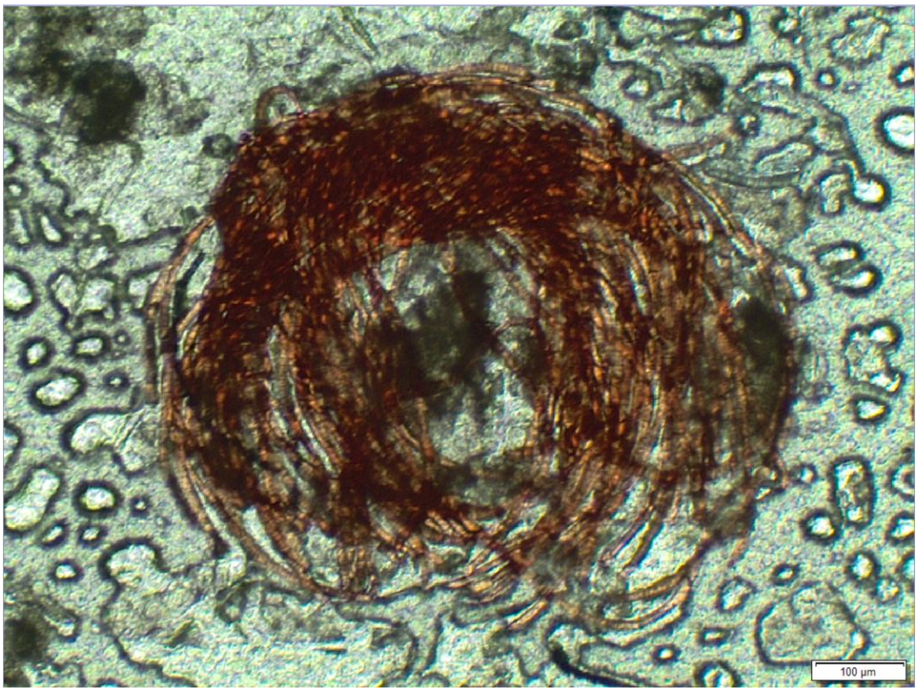


Microplastic Release after Laundry of Synthetic Garments

Master's thesis in Infrastructure and Environmental Engineering

ANTHI GKIRINI

Supervisors:

Sebastien Rauch (Chalmers University of Technology)

Thomas Meyn (Norwegian University of Science and Technology)

Department of Architecture and Civil Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2019

Master's Thesis 2019

Microplastic Release after Laundry of Synthetic Garments

Master's thesis in Infrastructure and Environmental Engineering

ANTHI GKIRINI

Publication Number: ACEX30-19-94

Supervisors:

Sebastien Rauch (Chalmers University of Technology)

Thomas Meyn (Norwegian University of Science and Technology)

Department of Architecture and Civil Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2019

Abstract

Plastic pollution is widely considered to an alarming problem due to the presence of plastics in water, soil and air. Microplastics are estimated to be the 3rd largest source of plastic pollution detected so far ending up in the marine environment. Microplastics can be a result of land based sources which can either come from care and cleansing products (e.g. toothpaste), breakdown products (e.g. fibers from synthetic textile, particles derived from car tyres) or deterioration of larger debris (e.g. plastic bags). Their main pathways are through stormwater, wastewater or direct release to sea. Their effects are largely unknown, although microplastics have been found in biota and in the human food web (e.g. in the salt, honey, etc). The amount of microplastics emitted from laundry remains very uncertain, with published emission rates ranging over several orders of magnitude.

The aim of the thesis is to estimate the release of microplastics fibers from synthetic clothing after washing under specified conditions. A method to collect samples is developed and applied to the washing of different materials. The release is estimated in both relative fiber weight and particle numbers. Additionally, the effects of repeated washing and use of the clothes were investigated and related to their initial release. Finally, complementary results were obtained by microscopy analysis, including measurement of fiber size and characterization of textiles.

The results show that the estimation of fiber emission from laundry is a challenging procedure. There is no standard method available and the quantification of emission rates in weight or particle number is affected by factors including the pore size of the filters, the presence of additives in textiles, the possible presence of environmental particles on the textiles and the large particle numbers. It is however clear from this study that microplastic fibers are released from laundry. Measured fiber emissions were found to be in the range of 97-2,3 mg per kg of textile or 0.8-2.6 million fibers per kg of textile (calculated taking into account the average number after use). Repeated washing caused a decrease in fiber emission. In contrast use of the textiles caused an increase in emissions. Microscopic observation of the textiles after washing and use clearly show deterioration of the materials that might explain the higher emission after use.

This study supports that the emission of fibers from laundry significantly contributes to the environmental microplastic load, even if some of the emitted fibers are retained by wastewater treatment plants.

Key words: microplastics, synthetic textile, length distribution, diameter distribution, ESEM analysis, EDAX analysis, annual release

Acknowledgements

The drawing up of the current thesis would be incomplete without the help and assistance of numerous people. To begin with, I would like to personally show my appreciation to Sebastien Rauch, my supervisor at Chalmers University of Technology, for his guidance and help in all the steps of the project. Without his knowledge, ingenuity and his creative ideas, the project would have been inevitable. Also, with his questions and feedback he gave me the essential motivation to complete my thesis. Finally, his trust in my choices and his availability facilitated our cooperation.

Throughout the thesis route, I couldn't be more grateful also for the help of Amir Saeid Mohammadi, Research Engineer at the Environmental Chemistry Laboratory at Chalmers. With his knowledge and cooperation my experiments and results became more interesting. Also, his supportive spirit eased our work in the laboratory.

This thesis is part of the Formas-funded Minshed project, which aims to create knowledge to help the textile industry to design clothes made of synthetic fabrics which do not emit microplastics.

Finally, I couldn't forget my family and friends who with their support facilitated my routine making it more fun and easy to handle the work load. Their psychological support, love and care encouraged my efforts to work harder.

I wouldn't be able to fulfill the research without the help of any of them, so thank you all once again!

Best regards,

Anthi Gkirini

Table of Contents

List of Figures

List of Tables

1. Introduction

In this chapter, the subject of the master thesis is presented, including the motivation for the study, the aim of the thesis and the research questions that will be address through the thesis project.

1.1. Problem Formulation

The pollution originating from plastics is a major environmental concern. Plastics are found in multiple environmental compartments, including water, soil and air. Since the massive production of plastics started in 1940s, the production-techniques were improved in terms of lightweight, durability, persistence and corrosion resistance to plastic varieties. However, these characteristics -especially their durability- are responsible for their presence in many forms such as plastic fragments, fibers and granules (E. Hernandez et al., 2017). In fact, plastics need many decades or even centuries to decompose, which means that they can still be present in more than 1000 years from now (M. Choudhari, 2018).

Microplastics, i.e. small plastic particles, can result from abrasion, weathering and fragmentation of larger plastic pieces, as well as the direct use of microplasctics. Several sources of microplastic have been identified including tyres, road paint, asphalt, cosmetics (e.g. microbeads from skin scrub products), laundry, deterioration of larger debris, etc (F.D. Falco et al., 2018). The focus of this project is on laundry of synthetic textiles, which seems to be a major source of pollution in the oceans. Synthetic garments are preferred by consumers because of their lower price, water and wind proof effect and also their shiny appearance. As a matter of fact, since 1980, the production of polyester is increasing more and more every year. Other materials used for synthetic clothing apart from polyester can also be acrylic, nylon, polyamide, etc (M. Choudhari, 2018).

Finally, the presence of microplastics can pose a great risk to environmental and human health. This can be a result of microplastics ingested by plankton or other marine microorganisms and eventually enter the human food web and be transferred to humans (F.D. Falco et al., 2018). Researchers have already detected microplastics in several animals consumed by humans, including chicken and fish (S. Raju et al., 2018)

1.2. Aim and Objectives

The aim of this project is to estimate the release of microplastic fibers from synthetic clothing after washing under specified conditions. A method to collect samples is developed and applied to the washing of different materials (i.e. fleece jackets, T-shirts and packs of socks mainly made of polyester and polypropylene). The release is estimated in both relative fiber weight and particle numbers. Additionally, the effects of repeated washing and use of the clothes were examined and related to their initial release. Finally, the results were evaluated with the help of microscopy analysis.

1.3. Hypothesis

The following hypotheses were defined for this study.

a. Washing textiles releases significant amounts of fibers.

b. Washing and using textiles affect the release of fibers.

1.4. Research Questions

In order to deepen the knowledge in the study, research questions were set. The master thesis project is based on those questions and their purpose is to give a direction both to the researcher and to the reader. The research questions are presented below:

1. How can the fibers be collected from the outflow of the washing machine?
2. How can the fiber emissions be quantified?
3. What is the effect of repeated washing and use on the fiber release?
4. How much textile fibers are released in Gothenburg and in Sweden?

2. Theoretical Background

This part of the thesis describes current knowledge on microplastic emissions based on available literature. That includes the definition of microplastics, their sources, their fates, pathways and effects, as well as their emission rates from different materials and the factors affecting emissions. Finally, similar experiments found in the literature review will be analyzed.

