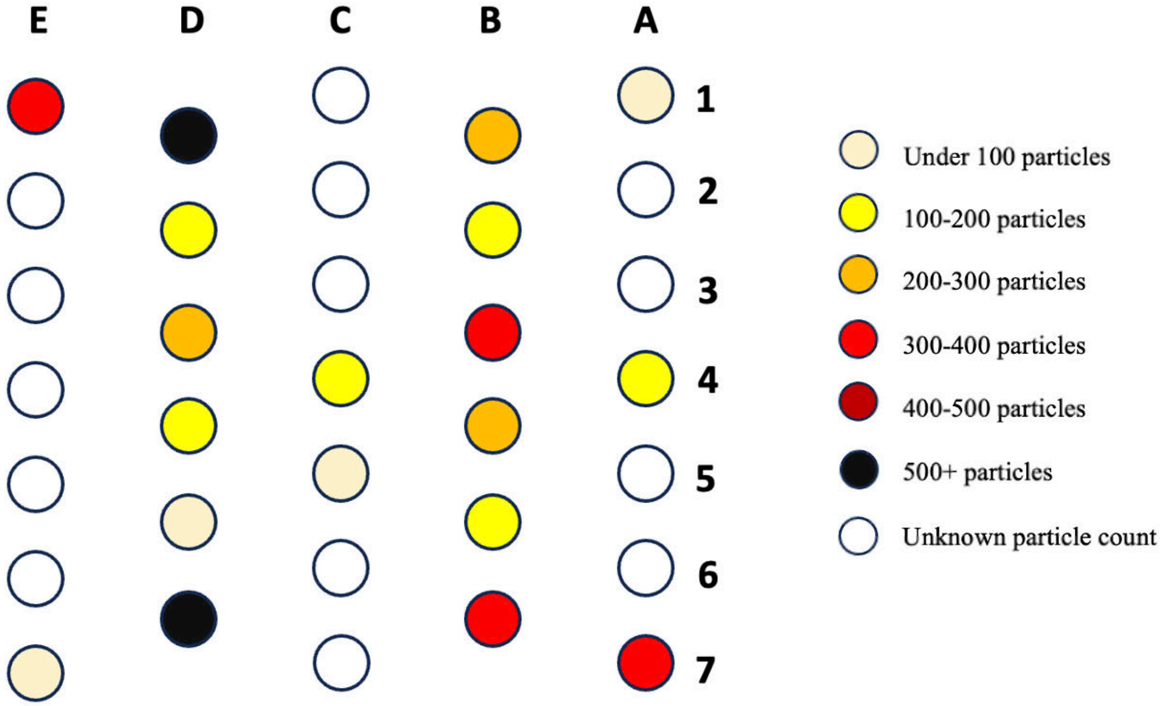

Figure 3.8. Weekly MP concentrations collected from each brush, standardized by the number of days deployed. Darker colors represent higher counts. Brushes that were not sampled on a weekly basis, but daily in the first week, or that were analyzed by PG were not considered here.

The highest particle counts came primarily from the outermost brushes, although the lower particle counts range across the device.

Of the eight brushes that were double sampled over the course of deployment (A4, B2, B5, C3, C5, D2, D5, and E4), five were unusable for this analysis, as either one or both samples were given to PG without implementing the pELAstic quantification. Of the remaining three brushes, all saw increases in plastic count and were left for a little over a month (ranging 31-39 days) between collections, as visible in Table 3.1. The first collection of all three brushes occurred during daily sampling (within the first three days), while the second collection was taken at weeks 5 and 6. Despite the difference in sampling time (daily versus weekly), the two sets of data are notable to display the increase in caught particles over the course of about one month.

Table 3.1. Three brushes that were collected twice throughout deployment, including MP particle counts and days between sampling.

Brush	Date	Particle Count	Days in Water
B2	September 16	16	0.08 (2 hours; 1/12 of a day)
B2	October 26	5932	39
A4	September 17	241	1
A4	October 19	3530	32
D5	September 19	76	3
D5	October 26	3211	37

B2 experienced the longest break between samples at almost a full 39 days and the most substantive particle increase—although A4 and D5 followed a similar pattern.

3.6. Discussion

This proof-of-concept study aimed primarily to test the Plastic Hunter’s ability to collect MPs from a lake-based ecosystem. This ability was confirmed by analysing 27 brushes samples over the six-week deployment. The second goal sought to quantify and identify the collected particles, which totalled 89,800 and consisted of primarily yellow MPs (PE). Lastly, trends or observations are discussed, including collection rate, MP characteristics, brush pattern, and limitations.

3.6.1. Collection rate

The total number of particles collected by sampling the Plastic Hunter (89,800) shows that the brush system is effective in its goal of collecting MPs from a lake-based ecosystem, although a definitive rate is difficult to determine. Using daily retainment rates, it is possible to extrapolate the device's weekly collection by averaging particle counts from the outer and inner brushes. The outside brushes, defined as A1, A4, A7, B1, B6, D1, D6, E1 and E7, average to about 286 particles accumulated per day. Together, the nine outer brushes could collect about 2574 MPs in one day. The inner brushes, consisting of B2-5, C4, C5, and D2-5, average to about 175 plastics daily. All ten inner brushes could collect about 1750 MPs each day. Added together, the entire device could retain about 4324 particles in one day. When multiplied by seven days, it can be estimated that weekly, the Plastic Hunter could collect around 30,268 MPs. It is important to note that this collection rate disregards potential discrepancies from unknown factors like the impact of the boom, the retainment limit of the brushes, and the small area of the lake surrounding the device. It is further limited by minimal sampling numbers and time, reducing the ability to identify robust and long-term trends.

3.6.2. Plastic characteristics

In addition to proof of concept, the quantities and behaviors of each polymer supported hypotheses and observations made in the field by various researchers. The blue (PET) particles were known to sink quickly, making them the least likely to be caught by the system, especially as the brushes only reached eight inches into the water column. The pink (PS) was known to slowly sink over time based on particle size, with large polymers settling in the first 24 hours and smaller particles taking a week or two (Rochman et al., 2024). This could explain why only a few PE polymers were caught by the Plastic Hunter. Yellow (PE) polymers remained on the surface of the water and were sometimes observed pooling in between brushes. The top eight inches of the water column were cleaned by the brushes, and it is likely that even more yellow plastics were collected from the surface or the pools as the brushes were lifted out of the lake. The high plastic counts, especially after the pontoon was moved outside of the boom, identifies that the boom was ineffective at preventing MP transport into the outlet area, although concentrations in each part of the lake were not compared (and therefore the severity of the boom bypass is unknown).

3.6.3. Brush pattern/orientation

Of the double-sampled brushes (B2, A4, D5), all three experienced increases in particle counts of at least 3000 between first and second collection, which ranged 31-39 days. While notable, these changes could also be in relation to moving the pontoon outside of the boom (see next section). Not many brushes were collected twice, and of the eight, five sets of data (whether the first, second, or both samples) were given to PG prior to the pELAstic quantification procedure. This rendered all five brushes useless when contributing to this comparison analysis;

with only three viable sets, these results require further substantiation. While each brush's particle count was also divided by days deployed to aid in comparisons, retainment rates are not identifiable. It is unknown how many particles truly adhered to the brushes each day or week; the device may have continued to accumulate plastics consistently, or possibly substantive gains were made in the first days or weeks, which then plateaued. There appears to be some correlation between brush orientation, but not one that confidently identifies a trend. The highest daily particle collections were made primarily by the outermost brushes, but the innermost brushes range from under 100 to almost 400 MPs. This could be indicative of a trend or could reflect wind and current conditions that cause the brushes and plastics to interact with each other in nuanced ways. Additionally, the brushes only hung eight inches into the water column. While collecting blue (PET) particles, which sink, would be unlikely, a deeper brush could collect more pink (PS) or give a better idea of the concentrations of the top of the water column. Furthermore, less of the brush would be wasted above the water, increasing the potential for improved efficacy.

3.6.4. Limitations

Several factors limit the wide applications of this research. First, the pontoon was anchored at one end of a lake. It is difficult to test device efficacy when exposed to only one small area, as opposed to assessing collection ability in different parts of the lake (shoreline/center) or when exposed to varying environmental conditions (wind or current may act differently one on side of the lake then the other). Additionally, once the pontoon was moved beyond the boom, the pontoon was limited to an even smaller area of water. The concentrations in this region, although higher than hoped given the use of a boom, were not representative of the whole lake, potentially skewing the base concentrations. Various environmental factors, like wind and water current, influenced the plastics in and on the water, as well as the orientation of the pontoon (it was anchored in one spot, allowing for slight drifting and spinning). This was poorly monitored and should be considered when identifying trends. The system wasn't deployed until late in the season, leaving only six weeks of sample collection. More time would've allowed additional sampling to gain better insight on retainment rate, pontoon design, and brush pattern. As such, it was hard to determine the durability and efficacy of the technology throughout the season and how many particles were collected over long periods of time (or with multiple rounds of sampling). Presumably by September, MP concentrations were likely higher than in June, when additions started. This impacted collection, as an earlier deployment may have had fewer particles to collect, and a longer deployment might reflect the increase in concentration throughout the additions.

