A Quantitative Analysis of Microfiber Production On and Off Allegheny College Campus



By

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Department of Environmental Science

Allegheny College

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Submitted in fulfillment of the senior thesis requirements of the Department of Environmental Science at Allegheny College and approved by the senior thesis committee.

Dr. Comp Advisor	**Date**	***Dr. 2nd Reader***	**Date**

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Abstract

Plastic has become one of the leading pollutants in aquatic ecosystems and projections predict pollution to exponentially increase with rising populations and demand. Microfibers, a subgroup of primary microplastics, are one of the most uncontrolled and difficult pollutants to eliminate once having entered the environment. Microfibers are small (<5mm) strings of plastic manufactured specifically in the textile industry. One of the main pathways for microfibers to enter the environment is through wastewater, specifically washing machine wastewater. In this study, the average weight of microfibers produced from a routine load of laundry is evaluated to understand an individual's contribution to microfiber pollution. Two separate testing sites were evaluated to understand the relationship between microfiber shed release and routine washing preferences. A wet-sieving technique was used to filter microfibers from washing machine wastewater. Fibers collected from the filtration system were dried and weighed and were calculated to estimate the average microfiber production produced by an individual in a 52-week year. This study found that there were no significant differences between microfibers produced and the testing sites. There were no significant differences between the microfiber production between the researcher and other Allegheny-student participants. This study found that an individual produces $5.278g$ of microfibers in a 52-week year and the Allegheny student body produces $9,500.4$ $g$in a 52-week year.

Introduction

Plastics can persist in the environment for hundreds of years due to high resistance to weathering, erosion, and degradation (Anbumani et al., 2018; Jing et al. 2019; Remy et al., 2015; Wong et al., 2020; Yang et al., 2019). The bioaccumulation of plastics in aquatic environments can lead to a drastic decline in the health and well-being of an ecosystem. With bioaccumulation, plastic can travel through trophic levels and is a possible contributing factor to biodiversity loss (Lusher et al., 2017; Remy et al., 2015; Li et al., 2019; Wong et al., 2020; Yang et al., 2019). Plastic can facilitate the absorption of toxins and the transfer of chemicals to organisms (Anbumani et al., 2018; Li et al., 2020; Napper & Thompson 2016).

The presence of plastics in water bodies can be the origin of many problems such as aesthetic and recreation issues, entanglement and suffocation of marine animals, and ingestion by fauna (Lusher et al., 2017; Remy et al., 2015; Zambrano et al., 2019). Plastic also contributes to the absorption of pollutants and toxins in plastic particles and their transportation into ecosystems (Zambrano et al., 2019). Sewage wastewater provides one potential route for the entry of microplastics. Other key vectors of microplastic pollution have been identified as fragmentation of larger items, the introduction of small particles that are used as abrasives in cleaning products, and spillage of plastic powders and pellets (Browne et al., 2011; Bruce et al., 2016; Falco et al., 2019; Napper & Thompson 2016; Prata et al., 2020; Wong et al., 2020).

Microplastics are plastic pollutants characterized by their small size, large surface area, and ability to absorb toxins and other pollutants (Anbumani et al., 2018; Jing et al., 2019; Masura, 2015; McCormick et al., 2014; Richardson & Kimura, 2019; Talvitie et al., 2017; Wong et al., 2020; Yang et al., 2019; Zhang et al., 2020). Microplastics are small (<5mm) and are characterized into two categories, primary and secondary microplastic. Primary microplastics, such as microbeads in personal care products, are produced at their small size intentionally (Columbia, 2019). Secondary microplastics are created from larger plastics degrading over time (Carr et al., 2016; Jing et al., 2019; Li et al., 2020; Masura et al., 2015; Prata et al., 2020; Wong et al., 2020). Microplastics leach into the environment through multiple sources such as wastewater effluent, groundwater contamination, surface and agricultural runoffs, and atmospheric microplastics (Prata et al., 2020; Wong et al., 2020).

There are several subgroups of microplastics categorized by shape, size, origin, and polymer composition, each having its unique physical characteristics that make them difficult pollutants to manage (Anbumani et al., 2018; Alabi et al., 2019). Subcategories of microplastics include microfibers, micropellets, microbeads, and general microplastics (Browne et al., 2011; Napper & Thompson 2016). Due to the different shapes and sizes of microplastics, they are extremely difficult to eradicate once they have entered the environment (Bruce et al., 2016; Habib et al., 1996; Napper & Thompson 2016; Zambrano et al., 2019).

While some microplastic pollutants have been addressed, like the cosmetic microbead ban in 2015, microfiber pollution has yet to be fully addressed and is one of the largest sources of plastic pollution (Bruce et al., 2016; Kettenman, 2016). One of the most prevalent and unregulated forms of microplastic pollution is microfibers **(**Browne et al., 2011; Carr et al., 2016; Corcoran, 2010; Kelly et al., 2019; McCormick et al., 2017; Richardson & Kimura, 2019; Talvitie et al., 2017).

Microfibers

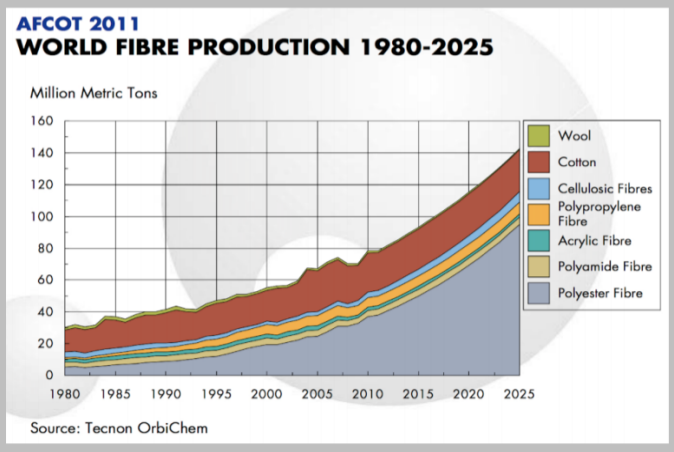
Microfibers are small (<5mm) secondary microplastics produced from manufacturing and washing synthetic textiles (Belzagui et al., 2019; Bruce et al., 2016; Carr et al., 2016; Haap et al., 2019). Due to their small size and strand configuration, microfibers pass easily through the wastewater treatment system and enter aquatic environments (Bruce et al., 2015; Napper & Thompson 2016; Yang et al., 2019; Wong et al., 2020). Synthetic microfibers cannot readily be decomposed by aerobic or anaerobic bacteria, meaning the fibers in wastewater will accumulate in sludge at dumping sites and persist in the environment for thousands of years (Anbumani et al., 2018; Falco et al., 2019; Jing et al. 2019; Remy et al., 2015; Talvitie et al., 2017; Wong et al., 2020; Yang et al., 2019**)**. Synthetic microfibers can cause habitat and ecosystem degradation through pollution and ecosystem decay and can enter the food chain through bioaccumulation (Browne et al., 2011; Corcoran, 2010; McCormick et al., 2017; Richardson & Kimura, 2019; Talvitie et al., 2017). Microplastics can be retained in the soil through rainwater and can enter a watershed through surface runoff and groundwater infiltration. Terrestrial river inputs are a significant source of microfibers deposited in coastal and marine environments, which can lead

to microfiber entrainment, settlement, degradation, and fragmentation which can cause entry into aquatic food chains (Kelly et al., 2019; Lusher et al., 2017; Li et al., 2020; Wong, 2020;). Microplastic debris can contain widely used plasticizers, such as phthalates and BPA, that affect the growth, development, behavior, reproduction, and mortality of aquatic animals (Falco et al., 2019; Haap et al., 2016; Oehlmann et al., 2009; Zambrano et al., 2019; Zhang & Chen, 2020).