2.1. Definition of microplastics and their Sources

Plastics are man-made polymers originating from petroleum and its derivates but also from non-synthetic polymers such as natural rubber (GESAMP 2015). Microplastics refer to small plastic particles which according to the literature are smaller than 5mm (5000μm) but with no lower limit (C. Jönsson, et al., 2018). Sometimes fibers might be longer than 5mm, but their diameter is considerably less than 5mm. Practically, there is a lack of a formal definition for the lower size limit of microplastics (I.E. Napper, et al., 2016). The microplastic fibers that have been found after sampling from the shorelines of Australia, Portugal and U.K were mostly polyester, acrylic, polypropylene and polyamide ones (M. A. Browne et al., 2011).

Additionally, there are several sources of microplastic. According to K. Magnusson et al. (2016), microplastics may derive from road wear and deterioration of tyres, artificial grass surfaces, laundry, wear from boats, plastic pellets, buildings maintenance and construction, etc. The sources of microplastics listed in K. Magnusson et al. (2016) are presented together with their yearly emissions in the environment.

Taking into account the values in K. Magnusson et al. (2016), the major source of microplastics is road wear and abrasion of tyres reaching 70% of the MP overly produced. Artificial turfs are following reaching 16% of the production. In the third place is laundry reaching 6% and next is wear from boats. Other sources come in smaller percentages and are presented in more detail in the pie chart below (Figure 1) which can give the overall picture of the sources.

Table 1: Sources of microplastics (MP) and their production in (tons per year) (K. Magnusson, et al., 2016)

Source	MP produced from the source (tons per year)
Road wear and abrasion of tyres	13 520
Artificial turfs	2 300-3 900
Laundry	180-2 000
Wear from boat hulls	480-1 360
Industrial production and handling of plastics pellets	310-530
Protective and decorative coatings on buildings etc	130-250
Wear from floating devices	2-180
Personal care products	60
Wear from fishing gear	4-46
Organic waste treatment	26 (>2mm)
Household dust	0.9-17
Littering	No data, large amounts assumed
Plastic recycling facilities	No data
Landfills	No data
Agricultural plastics	No data
Discharge from ships	No data
Abrasive blasting with plastic media	No data, but low amounts are assumed
Pharmaceuticals	No data, but low amounts are assumed

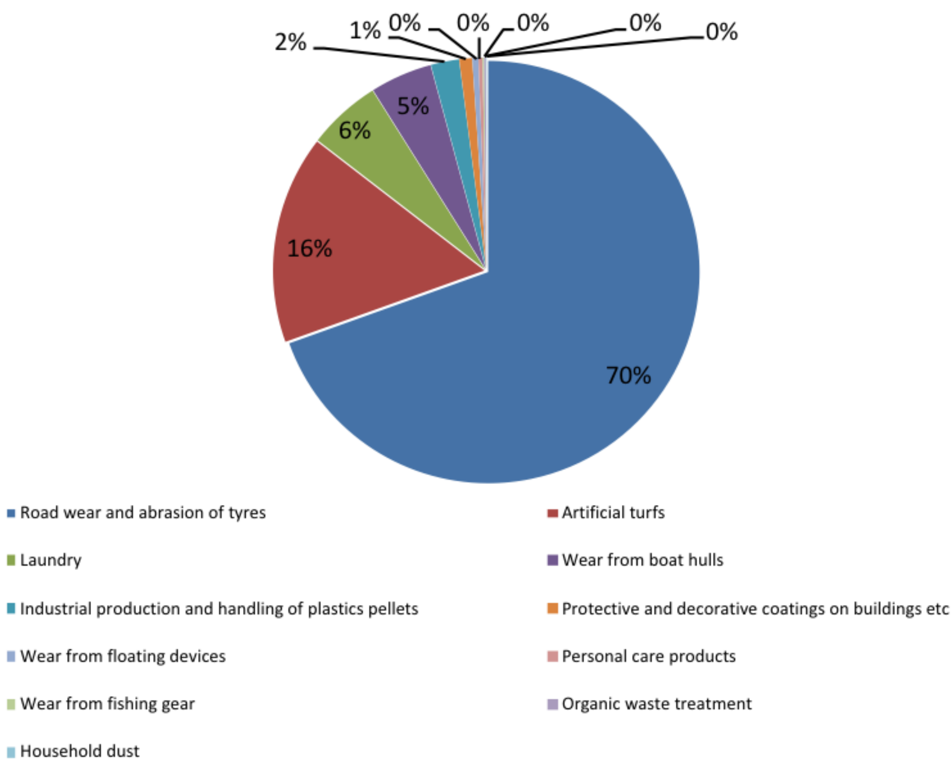


Figure 1: Pie chart based on the average values of K. Magnusson, et al., (2016) on the MP produced from different sources in tons per year.

The microplastics derive mainly from land-based sources (M. Wagner et al. 2014) and can be divided into two different categories: the primary microplastics and the secondary microplastics (C. Jönsson, et al., 2018, R. Dris et al., 2016). Primary microplastics found in domestic sewers and Wastewater Treatment Plants (WWTP) include beads coming from cleaning products or from cosmetic and day care products. In this category, scrub cleansing and toothpaste products are included. The secondary microplastics found are the result of breakdown products, such as fibers and filaments released after washing synthetic textile. In this category, different types of fibers are included such as polyester, acrylic, polyamide, etc (E. Hernandez et al., 2017). However, in the freshwater ecosystems secondary microplastics can also derive from the deterioration of debris of large dimensions such as bags, pack-aging, etc (F.D. Falco et al., 2018). In Table 2, an overview of the primary and secondary microplastics is presented with all the possible sources and compositions of microplastics that can be found in the environment.

Table 2: Source and composition of microplastics (S. Raju et al. ,2018)

Type of microplastics	Sources	Polymer type/composition
Primary microplastics	Personal care products, cleaning agents (scrubbing agent), airblasting media, powders for injection moulding	PE, PP, PS granules, PPS
Secondary microplastics	Polyester fabric, rayon fabric, nylon fabric, carpets, ropes, fishing gear, industrial wastewater	Nylon, PP, PVA fibres

2.2. Microplastics' Fate, Pathways and Effects

Synthetic microplastic fibers are frequently reported in the samples from sediments, water columns and biota (I.E.Napper, et al., 2016). As a matter of fact, there are different pathways that microplastics can follow in order to end up in the marine environment. The first big one is considered via stromwater taking into account that the highest microplastic pollution is coming from the road wear and abrasion of tyres which are lead to the sea through the rain water. Similar example is also for the artificial grass surfaces which arrive eventually to the sea through stormwater (K. Magnusson et al., 2016).

Another trail that microplastics could follow is by traveling via the wastewater though the WWTPs. An example of that path would be the waste effluent of the washing machines which, as an extend, include the fibers released from synthetic textiles. There, microplastics cannot be removed in the pre-treatment part of the WWTP due to their small size. As a result, the microfibers travel through the rest of the treatment stages. In the biological stage of the WWTP, the synthetic fibers are not readily decomposed by aerobic or anaerobic bacteria, so part of the microplastics accumulates in the sewage sludge (I.E.Napper, et al., 2016). According to B.M.C. Almroth, et al., 70-90% of microplastic particles can be retained in the sludge. Consequently, if the sludge is returned to the land or dumped in the sea the fibers are released back in the environment. However, there are remaining microplastics that derive directly from the sewage treatment and are directly released in to the water (I.E.Napper, et al., 2016).

As a result, the microplastics' ubiquity has potentially negative environmental consequences. Contamination is detected in environmental habitats and the surrounding wildlife. The effects though of long-term microplastic presence are largely unknown (C. Völker, et al., 2017, S. Rist et al., 2018). Microplastic fibers have been found though in several human consumed products such as blue mussels, honey, table salt, beer, (B.M.C. Almroth, et al., 2018) and in chickens (S. Raju et al., 2018). In the range of 2-200μm, microplastics can be mistaken from plankton and ingested by aquatic species (C. Jönsson, et al., 2018, A. Anastasopoulou et al., 2013, S.C. Gall and R.C. Thompson, 2015). Apart from their effect when entering the human web, their presence when deposited in the soil can additionally have an effect on the bulk density, the water holding capacity of the soil and the functional relationship of the microbial activity (S. Raju et al., 2018).

2.3. Microplastic Emissions from laundry

According to the study of M. A. Browne et al. (2011) that used samples from the outflow of domestic washing machines, each garment could produce >1900 fibers per wash. Part of the study also included taking samples from sewage treatment plants and that resulted in having in higher concentration of polyester (67%), as well as acrylic (17%) and polyamide (16%). Finally, after analyzing marine sediment samples, it was found that also presence of microplastics in the following percentages: 78% polyester, 9% polypropylene, 5% acrylic.

A more recent study by I. E. Napper et al. (2016) confirmed the results of M. A. Browne et al. (>1900 fibers released) and realized that the highest fiber released derived from the acrylic garment followed by polyester and polyester-cotton blends as also showed in Figure 2.