3.7. Conclusion

This proof-of-concept study confirmed the ability of the PG filtration system to collect MPs from a freshwater lake. It has also quantified the number of particles and identified the polymers, within the guidelines of the pELAstic project. Substantive particle counts were collected over six weeks, reaching almost 8000 on a single brush, a potential daily collection of about 540, and 89,800 in total across all sampled brushes. Most MPs collected were PE (yellow). These findings support the potential for MP removal technology, especially in semi-contained freshwater ecosystems. Various factors may have impacted particle retainment and polymer type, including the length of deployment, environmental factors such as wind and water currents, and the orientation and location of the pontoon and brushes. This proof-of-concept study has provided a baseline alongside which other MP removal devices can undergo meaningful field testing. As such, further technological development and testing is crucial to better identify and evolve effective approaches. Specific focus is suggested on understanding filter retainment capacity and adapting the design to different aquatic ecosystems (e.g., lake, river, estuarine and marine).

Chapter 4: Existing and emerging technologies for aquatic microplastic removal

4.1. Introduction

Microplastics (MPs), measuring less than 0.5 cm (Boyle & Örmeci, 2020) are a pervasive form of plastic pollution. Plastic pollution is difficult to tackle due to variety in polymer, particle size, degradation, and ecosystem interactions (Fiore et al., 2022). Despite global action to combat pollution, the severity of the issue continues to grow, with an estimated 710 million metric tons of plastic waste entering aquatic and terrestrial environments between 2016 and 2040 (Lau et al., 2020).

MPs are often defined by their intended production; primary plastics, like microbeads, are purposefully engineered in microscope size (Wu et al., 2016). Secondary MPs come from the breakdown and fragmentation of larger plastics that already exist in the environment due to improper disposal or accidental release (Boyle & Örmeci, 2020). Primary plastics may also be subject to further degradation into smaller and more varied particles (Guo & Wang, 2019). Plastic particles can be released into the air, waste or stormwater systems, or be carried by surface runoff (Dris et al., 2015; Xia et al., 2020). From the atmosphere, MPs can settle back on land or the surface of water bodies (Klein & Fischer, 2019). Although the harmful effects of MPs on organisms are not consistently demonstrated, according to Lau et al. (2020), "ingestion has been document documented across trophic levels and at all depths of the ocean." MPs also carry chemical impacts, leaching additives and toxins absorbed at its origin (Boyle & Örmeci, 2020). Humans face health impacts from MP pollution, as well; particles can infiltrate the body through ingestion (Dey et al., 2021), inhalation (Ahmed et al., 2022), and direct contact with the skin (Revel et al., 2018).

Oceans were once considered primary sinks for MPs, but terrestrial and freshwater ecosystems are the primary source of plastic particles (Dey et al., 2021). An increasing number of studies over the past several years have shown MPs to be ubiquitous in global freshwater systems, including lakes, rivers, estuaries, and wetlands (Lu et al., 2021). Rivers, for example, transport plastics to larger freshwater bodies and to the ocean (Boyle & Örmeci, 2020). Freshwater matrices are also significant for their proximity to MP point sources and highly urbanized areas (Szymańska & Obolewski, 2020).

While research continues to identify, monitor, and characterize MPs and their interactions within the environment, some scientists recommend minimizing current pollution by developing plastic removal technologies (Schmaltz et al., 2020; Wu et al., 2016; Boyle & Örmeci, 2020; to name a few). More specifically, these technologies should either prevent plastics from entering waterways or collect particles from marine and freshwater sources (Schmaltz et al., 2020). Schmaltz et al. (2020) also points out that, to date, few reports have focused on such technologies and while current efforts are notable, their capacity and lack of widespread implementation present a limitation when compared to the vastness of MP pollution. Existing technologies are heavily focused on collecting MaPs and are primarily implemented in marine ecosystems (Schmaltz et al., 2020). While policy has an important role to play in curbing pollution, the global nature of MPs dictates that such efforts are more effective when coupled with private industry action and technological innovation (Schmaltz et al., 2020).

A terminology distinction within the MP removal conversation is important for better understanding current technological development. Many papers (Y. Zhang et al., 2021; Dey et al., 2021; Ahmed et al., 2022) discuss “technologies” to remove MPs from aquatic medium; these, however, can be better understood as techniques, as they represent different ways to collect particles that can then be implemented when developing devices. For the purposes of this research, removal "technologies" will refer to the system used to remove MPs, whereas "techniques" will reference the implementable and proven methods, as further described below. The terms "system" and "device" will be used interchangeably with "technology." Overall, numerous removal techniques have been identified and developed, including: adsorption, biofiltration, magnetic extraction, coagulation, electrocoagulation, membrane filtration, conventional activated sludge, biological degradation, and photocatalytic degradation (Dey et al., 2021), fungal pelletization (Wang et al., 2023), froth flotation and separation by oil film or density (Y. Zhang et al., 2021). However, no technique(s) has been identified as "best," and there has been little to no implementation on a global scale (Beladi-Mousavi et al., 2021).

This short systematic review summarized various approaches to aquatic, in-situ MP removal and identified existing technologies. Each was assessed using the following criteria, including which technique was employed, whether the device collects MP or MaP (or both), the aquatic medium, and current stage of scalability. Technologies trends were identified and summarized. The Plastic Hunter, designed by PolyGone Systems (PG), was contextualized by discussing its position amongst industry trends and other available MP removal methods.

4.2. Methodology

This study was guided by that of Schmaltz et al. (2020) and the subsequent Plastic Pollution Prevention and Collection Inventory, managed by Duke University's Nicholas Institute for Energy, Environment and Sustainability. Similar processes (although not as detailed) were followed, and the database served as a baseline for this research. A systematic literature review was performed to collect a list of MP removal technologies, beginning with looking through those documented in the Plastic Pollution Prevention and Collection Inventory, as some fit the criteria for this study and others did not. The criteria for this study are:

1. Technology must collect/remove at minimum MPs; those that also collect macro or NPs will be included to prioritize documenting all MP-relevant systems, but macro or nano-only devices will be excluded.
2. Collection/removal must happen in-situ, as opposed to preventing particle entry into a waterway. This includes common technologies like laundry machine filters.
3. All technology must be designed for aquatic medium, whether this be freshwater, marine, or otherwise.

No limitations will be applied to the efficacy or scalability of a device.

When first sorting through the Plastic Pollution Prevention and Collection Inventory, filters were applied to systems that sorted either only MPs or both MPs and macroplastics. Next, Scopus and Google searches were used to find both peer-reviewed papers and commercial coverage of technologies, using the query "microplastic" AND ("removal" OR "collection") AND "technology" AND NOT "wastewater." The exclusion of wastewater was necessary as multiple devices exist for this type of MP removal, but they aren't applicable to in situ cases. No other restrictions, like date range, were applied to identify all potential systems. A variety of sources were considered, ranging from peer-reviewed papers to press releases to media coverage, as the industry is small, and many MP technologies have yet to undergo detailed field testing and publication. The last method for identifying potential devices was applying the above query to patent databases, specifically for the United States (US), Canada, and the European Union (EU). The goal was to include new technologies that may not be featured in published content and that the previous searches may have missed. The search query for all three patent sites was identical and like above: “microplastic” AND (“removal” OR “collection”) AND “technology.” The wastewater exclusion was not added, as AND NOT was not an available Boolean operator. Additional, one-off searches were then made based on a case-by-case basis, often times to track down mentions of other potential technologies. Once all systems were compiled into one spreadsheet, duplicates were removed. Targeted searches were performed with the remaining technologies on when important details for categorization were missing. This review was conducted by one individual, meaning that although each search was screened more than once, risks of incomplete submissions, missing details, or bias are possible. Finally, all MP removal devices were identified by the following characteristics:

1. Name
2. Affiliation (if the technology is funded/designed by a company or entity, as opposed to an individual)
3. Particle size
4. Aquatic medium
5. Type of technology (what technique is responsible for the removal)
6. Current state (Is this a pilot design? Is it in commercial use?)
7. Link to corresponding source
8. Other relevant details/thoughts about the systems
9. If the technology is in the Plastic Pollution Prevention and Collection Inventory, as this served as the study’s starting point
10. The last date that the device was researched for this study
11. If the technology has been cited in peer-reviewed work, and if so, which publication

A flowchart of the methodology is visible in Figure 4.1.

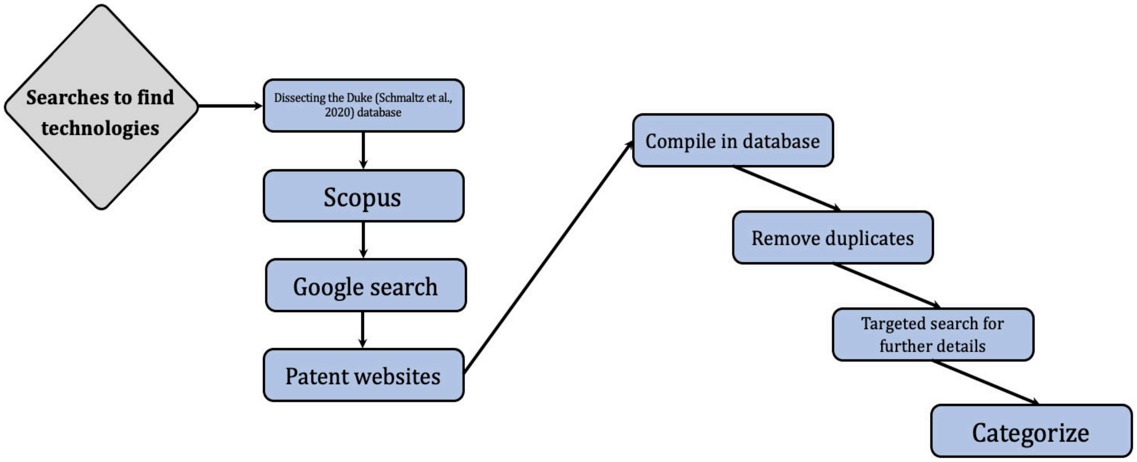

Figure 4.1. A simplified methodology employed in this study to assemble a list of aquatic MP removal devices.

