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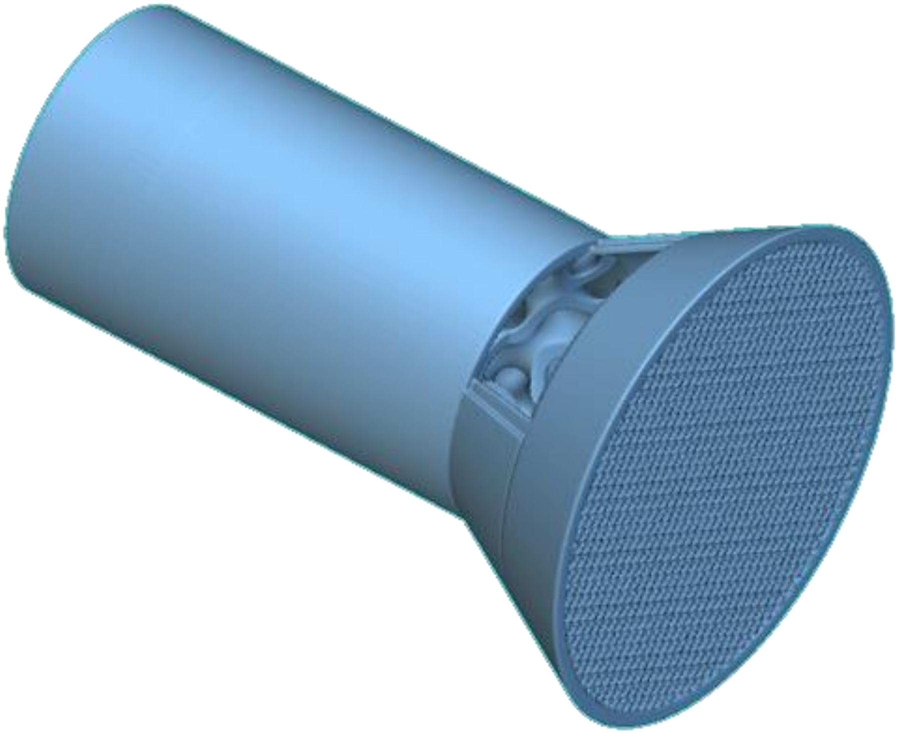
MicroTRAP

Towards Mitigating Plastic Pollution: Implementing a 3D Printed Device with Integrated Lattice Structures for Filtering Microfibers from Wastewater



Project Team Members
Alex Inoma – Mechanical Engineering, University of Alberta
Afrida Nurain – Civil and Environmental Engineering, University of Alberta
Joseph Orakwe – Mechanical Engineering, University of Waterloo
Osezua Ibhadode, Ph.D. – Advisor, Mechanical Engineering, University of Alberta
Olubukola Alimi, Ph.D. – Advisor, Civil and Environmental Engineering, University of Alberta

CONTENT

Executive Summary

The escalating concern over microplastic pollution, particularly from plastic waste, necessitates urgent solutions to mitigate its adverse impacts on human health and the environment. In response, the development of the MicroTRAP (Microfiber Filtration Device) emerges as a crucial innovation aimed at significantly reducing microfiber discharge, primarily originating from everyday household activities like laundry.

The MicroTRAP's design addresses critical functional requirements, ensuring robust filtration, durability, and seamless fiber extraction for proper disposal. Computational simulations show that the gyroid structure towards the inlet helps to improve mixing and reduce influent pressure on the strut-based BCC filter. Moreover, experimental evaluations demonstrate its exceptional effectiveness, achieving over 99.9% microfiber removal efficiency. Additive manufacturing using SLA technology enables cost-effective production with minimal post-processing, facilitating consumer-level manufacturing and widespread adoption. The deployment of the MicroTRAP between laundry machine outlets and sewage systems presents a practical solution to mitigate microfiber pollution. Regular servicing ensures optimal performance and extends the device's lifespan. Leveraging digital infrastructure and diverse manufacturing avenues further enhances efficiency in production and distribution.

MicroTRAP’s significance extends beyond environmental protection to social sustainability and acceptability. Addressing a pressing environmental concern contributes to improving human health and preserving ecosystems. With estimated production costs of $23.48 per part, its suitability for consumer-level manufacturing underscores its cost-effectiveness and potential for widespread adoption. In conclusion, the MicroTRAP represents a pivotal innovation in mitigating microfiber pollution, embodying sustainability principles through its design, effectiveness, and social acceptability. Its development marks a crucial step towards safeguarding the environment and fostering a more sustainable future.

1. Industry Overview

Over the last few years, a new class of pollutants from plastic waste, called “microplastics,” has become a primary public concern. Plastic pollution is growing at a rate estimated to exceed current and projected efforts aimed at its reduction (Borrelle et al., 2020). With the current global plastic production rate standing at 320 million tons per year (Wright & Kelly, 2017) and less than 10% of plastics being recycled, along with few mitigation strategies, the growth rate of plastic pollution is estimated to surpass current and projected reduction efforts.