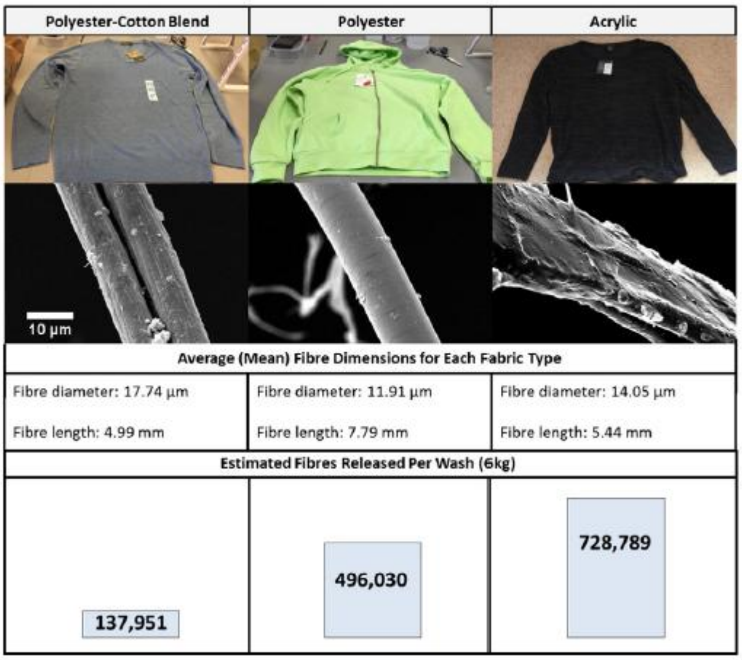


Figure 2: Garments used in experiments and a scanning electron microscopy image of a typical fiber from each garment (the scale bar for all images is 2500x magnification). Fiber diameter and lengths are included and finally the estimated fibers release each wash (I. E. Napper et al., 2016)

In fact, there are several factors affecting the microplastic emissions, including the washing conditions, the type of fabric used, the way of cutting and processing the fabric, the construction of the garment, the drying process. A list of these parameters is presented in Table 3 (C. Jönsson et al. 2018).

Table 3: Parameters affecting microplastic emissions during laundry (C. Jönsson et al., 2018)

Parameter	Examples of Values
Polymer type	Polyester, Nylon, Acrylics
Polymer origin	Virgin fossil, mechanically recycled, chemically recycled, bio-based
Yarn size	Micro-sized, medium-sized
Yarn length	Filament, staple
Brightness	Bright, semi-dull, dull
Twist	High twist, low twist
Fabric construction, knitted	Single jersey, interlock, rib nit, warp knit
Fabric construction, woven	Plain weave, satin, twill
Fabric finishing, mechanical	Shearing, brushing
Fabric finishing, chemical	Softeners
Cutting	Mechanical, laser, ultrasound
Sewing	Mechanical, ultrasound
Storage	Storage at the factory/store/at home
Washing	Time, temperature, equipment, detergents, softeners
Drying	Time, temperature, equipment

2.4. Literature Review

Available literature describes different tests to estimate the release of microplastics from the synthetic garments. Each of these tests investigated different aspects. Washing characteristics are summarized in Table 4 below.

To begin with, F. D. Falco et al. in their survey in 2018 aimed to assess the factors affecting the washing process of synthetic fabrics. So, they conducted experiments using different fabrics (plain weave polyester, double jersey polyester, plain weave polypropylene) simulating both domestic and an industrial washing. In the experiment, they used different detergent (either liquid or powder ones) doses and fabrics. The temperatures used for the domestic washing case were at 40°C and the duration 45 min while for the industrial washing were at 75°C for 60 min. The second part of their research included testing different temperatures and different washing durations. All the experiments were conducted in a Linitest apparatus which is a laboratory simulator of a real washing machine. The counting method was conducted with the help of the scanning electron microscopy (SEM). In more detail, for every filter that they obtained, it was separated into 21 micrographs to make it easier to observe the filter from the border to the center of the filter. The amount of fibers was counted in each of the micrographs and with further calculations the average number of fibers per filter was retrieved, considering the surface area of each micrograph.

In 2017, E. Hernandez et al. conducted a similar study that aimed to test synthetic textiles as a source of microplastic. Interlock fabric was used from 100% polyester yarns and also plain single knit jersey fabric with the same polyester yarns but with an extra 2% of spandex plating too. Two washing procedures were followed: The experiments were conducted in a Washtex-P Roaches laboratory washing machine and a Keyence Digital Microscope system with VHX Digital Microscope Multi Scan Lens was used to image the filters. The next step was to take 30 individual images of the whole filter. Then the individual images were automatically aligned by the microscope computer to give one single image as a final result. The image processing resulted in counting the number of fibers, the fiber length distribution and finally the fiber mass.

In 2018, C. Jönsson et al. aimed to develop a method for measuring microplastic shedding of textiles washed in domestic conditions. The textiles that were tested in this study were only polyester based and were cut and welded by the research team. The cutting was either conducted with scissors or with ultrasonic cutting machine to be able to differ between microplastics that are released from the surface and the ones released from the edges. The experiments were conducted in a Gyrowash machine and an optical microscope was used in order to count the fibers and analyze the fibers' length-width ratio. The washing temperature was at 40°C and lasted for 60min.

In 2016, I. E. Napper also worked on the microplastic release from domestic washing machines and washing conditions. In order to conduct their experiment, three fabric types were selected: a black 100% polyester fleece, a green 100% acrylic blouse and a blue 65% polyester/35% cotton blouse. The washing machine used for the experiments was a Whirlpool WWDC6400 as it is a popular domestic brand. The fibers were collected with a filter which was put in the outflow of the washing machine with a pore size of 25μm. Then the filters were dried at 30°C and weighted. During the experiment, there were several factors taken into account such as the different fabric type, the temperature factor (30°C and 40°C), the detergent and the conditioner used. The wash duration was constant to 1h 15min. The final number of the fiber was estimated taking into account the density, the length, and the diameter of the fibers. The fibers were visualized by SEM and the length and width of the fibers a sample of 10 individual fibers were analyzed.

In 2018, B.M.C. Almroth et al., also worked with quantifying the shedding of synthetic textiles. Part of their work included to produce their own fabrics. In order to do that, 10x10cm pieces of cloth were cut using laser. The clothes were initially pre-washed at 40°C for 15min in an Electrolux washing machine and then normally washed using a Gyrowash one bath 815/8 machine. The samples mashing temperature was 60°C for 30min. The wash water was then filtered using a filter of 1.2 μm pore size. Then the filter was divided into 4 areas and each of them was divided into another 4 areas. Then, the fibers in each area were manually counted with the help of microscopy.

In 2011, M.A. Browne et al. did one of the initial efforts to try to estimate the synthetic fibers released from the washing machines. In their experiments they used three different washing machines: Bosch WAE24468GB, John Lewis JLWM1203 and Siemens Extra Lasse XL 1000. The washing temperature was at 40°C and they used three kinds of garments: polyester blankets, fleeces, shirts. In between the washes a 90°C wash was conducted for continuously 3 cycles. The effluent was eventually filtered and the microplastic was counted.

Table 4: Summary of the washing temperature and washing duration of the literature review papers

Sources	Washing Temperature	Washing Duration
I.E. Napper et al. (2016)	30°C and 40°C	1h 15min
F.D. Falco et al. (2018)	40°C/70°C	45min/60min
C. Jönsson et al. (2018)	40°C	60min
E. Hernandez et al. (2017)	40°C/ 25 °C-40°C and 60°C	45min/1, 2, 4, 8h
B.M.C. Almroth et al. (2018)	60°C	30min
M.A. Browne et al. (2011)	40°C	-

3. Methods

In this part of the thesis, the experimental set up is described by providing information on the materials, the machines and devices used and also their functional systems. All the experiments took place at the Environmental Chemistry Laboratory at Chalmers and the measurements at the HSB Living Lab.

3.1. Textile characteristics

In order to test the microplastic release, synthetic clothes were bought and washed under specific conditions. In total 3 fleeces, 3 T-shirts and 3 packs of socks were washed. Further details are provided in Figures 3 - 5.

Composition:

84% polyester

16% elastane

Initial Average Weight:

360.07g

Figure 3: Fleece jacket with hood with its characteristics in composition and average initial weight.

Composition:

87% polyester

13% elastane

Initial Average Weight:

146.36g

Figure 4: Short-sleeved workout T-shirt with its characteristics in composition and average initial weight.

Composition:

74% polyamide

17% polyester

7% elastodiene

1% elastane

Initial Average Weight:

260.25g

Figure 5: 5-pack sports socks used in the experiment with their characteristics in composition and average initial weight.

3.2. Description of experimental procedures

The experimental procedure was performed in three parts. Fibers were collected for the 1st wash of new garments, the 5th wash of the same garments (fibers were not collected for washes 2-4) and the 6th wash of the same garments after they were worn by volunteers for 12h. The weight of released fibers, their length and their diameters were measured for each collection. The collection was performed in triplicate, with garments being washed individually for the fleeces and T-shirts, and by packs of 5 for the socks. All three parts followed similar procedures of pre-wash preparation, washing stage and after-washing as described further below.

3.2.1. Pre-washing preparation

The pre-washing preparation was the same in all the parts. In more details, it included the filter preparation, the weighting of both the filters and the clothes and the pre-washing of the washing machines. Part of the pre-washing was cutting small parts of the clothes to see their visual differences by Environmental Scanning Electron Microscopy (ESEM).

<u>The filters preparation:</u>

In order to catch the fibers released during each wash, specific filters were ordered whose characteristics are showed in the Table 5 below.