After categorizing the list of devices, trends were identified to assess the current state of MP removal technology. Characteristics like use status, particle size, and aquatic medium were examined across all entries to track development and highlight gaps. It is important to note that this list is likely not all-inclusive, especially as the patent databases of all countries could not be considered, so some systems may have been unintentionally excluded.

4.3. Results

4.3.1. Number of technologies

A total of 38 technologies were identified to fit the criteria for this study, found through Duke University's Plastic Pollution Prevention and Collection Inventory, Google searches, peer-reviewed literature and patent databases. Some devices had easily identifiable characteristics, while others left little to assess and were likely not up to date. A complete list of the technologies, their capabilities, and current status can be found in Table 4.1.

Table 4.1. The 38 aquatic MP removal technologies identified to fit the required criteria, as pulled from existing inventories, Google searches, peer-reviewed literature, and patent databases.

Device name	Affiliation	Particle size	Aquatic medium	Technique	Current state	In Duke Inventory?	Cited?	Last date checked
Seabin	Cleaner Oceans Foundation Ltd	All	Marinas/ports	Filter; skimmer	In use	Yes	Schmaltz et al. (2020), Fiore et al. (2022)	4/16/24
Cloud of Sea		Micro	Attached to vessels	Filter; skimmer	Designed for competition	No	Fiore et al. (2022)	4/16/24
	Mitsui OSK Lines, Miura Co, Ltd	Micro	Attached to vessels	Filter	Pilot	No	Fiore et al. (2022)	4/16/24
Plastic Hunter	PolyGone Systems	Micro	River/streams, lakes	Filter, brushes	Pilot	Yes		4/16/24
LADI	Civic Laboratory for Environmental Action Research	Micro	Open water	Filter, trawl	In use	Yes		6/13/24
Amphibious Vehicle	British International Education Association	Micro, specifically PS	Open water	Infrared drone to identify plastic and hydraulic arm to collect	Designed for competition	Yes		6/13/24
Skroow Trash	Northern Arizona University	Micro	Attached to vessels	Filter	Designed for competition	Yes		6/13/24
	Suzuki Marine	Micro	Open water	Filter	In use	Yes		6/13/24
GoJelly	EU Horizon (2020)	Micro	Open water	Filter	Unknown	Yes	Schmaltz et al. (2020)	6/14/24
YUNA	James Dyson Award	Micro	Open water	Filter	Designed for competition	Yes		6/14/24
Marine Bot Cleaner	GEMS United Indian School	Micro and macro	Open water	Debris receptacle	Not in use	Yes		6/14/24
Clearbot		Micro and macro	Open water	Boom (mini)	In use	No		6/14/24
	Sichuan University	Micro	Open water, surface	Adsorption	Not in use	No		6/14/24
	University of Chemistry and Technology, Prague	Micro	Open water	Magnetism	Not in use	No		6/14/24

	Sepuluh Nopember Institute of Technology	Micro	Concentrated flow	Sound waves	Not in use	No		6/14/24
	Fionn Ferreira	Micro and nano	Contained waterbody	Ferrofluid	Designed for competition	Yes	Schmaltz et al. (2020)	6/14/24
OC-Tech	Ocean Cleaner Technology	Micro and macro	Unknown	Debris receptacle	Unknown	Yes	Schmaltz et al. (2020)	6/20/24
Marina Trash Skimmer		Micro and macro	Marinas/ports	Filter; skimmer	In use	Yes	Schmaltz et al. (2020)	6/20/24
LittaTrap	EnviroPod	Micro and macro	Concentrated flow	Filter	In use	Yes		6/20/24
The Great Bubble Barrier		Micro and macro	River	Bubble curtain	In use	Yes	Schmaltz et al. (2020), Fiore et al. (2022)	6/20/24
Cobalt	Ichthion	Micro and macro	River, coastal	Filter, membrane	Pilot	Yes		6/20/24
Ultramarine	Ichthion	Unknown	Attached to vessels	Filter	Pilot	No		6/20/24
	Surfrider Europe/Surfing for Science	Micro	Open water	Filter, trawl	Pilot	No	Camins et al. (2020)	6/22/24
Microplastic sensor	Ocean Diagnostics	Micro	Unknown	Unknown	In development	No		6/22/24
Ascension		Micro	Unknown	Filter	In use	No		6/22/24
ASTM D8332		Micro	River	Filter, sieve	Not in use	No	Bryska et al. (2024)	6/22/24
AquaPod	Clean Sea Solutions	Micro and macro	Marinas/ports	Debris receptacle	In use	No	Fiore et al. (2022)	6/22/24
	Blue Whale Ocean Filtration	Micro and macro	Unknown	Filter	Pilot	No		6/25/24
"Aquatic Remediation System"	Rodney Herring	Unknown	Unknown	Unknown	Unknown	No		6/25/24
"Methods, Apparatus, and Systems for Detecting and Removing Microplastics from Water"	AIZACO	Micro	Unknown	Unknown	Pilot	No		6/25/24

"Method for removing nano and micro plastics in water body by utilizing light energy driving"	Nanjing Medical University	Micro and nano	Unknown	Bubble separation with light energy	Unknown	No		6/25/24
"Integrated solar unmanned ship capable of collecting water surface microplastics and algae and drop aeration"	Changsha University of Science and Technology	Micro	Unknown	Unknown	Unknown	No		6/25/24
JFE Ballast Ace	JFE	Micro	Attached to vessels	Filter	Unknown	No		6/25/24
"Flocculation Cyclone Device, Marine Plastic Removal System Using The Same, Ship Provided With The System, And Operation Method For The Ship"	Akira Mochizuki	Unknown	Unknown	Unknown	Unknown	No		6/25/24
"Enhanced Microplastic Removal"	Thomas Robert Swanson	Micro, at minimum	Unknown	Unknown	Unknown	No		6/25/24
"Methods, Apparatus, and Systems for Detecting and Removing Microplastics From Water"	Carlos Alberto Hernandez Gutierrez	Micro, at minimum	Unknown	Unknown	Unknown	No		6/25/24
"Microplastic Cleaning, Collection, And Autonomous Filtration"	James McDonagh/IBM	Micro, at minimum	Unknown	Unknown (filter?)	Unknown	No		6/25/24

"Aquatic Biofiltration System"	Hans Gude Gudesen	Unknown	Unknown	Unknown (filter?)	Unknown	No		6/25/ 24

4.3.2. Source

Of the 38 devices, 39.47% (n=15) were identified from the Plastic Pollution Prevention and Collection Inventory to fit the necessary criteria. Another 13.16% (n=5) were found through peer-reviewed work, including Fiore et al. (2022), Camins et al. (2020), and Bryska et al. (2024). Some of those identified through the Inventory were also cited in Schmaltz et al. (2020). Around 18.42% (n=7) were discovered through Google searches and the last 28.95% (n=11) are from patent databases from the US, Canada, and the EU. Figure 4.2. depicts the breakdown of technologies from each source.

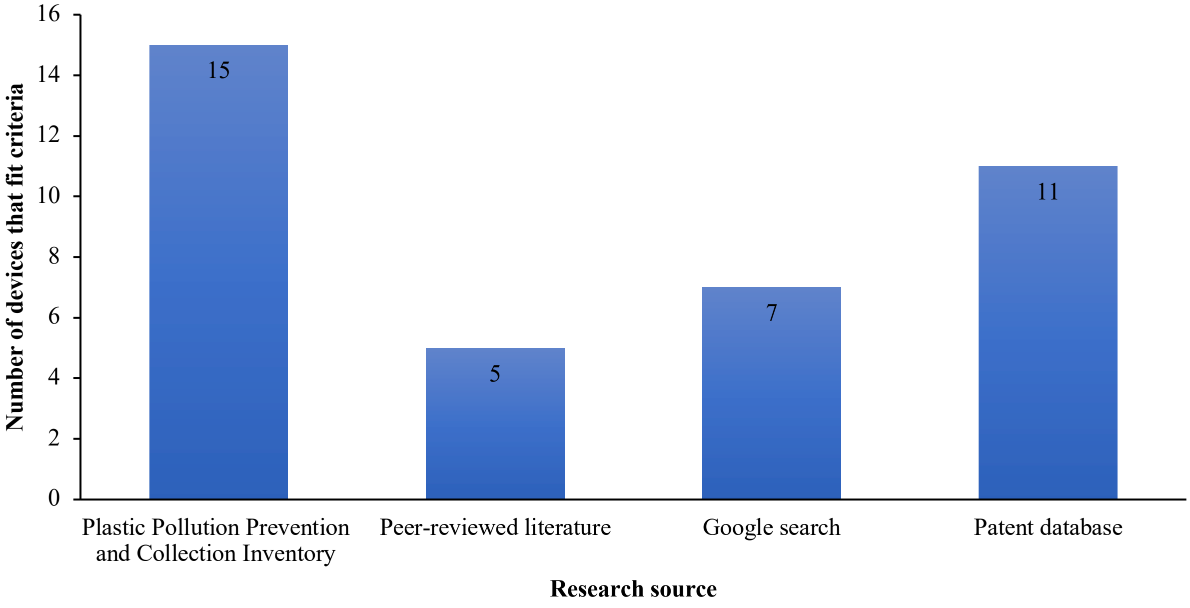

Figure 4.2. Distribution of MP removal devices found from each search source.