Microplastic pollution has emerged as a significant environmental problem due to the documented and growing evidence of its biological, chemical, and physical effects on human health and the natural ecosystem (Missawi et al., 2021). Some concerns about microplastics are specifically related to their ability to be highly mobile, release toxic chemicals, bioaccumulate, biomagnify, and act as transport vehicles for other emerging contaminants (Alimi et al., 2023; Missawi et al., 2021; Rochman, 2016). Primary microplastics, usually found in personal care products or paints, can be intentionally produced. Another category, secondary microplastics, is naturally released due to environmental stresses such as mechanical abrasion and UV exposure (Alimi et al., 2018). Among the sources of microplastics in the environment, a subgroup called microfibers represents a significant source of microplastic pollution in the aquatic environment (Acharya et al., 2021). Microfibers are released during the life cycle of fabric, from the textile manufacturing phase to clothing production, use, laundry, and disposal phases. Laundry activities have been identified as one of the most significant sources of microfiber release into the aquatic environment (Hernández-Cid et al., 2020; Yang et al., 2019). Due to microfiber dimensions, wastewater treatment plants cannot wholly remove microfibers. Hence, despite treatment, millions of microfiber particles are released into seas, oceans, and rivers.

Given the widespread occurrence of microfibers, their risk to the ecosystem, and the threat to humans, there is an urgent need for mitigation strategies to stop microfiber pollution at its source. Removing large quantities of microfibers from the environment poses significant technical and economic challenges. Therefore, it is crucial to prioritize prevention measures to minimize the release of microfibers into the environment. Several strategies have been employed and proposed to reduce the release of microfibers during laundry. One proposed strategy includes washing under specific conditions that reduce fiber shedding, such as using low washing temperatures and less detergent (Cotton et al., 2020). However, this method does not significantly reduce the release of microfibers. Another emerging method of preventing microfibers from reaching drainage and wastewater treatment systems is incorporating traps and filters into the laundry process. These include laundry bags and balls placed inside the washing drum, or filters attached to the effluent hose or pipe of the washing machine. Generally, outlet filters exhibit microfiber removal efficiencies ranging from 65% to 89%, making them more efficient in capturing microfibers than in-drum traps, ranging from 10% to 54% (see Table 1). While some advantages to the existing commercial microfiber capture technologies are highlighted in Table 1, numerous limitations to these designs need to be addressed.

These include:

1. Trapped microfibers must be removed from the GuppyFriend bag and Coral ball after every wash.
2. Limited reusability of the in-line filters
3. Lack of sustainable disposal of trapped microfibers
4. Generally low to average removal efficiencies.
5. High cost associated with products with better removal efficiency.

The ecological impact of microfibers in natural waters is a global problem. A microfiber trapping device that sufficiently overcomes these limitations (listed in 1 to 5 above) will significantly advance efforts in addressing this global problem.

Table 1. Industry overview of existing technologies for capturing microfibers

Product	**Price**	**Published microfiber removal efficiency**	**Design location**	**Material**	**Removal efficiency references**
Lint LUV-R	140 CAD	87%, 65 - 74%	External in-line filter	Stainless steel	(McIlwraith et al., 2019), (Browne et al., 2020)
Filtrol 160	140 USD	89%	In-line filter	Bag filter	
GuppyFriend washing bag	37 CAD	54%, 39%	In-drum trap to prevent microfibers from escaping the bag	Polyamide bag	(Napper et al., 2020), (Kärkkäinen & Sillanpää, 2021)
Coral Ball	20 USD	26%, 10%	In-drum trap to remove floating microfibers	100% recycled and recyclable plastic	(McIlwraith et al., 2019)
XFiltra		78%	External in-line filter		(Napper et al., 2020)
PC system	Not sold	64%	External in-line filter		(De Falco et al., 2021)

2. Design Functionality and Durability

2.1. Objective

This project aims to conceptualize, design, and manufacture a device capable of significantly reducing the quantity of microplastics discharged into water systems, mainly stemming from everyday household activities such as laundry.

2.2. Functional Requirements

The functional requirements encompass critical considerations throughout the design and manufacturing phases to ensure the development of a robust filtration device, as outlined in Table 2.

As previously discussed, existing technologies have achieved a maximum efficiency of 89% in filtering microfibers from laundry wastewater. The device under development aims to surpass this efficiency target, capturing 90% of microfibers released during the laundry process and significantly reducing their presence in water systems. Moreover, the device must withstand regular washing conditions, where high water pressure can potentially compromise filtration efficiency and filter lifespan. To address this challenge, it is imperative to reduce water pressure adequately to prevent fiber escape while maintaining efficient wastewater outflow.

Additionally, ensuring the turbulent mixing of released wastewater within the system is essential for enhancing the separation of the continuous phase (water) from the discrete phase (microfibers). Anticipating potential clogging over extended use, an extraction system must be integrated to facilitate the seamless removal of captured fibers for proper waste disposal, thereby preventing flow restriction or damage to the washing machine.

Manufacturing requirements depend on the additive manufacturing technology chosen, necessitating adherence to minimum detail resolution and avoidance of overhangs and support structures to minimize material usage and post-processing needs. Finally, material selection is crucial. The chosen material must be non-toxic to ensure the safety of both users and the environment, enabling wastewater disposal into the water system without additional treatment.

Table 2: Summary of the functional requirements for the microfibre filtration device

Product Requirement	**Process Requirement**	**Material Requirement**
Filters up to 90% of the micro-fibers found in laundry wastewater	Manufacture the part without overhangs or support structures	Should be safe before and after interaction with wastewater
Ensure practical feasibility of the device in a regular washing condition	Ensure minimum part detail falls within the acceptable resolution for the selected 3D printing technology	Should be affordable and easily accessible
Seamless extraction of the captured fibers for proper waste disposal		
Ensure turbulent mixing of water to improve the separation of water and fibers		

2.3. Proposed Solution

The MicroTRAP Water Filtration System, shown in Figure 1, is an innovative solution to water bodies' microplastic pollution. Consisting of three key components—the Graded Gyroid Inlet, Collection Pocket, and BCC-Lattice Filter—this system efficiently captures microplastic fibers from gray water streams, ensuring cleaner water for various applications.