Table 5: Characteristics of the filter used to capture the fibers

Pore size (μm)	50
Length (mm)	25

Width (mm)	10.5

The shape of the filter is cylindrical to prevent from clogging of fibers during the wash and at the same time to fit to the outflow of the washing machine which was an extended cylinder at the bottom of the machine. In Figure 6 below is a visualization of the filter:

Figure 6: Filters used to conduct the experiments

Because the filter was open at both sides, it had to be closed with a patent and be attached to the machine outflow. The issue was solved with the help of a clip which was used after folding 2 times the edge of the filter. Then, the filter was attached to the outflow with the aid of tire ups keeping it attached as shown in Figure 7.

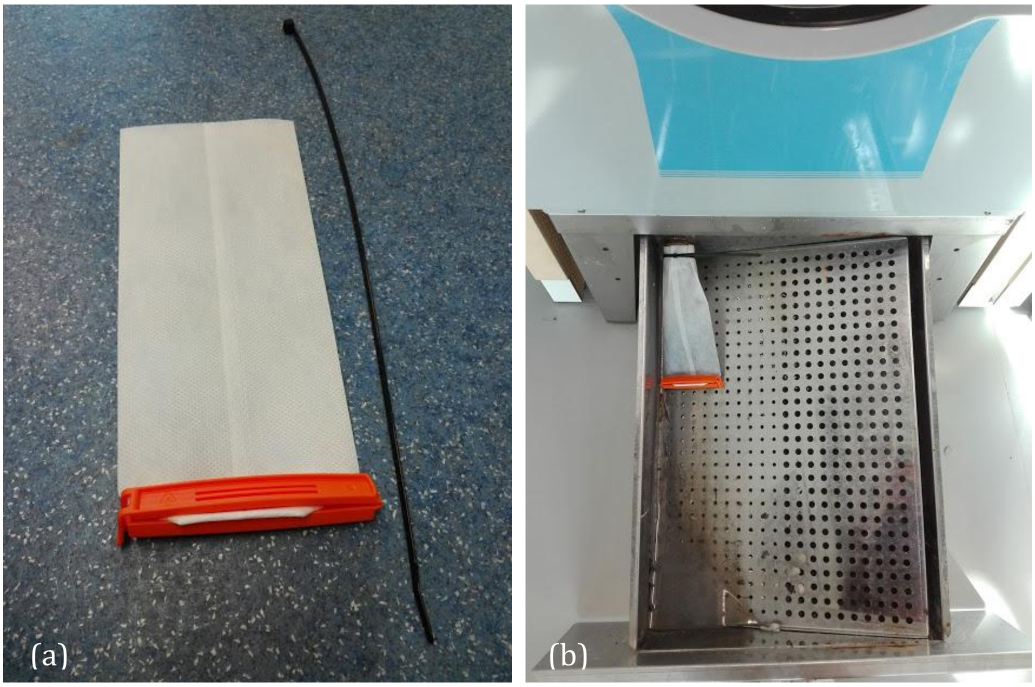


Figure 7: (a) Filter with the patent to close the bottom of the filter and the tire up used to attach it to the outflow of the washing machine. (b) Filter attached to the outflow of the washing machine.

Before each wash, the filter was washed by holding it for 3 minutes under the tap water, in order to clean it from unexpected dirt during its manufacture. Then the filters were dried in the laundry's drying machine in the "Normal" function of the dryer which lasted for 30 minutes. The dryer was part of the Living Lab equipment and its model was Electrolux TS5140LE (Figure 8). Afterwards, the filters were kept in the desiccator in order to let them cool down and reach room temperature. Then, the initial weight of the filters was measured in the laboratory's scale (Sartorius Analytic).

Figure 8: Electrolux DryerTS5140LE used for drying the filters (Electrolux).

Weighting the clothes:

Another part of the pre-washing was the weighting of the clothes to know their initial weight before washing them. The scale used was part of the lab equipment and its model was Sartorius Quitnix 5102-1S.

Pre-washing the washing machines:

Finally, the last part of the prewashing was the wash of the washing machines. The washing machines' buckets and pipes had to be as clean as possible in order not to have fibers remainders from previous washing present in our filters which could alter the final result. The washing machine settings for the prewash were presented in Table 6.

Table 6: The settings of the washing machine during the prewash of the machines

Detergent	✖
Softener	✖
Duration (min)	32-33
Temperature (°C)	30
Program	Quick/Normal colour

The washing machines available in the Living Lab were Electrolux W575H LE models as shown in Figure 9. The bottom part of the washing machine was a drawer which was used as a filter for the bigger particles released after each wash driven to the outflow as it can be seen in Figure 7b. In terms of duration, the machines had small differences and as a result their durations during the prewash were ranging from 32-33min.

Figure 9: Washing machines in the Living Lab (The Research Hub by Electrolux ™ Professionals)

3.2.2. Washing Stage

During the washing stage, all the clothes were washed similarly. The program setting of the machines is presented in Table 7:

Table 7: The settings of the washing machine during the wash of the clothes

Detergent	✓
Softener	✗
Duration (min)	41-48
Temperature (°C)	40
Program	Eco/Normal colour

Each item was washed separately. This means that for example 1 pack of socks was washed in one wash, the 2nd pack of socks was washed in another wash and so on. In terms of duration there were several differences depending each machine. The differences are a result of the different weights of the clothes which was automatically set by the machine. A table with the durations can be found it in the Appendix I.

3.2.3. Sample preparation for fiber quantification

During the after washing stage similar procedures were followed to all the clothes. The after washing stage included the removal of the filter from the washing machine outflow, the drying of the filter and the clothes and the lab analysis.

The filter removal was followed by a washing out with 800mL of warm water to remove the remaining detergent from the fibers and the filter. After that, both the filter and the clothes were put in the Electrolux dryer TS5140LE in the normal program for 60min. After drying them, the filters were put in the desiccator and the clothes were left aside so that both can reach room temperature. Eventually, they were both weighted; the filters in the Sartorius Analytic and the clothes in the Sartorius Quitnix 5102-1S.

The next step, after weighting the filters, was to examine the length and diameter of the fibers in each filter under optical microscopy. The microscope used for the occasion was an Olympus BX53. The first attempt was to try to analyze under the microscope the filter itself after cutting it in half. However, because of the uneven surface of the filter and the different levels of the fibers, the analysis was quite challenging. As a result, a translucent tap was applied on the filter and then fit to the microscope slide. In that way, the microscopy analysis was easier as all the fibers were at the same level and easier to measure. The magnifying lens x10 was the one used for the analysis.

Additionally, it was decided to record the length and diameter of 100 fibers from one filter of each of the garments. In order to have a better picture of the fibers' length and diameter, tape-samples were taken from 3 different parts of the filter. The total number of fibers from all three parts was 100 (33+33+34). The reason the filter was divided into 3 was to check if there are any differences from different parts of the filter and at the same time have a better picture of the filter in total.

Finally, the samples were cut from the clothes and were analyzed with the help of ESEM and Energy Dispersive X-ray spectroscopy (EDAX) analyses. The model used was Quanta 200 ESEM FEG from FEI (Figure 10) which is a special type of high performance scanning electron microscope (FEI Quanta200 ESEM). The ESEM analyses were used to compare the texture of the garments before and after the washes and also after their use. In more detail, according to Weillie Zhou et all., ESEM analysis is based on electrons that can be deflected by the magnetic field. In comparison to light microscopy, the light source is replaced with high energy electron beams. In terms of the EDAX analysis, it is referred to another sort of sign generated by the interaction of the primary electron beam with the specimen also know as x-rays. This x-ray analysis (EDAX) offers chemical information with the help of the emission of the x-ray photons after electrons collisions. In more detail EDAX makes use of the X-ray spectrum emitted by a solid sample bombarded with a focused beam of electrons to obtain a localized chemical analysis (Introduction to Energy Dispersive X-ray Spectrometry (EDS)). The settings of our analysis included low vacuum, spot size 4, aperture 4 and changing current (mentioned in the pictures in Chapter 4). The detector was Solid State Backscattered Electron Detector (SSD-BSD) and the cloth samples were mounted directly on the sample holder using a carbon tape. There was no pretreatment performed to the samples.

Figure 10: Quanta 200 ESEM used for the analyses of the garments

3.3. Counting Methods

In order to count the fibers released from each wash a specific method was applied. Firstly, manual counting was considered an option. However, its disadvantage was a time consuming and uncertain method. As a result it was decided to estimate their number with the help of the following equations. The fibers were assumed to be of cylindrical shape.

The data that we attained from our measurements were

- the length (L) and

- the diameter (D) of 100 fibers and
- the weight of all the fibers collected in the filter (m_{filter}).

So the volume of the each of the 100 fibers (V_{fiber}) was calculated accordingly:

$$V_{fiber} = \pi(\frac{D}{2})^2 L$$

Next thing was to multiply with the density of each garment (d) to find the mass of each fiber (M_{fiber}):

$$M_{fiber} = V_{fiber} * d$$

Then their average fiber mass was found using the "Average" command in Excel ($M_{fiber, ave}$).

Eventually, the number of the fibers could be estimated by dividing the mass of all the fibers in the filter (m_{filter}) with the average mass of each fiber ($M_{fiber, ave}$):

$$N = \frac{m_{filter}}{M_{fiber,ave}}$$

Additionally, the density of each garment was experimentally measured for each of the clothes. A big part was cut from each of them and it was weighted in the Sartorius Analytic (m_{cloth}). Then, a cylinder was used which contained water at a certain level. After dipping the cloth in the cylinder, the difference in its volume was the volume of the cloth (V_{cloth}). The density of the cloth was calculated accordingly:

$$d = \frac{m_{filter}}{V_{cloth}}$$

The procedure was repeated for all three garments.