Across the three patent sites, there were multiple overlapping submissions (Figure 4.3.). Independent of each other, there were two US and three EU patents. When overlapping submissions were considered, one was found in both the American and Canadian databases, three in both the US and the EU, and two shared between the EU and Canada.

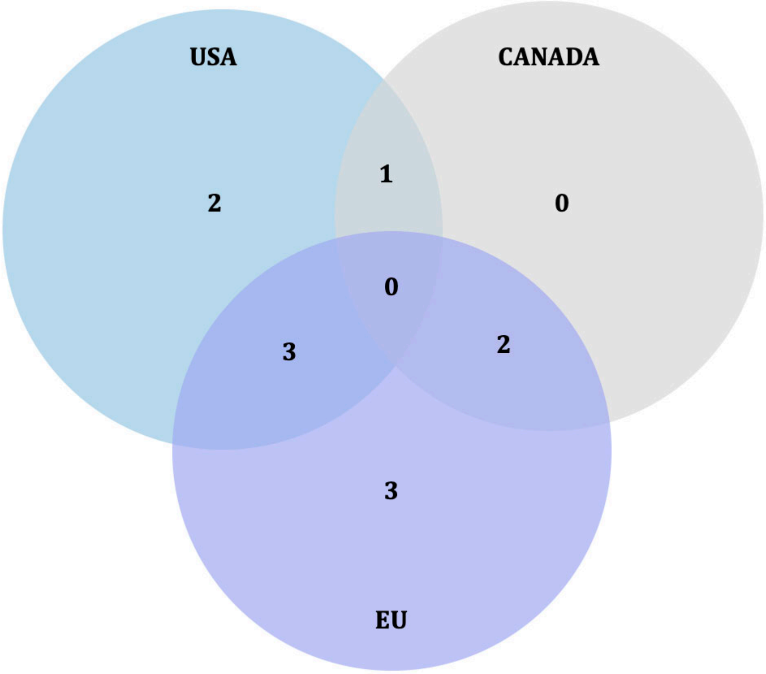

Figure 4.3. Of the devices found through patent databases, some overlaps between regions occurred. The figure displays the overlap of devices found through the US, EU, and Canadian patent sites.

4.3.3. Aquatic medium

Global MP studies have largely focused on marine systems until recently, and it was expected that MP removal technologies would also neglect freshwater medium. Each device was identified by the ideal waterbody, whether that be in a river, lake, ocean, or any variation (Figure 4.4.). Very few, only 10.53% (n=4) were designed specifically for a freshwater source. Many were vague, requiring simply an open area of water (26.32%; n=10). Of these, one specified in surface water (although neglected to clarify fresh or marine water). Three (n=3; 7.89%) were designed for use in a marina or port, but again, whether this was by a lake, or the ocean was not identified.

A few, at 13.16% (n=5), require attachment to a ship for use, with two specific to ballast water, two designed for maritime vessels, and one with little specification. Three more systems (n=3; 7.89%) identified a contained or controlled water source; one requires a contained body of water and the other two benefit from a concentrated flow. Much broader, 34.21% (n=13) remained unknown and did not specify any kind of aquatic medium.

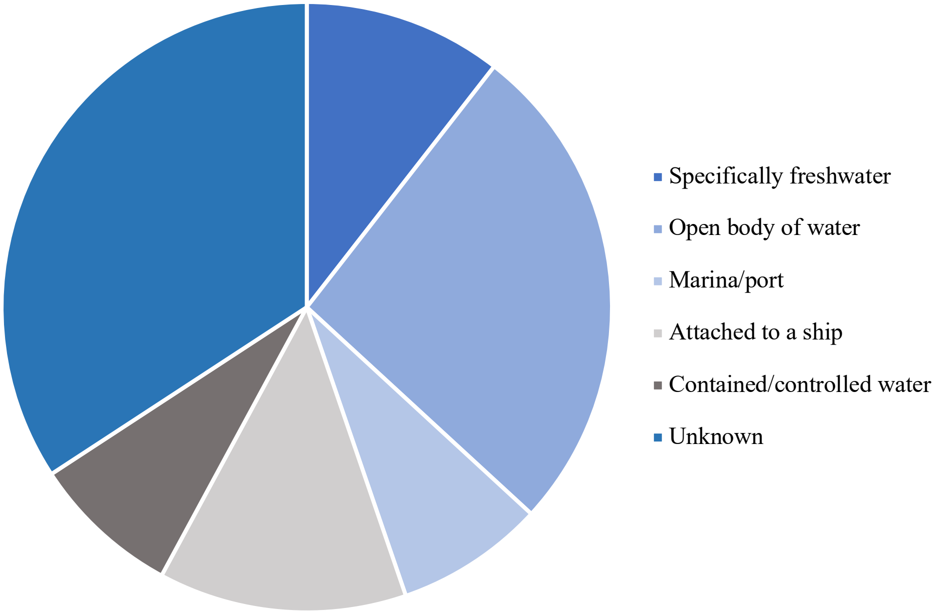

Figure 4.4. Distribution of MP removal devices and their suggested aquatic mediums.

4.3.4. Particle size

The plastic polymer size targeted by each removal technology is as equally defining as the designated aquatic medium. Macroplastic removal devices are more common given the larger debris size and increased ability to see and characterize polymers, which aids in proper disposal and policy development. Given the small size of MPs, many macro-specific technologies are unable to consistently collect these particles. However, the global and ecosystem-wide pervasiveness of MPs intensifies the urgency and need to establish effective removal methods. In this study, macroplastic-only devices were excluded, focusing on those that collect only MPs or additionally nano or macro particles (the ability to remove all three is unlikely). By this criterium, all 38 technologies should collect MPs; however, 10.53% (n=4) remained unknown due to vague product descriptions. These were kept in the final list because they were found through queries that included “microplastic” as a search term. Beyond these, half (50%; n=19) are designed exclusively for MP removal. A little over one third (n=13; 34.21%) collect MPs and macroplastics; this includes three technologies that, based on device names and descriptions, likely collect at least micro-sized particles, although this is not confirmed. Examples include two of the US patents, titled "Methods, Apparatus, and Systems for Detecting and Removing Microplastics From Water" (#20220306488 A1) and "Microplastic Cleaning, Collection, And Autonomous Filtration" (#11034592 B1). The remaining 5.26% (n=2) collect micro and nano polymers (Figure 4.5.).

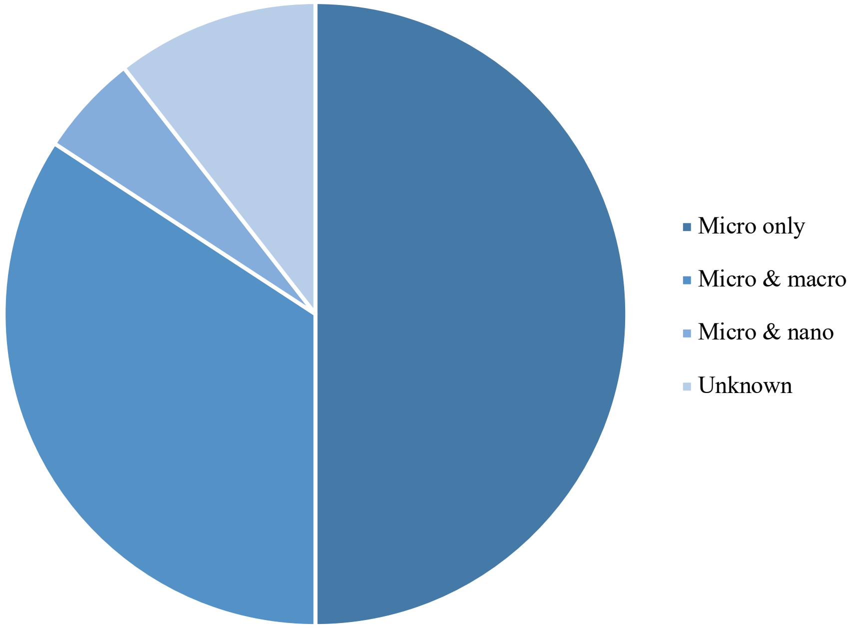

Figure 4.5. The size of plastic polymer designed to be caught by the devices.