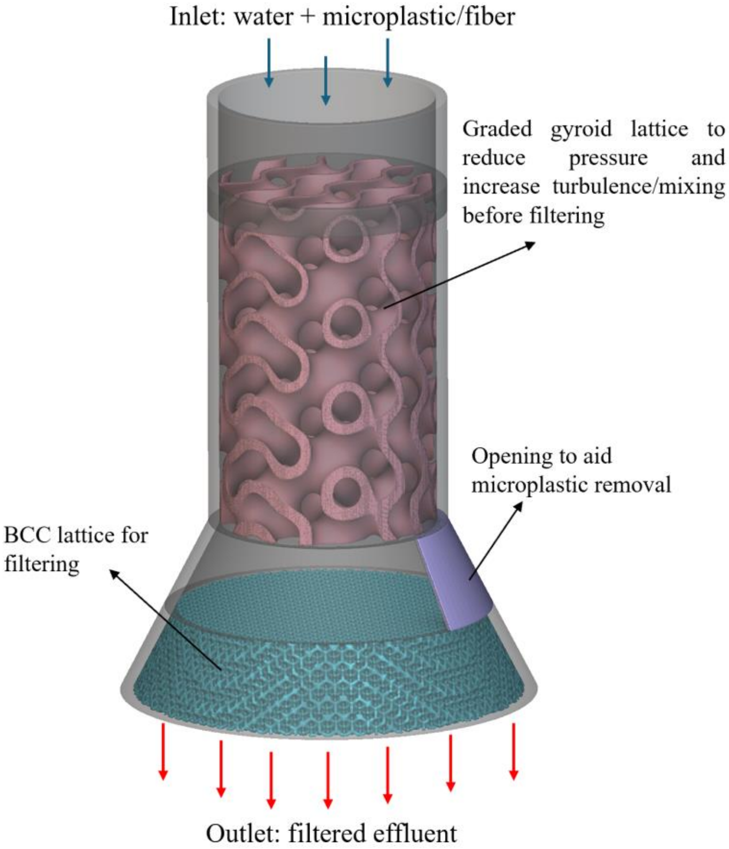


Figure 1: MicroTRAP system showing the various functional sections.

2.3.1. Graded Gyroid Inlet

The Graded Gyroid Inlet is the entry point for gray water into the MicroTRAP system. It features a gyroid lattice structure with a gradual grading from 1.5 mm to 3.5 mm wall thickness. The gyroid's primary objective is to reduce the pressure of the incoming water flow and enhance disturbance/mixing within the water stream. By doing so, the Gyroid Inlet facilitates the separation of micro-plastic fibers from the water, making subsequent filtration more effective.

2.3.2. Collection Pocket

Following the Graded Gyroid Inlet, the gray water enters the Collection Pocket, a crucial component for efficiently removing trapped micro-plastic fibers. This pocket is strategically designed to allow easy access for fiber removal, facilitated by a replaceable gate mechanism. Proper disposal of trapped fibers is essential to prevent the reintroduction of pollutants into future water streams. Using tweezers for the removal process is recommended to ensure thorough cleaning and maintenance of the MicroTRAP system.

2.3.3. BCC-Lattice Filter

The final stage of the MicroTRAP Water Filtration System is the BCC-Lattice Filter, which plays a pivotal role in separating microplastics from the gray water stream. This filter is constructed using a semi-permeable stack of lattices, characterised by a porosity of 0.7 millimeters. The low porosity, combined with multiple layers of Body-Centered Cubic (BCC) struts, enables the efficient capture of micro-plastic fibers ranging from 1 to 5 millimeters in size. Meanwhile, water molecules are allowed to flow freely through the filtration system, ensuring minimal disruption to the overall water flow.

2.4. Technical Drawings

Drawings were prepared according to GD&T standards, as shown in Figure 2 and Figure 3**.** To ensure a snap fit of the plastic gate and the filtration device, a tolerance of ±0.2mm was used.