The main polymer constituents of microfibers found in freshwaters have been identified as polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET) (Falco et al., 2019; Li et al., 2020). Polychlorinated biphenyl (PCB) and nonylphenols (NP) are also prevalent toxins associated with the crystalline structure of microfibers (Anbumani et al., 2018; Browne et al., 2011; McCormick et al., 2017; Solarski, 2005; Zhang & Chen 2020).

Polyester, the most common source of microfiber pollution, makes up over 95% of the future global synthetic fiber production and is expected to reach 84 million metric tons by 2025 (Bruce et al., 2016). Nylon is another common constituent of microfiber pollution. In 2014, 4 billion tons of nylon were produced and the production of nylon appears to be trending upwards (Carmichael et al., 2015). Materials such as rayon, have been increasing in popularity due to their cotton-like characteristics. In the last ten years, rayon production has increased to 5.2 million tons produced a year (Carmichael et al., 2015). Other synthetic fibers that are commonly used in the textile industry include acrylic, polyamide, spandex, nylon, and rayon (Bruce et al., 2016).

Polyester fiber production is increasing exponentially.



Historical and projected global fiber production (in million metric tons) from 1980 to 2025. Source: Yang, 2014.

Figure 1: Predictions of microfiber production without regulations. As demand for this textile rises, environmentalists are becoming increasingly concerned about the life cycle effects of this fiber (Bruce et al., 2016).

Organic Microfibers

Organic textiles, such as cotton, wool, and silk, can also produce microfibers. While cotton fibers are produced from washing, they can naturally biodegrade over time. (Pirc et al., 2016; Remy et al., 2015; Wong et al., 2020; Zambrano et al., 2019). When cotton and other natural fibers are coated with toxins such as forms of protectants, dyes, and retardants, they are less likely to biodegrade and are therefore more harmful to ecosystems (Alabi et al., 2019). Natural fibers can be difficult to separate once mixed with synthetic materials (Flaco et al., 2019). . The difficulty of separating these natural fibers from synthetics has prompted this study to specifically consider synthetic fibers that have been washed away without natural materials.

Microfiber toxicity

Chemical additives on microfibers can absorb organic contaminants and increase wildlife exposure to toxic materials. These organic contaminants, in turn, can cause fatalities through the food web (Anbumani, 2018; Richardson & Kimura, 2019; Solarski, 2005). Previous studies have shown that microplastics can adsorb toxic compounds such as PCB's, dichloro diphenyl trichloroethane (DTT), hexachlorocyclohexane (HCH), polycyclic aromatic hydrocarbons (PAHs), polybrominated diphenyl ethers (PBDE), hexabromocyclododecane (HBCD), heavy metals, NP's, and perfluoroalkyl substances (McCormick et al., 2014; Richardson et al., 2019; Zambrano et al., 2019).

Nanoparticles, antibacterial solutions, and UV absorbents can be transported in aquatic ecosystems through shed microfibers. (Bruce et al., 2016; Zhang & Chen, 2020). Other common additives to plastics are plasticizers, flame retardants, acid scavengers, heat stabilizers, slip compounds, antistatic agents, and thermal stabilizers which can all be applied to fibers during textile production (Anbumani, 2018; Browne et al., 2011; Bruce et al., 2016; Luongo et al., 2014) Toxic metals and other pollutants applied during textile production can be absorbed and released from fibers, which may bioaccumulate in ecosystems (Andrady, 2011). These toxins can cause liver problems in animals and reduced fertility and birth weight in humans (Webster, 2010).

Plastic waste pollution occurs in areas that are more densely populated and areas where textile manufacturing companies are located (McCormick et al., 2017; Prata, 2018; Yang et al., 2019). Tidal cycles, storms, floods, and other human activities can spread microplastics throughout aquatic environments (Bruce et al., 2016; Hernandez et al., 2017; Talvitie et al., 2017).

Microfibers from washing machine water waste

A significant source of microfiber pollution comes from wastewater effluent (Carr et al., 2016; Columbia, 2019; Hernandez et al., 2017; Jing et al., 2019; Prata, 2018; Talvitie et al., 2017; Yang et al., 2019; Zhang & Chen, 2020). Due to the washing chemistry, temperature, washing duration, and mechanical stress of the cycle, microfibers made of polyester and other synthetic materials can be found in wastewater effluent produced directly from washing machines (Browne et al., 2011; Bruce et al., 2016; Falco et al., 2019; Haap et al., 2019; Hernandez et al., 2017; Zambrano et al., 2019).

Fibers mix with wastewater effluent that can elude the wastewater treatment process and enter aquatic ecosystems (Almroth, 2018; Browne et al., 2011; Bruce et al., 2015; Hernandez et al., 2017; Jing, 2019; Zambrano et al., 2019). A study by Wong et al. (2020) determined that wastewater and sewage treatment plants are the largest contributors to microplastic production. It is estimated that 35% of microplastics in the oceans are fibers from synthetic textiles (Columbia, 2019; Haap et al., 2019; Prata, 2019; Wong et al., 2020).

In a study quantifying microplastic and microfiber shedding from textile fabrics, Yang et al. (2019) found that 0.9 m^2 of acetate fabric produced 74,816 ± 10,656 microfibers/m^2 per wash. Another study found that a single synthetic garment can produce more than 1900 fibers per wash (Browne et al., 2011). Microfiber samples were measured through a wet-sieving technique, collecting fine sediments, particles, and microfibers in a closed parameter study (Carr et al., 2016; Browne et al., 2011; Bruce et al., 2015; Belzagui et al., 2016; Habib et al., 1996; Napper & Thompson, 2016; Pirc et al., 2016; Sillanpaa et al., 2017; Zambrano et al., 2019). Wet-sieving is a technique using various mesh filters to separate substances in a mixture, in this case, by separating plastic pieces from washing machine effluent. Wet sieving is an accurate particle size determinator due to the researcher's ability to control mesh-filter sizes, therefore controlling microfiber versus larger debris collection.



Figure 2: Wet Sieving Technique is used to separate solids from liquids, i.e separating microfibers from wastewater. This image shows that the technique is frequently used for geological purposes. For this study, it was used to separate synthetic microfibers from washing machine waste water.

Past Studies

Several past studies have attempted to quantify microfiber pollution created from laundry effluent. Microfiber pollution quantities are influenced by a variety of parameters including wash load temperatures, clothing materials, the life cycle of clothing, detergent concentrations, water used per load, and type of machine (Browne et al., 2011; Falco et al., 2019; Hernandez et al., 2017; Yang et al., 2019; Zambrano et al., 2016). Multiple confounding variables have been found to influence the production of microfiber shedding during the washing process.