4.3.5. Collection method

Many studies on MP removal, including those by Y. Zhang et al (2021), Dey et al. (2021), and Ahmed et al. (2022), discuss methods for collecting particles from the environment, like filtration, adsorption, or degradation. Some techniques are more effective, scalable, or cost-conscious, while others may be difficult to implement and manage. The methods found through this study are displayed in Figure 4.6. Unsurprisingly, filtration proved to be the most common method amongst the identified technologies (47.37%; n=18), as filters are durable and require lower management/oversight. Of those, 7.89% (n=3) specified use of a skimmer, 5.26% (n=2) with a trawl, 2.63% (n=1) with a sieve, 2.63% (n=1) with brushes, and 2.63% (n=1) with a membrane filter. Three devices (n=3; 7.89%) collect or push debris into a storage basket or bag. Nine (n=9; 23.68%) do not have identifiable removal methods, although two are likely filters based off their patent names, "Microplastic Cleaning, Collection, And Autonomous Filtration" (#11034592 B1) and "Aquatic Biofiltration System" (#20200120908 A1). The remaining eight technologies each represent a different technique (n=1, 2.63%):

- The Amphibious Vehicle uses an infrared drone to identify plastic and a hydraulic arm to collect particles.
- Clearbot employs a mini boom.
- An unnamed device from Sichuan University utilizes adsorption.
- Another unnamed technology from University of Chemistry and Technology, Prague uses magnetism.
- An unnamed device from Sepuluh Nopember Institute of Technology employs sound waves.
- Another unnamed technology designed by Fionn Ferreira utilizes ferrofluid.

- The Great Bubble Barrier uses a bubble curtain.
- A patent from Nanjing Medical University (#202110765580A·2021-07-07), "Method for removing nano and micro plastics in water body by utilizing light energy driving," uses light energy for bubble separation.

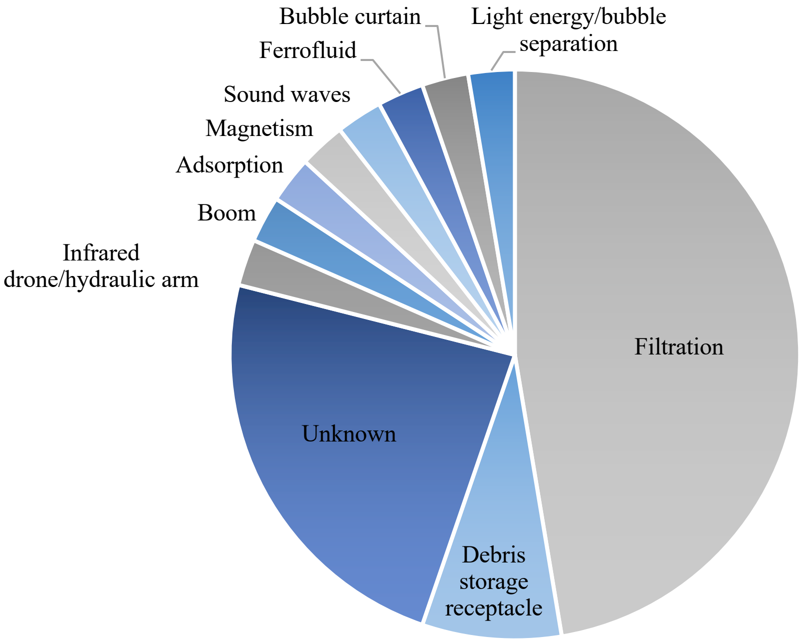

Figure 4.6. Collection methods used by MP removal devices.

4.3.6. Use status

Schmaltz et al. (2020) discusses that despite the efforts of current technological developments, a lack of capacity and widespread implementation presents a limitation when compared to the vastness of MP pollution. This issue is apparent in this study, as many technologies have not passed the pilot phase, with several being inventions for a scientific competition and never seeing further development. In total, just under half (n=17; 44.74%) are in some sort of active use, whether this is commercialized use (n=9; 23.68%), pilot testing (n=7;

18.42%), or in earlier stages of development (n=1; 2.63%). Ten devices (n=10; 26.32%) are not actively in use, with half of those (n=5; 13.16%) designed for a scientific competition or challenge, but never developed further. The status of the remaining 28.95% (n=11) remain unknown. Figure 4.7. depicts the distribution of technologies across different use statuses, including further dividing the active category.

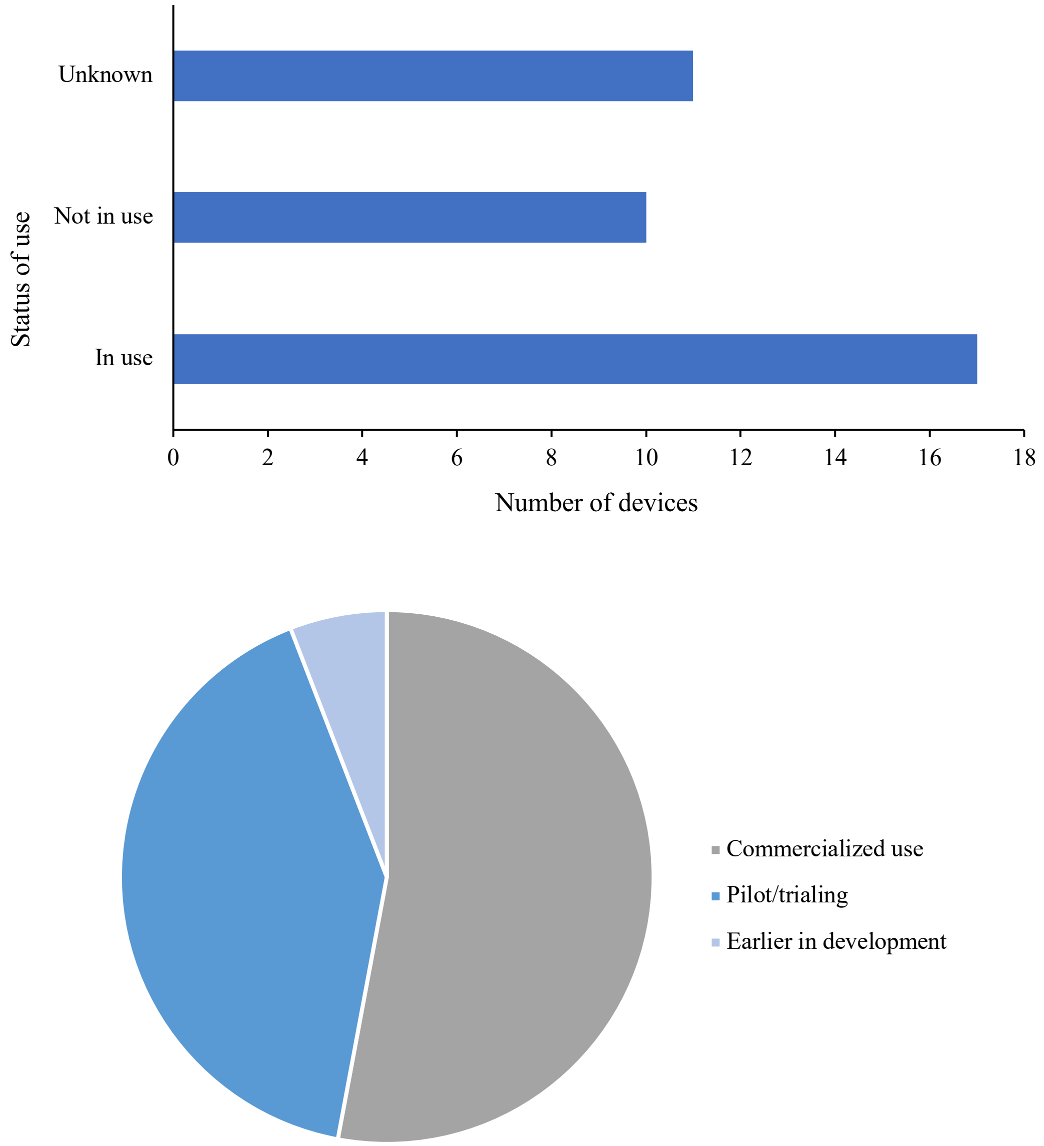

Figure 4.7. The use status of the identified MP removal technologies. The "in use" category can be further broken down between commercialized, pilot/training, and earlier stages of development.

4.4. Discussion

Most technologies identified in this study were found in Duke University's Plastic Pollution Prevention and Collection Inventory, which serves to facilitate comparisons between solutions and assess the current standing of solutions to plastic pollution (Schmaltz et al., 2020). As such, and as likely the most recently updated compilation of removal/collection technologies, it was used as a baseline. However, there have been no known additions since 2022 and the criteria to be included in the inventory differed from this study, which prioritized in-situ, aquatic MP removal systems. Google searches, peer-reviewed literature, and patent databases were used to supplement the inventory findings, with inconsistent results, as not every technology has defined and accessible details. As such there are limitations to the completeness of this list, which should be considered when analyzing trends. Additionally, this discussion will contextualize the Plastic Hunter in the larger discussion of MP removal, but as this device was field tested and thoroughly examined in the previous chapter, it is better known and this skew in information should be noted.

4.4.1. Freshwater removal technology

Aquatic plastic pollution has long focused on marine ecosystems, with recent studies and field tests branching into freshwater lakes, rivers, and other bodies. The pervasiveness of MPs is thought to originate in many freshwater sources due their proximity to highly urbanized areas, and these waterways contribute significantly to the transport of particles to other bodies, whether freshwater or marine. However, MP removal technology still neglects properly addressing freshwater sources, with only four of the technologies in this study specifying use in a river or lake: the Plastic Hunter (PG), The Great Bubble Barrier, and the ASTM D8332 exclusively cite rivers, streams, and/or lakes, and the Cobalt (Ichthion) mentions both rivers and coastal regions.