3.4. Counting Methods

Finally, the annual fiber release in Göteborg and Sweden was estimated based on the following assumptions (H. Ejhed et al., 2018)

$$\left.\begin{array}{l}\boxed{\text{140 washes/household/year}}\\ \boxed{\text{1.9 persons/household}}\end{array}\right\} \rightarrow \left.\begin{array}{l}\boxed{\text{74 washes/person/year}}\\ \boxed{\text{3-4 kg/each wash}}\end{array}\right\} \rightarrow \boxed{\text{220-300 kg/persons/year}}$$

The number of people living in Göteborg and Sweden were obtained from the last PPP in 2017m (i.e. 9.995 million in Sweden and 1016000 in Göteborg). For

Göteborg, the population in the metropolitan area was taken into consideration. Also as the mg fiber/kg wash was used average value after the 5^{th} wash from the measurements of all the garments.

4. Results

In this chapter, the results of experiments will be presented. In more detail, the results contain information about the weight of the filter and the fibers and their length and diameter during all the three washes that have been carried out. Also photos from the ESEM analysis and optical microscopy will be presented in comparison during the washes.

4.1. Fleece

First Wash (1st Wash)

Fleece 1 reached 0.140 g of fibers while Fleece 2 and Fleece 3 reached 0.136 g and 0.108 g respectively. Additionally, it can be seen that the weight of the fleeces was also reduced after the first wash. Fleece 1 lost 2.64 g while Fleece 2 and 3 lost 3.21 g and 3.10 g respectively. The comparison between those values show that the weight of fibers released are almost 30 times less than the weight of each fleece lost. That means that the garments are losing more than just fibers. According to the literature (I.E. Napper et all, 2016) oils and waxes are used in textiles, and can be removed after a wash with synthetic detergents. The 30 times higher loss of weight than fibers released value can be explained, considering that after wash waxes and oils used for the fleeces might be removed too making it be lighter in weight. More analytical values can be seen also in Table 8 below:

Table 8: Values of fibers released after 1st wash of Fleece 1, 2 and 3 and the weight loss of each of the fleeces

FLEECE, 1st Wash			
	Fleece 1 (g)	**Fleece 2 (g)**	**Fleece 3 (g)**
Initial Weight of **fleece**	356.96	365.02	358.23
Final Weight of **fleece** (after 1st wash)	354.32	361.81	355.13
Initial Weight of **filter**	4.369	4.383	4.451
Final Weight of **filter** (after 1st wash)	4.509	4.518	4.559
Fibers released after 1st wash	0.140	0.136	0.108
Lost weight from **fleece** after 1st wash	2.64	3.21	3.1

Fifth Wash (5th Wash)

After the 5th Wash of the fleeces it can be noted that there is a decrease in the fibers released in the filter. For Fleece 1 it dropped to 0.046 g, for Fleece 2 to 0.041 g and for Fleece 3 to 0.027 g. In other words, the drop is estimated to be about 0.100 g. At the same time the loss of weight of the clothes is also decreased. For Fleece 1 the loss is 0.80 g, for Fleece 2 is 0.82 g and for Fleece 3 0.79 g. The difference between the fibers released and the weight loss of garments is still high which can be possibly attributed to wax and oil remainders on the clothes or due to loss of smaller than 50 micron fibers. More analytical values can be seen in the Table 9 below:

Table 9: Weight of fibers released after 5th wash of Fleece 1, 2 and 3 and the weight loss of each of the fleeces

FLEECE, 5th Wash			
	Fleece 1 (g)	**Fleece 2 (g)**	**Fleece 3 (g)**
Initial Weight of **fleece**	353.28	361.12	354.54
Final Weight of **fleece** (after 5th wash)	352.48	360.3	353.75
Initial Weight of **filter**	4.640	4.275	4.433
Final Weight of **filter** (after 5th wash)	4.687	4.316	4.462
Fibers released after 5th wash	0.046	0.041	0.030
Lost weight from **fleece** after 5th wash	0.80	0.82	0.79

Sixth Wash (6th Wash, after 12h use)

Finally, after the 6th wash where the clothes were worn for about 12 h, the fibers' release seems to increase reaching 0.109 g. That means that it increased about 0.60 g. That can be associated with the higher fiction tenses during its use which can destroy several fibers making them more lose which lead them to be released from the garment during laundering. This increase can be a result of dust particles coming from the outside environment. The latter can also be linked to the higher initial weight of Fleece 2 before 6th Wash compared to the final weight of Fleece 2 after 5th Wash (361.47 g and 360.03 g respectively) (Figure 11). In Table 10 the values of the fleeces and the filter are featured in more detail.

Table 10: Weight of fibers released after 6th wash of Fleece 2 and the weight loss of the fleece

FLEECE , 6th Wash	
	Fleece 2 (g)
Initial Weight of **fleece**	361.47
Final Weight of **fleece** (after 6th wash)	360.73
Initial Weight of **filter**	4.4307
Final Weight of **filter** (after 6th wash)	4.539
Fibers released after 6th wash	0.109
Lost weight from **fleece** after 6th wash	0.74

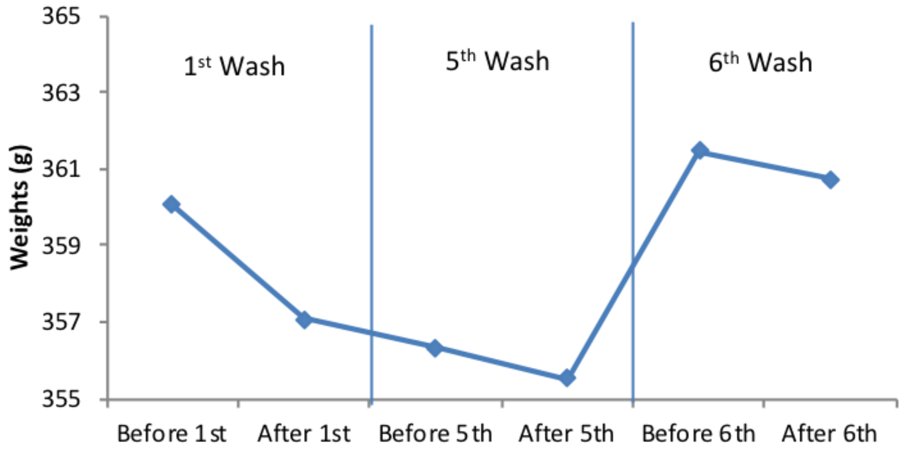


Figure 11: Fluctuation of fleece weights during the washes

To sum up, the fibers released per weight of textile were higher after the 1st wash. After the 5th wash, their weight is dropping almost 70% and finally, after use, their weight is rising again reaching almost its initial release (Figure 12):

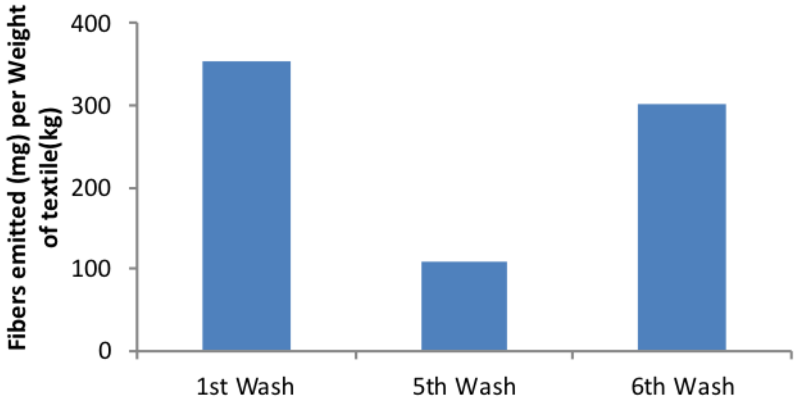


Figure 12: Fibers emitted (in mg) per weight of textile (in kg) during the 1st, 5th and 6th Wash for the fleece.

During the microscopy analysis the fibers were classified according to their length. In the small category (S) belonged the fibers whose length was smaller than 200µm, in the medium category (M) belonged the fibers whose length was between 200-500µm, in the large category (L) those fibers that are between 500-1000µm and finally in the extra large category (XL) those longer than 1000µm. Their results vary from wash to wash and are shown in more detail in Appendix II. The diameter also varied a lot through the different samples. From Figures 13 and 14 below it can be identified that from the high standard deviation values both on the length and their diameters. Some examples of fibers under the microscope having different shapes (Figure 15).