Past studies have found that the use of detergent promoted the release of microfibers from synthetic fabrics (Bruce et al., 2016; Yang et al., 2019; Zambrano et al., 2019). Yang et al. (2019) found that microfiber shed increased by 1.22–5.62-fold with the use of detergents. The temperature of the wash was also a significant factor in the microfiber shed. Zambrano et al. (2019) found a statistically significant increase in microfiber shed when using detergents at 66ºC when compared to microfiber shed with the temperature set at 40ºC. Zambrano et al. (2019), also

found that the mass of microfibers shed from the clothing increased at higher temperatures for all the fabrics that were tested (polyester, cotton, rayon, polyester/cotton mix). These studies suggest that two of the most integral variables of increasing microfiber shed during washing are temperature and detergent use.

In a study by Yang et al. (2019), researchers quantified the amount of microfiber shed from popular synthetic textile fabrics including polyester, polyamide, and acetate fabrics. The study also quantified the difference in microfiber production between the washing machine types, temperature, and detergent using a closed system for analysis. Each fabric was weighed and pre-washed with filtered tap water. For the experiment, a household laundry detergent was used (Reward, China) and two types of commercial household laundry machines, a pulsator laundry machine, and a platen laundry machine, were used (Yang et al., 2019). The washing effluent was collected through the discharge pipe and then poured over a 5.0 μm pore size filter to collect microfiber samples (Yang et al., 2019).

The study found that higher temperature wash experiments produced significantly more microfibers than low-temperature wash experiments. Polyester washed at 30ºC produced 788 ± 402 microfibers, and polyester washed at 60ºC produced 13960 ± 2406 in a platen washing machine. The study also found that detergent increased microfiber shedding and polyamide fabric produced the most fibers (Yang et al., 2019). A study conducted by other researchers found similar results that there is a statistically significant increase in microfiber shed when detergents are used and the temperatures are changed from 40ºC to 66ºC (Zambrano et al., 2019). Zambrano et al. (2019) also found that the mass of microfibers shed from the clothing increased at higher temperatures for all the fabrics that were tested in their study (polyester, cotton, rayon, polyester/cotton mix).

In another study, Hernandez et al. (2017) quantified microfiber production based on the types of detergents used. A variety of household detergents were used and microfiber pollution was compared. This study concluded that the different types of detergents tested contained microbeads and microplastic fragments. The study found that microfiber shed exponentially increases by the detergent's interaction with fabrics. The study found that 75% more microfibers were released when using detergent regardless of type (liquid, powder, or surfactant) and dosage (Hernandez et al., 2017). The microfibers were collected by filtering wastewater during laundering on a glass microfiber filter. The filters were weighed from each load and compared to

determine if detergent type produced a significant difference in microfiber production (Hernandez et al., 2017).

In the Falco et al. (2019) study, researchers controlled the type of clothing, detergents used, washing cycle, temperature, and machine use. This study used different washing trials to quantify the release of microfibers from multiple loads of laundry. Each washing test was conducted on a washing load of 2–2.5 kg of identical clothes with the same liquid detergent. The control load was washed ten times. This study aimed to determine the rate of microfiber production from clothing as it was washed. The study found that while microfibers are still shed after each wash, newer fabrics generate more microfibers than older ones (Falco et al., 2019)

This Study

While several studies have investigated the importance of wash parameters on microfiber pollution, few studies have quantified microfiber releases from everyday lifestyles. This study intends to observe and quantify the weight of microplastics coming from domestic wash loads. This study compares the production of microfibers from two different locations, Site 1 and Site 2. Site 1 is a three-person middle class (yearly income $70,000 to $140,000 (U.S. Census, 2020) and Site 2 is Allegheny College.

Previous research has closely controlled washing parameters such as temperature settings, the weight of clothing washed, number of clothing articles, the volume of water, specific synthetic make-up of the clothing, and the specific knit structure (Columbia, 2019; Falco et al., 2019; Kelly et al., 2019; Yang et al., 2019). In this study, the average weight of microfibers from an individual at the two sites was collected using a wet-sieving filtration system.

For context, the average weight of the researcher's microfiber production at Site 1 and Site 2 will be compared to four additional Allegheny student-participants with similar demographic characteristics. Each woman is highly active (exercising once a day) and middle class ($70,000-$140,000 combined yearly), background. In addition to quantifying synthetic microfiber pollution, the wash parameters including clothing composition, temperature, cycle length, detergent, and water use to identify the most likely causes of synthetic microfiber pollution and identify potential strategies for pollution reductions.

This study looks to answer four questions about the weight of microfiber pollution created by individuals through washing machine wastewater. Question 1: Is the average weight of microfibers produced from Site 1 statistically different than the average weight of microfibers collected from Site 2? Question 2: Are the average weight of microfibers collected by the researcher statistically different from the weight of microfibers produced from four Allegheny student participants? Question 3: What is the average weight of microfibers produced by an individual in a 52 week year? Question 4: What is the average weight of microfibers produced by the Allegheny College student body in a 52 week year?

Process and Approach

This study collects and quantifies microfibers from washing machine wastewater. Two separate testing sites were observed to understand the range of lifestyles experienced by a senior at Allegheny College.

Site 1 was located in a three-person middle-class American household (yearly income $70,000 to $140,000 (U.S. Census, 2020)). The test subject for Site 1 was the researcher, an active (exercising once a day) 21-year-old woman. Site 1 samples were collected between January 5th-February 17th 2021. An Amana top-loading conventional washer model: NTW4516FW (Amana, 2021) was used for the washing process at this location. Samples were weighed to measure the average weight of microfibers produced from one load of laundry at both locations. Ten samples were collected from each location to quantify the average weight of microfibers produced by washing machine wastewater per a load of laundry at Allegheny College and a resident household.

Site 2 was located at Allegheny College, a small (1,800 students) liberal arts college in Meadville, Pennsylvania. The main test subject, the researcher, participated in measurements at both Site 1 and Site 2. Four other participants volunteered to participate in this experiment at Site 2.

Subjects at this site were four active (exercising every day), 21-year-old middle-class women that come from homes with incomes between $70,000 to $140,000 annually. The subject from Site 1 was also a participant at Site 2 to measure the lifestyle changes between the two sites. All ten samples for Site 2 were collected from March 1st-March 8th 2021. A Maytag commercial front load washer, model type: MHN33PRCWW (Maytag, 2021), was used at Site 2. Each clothing article was worn at least once before washing.

The main test subject, the researcher, participated in measurements at both Site 1 and Site 2. The four other Allegheny student participants at Site 2 provided data that could describe a range of microfibers produced based on different washing preferences. Water samples from both sites were collected from washing machine wastewater. Water samples were wet-sieved and collected onto 60-micron mesh filters which were then dried and weighed using a scale to determine the weight of microfibers produced from a typical load of laundry.

A total of twenty samples were taken; ten samples from the testing site at Allegheny College (Site 2) and ten from the three-person household (Site 1). Participants' clothing samples were washed based on need. These samples were observed as routine laundry requirements of the five participants. Each participant selected their sample of clothing that was washed for the microfiber collection. The samples were sorted by the researcher and all natural-material clothing (cotton, wool, and silk) was removed from the study to ensure microfiber samples were composed of synthetic-material clothing (polyester, spandex, nylon, elastane) (Bruce et al., 2016).