The remaining technologies face the same barrier; they were either vague about use or their ideal water type was unable to be determined. Of the former, the LADI (Civic Laboratory for Environmental Action Research), the Amphibious Vehicle, the filter by Suzuki Marine, the GOJelly (EU Horizon), the YUNA (James Dyson Award), the Marine Bot Cleaner (GEMS United Indian School), the Clearbot, the systems by Sichuan University and the University of Chemistry and Technology, Prague, and the Surfrider Europe filter, all state use in “open water,” with no differentiation between freshwater or marine ecosystems. Similarly, three technologies required a controlled or concentrated flow of water: the LittaTrap by EnviroPod and the devices from Sepuluh Nopember Institute of Technology and Fionn Ferreira. However, there is again no further detail about the ideal ecosystem for deployment.

Eight technologies are specific about physical deployment location but not water type (except for one). Three are deployed in a port or marina, but this could be on a lake, river, or coastline: the AquadPod (Clean Sea Solutions), the Marina Trash Skimmer, and the Seabin (Cleaner Oceans Foundation, Ltd.). Five specify attachment to a vessel or interaction with ballast water, with only one specifying a maritime vessel (the filter by Mitsui OSK Lines, Miura Co, Ltd.).

It is possible that the vagueness represents an indifference between different aquatic ecosystems, and that many devices can be used in fresh or marine sources. However, as rivers, lakes, and streams differ greatly in hydrogeology and biochemical properties, a lack of purpose-designed technology poses a barrier in effective MP removal and commercial scalability.

4.4.2. Micro-specific plastic removal

Schmaltz et al. (2020), which served as a guide for this study, gathered a majority (59%) of MaP removal technologies for the inventory. The list compiled here does not reflect that trend, as devices that targeted MaP were deliberately excluded to focus on MP opportunities. The majority of systems that fit this criterion was exclusively designed for MPs, which is a positive trend for purpose-designed, effective technology. However, other factors, like vague deployment location (see previous section) and a lack of development (see next section) still present barriers for the broader MP removal industry.

Of the devices that were designed exclusively to collect MPs, only one specified a target polymer. The Amphibious Vehicle, which was submitted for a competition with the British International Education Association, aimed to removal polystyrene (PS), which is found in items like food packaging, building insulation, electrical and electronic equipment, and eyeglasses frames (Tursi et al., 2022). While an interesting goal, it is worth debating whether polymer-specific collection is better suited as a form of pollution prevention, as opposed to environmental recovery. Additionally, it can be argued that given the current widespread and growing status of MP pollution, it is more effective to collect all particles possible, as opposed to narrowing in on one.

Fifteen technologies collected more than just MPs; thirteen, including the OC-Tech (Ocean Cleaner Technology) and the device by Blue Whale Ocean Filtration also targeted macroplastics. This is unsurprising, as macroplastics can be small (down to 0.5 cm, depending on the characterization) and even large debris is more likely to be caught. On the other end of the spectrum, the "Method for removing nano and micro plastics in water body by utilizing light energy driving" (Nanjing Medical University) and the system by Fionn Ferreira collected both micro and nanoplastics. Seabin (Cleaner Oceans Foundation Ltd) claims to collect all plastic particles. The range is impressive and opens a new door to plastic removal technology, as nanoplastics are increasingly small and varied in polymer and shape, making their collection even more difficult than that of MPs.

4.4.3. Removal method

As discussed earlier, there are several techniques that can be employed when removing MPs from aquatic milieu, but none have been identified as best. However, the most commonly used methods amongst different devices can highlight what may be the most affordable, scalable, effective or convenient. Aside from the nine technologies with unidentifiable collection techniques, an overwhelming majority (47.37%) employ filters. The type of filter varied, with the most popular options being a skimmer (Seabin by Cleaner Oceans Foundation Ltd., Cloud of Sea, and Marina Trash Skimmer) or a trawl (LADI by Civic Laboratory for Environmental Action Research and the device by Surfrider Europe). Other filters employed brushes (Plastic Hunter by PG), a sieve (ASTM D8332), or a membrane filter (Cobalt by Ichthion). This identifies skimmers and trawls as common choices for MP filtration, but not the only options. While filters appear to be a strong choice, further research into their efficacy and convenience is necessary to make a more definitive claim about best removal methods.

The next most popular method was pushing or collecting debris in a receptable. OC-Tech (Ocean Cleaner Technology) and Marine Bot Cleaner (GEMS United Indian School) both utilized a debris storage basket, whereas the AquaPod (Clean Sea Solutions) uses a mesh bag for containment. The use of a debris containment system is likely popular because of how little maintenance and monitoring this process requires. It also requires less installation effort in an area with existing infrastructure, like in a port or on a vessel or bridge.

Several collection and removal techniques were featured, although only each was only represented by one system. The technologies from Sichuan University, the University of Chemistry and Technology, Prague, Sepuluh Nopember Institute of Technology employed adsorption, magnetism, and sound waves, respectively. Fionn Ferreira's device uses ferrofluid. Clearbot uses a mini boom, The Great Bubble Barrier benefits from a bubble curtain, the system from Nanjing Medical University ("Method for removing nano and micro plastics in water body by utilizing light energy driving") uses light energy to drive bubble separation, and the Amphibious Vehicle uses a hydraulic arm to collect identified particles. While all technologies are notable in their development and efforts, these methods are difficult to employ on a large scale and require continual oversight.

4.4.4. Scalability

Schmaltz et al. (2020) identifies scalability as one of the biggest barriers to mass aquatic MP removal. Various technologies and techniques are a good indicator of plastic pollution as a priority, but until these solutions are deployable at a commercial level, in tandem with policy and prevention mandates, there is little hope for the future of aquatic ecosystems.

The technologies identified in this study, luckily, are well balanced across the spectrum of development. Several are not in use, but many are currently in regular deployment, including Seabin (Cleaner Oceans Foundation Ltd), the device from Suzuki, Clearbot, the Marina Trash Skimmer, LittaTrap (EnviroPod), The Great Bubble Barrier, Ascension, AquaPod (Clean Sea Solutions) and LADI (Civic Laboratory for Environmental Action Research). The frequency and caliber of use are unknown, but these technologies prove that scalable removal solutions are possible for aquatic MP removal. Similarly, several devices are in development, either undergoing trials or pilot tests. This category includes the systems from AIZACO ("Methods, Apparatus, and Systems for Detecting and Removing Microplastics from Water"), Surfrider Europe, Blue Whale Ocean Filtration, Mitsui OSK Lines, the Plastic Hunter (PG) and Ultramarine and Cobalt (Ichthion). The microplastic sensor from Ocean Diagnostics is also in development. Altogether, about half of the technologies that met the criteria for this study are in use or headed in that direction.

It is problematic that the other half are either not in use, or their status is unknown (like the JFE Ballast Ace). The most notable subcategory is those that were designed for a competition or awards but never furthered, including Skroow Trash (Northern Arizona University), YUNA (James Dyson Award 2019), the device by Fionn Ferreira (Google Science Fair), the Amphibious Vehicle (British International Education Association), and Cloud of Sea (James Dyson Award 2020). There is significant value in encouraging the invention of such solutions, especially amongst youth and in academia, but there is little benefit for the grander problem if the project ceases after winning a prize.

4.4.5. Unknowns

Throughout this discussion, several technologies have been neglected as a significant amount of information is missing. It is notable that these vague devices were found through the patent database search, although they aligned with the search query, which specified aquatic MP removal or collection technology.

Table 4.2. Seven systems that were found through the patent database search contain vague or few details, making it difficult to assess their relevancy in this research.

Device name	**Affiliation**	**Patent number**
“Aquatic Remediation System”	Rodney Herring	#CA 3110376/CA 3150206
"Integrated solar unmanned ship capable of collecting water surface microplastics and algae and drop aeration"	Changsha University of Science and Technology	#CN 201910833844A·2019-09-04
"Flocculation Cyclone Device, Marine Plastic Removal System Using The Same, Ship Provided With The System, And Operation Method For The Ship"	Akira Mochizuki	#US 20240189834 A1/#JP 2021-081578
"Enhanced Microplastic Removal"	Thomas Robert Swanson	#US 20240124325 A1
"Methods, Apparatus, and Systems for Detecting and Removing Microplastics From Water"	Carlos Alberto Hernandez Gutierrez	#US 20220306488 A1
"Microplastic Cleaning, Collection, And Autonomous Filtration"	James McDonagh/IBM	#US 11034592 B1
"Aquatic Biofiltration System"	Hans Gude Gudesen	#US 20200120908 A1

It is worth noting that not all patent finds were like this; many had additional details found through independent Google searches. However, little information was found on these seven technologies, rendering them potentially unreliable; this is acknowledged as they may skew trend analysis. This instance also highlights a more serious, possibly ongoing problem within MP removal technology development where solutions are not followed through to commercialization and difficult to track, impeding the progress of organizations and governments that want to commit to aquatic remediation.

4.4.6. PG's Plastic Hunter

The previous chapter of this thesis field tested a pilot device by PG, the Plastic Hunter, to determine efficacy in a contaminated lake ecosystem and monitor the behavior of different polymers. It was determined that the filter brushes were effective, although the project-specific design may not be ideal for further implementation.