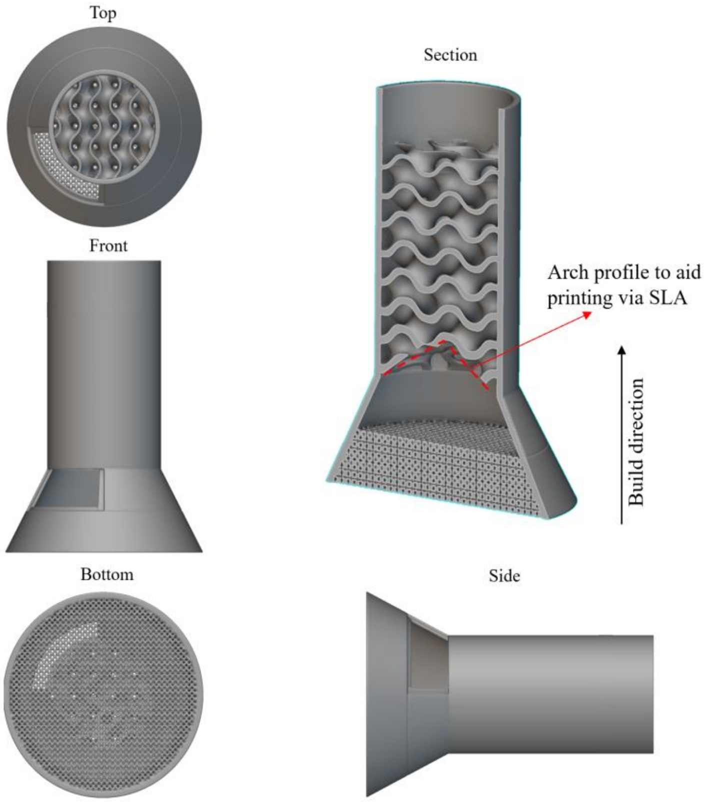


Figure 2: 3D models of the MicroTRAP filtration device

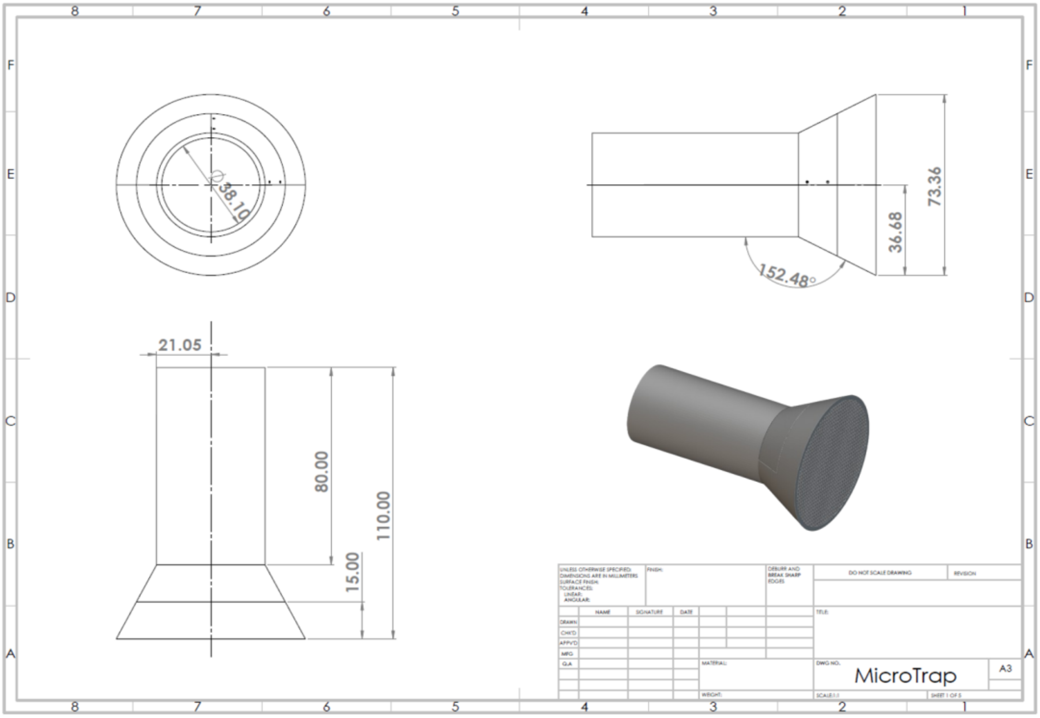


Figure 3: Technical drawings showing critical dimensions of the MicroTRAP (all dimensions are in mm).

2.5. Simulation Study

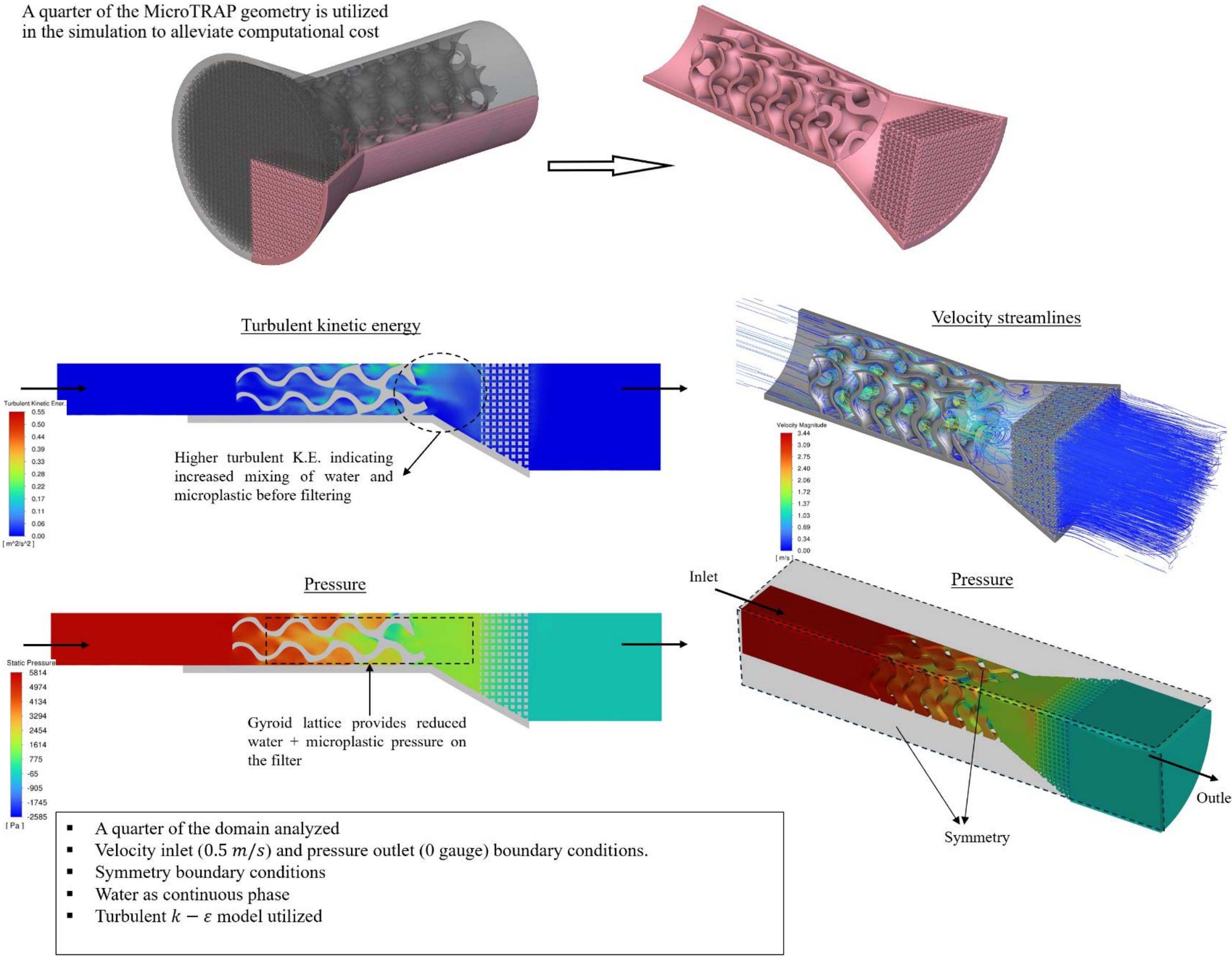
In accordance with the functional requirements, the wastewater passing through the device must achieve the following objectives:

- Reduce water pressure sufficiently to prevent fiber from being forced through or damaging the filtration mesh while ensuring uninterrupted wastewater outflow.
- Facilitate turbulent mixing of water to enhance the separation of water and fibers.

A study was conducted using Ansys Fluent to assess the effectiveness of the Gyroid-Graded Inlet in meeting these requirements. The findings, summarized in Figure 4, indicate a notable increase in turbulence within the device following interaction with the gyroid lattice. This outcome is expected to enhance mixing efficiency and promote effective separation of gray water from microfibers.

Furthermore, the results demonstrate a significant decrease in pressure within the device, from a maximum of 5814 Pa to 1614 Pa in the collection pocket, under the selected inlet parameters. This observation underscores the graded gyroid's capability to reduce water pressure, prolonging the

MicroTRAP's lifespan and improving its filtration efficiency.



- A quarter of the domain analyzed
- Velocity inlet (0.5 m/s) and pressure outlet (0 gauge) boundary conditions.
- Symmetry boundary conditions
- Water as continuous phase
- Turbulent $k-\varepsilon$ model utilized

Figure 4: Simulation of the continuous phase turbulent flow

2.6. Experimental Study

The purpose of this experimental study is to evaluate the efficiency of the MicroTRAP device in capturing microfibers from a stream of water.

2.6.1. Material

For this experiment, two new polyester fabrics, shown in Figure 5, were purchased from a local fabric store in Edmonton, Canada, and used:

- Velvet fabric
- Fleece fabric

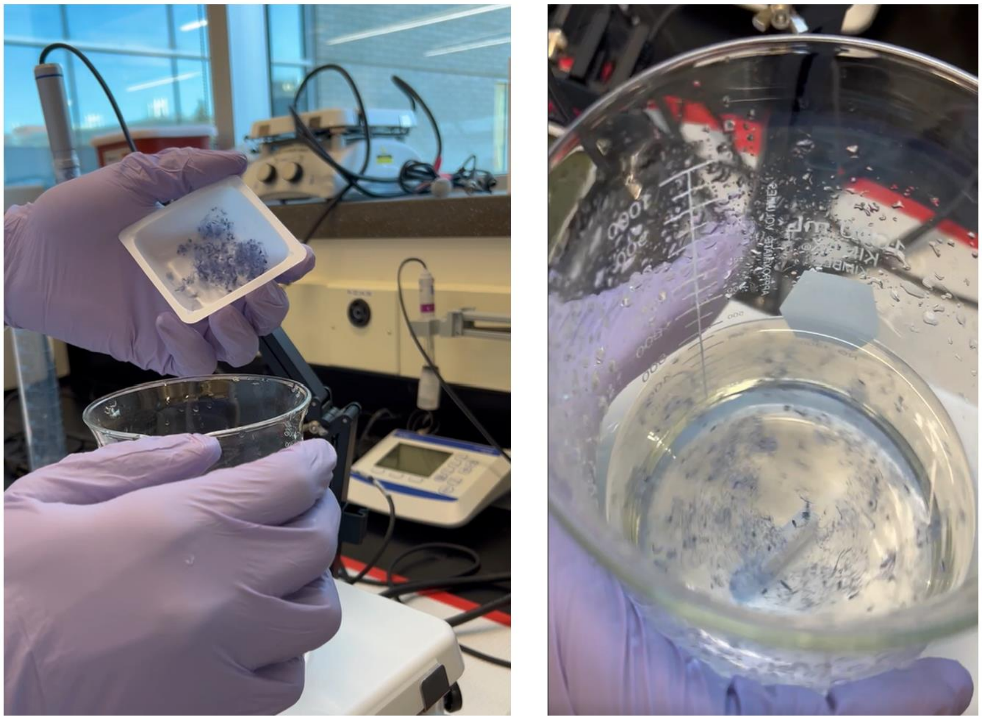
Microfibers were extracted from these materials to simulate their release during washing. The microfibers were then collected and weighed on a scale.