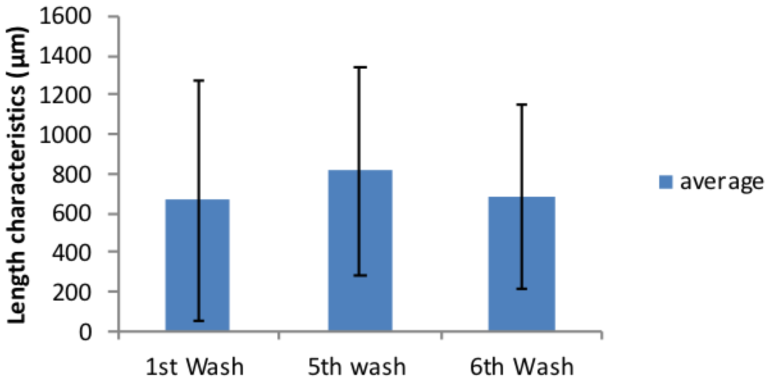


*Figure 13: Bar-graph showing the average **length** of fibers with their standard deviations through the different washes for the fleece.*

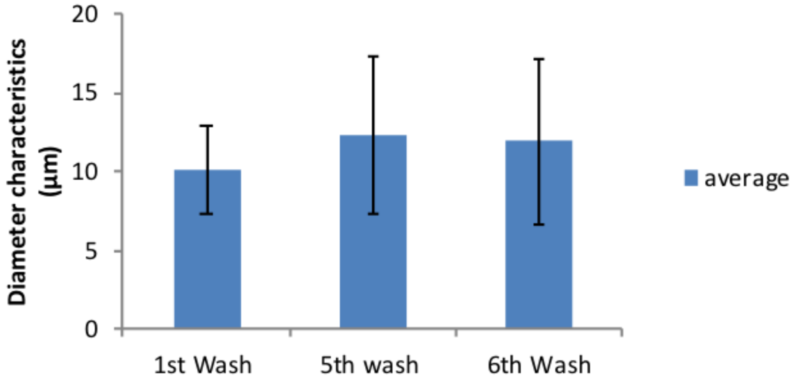
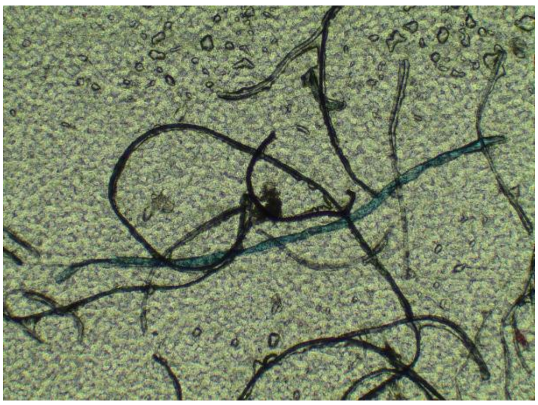
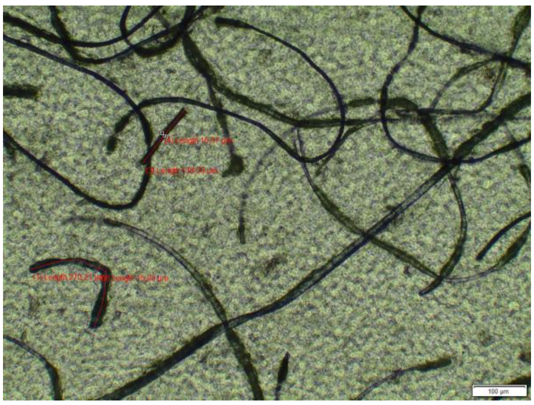


*Figure 14: Bar-graph showing the average **diameter** of fibers with their standard deviations through the different washes for the fleece.*





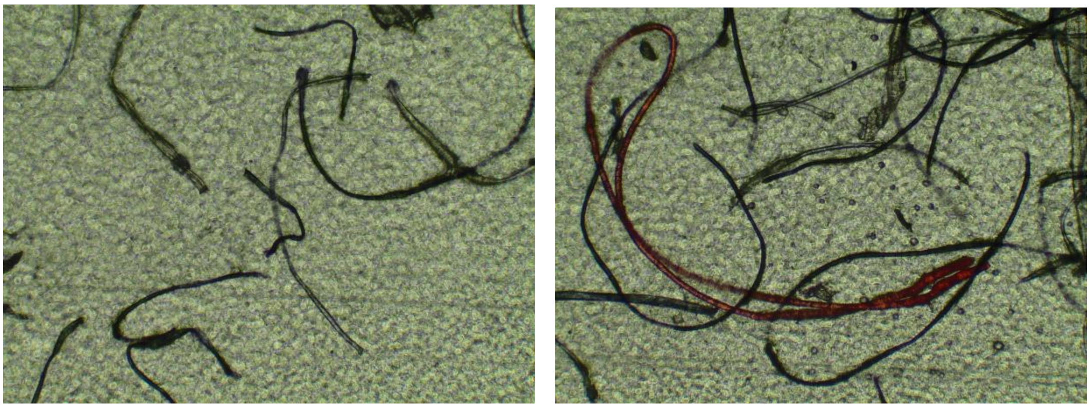


Figure 15: Pictures from optical microscopy of the fleeces' fibers in different lengths and diameters. (Upper left: from 1st wash), (Upper right: from 1st wash), (Bottom left: from 1st wash), (Bottom right: from 1st wash).

The next step was the density calculation which was found to be 1.1844 g/cm³. After that the number of fibers was estimated. It can be seen that fibers released after the 1st wash reach up to about 2,000,000 while after the 5th wash their number is dropping as expected and reaches about 400,000 fibers. Eventually, after the 6th wash they are increasing to 125,000 fibers. See Figure 16 for more details:

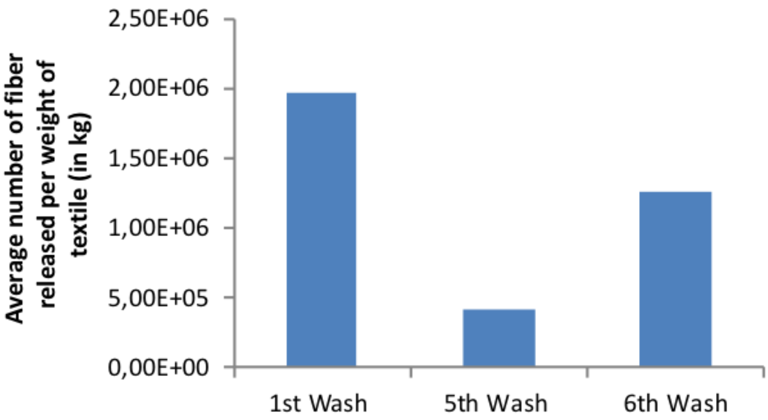


Figure 16: The average number of fibers released during the 1st, 5th and 6th Wash for the fleece

4.2. T-shirt

1st wash:

After the 1st wash, it can be that the T-shirt has lower fiber release compared to the fleece. T-shirt 1 emitted 0.082 g, T-shirt 2 0.051 g and T-shirt 3 0.082 g. These values are on average 40% lower than the fleece's one. This is normal since the T-shirts were also lighter than the fleece too by almost 60%. In addition, the weight loss from the T-shirt 1 was 0.58 g; while from T-shirt 2 and 3 was 0.51 g and 0.79 g respectively. There is also here a big difference between the fibers released and the weight loss of the T-shirt. Similarly with the fleece, the latter fact is attributed to the loss of wax and oils used on the garment. Another factor could also be the evasion of smaller than 50 microns fibers. Analytical values of the measurements are presented below in Table 11.

Table 11: Weight of fibers released after 1st wash of T-shirt 1, 2 and 3 and the weight loss of each of the T-shirts

T-shirt, 1st Wash			
	T-shirt 1 (g)	**T-shirt 2 (g)**	**T-shirt 3 (g)**
Initial Weight of **T-shirt**	145.35	147.21	146.53
Final Weight of **T-shirt** (after 1st wash)	144.77	146.7	145.74
Initial Weight of **filter**	4.283	4.406	4.392
Final Weight of **filter** (after 1st wash)	4.365	4.457	4.458
Fibers released after 1st wash	0.082	0.051	0.082
Lost weight from T-shirt after 1st wash	0.58	0.51	0.79

5th Wash:

After the 5th Wash, the fiber release drops even more reaching about a 35% fall from their 1st wash. Thus, T-shirt 1 declined to 0.027 g, T-shirt 2 to 0.029 g and T-shirt 3 to 0.019 g. This decrease it considered regular, since during the 1st wash there are usually more debris from the manufacture of the cloth. The indication for the higher loss of weight is laying on the same fact of the wax and oil remainders on the cloth or the leakage of the smaller particles from the filter. For T-shirt 2, the number of fibers lost is 0.17 g and for T-shirt 3 is 0.15 g. Values in more detail are to be found in Table 12 below:

Table 12: Weight of fibers released after 5th wash of T-shirt 1, 2 and 3 and the weight loss of each of the T-shirts

T-shirt, 5th Wash			
	T-shirt 1 (g)	**T-shirt 2 (g)**	**T-shirt 3 (g)**
Initial Weight of **T-shirt**	144.57	146.53	145.86
Final Weight of **T-shirt** (after 5th wash)	144.60	146.36	145.71
Initial Weight of **filter**	4.612	4.282	4.397
Final Weight of **filter** (after 5th wash)	4.639	4.310	4.416
Fibers released after 5th wash	0.027	0.029	0.019
Lost weight from T-shirt after 5th wash	n.a.	0.17	0.15

6th Wash, after 12h use:

Finally, after the 6th wash it is observed that their number is increasing again reaching 0.082 g of fibers. Compared to the 5th wash, it seems that they are increased by almost 4 times. The weight loss of the T-shirt is also greater than before reaching 0.35 g. Particularly, this means that the weight of fibers lost is more than doubled. See Table 13 below for more details:

Table 13: Weight of fibers released after 6th wash of T-shirt 1, 2 and 3 and the weight loss of each of the T-shirts

T-shirt, 6th Wash	
	T-shirt 2 (g)
Initial Weight of **T-shirt**	147.02
Final Weight of **T-shirt** (after 6th wash)	146.67
Initial Weight of **filter**	4.414
Final Weight of **filter** (after 6th wash)	4.496
Fibers released after 6th wash	0.082
Lost weight from T-shirt after 6th wash	0.35

In terms of how the weight of the T-shirt is evolving during the washes it can be evaluated through Figure 17. According to the latter, between the 1st and 5th wash the changes are brief. However, after the 6th wash a leap is detected which can be justified taking into account the high friction tenses applied to the garment during the 12 h use and also the external use factor which means that particles could be deposited for the outer environment on the textile.