Within the scope of this study, the Plastic Hunter aligns with the majority trends for most of the criteria. The brushes are designed to mimic natural root filtration and aimed for use in freshwater ecosystems and WWTPs—the former of which is crucial for growing removal solutions that are specific to freshwater bodies. Additionally, the tech is aimed at MP collection and not limited by polymer, other than when hydrophysical conditions inhibit the interaction of certain particles with the brushes (the blue PET used in the pELAstic project are known to sink in the lake, minimizing overlap between those polymers and the shallow filter). The system employs a version of filtration, which was determined to be the most common method in this study. The filter brushes require minimal maintenance and repair when in field, aside from sampling. However, it must be noted that the particle load and retainment rate were not able to be determined. Lastly, PG is well positioned for scalability as they currently undergo various pilot tests across North America, including with the pELAstic project and WWTP in New Jersey. The company has won numerous awards, including a recent $1.9 million grant from the National Sea Grant Infrastructure Investment and Jobs Act (IIJA) Marine Debris Challenge Competition to use in conjunction with the New York Sea Grant (NYSG), a cooperative program between the State University of New York, Cornell University, and the National Oceanic and Atmospheric Administration. While this does not guarantee the success of a technology, PG is situated to pursue further development and scaling of the Plastic Hunter, which is a barrier faced by other devices.

4.5. Recommendations

This study has offered a brief review of existing and emerging aquatic MP removal technologies and an assessment of defining development trends. Recommendations are as follows.

1. **Global tracking and monitoring of MP removal technology and programs:** While databases like Duke University's Inventory are important steps in collecting information on existing and emerging solutions, an adaptable and evolving monitoring system is necessary to keep up with technological development and changes. A significant issue faced in this study was a lack of detail for certain devices, as well as vague or outdated information. This could be combatted with an ongoing initiative to track and record technological advancements, in turn better understanding industry activity and facilitating productive discussion and communication.
2. **Encouraging advancement beyond initial design, especially in competitions:** Several of the technologies that were not in active use were invented for a science competition or program. While supporting technological advancements in field of MP pollution is critical, it is necessary to go beyond this first step. With proper resources, or by shifting the competition's goals to include commercialization, these devices could move beyond initial thought and a prize. A technology competition is only as effective as the solutions it can mobilize for change.

3. **Increased funding and support for pilot testing and commercialization:** One of the trends identified in this study highlight a positive number of technologies that are in use. Furthermore, there are almost as many devices in the trialing phase as those that that are already commercialized. This signals that resources are available for development, and that by increasing funding and support (whether for data collection, networking, or trialing) more startups can take implement their devices widely and quickly.
4. **Further research in effective, convenient, and scalable removal techniques:** This study began analyzing MP removal and collection methods, identifying filtration as a common option—likely due to low maintenance and durability in an aquatic environment. However, research was not conducted to fully understand each technique and its benefits and drawbacks; this could be assessed by considering factors like cost and device composition (to ensure materials are sustainably sourced and won't further contribute to pollution). Additionally, devices should not pose a threat to aquatic organisms, habitats or processes, which includes avoiding bycatch, or the removal crucial nutrients or biology from that ecosystem. This information would not only be helpful in determining if current trends represent efficacy, but it would inform new and evolving companies how to best tackle MP pollution without imposing further harm.

4.6. Conclusion

This review assembles existing and emerging technologies used to remove or collect MPs from freshwater environments and identifies trends across the devices to inform future development. The study identified 38 devices, starting with Duke University's Plastic Pollution Prevention and Collection Inventory and continuing with searches through peer-reviewed literature, Google and patent databases. Common trends were technologies that were designed solely for MP removal (as opposed to both micro and macro or nano particles), the use of filtration as a collection method, and development aimed towards pilot testing and commercialization. However, few technologies were designed specifically for freshwater sources, and many were vague, preventing highly effective application. Additionally, many devices had limited details available, making complete analysis difficult. Moving forward, it is imperative to continually monitor and track MP removal technologies to ensure complete and up to date information. Concerns over a lack of scalability amongst early system designs should be remedied with increased support from scientific bodies and programs. Additional funding and resources will help other startups, like PG, further advance their technology for mass commercialization. Uncertainties around trends and gaps in determining the most effective and affordable solutions should be met with increased research. Overall, this study points towards further monitoring, funding and resources, and research to better understand MP removal technology as a field and next steps for meaningful, global change.

Chapter 5: Conclusion

5.1. Summary of research

This thesis presents the findings of assessing a novel MP removal filtration system design by PolyGone (PG) Systems in a freshwater lake and identifying trends across similar existing and emerging technologies. The five objectives of this study were:

a. Test the ability of PG's system to collect MPs from a lake that has been previously dosed with plastics;
b. Determine the efficacy of PG's filtration system in terms of design and brush placement;
c. Identify the MP polymers collected by the Plastic Hunter;
d. Identify existing aquatic MP removal technologies using pre-determined criteria; and,
e. Discuss existing devices based on various characteristics, like ideal particle size, collection method, intended ecosystem and current status/use.

The first three objectives were achieved through field testing the Plastic Hunter in a contaminated lake at the IISD Experimental Lakes Area (IISD-ELA). This was in collaboration with the pELAstic project, which managed a biweekly MP dosage of a lake (L378) and coordinated several ecosystem fate and effects experiments. The Plastic Hunter was deployed in L378 for six weeks and sampled regularly; brushes were collected every day for the first five days, and then weekly for the remainder of deployment. In lab analysis consisted of cleaning the brushes and putting the more concentrated samples through hydrogen peroxide (H_2O_2) digestion. Particle quantification used two subsampling techniques, one with a 10% Alcojet solution followed by a tally counting process. The fourth and fifth objectives were met through a literature and search query review to identify emerging and existing aquatic MP removal devices. The process began with Duke University's Plastic Pollution Prevention and Collection Inventory, which, along with Schmaltz et al. (2020), served as a guideline for the research. Following analysis of the Inventory, searches took place on Scopus and Google and in patent databases for additional findings, as many emerging technologies are not featured in peer-reviewed work. All identified technologies had to meet predetermined criteria, and their characteristics and use status were analyzed to identify industry trends and gaps.

5.2. Research findings

This study has confirmed proof of concept for the Plastic Hunter device, specifically in a contaminated lake. The results imply that the brushes are effective at collecting substantial numbers of MPs over the course of several weeks and that there is little variation when considering brush orientation, although retainment rates are inconclusive. Collection trends regarding polymer type supported a larger hypothesis on particle behavior in a freshwater ecosystem. The findings suggest further research into effective and manageable solutions, especially in different aquatic medium. For the Plastic Hunter, further research into brush retainment rate, ecosystem-specific design, and efficient sampling are suggesting. Overall, the results show the Plastic Hunter as a viable tool and the larger experiment stands as a positive example for field testing other MP removal technologies.

The second part of this research has led to a compilation of aquatic MP removal or collection systems and identified trends for future development. Devices were found from existing inventories, peer-reviewed literature, Google, and patent databases to amass technologies from all stages of development and use. A list of criteria was set to refine the search, and of those that matched, many were specifically designed for MPs, as opposed to including both micro and nano or macro particles. Trends depicted some specifications for freshwater bodies, although this category was lacking. Many devices used filtration as a removal method and were in some stage of active use or development. Concerns were noted, like scientific competitions that encourage technological invention but provide no further development support, which signifies a shortcoming. It is suggested that MP removal technologies are better monitored and tracked throughout stages of development and that more funding and resources are provided for scalability. Additionally, further research is needed to determine best techniques and features for effective, convenient, and affordable MP removal solutions.

5.3. Study limitations

While this study served as an effective proof of concept for PG's device, supported particle behavior hypotheses, and identified trends amongst emerging and existing removal technologies, there were limitations that impede its applicability alongside other assessments. The largest barrier was time, with the pontoon only deployed for six weeks (mid-September until the end of October). A lack of ample time for field testing came from a change in ecosystem conditions that required a redesign of the system, which was unpredictable and unavoidable. Six weeks was sufficient for preliminary data, but more robust and defined trends would've benefitted from a longer deployment of at least half the field season. The late start meant that the lake was already sufficiently contaminated, which helped proof of concept but limited the understanding of MP behavior at earlier points of dosing. Additionally, it is difficult to measure seasonality and how collection trends may vary when deployment occurred strictly in the fall season. The shorter testing time also led to a lower sample size, as brush collection only occurred over six weeks and allowed for no more than four brushes per instance (this was also bound by limited glass jars for brush transport from the field to the lab). With fewer samples, it was difficult to double test and a few brushes were never collected altogether. This primarily inhibited determining retainment rates, which is crucial data for the device's success. Additionally, overall trends were less confident and robust.

Physical and ecosystem-specific conditions also impaired the study. With the outflow stream dried up, a new design was sought out, but it was ultimately impossible to test the pontoon with a concentrated flow. The Plastic Hunter sat in the outflow region of the lake, but it was impossible to control or track the water that it cleaned. Additionally, the device sat behind a boom that was supposed to prevent plastic contamination into the outflow. As apparent by the system's success, the boom was at least partially ineffective, although the levels of contamination on either side of the boom were not considered in this study. This, along with the assumption that water bypassed the boom continually (moving from side to side), made it difficult to understand the immediate water quality and draw conclusions about the pontoon's efficacy. Changing weather and water conditions could affect water levels, composition, and flow, also impacting the ecosystem that the device interacted with. Lastly, the pontoon was anchored in one spot, allowing it to turn with the current and winds, further convoluting efficacy and many trends regarding brush orientation.