Microfiber Separation

Experimental samples were a selection of synthetic clothing chosen by each participant based on the items normally worn and washed weekly. To differentiate between synthetic and natural fibers during microfiber collection, clothing that was a majority or fully synthetic was selected for washing and testing. Clothing that was a majority or fully made of natural fibers was

thrown out from the sample and was not tested for microfibers. For example, an article of clothing that is 80% polyester and 20% cotton, was washed with synthetic material clothing. Only wastewater from the synthetic wash load was tested.



Figure 3: Wastewater effluent usually enters the drainage system through the sink at Site 2. In this study, wastewater was collected in two five-gallon buckets and filtered for microplastics through a PVC pipe apparatus. Wastewater from the washing machine enters the testing bucket through a tube attached to the washing machine. This water was then filtered for microfibers.

Filtration System

A filtration system was created to collect microfiber samples from washing machine wastewater (Figure 4). The system was created using two 24 inch-PVC pipes with a 47mm diameter, 47mm plastic joiners, a funnel, and five-gallon buckets. The two PVC pipes were connected by a plastic joiner to create a single 48 inch PVC pipe. Micromesh filters were located within the joiners to collect microfibers and other materials.

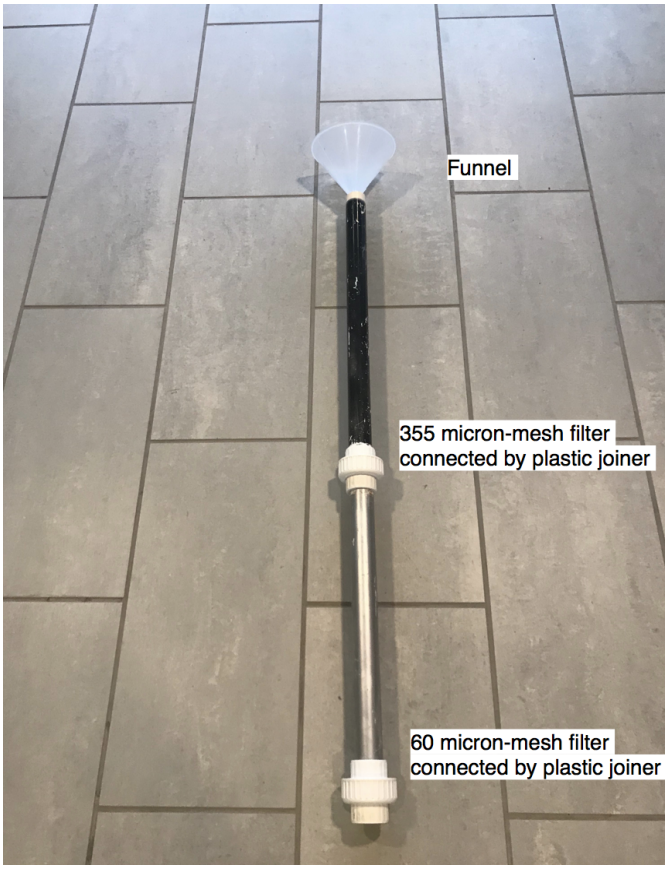


Figure 4*:* The filtration system used to collect microfibers. Washing machine wastewater was poured through the top funnel. A 355 micron-mesh filter was placed in the middle joiner, and a 60 micron-mesh filter was placed at the bottom joiner. Filtered water was disposed of down the sink.

The release tube from the washing machine was placed inside the five-gallon buckets and outpour wastewater was collected throughout the entire washing process (Figure 3). From the five-gallon buckets, wastewater was transferred to a 3.3L bucket. Wastewater was then poured from the 3.3L bucket through a funnel that was placed inside the 48-inch vertical PVC pipe. At the end of the filtration process, the five-gallon buckets and 3.3L bucket were then washed with tap water and poured through the filtration system to collect excess microfibers.

Two separate filters were joined in the PVC pipe at different locations. In the middle of the pipe (24 inches from the top), a 355-micron mesh filter with a 47mm diameter was placed in the joiner. This filter, 355-micron mesh (Tisch Scientific ME 17239), was used to catch materials from clothing that were larger than 5mm, such as hair and other debris. The second filter, a 60-micron mesh with a 47 mm diameter (Tisch Scientific ME 17255), was placed in the PVC joiner at the bottom of the pipe. Microfibers collected on the 60-micron mesh filters were considered microfiber samples for each load. A study by Flaco et al, (2018) found that the 60 micron-mesh filter was able to retain 75-80% of the total amount of microfibers released per wash.



Figure 5: The 60 micron-mesh filter inside the PVC pipe plastic joiner. This filter collects microfibers as they are poured through the PVC filtration apparatus (see Figure 4 for placement).

Once sample water was poured through the PVC pipe, filtered water was then rinsed down the drain. The vertical configuration of the filtration system pulled wastewater through the PVC pipe and filters and into the sink.

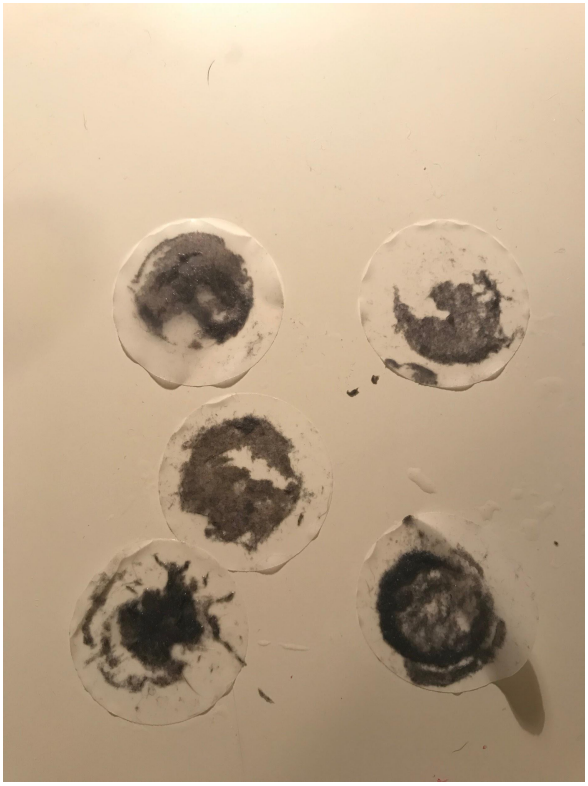


Figure 6: Microfibers collected on the 60 micron-mesh filters. Filters from Sites 1 and 2 were moved using forceps into dry plastic bags labeled with the gallons of water produced from the wash, the number of clothing articles in the load, the temperature of the wash, and the cycle style chosen.