(a) (b)

Figure 5: (a) Velvet fabric (b) Fleece fabric

2.6.2. Simulated washing and filtration experiments

A clean beaker free of fibers was filled with 500 mL of water. Then, the fabric-released microfibers with known weight were poured into the beaker as shown in Figure 6 (a) and stirred continuously for over 10 minutes to disperse the fibers in the suspension shown in Figure 6 (b). An aliquot of 60 ml was pipetted from the evenly mixed solution and drop cast on a 1.2 microlite membrane filter (MF-Millipore) to characterize the concentration of microfibers in the influent suspension before filtration.



(a) (b)

Figure 6: (a) Microfibers being suspended in the water solution, (b) Microfiber suspension.

To evaluate the filter's effectiveness, the suspension was poured into the MicroTRAP, passing through the graded-gyroid lattice and the BCC filtration system. After this filtration step, the effluent suspension was vacuum filtered into a 1.2 microliter hydrophilic membrane filter and later analyzed for microfiber count. Figure 7 (a) shows the clear effluent after filtering, Figure 7 (b) shows the filtered microfibers retrieved from the MicroTRAP, while Figure 7 (c) shows the filtered microfibers in the MicroTRAP.

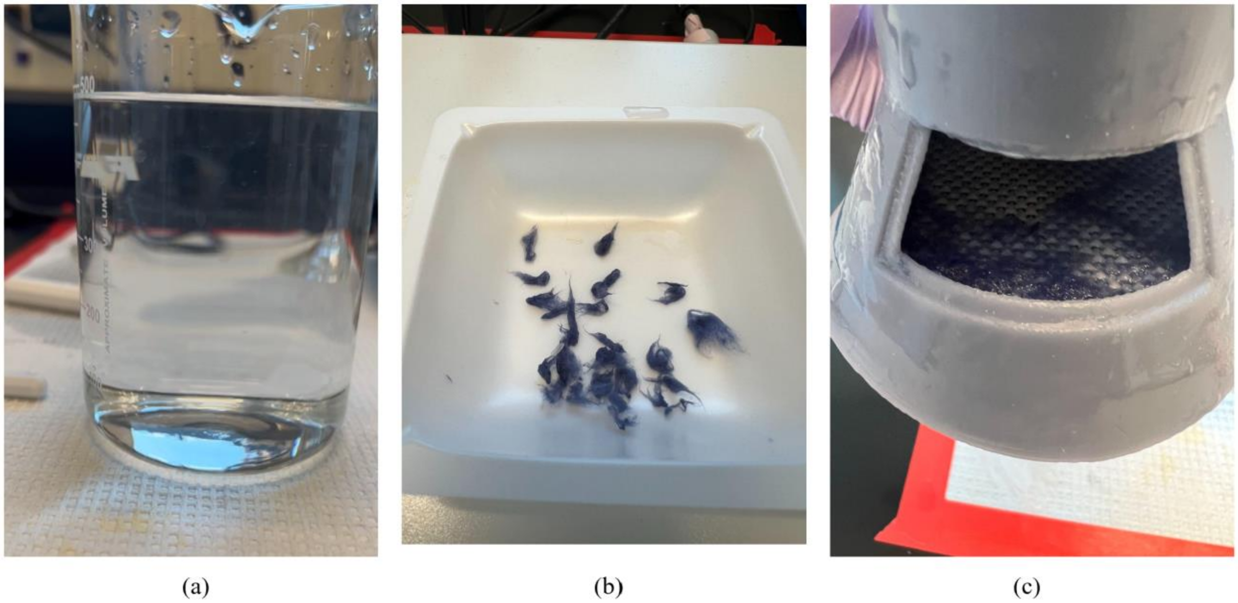
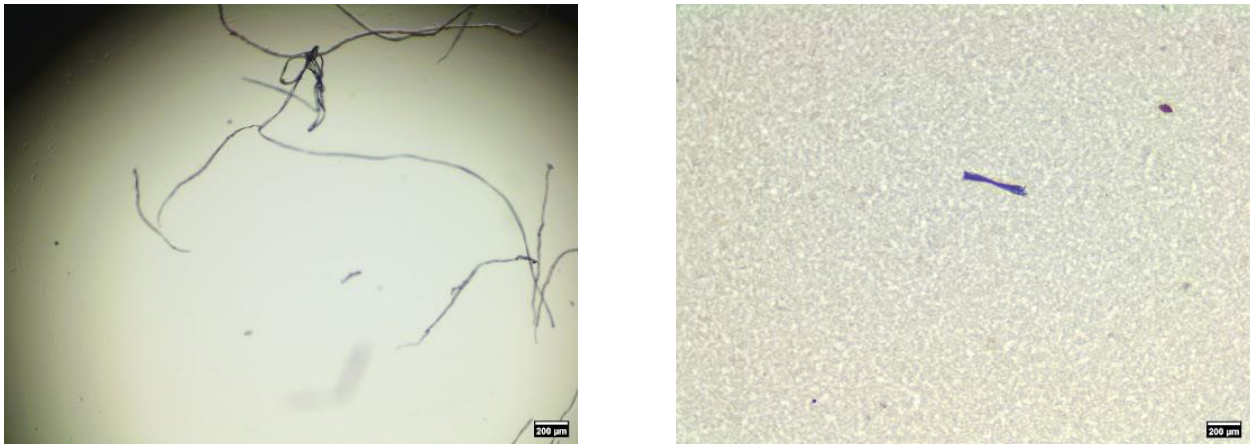

(a) (b) (c)

Figure 7: (a) Effluent water suspension after filtration with MicroTRAP (no visible fibers), (b) clumps of microfiber extracted from the collection pocket of the MicroTRAP after the filtration process, (c) captured microfibers in the MicroTRAP device.