The last limitation for the field study was that several samples were given to PG to analyze, which was a different procedure than that set by the pELAstic project. At the time, the implications of this did not seem severe, and it was beneficial for PG to quantify samples by their own methodology to further device development. However, those samples were not able to be included with this analysis, as PG quantified all MPs and the pELAstic protocol only examined the polymers used for dosage. This limitation connects back to time; with a longer deployment and more samples, different quantification processes would've been less detrimental to this study's analysis.

The technology inventory faced a few limitations, the most impactful of which was missing information. Despite searches across multiple platforms and countless follow-ups, details about many of the devices were unavailable or impossible to find. Some technologies were almost impossible to include in trends, as factors like collection technique, particle size, and use status remained unknown. Additionally, commercial technologies are rarely included in peer-reviewed publications, instead commonly featured in consumer and trade media to reach their ideal audiences. Some, especially in the early stages of development, have little to no coverage, rendering them virtually unknown to the wider world. This begs the question if it's ever possible to identify every qualifying technology, and if the subsequent trends are completely accurate and applicable to others. The last limitation is that many websites and documents are not up to date. Most technologies were featured in publications from the past few years, but even less had recent (less than six months) updates, even on their own websites. This highlights a risk in citing outdated information, and further suggests the need for better monitoring of industry advancements.

5.4. Recommendations and future research

1. **Increased support for field testing and pilot technologies:** The Plastic Hunter field test made it clear that aquatic MP removal is viable, even on a small scale. Many more technologies need to join the industry if a global impact is to be felt. The device compilation found numerous devices that had been invented for a competition but never further, highlighting a shortcoming of scientific bodies to support solutions from creation

to completion. More funding and resources need to be available to startups and early inventors, as well as to those in the trialing stage. Without support, the path to commercialization is daunting and sometimes impossible.

2. **Increased testing of freshwater MP removal techniques:** This study has highlighted a successful filtration device and identified trends across technological development. However, further testing is required to better understand the best techniques. More specifically is the need to understand how to design for freshwater MP removal, independent of the more common macro debris and marine ecosystems. It is also necessary to prioritize adaptable designs for varying ecosystem. Within a device, retainment rates are crucial for effective deployment, as this will vary across removal technique and aquatic milieu. For PG, this includes the ideal time between resampling the same brush and if orientation impacts collection. Increased deployment time will ensure more monitoring and a larger sample size, guaranteeing more stable and robust trends.
3. **Continued monitoring of aquatic MP technologies:** The tech inventory maintains that removal devices are on the market or racing to get there soon. However, there are numerous gaps and unknowns, as well as no guaranteed method of assembling all solutions. Not only is a living inventory important to gather details that may be otherwise difficult to find, but it's crucial for an up-to-date and reliable reflection of the industry. This is necessary to inform not only other startups or early inventory of what works best, but it advises policymakers and organizations of available solutions. MP pollution can't be solved by one angle alone; by making an inventory of removal devices readily available and accurate, technology can be an effective and reliable part of the solution.

5.5. Conclusion

This study tests a MP removal device in a freshwater lake and not only proves its viability but assesses factors of efficacy. The Plastic Hunter by PG was effective at collecting high numbers of particles from a contaminated lake over the course of its six-week deployment. The quantification of these MPs also supported external hypotheses of polymer fate and behavior. While limitations related to time, surrounding conditions, and differing analyses reduced the sample size and confidence of trends, the device did prove capable of collecting plastics and highlights the importance and possibility of field-testing other pilot technologies. Further studies will ideally deploy the system for a longer time, taking more samples and assessing total device efficacy, from placement to design. Additionally, increased funding and support for MP removal technologies will increase commercialization and better support a multifaceted solution to aquatic plastic pollution.

The second part of this study compiled a list of emerging and existing aquatic MP removal devices based on predetermined criteria. The inventory pulls from another preexisting list, peer-reviewed work, Google, and patent databases. It reflects common trends of MP-specific technology and filtration as a collection technique, as further employed in the Plastic Hunter, but not many devices are designed for freshwater ecosystems. Use status varies; many technologies are currently deployed or in development, but several are not in use or unable to be determined. Limitations of missing details and updated information advise future efforts, and initial trends can still be identified as an industry benchmark. Further research is advised to better understand the successes and gaps of aquatic MP removal technology, as well as to better inform other companies, policymakers, and organizations keen on remediation. Additionally, further funding and support can be given to inventors early on, whether through grants or competition programs, to ensure successful continuation of their work and scalable solutions into the future.

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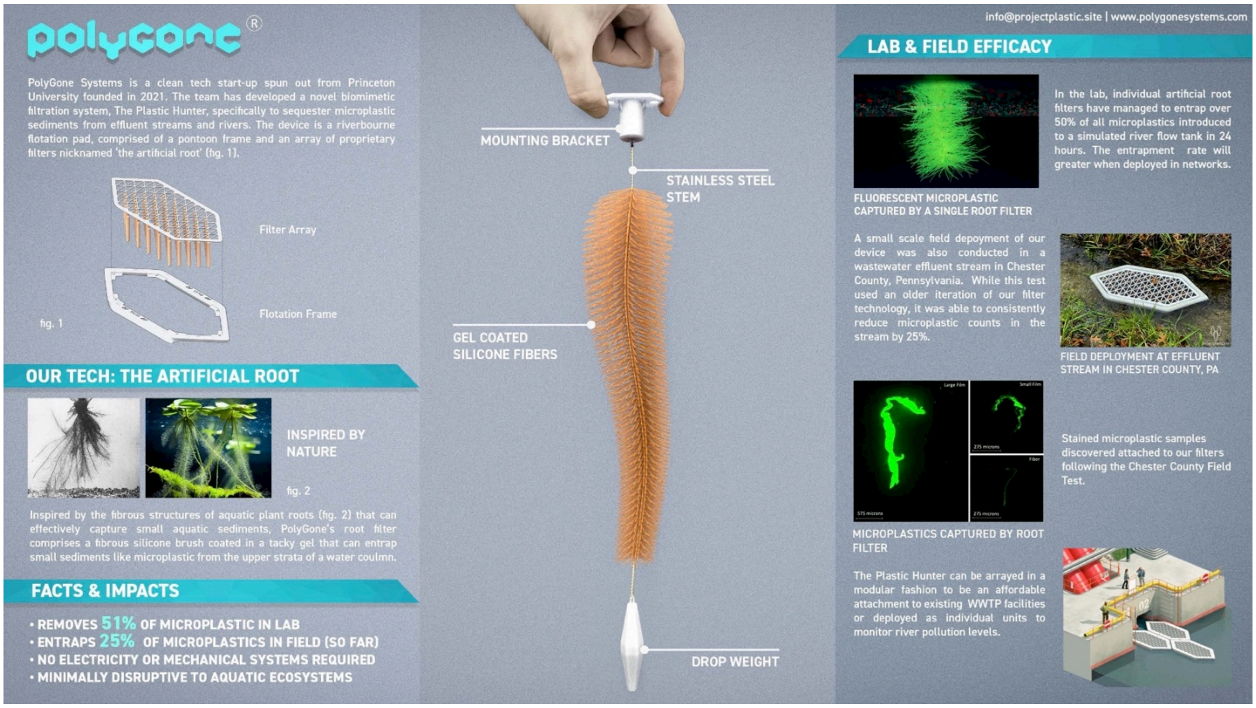
Appendix A: Supplemental PG infographic



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polygone®

PolyGone Systems is a clean tech start-up spun out from Princeton University founded in 2021. The team has developed a novel biomimetic filtration system, The Plastic Hunter, specifically to sequester microplastic sediments from effluent streams and rivers. The device is a riverbourne flotation pad, comprised of a pontoon frame and an array of proprietary filters nicknamed 'the artificial root' (fig. 1).

OUR TECH: THE ARTIFICIAL ROOT

INSPIRED BY NATURE

Inspired by the fibrous structures of aquatic plant roots (fig. 2) that can effectively capture small aquatic sediments, PolyGone's root filter comprises a fibrous silicone brush coated in a tacky gel that can entrap small sediments like microplastic from the upper strata of a water coulmn.

FACTS & IMPACTS

- REMOVES 51% OF MICROPLASTIC IN LAB
- ENTRAPS 25% OF MICROPLASTICS IN FIELD (SO FAR)
- NO ELECTRICITY OR MECHANICAL SYSTEMS REQUIRED
- MINIMALLY DISRUPTIVE TO AQUATIC ECOSYSTEMS

LAB & FIELD EFFICACY

FLUORESCENT MICROPLASTIC CAPTURED BY A SINGLE ROOT FILTER

In the lab, individual artificial root filters have managed to entrap over 50% of all microplastics introduced to a simulated river flow tank in 24 hours. The entrapment rate will greater when deployed in networks.

A small scale field depoyment of our device was also conducted in a wastewater effluent stream in Chester County, Pennsylvania. While this test used an older iteration of our filter technology, it was able to consistently reduce microplastic counts in the stream by 25%.

FIELD DEPLOYMENT AT EFFLUENT STREAM IN CHESTER COUNTY, PA

MICROPLASTICS CAPTURED BY ROOT FILTER

Stained microplastic samples discovered attached to our filters following the Chester County Field Test.

The Plastic Hunter can be arrayed in a modular fashion to be an affordable attachment to existing WWTP facilities or deployed as individual units to monitor river pollution levels.

Figure A.1. An infographic made by PG depicting some of the features and faces of the Plastic Hunter system.