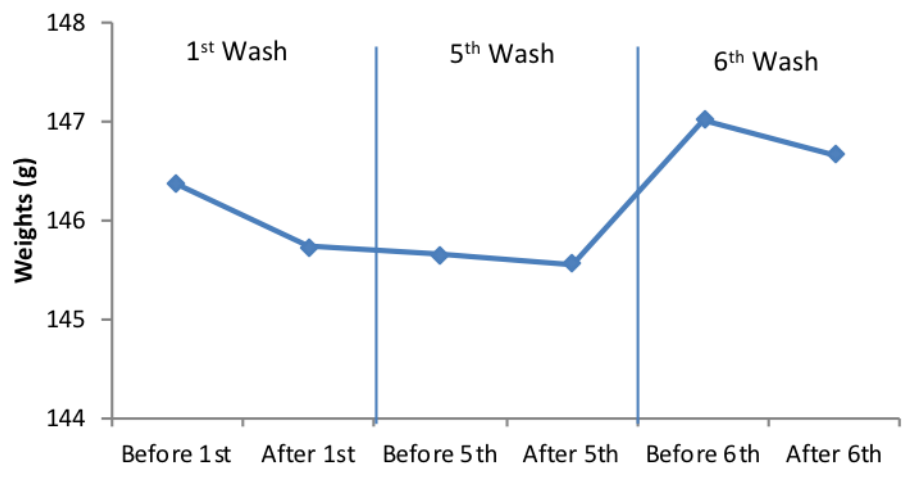


Figure 17: T-shirt Weight Fluctuation during the washes

To sum up, taking into account the fibers emitted per weight of textile (Figure 18), it is still obvious the drop after the 5th wash. So is the jump after the 6th wash which is even exceeding the initial release reaching 450 mg per kg of T-shirt.

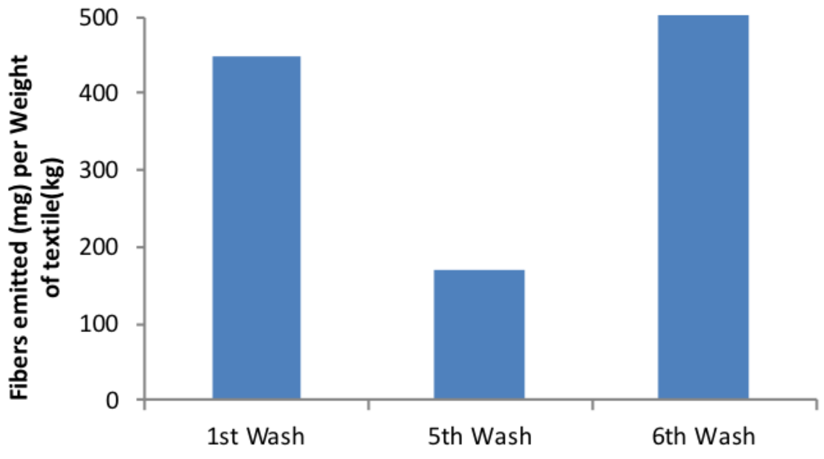


Figure 18: Fibers emitted (in mg) per weight of textile (in kg) during the 1st, 5th and 6th wash for the T-shirt.

Another parameter examined was the range of the length and diameter among the different washes. These can be observed in Figures 19 and 20 where the standard deviation of the lengths and the diameters is also elevated.

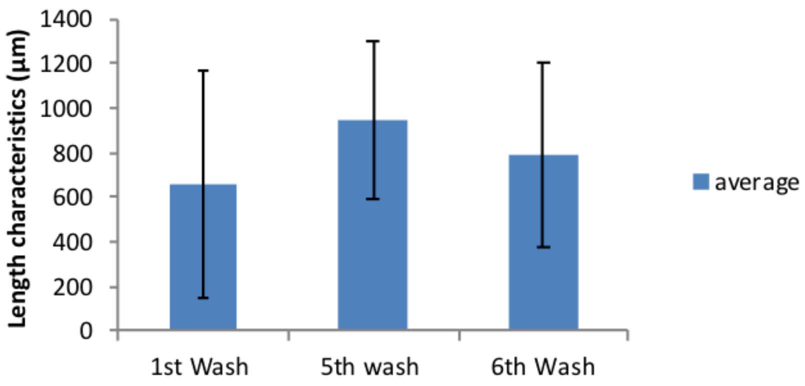


*Figure 19: Bar-graph showing the average **length** of fibers with their standard deviation through the different washes for the T-shirt*

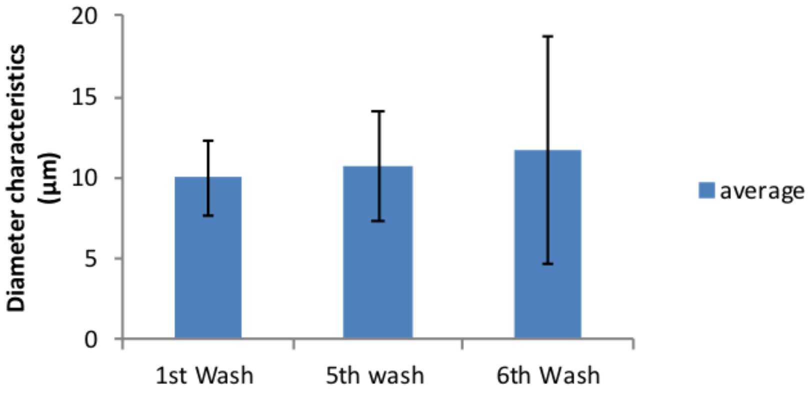


*Figure 20: Bar-graph showing the average **diameter** of fibers with their standard deviation through the different washes for the T-shirt*

A sample of fibers shown in the optical microscope with different lengths and diameters are presented below (Figure 20).

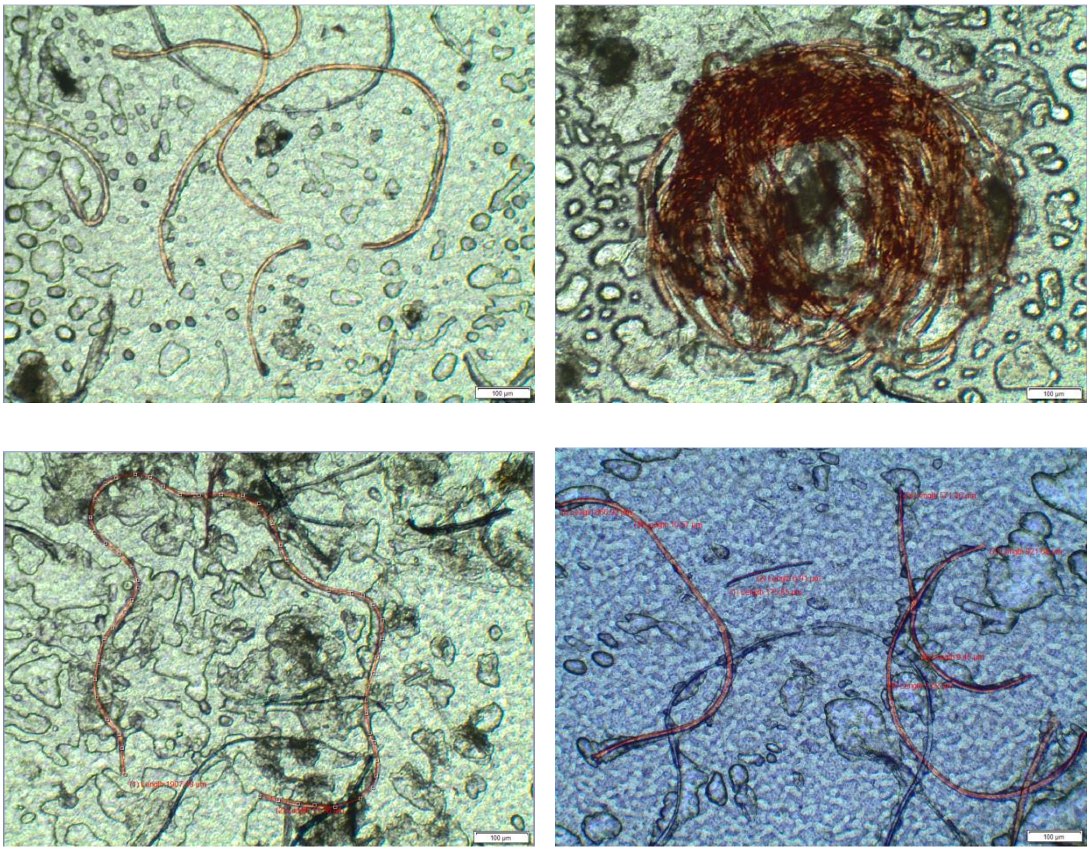


Figure 21: Pictures from optical microscopy of the T-shirt's fibers in different lengths and diameters. (Upper left: from 5^{th} wash), (Upper right: from 6^{th} wash), (Bottom left: from 6^{th} wash), (Bottom right: from 1^{st} wash).