2.6.3. Quantification of microfibers in the influent and effluent water stream

The microfibers released were analyzed for their number and mass concentrations using optical and gravimetric techniques. For the mass concentration, preliminary experiments showed high removal of microfibers using the filter; hence, it was difficult to weigh the microfibers in the effluent suspension due to their negligible mass. The number concentration was then used to characterize the microfibers. An optical microscope was used to evaluate the microfiber count on the membrane filter to determine the count. The concentration of microfibers in all experiments ranged from approximately 2.5 - 3.5 million microfibers in the influent water suspension to approximately 200 to 300 microfibers in the effluent suspension. Based on this range of influent and effluent microfiber concentrations, the microfiber removal efficiency of the MicroTRAP was repeatedly estimated to be **greater than 99.9%.**



(a) (b)

Figure 8: Microscope image of a sample of the suspension showing microfibers (a) before filtration (b) after filtration

2.6.4. Quality Control

To avoid cross-contamination, under- or overestimation of the microfibers, all glassware was rinsed with deionized water before and after usage. Cotton lab coats and nitrile gloves were worn during all the experimental work. Filtration experiments were carried out in the fume hood. Fabrics with distinct colors were chosen for easy detection during counting.

3. Design Integration and utilization of DDM materials and processes.

3.1. Additive Manufacturing Material

As section 1 of this report mentions, various materials are traditionally used in microplastic filtration. These materials include stainless steel, bag filters, polyamide bags, and 100% recycled plastic. Since plastics are readily available, affordable when manufactured with additive manufacturing, and recyclable when disposed of appropriately, this is the top choice for the AM material. The specific choice of plastic depends on the AM process selected, as each process can be used with specific materials.

3.2. Additive Manufacturing Process

Given that water filters are traditionally made from plastics, which may be infused with other materials such as charcoal or sand, the selected Additive Manufacturing technology had to be capable of producing suitable plastics. Two popular plastic AM technologies, StereoLithography Apparatus (SLA) and Fused Deposition Modelling, were compared in Table 3 to understand the advantages and drawbacks of either technology.

Table 3: A comparison of StereoLithography Apparatus (SLA) and Fused Deposition Modeling (FDM) technologies

S/N	Theme	StereoLithography Apparatus (SLA)	Fused Deposition Modeling (FDM)
1	Precision/Resolution	Offers high precision and accuracy with finer details	Lower precision, visible layer lines, and rougher surfaces
2	Manufacturability	Suitable for intricate and complex designs with fine details	It is ideal for simpler designs and rapid prototyping

3	Cost	Initial equipment and material costs are relatively high but significantly lower than industrial AM technologies	More cost-effective in terms of equipment and material costs
4	Availability	SLA machines and materials are readily available	FDM technology is more widely available

Although FDM is comparable in affordability and more widespread in availability, SLA has superior precision, making it the optimal choice for manufacturing intricate lattice structures with extremely low porosity, reaching as fine as 0.7mm. This precision makes SLA the preference for this specialized manufacturing need.

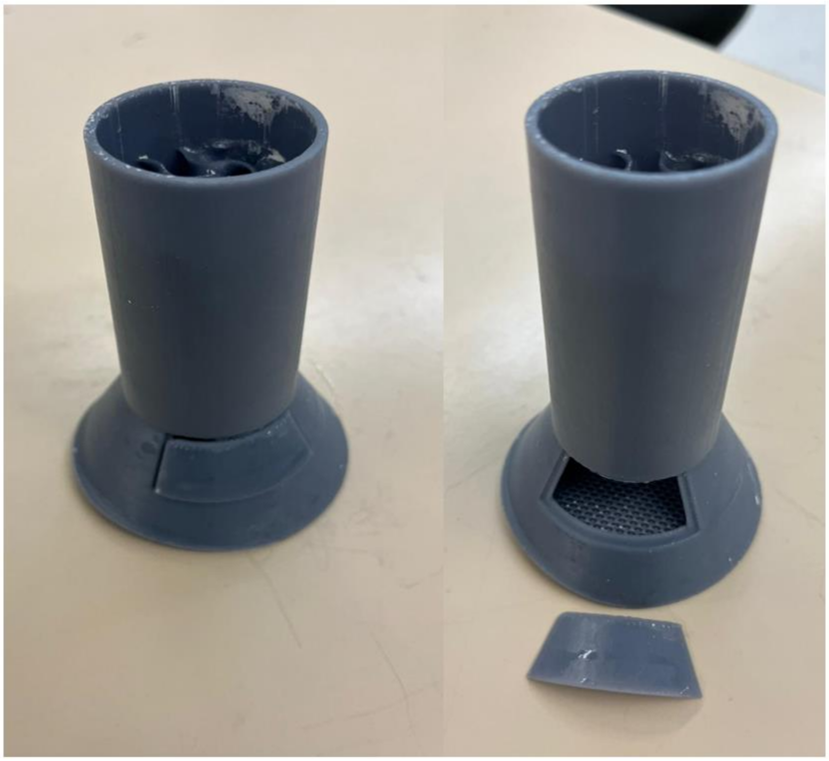


Figure 9: Additively Manufactured (SLA) MicroTRAP device

Additive manufacturing of the part using SLA (Anycubic Mono M5) requires the following steps:

- Prepare a 3D model and save it as a 3MF file.