Site 1 Procedure

At Site 1, 28 gallons of water were produced from the top-load conventional washer. To avoid debris buildup in the filtration system, the filters were replaced after 14 gallons of water were sieved. After the 28 gallons of wastewater were filtered, the PVC pipe and funnel were washed with 3.3L of tap water and filtered for excess fibers (Yang et al., 2019; Masura, 2015; Tolmachoff, 2020). Debris collected by the 355-micron mesh filters were not used for measurements in this experiment and were disposed of. Most of the debris from the samples was collected on the 355 micron-mesh filters, meaning microfibers were not the main source of shedding from clothing materials. Debris collected consisted of hair, turf material, and other non-microfiber-based materials. The 60-micron mesh filters were removed using forceps and placed in a dry plastic Ziploc bag for storage (figure 5). The Ziploc bags were labeled based on the number of articles washed per load, the gallons of water produced, the temperature of the wash, and the chosen cycle.

Site 2 Procedure

At Site 2, Allegheny College, the commercial front-load washers produced ten gallons of wastewater. Wastewater was produced from the washing machine through a dispensing tube (Figure 3). Wastewater was collected in five-gallon buckets and then water was transferred to a 3.3L bucket for easier transportation. Water was then poured through the funnel and the PVC filtration system. After the 10 gallons of wastewater were filtered, the PVC pipe and funnel were washed with 3.3L of tap water and filtered for excess fibers Both the 355 micron-mesh filters and the 60 micron-mesh filters were changed after 5 gallons of water were sieved resulting in two filters of each kind used for one load.

Debris collected by the 355 micron-mesh filters was not used for measurements in this experiment and was disposed of. Debris collected from the 355 micron-mesh filter at Site 2 also consisted of non-microfiber materials, as in Site 1. The 60-micron mesh filters were removed using forceps and placed in a dry plastic Ziploc bag for storage and labeled based on the load number, the number of articles washed, the temperature used, and the cycle used for washing.

Drying Filters

After sample collection, each filter was dried in a conventional oven. Filters were placed on a baking sheet lined with parchment paper and baked in the conventional oven at 170ºF for twenty minutes to ensure a dry sample.



Figure 7: The 60-micron mesh filters were dried using a conventional oven on 170ºF for 20 minutes. The samples collected here are from Load 1 Site 2. Each load used more than one filter and each site consisted of 10 loads.

Data Analysis

The numbers used in the following equations consist of actual data collected in this study. Real numbers are used to better understand the equations, with the eventual goal of comparing the weight of microfibers produced from Sites 1 and 2, as well as the annual weight of microfiber pollution produced from an individual and from Allegheny College campus.

Question 1: Is there a significant difference between data collected from Sites 1 and 2?

To determine if the average weight of microfibers produced from Site 1 was statistically different from Site 2, the weight of microfibers from each load was calculated using *Equation 1*. The dry weight of the 60-micron mesh filter was used throughout the whole experiment- 0.074g. The weight of the dry 60-micron mesh filter (0.074g) was subtracted from the weight of the microfiber sample collected from each load. If more than one filter was used for sampling, then the mass of the dry filter was multiplied by the number of filters used to collect the sample.

Ex:
Load 1 Site 1 used 2 60-micron mesh filters.
$2\ X\ 0.074g\ =\ 0.148g$

Equation 1.

$$0.475g\ of\ microfibers\ and\ filters\ -\ 0.148g\ of\ dry\ filter\ =\ 0.327g\ of\ microfibers\ produced\ fro$$

Equation 1 was used to determine the weight of microfibers produced from each load at both Sites 1 and 2. The average weight of microfibers produced from Site 1 was collected by adding the weight of each of the 10 loads and dividing by 10. The average weight of microfibers produced from Site 2 was calculated the same way.

A two-tailed uncorrelated t-test statistical analysis was run to determine a statistically significant difference between the average weights of the microfibers collected at Site 1 and Site 2.

Question 2: Are the microfibers produced by the researcher statistically different from the microfibers produced by the Allegheny-student participants?

Site 2 loads were split based on loads of the researcher and loads of the four Allegheny-student participants. Loads 1 and 5 were based on the researcher's preferences of clothing articles, temperature, and cycle. Loads 2, 3, 4, 6, 7, 8, 9, and 10 were based on the wash preferences of the Allegheny-student participants. The average weight of microfibers from the researcher's loads and the participant's loads was calculated and the standard deviation was determined using the Standard Deviation formula on Google Sheets. A two-tailed uncorrelated t-test was used to understand the relationship between the participant's washing styles and the weight of microfibers produced.

Question 3: How much microfiber pollution is created by an individual?

To first determine the weight of microfibers produced by an individual in a week, the number of articles washed per week and the weight of microfibers per article was calculated. The number of articles washed per week was calculated by deriving the average number of articles washed per load per site. The average weight of microfibers per clothing article washed was calculated using *Equation 2*.

Equation 2

Site 1: $(0.127g\ of\ microfibers\ produced\ from\ Site\ 1 \div 6.7articles = 0.0189g)$

Site 2: $(0.1013g\ of\ microfibers\ produced\ from\ Site\ 2\ \div\ 7articles\ =\ 0.0145g)$

To determine the amount of pollution produced by an individual in a week, the average number of articles washed per week was multiplied by the average weight of microfibers produced per article of clothing using *Equation 3*.

Equation 3

$7articles\ X\ 0.0145g\ =\ 0.1015g\ of\ microfibers\ produced\ by\ one\ person\ in\ a\ week\ washing\ 7\ articles$

To determine the weight of microfibers produced in a 52-week year, the number of articles washed in a year must first be calculated using *Equation 4*.

Equation 4

$52weeks\ X\ 7\ articles\ per\ week\ \ =\ 364\ articles\ washed\ in\ a\ year$

The number of articles washed in a year is then multiplied by the number of microfibers produced from one article to determine the average weight of microfibers produced in a 52 week year.

Equation 5

$364\ articles\ washed\ in\ a\ year\ X\ 0.0145g\ of\ microfibers\ produced\ from\ one\ article$

$=\ 5.278g\ of\ microfibers\ produced\ by\ an\ individual\ in\ one\ year$

$364\ X\ 0.0145g\ =\ 5.278g$

Question 4: How much pollution is created campus-wide?

The weight of microfibers produced in a single year from the student body at Allegheny College was calculated to determine the amount of pollution created campus-wide. There are roughly 1,800 students who attend Allegheny College (Allegheny College, 2021). The weight of microfibers produced by an individual in a single year was multiplied by the number of students

at Allegheny College in *Equation 6* to determine the weight of microfiber pollution created campus-wide.

Equation 6

$$1,800\ students\ X\ 5.278g\ of\ microfibers\ =\ 9,500.4\ g\ of\ microplastics\ produced\ in\ a\ year$$

Results

Question 1: Is the average weight of microfibers produced from Site 1 statistically different from the average weight of microfibers collected from Site 2?

Figure 8. The average overall weight of samples from Site 1 and Site 2 compared.

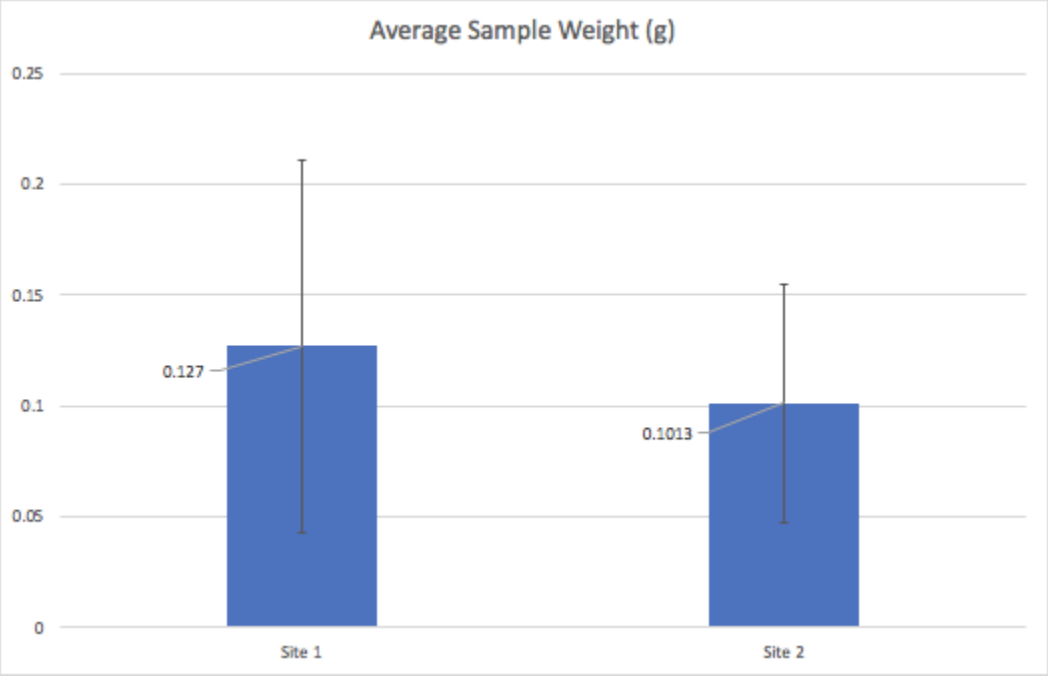


Figure 8. The combined average from each load of laundry at both measured at the two different sites respectively. Data collected from 10 samples at Site 1. A dry 60 micron-mesh filter was

weighed and used as a representative weight for all 60 micron-mesh filters during sample collection (0.074g). The average weight of the microfiber shed from Site 1 was 0.127g. The standard deviation from this average was +/- 0.084g of synthetic microfibers. The weight of the dry micron-mesh filter was used (0.074g) to determine the weight of microfibers produced from Site 2. The average sample weight from Site 2 with 10 loads of laundry was 0.1013g with a standard deviation of +/- 0.053g. The error bars represent the standard deviation of the average weight of microfibers produced from loads at Sites 1 and 2.

Site #	**Average Number of Articles Washed**	**Average Weight per article washed (g)**
1	6.7	0.0189
2	7	0.0145

Table 1: The average weight of microfiber production per article of clothing washed was collected by dividing the number of articles washed by the average weight of microfibers produced.

Site 1: $(0.127g \div 6.7articles = 0.0189g)$

Site 2: $(0.1013g \div 7articles = 0.0145g)$

T-test

A two-sample t-test was run to determine whether or not the average microfiber weight per load of laundry was equal between sites 1 and 2. The t score from the two-sample t-test for the two sites was 0.81 and p=0.43 (T=0.81; df=18; p=0.43). Since the p-value is greater than 0.05, we accept the null hypothesis that there is no statistically significant difference between the average microfiber weight per load of laundry from samples collected at sites one and two.

Question 2: Are the average weight of microfibers collected by the researcher statistically different from the weight of microfibers produced from four Allegheny student participants?

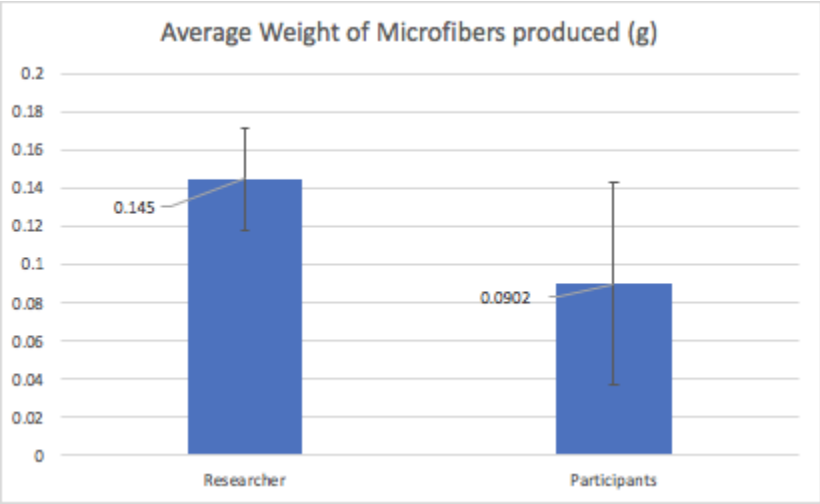


Figure 8. The average weight of microfibers produced (g).

The average weight of microfibers produced from loads 2, 3, 4, 6, 7 8, 9, and 10 was 0.0902g with a standard deviation of +/- 0.053g. The average weight of microfibers produced from loads 1 and 5 was 0.105g with a standard deviation of 0.027g. The p-value= 0.125 shows that the average weight of microfibers collected from loads 1 and 5 are not statistically different from the average weight of microfibers produced from loads 2, 3, 4, 6, 7, 8, 9, 10 at Site 2. The error bars represent the standard deviation.

Site 2 Washing Habits Per Load.

Load #	Temperature	Cycle
1	Warm	Delicate
2	Warm	Normal
3	Hot	Normal
4	Cool	Normal
5	Warm	Delicate
6	Hot	Delicate
7	Warm	Normal
8	Cool	Normal
9	Warm	Delicate
10	Hot	Normal

Table 2: The washing habits per load at Site 2. 60% of the loads were washed using the "normal" setting and 40% of the loads used the "delicate" setting, and 0% used the "powerwash" setting. 50% of the load washes from Site 2 used the "warm" temperature setting, 30% used the "hot" setting, and 20% used the "cool" wash setting.

Discussion

Question 1: Is the average weight of microfibers produced from Site 1 statistically different from the average weight of microfibers collected from Site 2?

The hypothesis of this study was that there would be a significant difference between the average weight of microfibers produced from Site 1 and Site 2. This hypothesis was supported by previous studies that found variables such as washing machine type (front load versus top load, commercial versus home) to play a significant role in microfiber production (Almroth et al., 2017; Belzagui et al., 2019; Kelly et al., 2019; **).** Previous research also suggests that changing variables such as cycle setting, sample size, water volume, and detergent could have an impact on the microfiber shed release (Almroth et al., 2017; Flaco et al., 2019; Kelly et al., 2019; Napper & Thompson, 2017; Sillanpaa et al., 2017; Yang et al., 2019; Zambrano et al., 2019).

In this study, microfiber shed was quantified by weighing the 60-micron mesh filters used during the filtration process. The weight of the microfibers collected from each load was calculated from both Site 1 and Site 2 (Figure 7). The average weight of microfibers collected per sample was 0.127g at Site 1 and 0.1013g at Site 2. A two-sample uncorrelated t-test was used to determine whether or not the average microfiber weight per load of laundry was equal between Sites 1 and 2. As a result, $p=0.424$. Since the p-value is greater than 0.05, we accept the null hypothesis that there is no statistically significant difference between the average microfiber weight per load of laundry from samples collected at Sites 1 and 2.