- Import and set object into Anycubic workshop and set parameters for the Mono M5 machine.
- Slice the part and export the gcode file to the machine's digital storage.
- Add resin into the machine vat and commence printing of part.
- Once printing is complete, extract the part, wash, and cure. The printed and cured MicroTRAP is shown in Figure 8.

The choice of this affordable technology makes this product “consumer-focused”, as anyone with access to an SLA machine and the MicroTRAP stl files can produce their own microfiber capturing device with little to no post-processing required.

3.3. Serviceability and Lifespan

The MicroTRAP device is expected to be installed and kept in place between the outlet of a laundry machine and the inlet of the water sewage system. However, it is recommended that the filter be serviced bi-monthly by removing the accumulated fibers to avoid clogging the device, which will slow down water ejection after laundry activities.

Given that plastic does not corrode, the lifespan is not dependent on this factor. Although the exact lifespan of the filtration mesh will vary, it can be determined to depend on the outlet pressure from the washing machine and the regularity of use. The MicroTRAP device is estimated to perform at threshold efficiency for 10 years with regular servicing.

4. Digital and physical infrastructure: Systems integration, utilization, value chain leverage, agility, lean and continuous improvement

The manufacturing of this product is focused on minimizing the supply chain by taking advantage of the digital infrastructure associated with additive manufacturing. The target is to harness the uniqueness of the several avenues utilized in the supply chain, including large corporations, service bureaus, or hobbyist makers.

Large corporations possess the capabilities, including resources, infrastructure, and reach, to enable mass production and distribution of this MicroTRAP device. However, this avenue of disseminating the design involves several moving parts that can lead to logistic delays, unnoticed defects, and increased waste.

Service bureaus offer an alternative route, especially for smaller-scale productions or rapid prototyping needs. These specialized facilities provide access to advanced manufacturing technologies like 3D printing, CNC machining, and injection molding, allowing for flexible and customizable manufacturing solutions. Utilizing service bureaus can expedite the manufacturing process and enable rapid iteration of designs. However, costs associated with outsourcing to service bureaus should be carefully considered.

Additionally, hobbyist makers or community-based manufacturing initiatives can bridge gaps in the supply chain and foster innovation at the grassroots level. DIY production can unlock creativity and offer unique insights into manufacturing processes. While hobbyist makers may lack the scalability and consistency of larger manufacturing entities, their contributions can enrich the design process and promote community involvement.

5. Cost Benefit/Value Analysis

The MicroTRAP plays a pivotal role in mitigating the adverse impacts of microplastic pollutants on human health, as outlined in Section 1 of this report. Microplastics release toxic chemicals, bioaccumulate, biomagnify, and act as carriers for other emerging contaminants, underscoring the immeasurable value of the MicroTRAP in improving human health. The estimated production cost per part, utilizing SLA (Anycubic Mono M5) as the manufacturing technology and Anycubic standard grey resin as the material, amounts to **$23.48**, factoring in the machine, material costs, and overhead as shown in Table 4. As there is little or no need for post-processing (besides washing and curing), this SLA process will require minimal labor costs and reiterates the suitability of this product to be manufactured by the consumer end of the supply chain (hobbyists and makers).

Table 4: Estimated production cost per part of the MicroTRAP

S/N	Item	Cost
1	Part volume	87.627 mL
2	Material cost	$200/L
	Part material cost	**$17.53**
1	Machine purchase cost (Anycubic Mono M5)	$835.31 (Amazon)
2	Machine lifetime	2 years
3	Machine utilization	90%
4	Parts per build volume	4
5	Build time per part	10 hours 27 minutes 53 secs
	Machine cost per part	**$0.53**
	Overhead cost	30%

	Total cost of producing each part	**$23.48 CAD**

Conclusions

The MicroTRAP represents a pivotal step in addressing the escalating issue of microplastic pollution, particularly from household activities like laundry. It offers a practical and effective solution to mitigate environmental degradation and protect human health by capturing a significant portion of microfibers released during the laundry process. Below is a concise list of fact-based conclusions derived from the comprehensive analysis in this report.

1. Microplastic pollution is a pressing environmental concern, posing significant threats to ecosystems and human health.
2. The current global plastic production rate of 320 million tons per year, coupled with inadequate recycling efforts, exacerbates the growth of plastic pollution, surpassing current mitigation strategies.
3. Microfibers, a subgroup of microplastics released during laundry activities, represent a significant source of aquatic pollution due to their inability to be wholly removed by wastewater treatment plants.
4. To address microfiber pollution, mitigation strategies must focus on prevention measures, such as incorporating traps and filters into the laundry process. Several current outlet filters exhibit 65% to 89% microfiber removal efficiencies.
5. The development of the MicroTRAP aims to significantly reduce microplastic discharge by capturing microfibers released during the laundry process, thereby mitigating environmental and health risks associated with microplastic pollution.
6. Computational simulations and experimental evaluations demonstrate the MicroTRAP's effectiveness, achieving over 99.9% microfiber removal efficiency.
7. Additive manufacturing using SLA technology enables cost-effective production of the MicroTRAP, with an estimated production cost per part of $23.48. This facilitates widespread adoption and societal engagement in combating microplastic pollution.
8. The MicroTRAP's design and manufacturability emphasize social sustainability, enabling consumer-level manufacturing and distribution while addressing critical environmental concerns.

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