In a similar study, Falco et al. (2019) found that the release of microfibers from textiles ranged from 0.124 to 0.308g per 1kg of washed synthetic fabric. In a study by researchers Yang et al. (2020), the mass of microfibers shed was compared to the square meters of fabric washed. This study found that the production of microfibers from polyester fabric ranged from 0.04-2.18

mg/m^2, polyamide fabric ranged from 1.03-18.35 mg/m^2, and acetate fabric ranged from 1.31-19.81 mg/m^2. The weight of microfibers produced from my study is comparable to that of past studies, suggesting that microfiber shed from synthetic fabrics may be similar to the fabrics listed above. Comparing the statistical values of previous studies to my study is difficult due to differences in fabric area, weight, water volume, and knit styles that may affect the microfiber shed during the washing process. The knit styles, or how the fabric is woven in an article of clothing, could be a contributing factor to microfiber release due to differences in the structural integrity of the garment (Almroth et al., 2017; Flaco et al., 2019; Kelly et al., 2019).

The volume of water used during the washing process was also a compounding variable that has the potential to change microfiber shedding and collection at the two sites. Wash loads at Site 1 used roughly 28 gallons of water during the washing process, while wash loads at Site 2 used 10 gallons of water. The effects of water volume on the release of microfibers were studied by researchers Kelly et al. (2019). In this study, the researchers found that a higher water volume increases microfibers from polyester materials (Kelly et al., 2019). The study found that high water-volume delicate wash cycles released 800,000 more microfibers (94mg/kg) per wash than a lower water-volume standard wash. These results indicated that a high water-volume-to-fabric ratio is influential on microfiber release (Kelly et al., 2019). While there was a difference in water volume at the two sites in this study, there was no significant difference between the weight of microfibers produced. Although there was no significant difference, water volume could still be a contributing factor to microfiber shed.

As a result, there are several compounding factors that could account for the data collected in this study. Based on the data collected from Sites 1 and 2, there is no significant difference in the average weight of microfiber shedding produced from the two sites.

Question 2: Are the average weight of microfibers collected by the researcher statistically different from the weight of microfibers produced from four Allegheny student-participants?

At Site 2, Allegheny student-participants selected washing parameters to replicate their routine washing styles (Table). Each participant presented the researcher with synthetic clothing articles that have been worn in a single week (Table 1). Loads 1 and 5 were chosen by the researcher while loads 2, 3, 4, 6, 7, 8, 9, and 10 were chosen by the participants. To determine if the researcher's washing habits were statistically different from that of the four other participants, the average weight of microfibers produced from the respective loads was calculated (Figure 8). Loads 1 and 5 produced an average of 0.145g and loads 2, 3, 4, 6, 7, 8, 9, and 10 produced an average of 0.0902g.

The hypothesis for this study determined there would be a significant difference between the average weight of microfiber shed release from loads using different washing parameters. Therefore, the average weight of microfibers produced between the researcher and the four other participants would be statistically different. This hypothesis was suggested due to the change in variables, such as cycle setting and temperature preference, as well as possible differences in the age of clothing washed and weight of clothing selected for each participant. Each of these confounding variables were believed to have a significant effect on microfiber release (Almroth et al., 2017; Flaco et al., 2019; Kelly et al., 2019; Napper & Thompson, 2017; Sillanpaa et al., 2017; Yang et al., 2019; Zambrano et al., 2019).

A two-tailed uncorrelated t-test was used to determine a significant difference between the average weights of microfibers produced from loads of the researcher and the participants. This test resulted in a p-value of 0.125. Due to the p-value being above 0.05, there is no significant difference between the production of microfibers produced by the researcher and the four other Allegheny Student-participants at Site 2. This result suggests that the null hypothesis can be accepted and that the different routines produced a similar effect on microfibers shed from synthetic materials despite changes in temperature and cycle.

In Table 1, the washing parameters of each load were recorded to determine which settings were used the most. This data was used as a representation of the Allegheny Student-participant's routine laundry choices. Based on the four Allegheny Student-participants and the researcher, 50% of the loads were done using the "warm" temperature preference, 30% used the "hot" option, and 20% used the "cool" option. The "cycle" options at the Site 2 Maytag commercial front load washer, model type: MHN33PRCWW (Maytag), were "Normal", "Delicate", and "Powerwash." From this study, 60% of loads used the "normal" setting, 40%

used the “delicate” setting, and 0% used the “powerwash” setting. Based on this data, it can be suggested that the most frequently used washing settings of the five Allegheny students tested was a normal cycle with the warm temperature setting.

The change in cycles was hypothesized to create a statistically significant difference in the microfiber shedding. The different cycles resemble changes in the mechanical agitation of the washing machine. The rotation speed of the washing drum, frequency of directional changes, and the length of pauses in the washing cycle also differ depending on the settings chosen (Kelly et al., 2019). The “delicate” cycle option results in a low agitation rate of the drum in front-loading washers (Kelly et al., 2019). In a previous study by researchers Kelly et al., (2019), the delicate wash cycle produced significantly more microfibers produced than the “normal” cycle in front load washers. While there was no significant difference found between the settings in this experiment, it is still a factor to consider.

Previous research has shown that temperature plays a significant factor in the number of microfibers shed from synthetic material. The higher the temperature of the wash, the more microfibers produced. A study found a statistically significant ($p<0.05$) increase in microfiber shed with detergents when temperatures changed from 40ºC to 66ºC (Zambrano et al., 2019). In a similar study, Napper and Thompson (2016) found that polyester released significantly more ($p<0.05$) fibers than acrylic at 40ºC when compared to 30ºC suggesting that different fabric types react differently to changes in temperature. Napper and Thompson (2016) also estimated a 6kg load of synthetic materials washed with detergent could produce between 137,951 and 728,789 microfibers.Yang et al. (2019) also found that polyester fabrics produced significantly more microfibers when washed at 60ºC compared to 30ºC. The study also found that the greatest number of microfiber shed during the experiment was from polyamide fabric at 60ºC (the highest temperature washed) with detergent (49,619 +/- 9,749 $microfibers/m^2$) (Yang et al., 2019). Falco et al. (2019) found a non-statistically significant increase in MF release at 60 °C compared to 40 °C in plain weave polyester garments.

However, in a study conducted by Hernandez et al. (2017), researchers found that there was no statistical difference in the mass of microfiber released from textiles at temperatures 25ºC, 40ºC, 60ºC, and 80ºC. Other compounding variables may be an explanation for the differing results as the studies were not replications of each other. Kelly et al. (2019) suggest that since previous research has reached different conclusions on the effects of temperature on

microfiber production, temperature is not the most important factor affecting microfiber release. These conclusions coincide with data collected from this study finding there was no significant difference in the average microfiber production despite the differences in temperature preferences (Table 1). While there was no significant difference found between the washing temperature parameters and microfiber shed release in this study, it is still an important compounding factor to consider.

Question 3: What is the average weight of microfibers produced by an individual in a 52 week year?

The results from this study allowed for the estimation of the average weight of microfibers produced from one person in a 52 week year (*Equations 2-5)*. This was achieved by examining the average number of articles washed in a week and the average weight of microfibers produced from a single article of clothing (Table 1). Since there was no statistically significant difference between microfibers collected from Sites 1 and 2, data from Site 2 was used to calculate microfiber production in a 52 week year.

Based on the Site 2 data, the average number of articles washed per week was 7 and the average microfibers produced per article was 0.0145g (Table 1, *Equation 2*). To determine the average weight of microfibers produced by an individual in one week, the articles washed were multiplied by the microfibers produced by one article (*Equation 3).* The number of articles washed per week was then multiplied by the number of weeks in a year, 52, to get a result of 364 synthetic articles of clothing washed by one person in a year (*Equation 4)*. The number of synthetic articles washed in a year was then multiplied by the average weight of microfibers produced from one article of clothing to get a result of $5.278 g\ of\ microfibers$ produced from one person in a year (*Equation 5)*.

Researchers Browne et al. (2011), estimated that a single garment could produce more than 1,900 microfibers per wash load. Using this data and the estimated 364 synthetic articles of clothing washed in a year from one person, it can be projected that 691,600 microfibers are

produced per person per year (1,900 X 364= 691,600). Using this estimation, 5.278g of microfibers is equivalent to 691,000 microfibers produced in one year by an individual.

Question 4: What is the average weight of microfibers produced by the Allegheny College student body in a 52 week year?

Assuming that the participants of this study are an accurate representation of the laundry habits of students at Allegheny College, the amount of microfiber pollution created campus-wide in a year was calculated. The estimated amount of pollution created by one person in a year was used as a representation of the pollution created by all students at the college (*Equation 5)*. The student population of 1,800 (Allegheny, 2021) was multiplied by the weight of microfibers produced by an individual in one year (5.728g) (*Equation 6).*

In one year, it is estimated that Allegheny College produces $9,500.4\ g$ of microfibers through laundry wastewater which can be converted to over 20 pounds of microfibers. Using the estimated 364 articles of clothing washed in a year per person, it can be estimated that the Allegheny College student body washes 655,200 articles of clothing in a year. A study by Browne et al. (2011), found a single garment can produce 1,900 microfibers, which can be used to estimate the number of fibers produced by Allegheny College students in a year. The number of microfibers produced from the student body at Allegheny College is approximately 1,244,880,000. Using this estimation, 9,500.4g of microfibers is equivalent to 1,244,880,000 microfibers produced in one year by the 1,800 student body at Allegheny College.

Understanding Microfiber Pollution

The quantity of microfibers is expected to increase within the decade due to the increasing population and no regulatory legislation (Carr et al., 2016; Miller et al., 2017; Napper & Thompson, 2016; Prata, 2018; Yang et al., 2019). Microplastics play a significant role in the degradation of aquatic ecosystems and are expected to continue to be leading pollutants in the ocean, Great Lakes, and other waterways (NOAA, 2021; Zhu et al., 2019). Microfibers continue to be a leading pollutant

Based on this study and previous research, a significant amount of microfibers are produced from wastewater which can end up in aquatic environments (Lusher et al., 2017; Remy et al., 2015; Li et al., 2019; Wong et al., 2020; Yang et al., 2019). Allegheny College is known for its environmental science and sustainability programs. With the college reaching carbon neutrality in 2020, it is vital for the college and its students to understand the impact they have on the environment. Allegheny College is located in Meadville Pennsylvania which is part of the French Creek watershed, one of the most biodiverse watersheds, and one of the most biologically important waterways in the country (FCVC, 2021). Microfibers from washing machine waste can enter aquatic ecosystems through poorly filtered wastewater, meaning microfibers from students at Allegheny College could enter the French Creek Waterway (Browne et al., 2011; Carr et al., 2016; Corcoran, 2010; Kelly et al., 2019; McCormick et al., 2017; Richardson & Kimura, 2019; Talvitie et al., 2017). Quantifying microfibers and identifying how different washing parameters affect microfiber production is critical to understanding microfiber pollution from individuals and as an environmentally conscious college campus.

Study Limitations

The purpose of this study was to develop an authentic presentation of the routine washing habits of students at Allegheny College. In order to achieve this goal, some external compounding variables were not controlled within this study. These variables include: specific knit structure of clothing, the weight of clothing tested, the surface area of clothing tested, specific washing settings, and specific synthetic fiber make-up of the clothing.

The researcher and the Allegheny Student-participants may not be an accurate representative sample for the College. There was no variation in the gender of the participants, the lifestyle activities of the participants, or the financial situation of the participants. To get a more diverse, representative, and accurate sample of Allegheny College students, more participants would be needed. Testing 20 loads at two separate sites instead of 10 could also result in a more defined and accurate representation of the average microfibers produced by individuals.

The weight of the clothing articles washed in this study was not recorded, having a potential effect on the weight of microfibers produced and collected from the washing process. Previous studies have found that the weight of the microfibers from the samples may be related to the weight per unit area of the fabrics chosen for the washing process (Yang et al., 2019). The weight per unit area of the fabrics is dependent on yarn diameter, yarn thickness, the thickness of the fabric, and linear density. That is, the number of microfibers will increase with the yarn count due to the larger amount of fiber per cross-section (Yang et al., 2019).

This data is assuming that the washer has consistent habits in every season. Almroth et al. (2017) suggest that habits may change depending on the season; in the colder winter months, heavier clothing with a larger surface area may be washed- resulting in inconsistent routine load numbers and therefore changes in estimated microfiber pollution production.

The knit styles of the fabrics could also play an important role in the behavior of microfiber release the production and microfiber shed from washing (Almroth et al., 2017; Flaco et al., 2019). The degree of shedding from clothing articles is related to how tightly the yarn is knitted into the fabric. Articles that have more tightly knitted fabric, resulted in a higher shedding production of microfibers (Almroth et al., 2017).

Further Research

In future studies, for more accurate differentiation between washing styles and microfiber production from Sites 1 and 2, the researcher could do 10 or more loads of their own laundry at both sites. Rather than only doing two of their own loads, it may be beneficial to increase the number of loads by the individual for a more accurate answer to questions 1 and 2.

Future studies could test the number of articles of clothing and the weight of the clothing sample to better determine the correlation between the number of clothing articles and microfiber production from washing machine wastewater. Future research could also use the weight of the clothing articles rather than the number of articles as a way of understanding the shed of microfibers released based on the weight of the articles washed.

Future research interested in looking at the woven structure and microfiber shed release could collect samples using different “sites” that have separate woven structures of the same

fabric. Rather than using location as the two dependent variables, different woven structures could be used for comparison.

A larger sample size could also be considered for future research, measuring more than ten articles of clothing at one time. It may also be wise for future researchers to test more than 10 loads of laundry at each location to get a more accurate representation of washing habits. If this study is replicated, it is advised that future researchers test 10 loads of their own laundry at both Sites 1 and 2 rather than only collecting 2 of their own laundry samples at Site 2. More samples at Site 2 could be important in adopting a more accurate comparison of the home and school washing habits and microfiber release changes.

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