Furthermore, the next step was to measure the density of the T-shirt which was 1.015 g/cm^3. Having this value, the number of fibers was next estimated. Taking into account, then, the average number of fibers emitted per wash (Figure 22), the 1^{st} wash contributed with a higher number of fibers, which after 5^{th} wash drops. However, the 6^{th} wash is not as high as after the 1^{st} wash as in Figure 17. That can be attributed to the shape of fibers. See Appendix III for the length distribution.

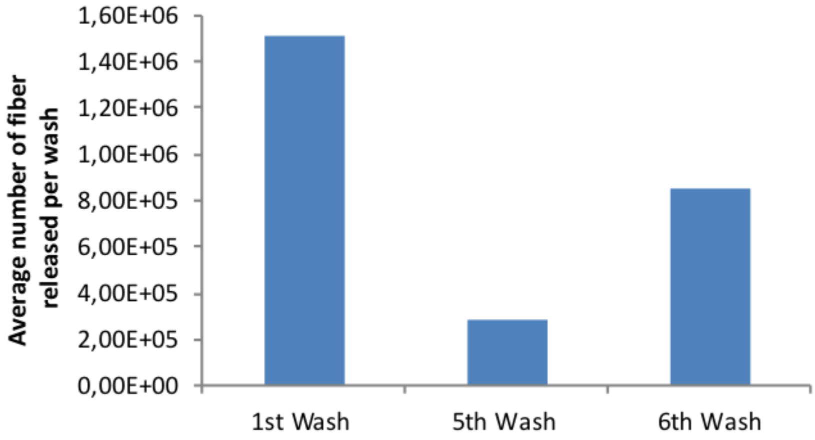


Figure 22: Average number of fibers released during the 1st, 5th and 6th Wash for the T-shirt.

4.3. Pack of socks

1st wash:

After the 1st wash, the socks seem to release the lowest amount of all the 1st washes compared to the rest of experiments. Socks 1 released 0.044 g, Socks 2 0.032 g and Socks 3 0.047 g which is more than 50% less than the fleeces and the T-shirts. In terms of the weight loss from the socks themselves, though, the difference is the highest of all. Socks 1 lost 3.24 g; Socks 2 4.26 g and Socks 3 4.48 g. Part of it is, as explained it the previous garments, washed out wax and oil. It could also be though an amount of fibers smaller than 50μm that can escape the filter. The results are presented in more detail in the Table 14 below:

Table 14: Weight of fibers released after 1st wash of T-shirt 1, 2 and 3 and the weight loss of each of the Socks

Socks, 1st Wash			
	Socks 1 (g)	**Socks 2 (g)**	**Socks 3 (g)**
Initial Weight of **pack of socks**	257.32	266.11	257.33
Final Weight of p**ack of socks** (after 1st wash)	254.08	261.85	252.85
Initial Weight of **filter**	4.514	4.774	4.746
Final Weight of **filter** (after 1st wash)	4.558	4.806	4.793
Fibers released after 1st wash	0.044	0.032	0.047
Lost weight from **pack of socks** after 1st wash	3.24	4.26	4.48

5th Wash:

After the 5th wash, the fibers emitted are less than the 1st wash and also less than all the other 5th washes. In more detail, Socks 1 discharged 0.031 g, Socks 2 0.016

g and Socks 3 0.028 g. Moreover, after the 5th wash, the weight loss of the socks declines also to approximately 50%. This drop was anticipated similarly to the previous results of the fleeces and the T-shirt. So, Socks 1 attained 1.98 g, Socks 2 1.95 g and Socks 3 2.51 g. The smaller fibers left and wax or oil removal during washing are most likely some reasons of this increase when comparing the number of fibers released after the 5th wash and the weight lost from the garment. More results are presented in Table 15 below:

Table 15: Weight of fibers released after 5thwash of T-shirt 1, 2 and 3 and the weight loss of each of the Socks

Socks, 5th Wash			
	Socks 1 (g)	**Socks 2 (g)**	**Socks 3 (g)**
Initial Weight of **pack of socks**	255.46	263.92	255.03
Final Weight of **pack of socks** (after 5th wash)	253.48	261.97	252.52
Initial Weight of **filter**	4.457	4.058	4.581
Final Weight of **filter** (after 5th wash)	4.488	4.075	4.609
Fibers released after 5th wash	0.031	0.016	0.028
Lost weight from **pack of socks** after 5th wash	1.98	1.95	2.51

6th Wash:

After the 6th wash of the socks the results were amazingly high compared to any other measurements. The fibers freed were more than 15 times higher than the 1st wash accomplishing 0.632 g release. Likewise, the material lost from the garments increased a lot, reaching nearly its initial levels after the 1st wash. For more details see Table 16 below:

Table 16: Weight of fibers released after 6th wash of T-shirt 1, 2 and 3 and the weight loss of each of the Socks

Socks, 6th Wash	
	Socks 2 (g)
Initial Weight of **pack of socks**	269.21
Final Weight of **pack of socks** (after 6th wash)	264.5
Initial Weight of **filter**	4.642
Final Weight of **filter** (after 6th wash)	5.274
Fibers released after 6th wash	0.632
Lost weight from **pack of socks** after 6th wash	4.71

According to the graph in Figure 23 it can be identified the additional weight to the socks before the 6th wash. That can be a result of particles trapped in the socks from the shoes or from the contact with the outer environment in general.

This fact can explain also the higher numbers recorded in Table 16 before and after the 6th wash.

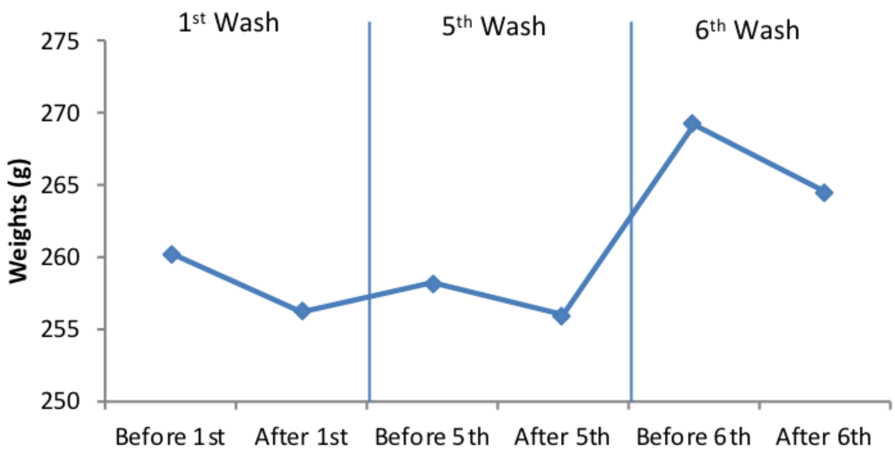


Figure 23: Socks Weight Fluctuation during the washes

To sum up, taking into account the fiber emitted (mg) per kg of textile washed, the 6th wash is by far the most fiber contributing one. Apart from the particles originating from the outer environment, another parameter would be the high friction tenses that it experienced from a human stepping on those for 12 h. That could make the fibers be looser and eventually depart from the cloth during the wash. The results from the Figure 24 shows that the fibers emitted per kg of textile washed are almost 2.4 g per kg of wash after the 6th wash.

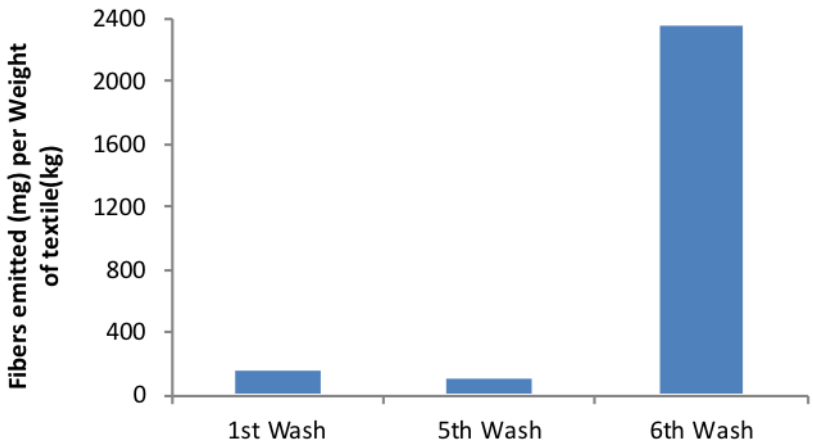


Figure 24: Fibers emitted (in mg) per weight of textile (in kg) during the 1st, 5th and 6th Wash for the socks.

Another parameter examined was how fibers could be the ranging in shapes. Analytical pie charts of them are available in Appendix IV. Also a good picture of how their shapes are changing can be provided in the Figures 25 and 26. The values of the standard deviation values are really high. In the case of the 1st wash the lengths has about the same standard deviation to the average length. The same situation is noted also after the 6th wash for the sock's diameter whose standard deviation is higher than the average number of fibers. That means that fibers with double length and diameter were also found.

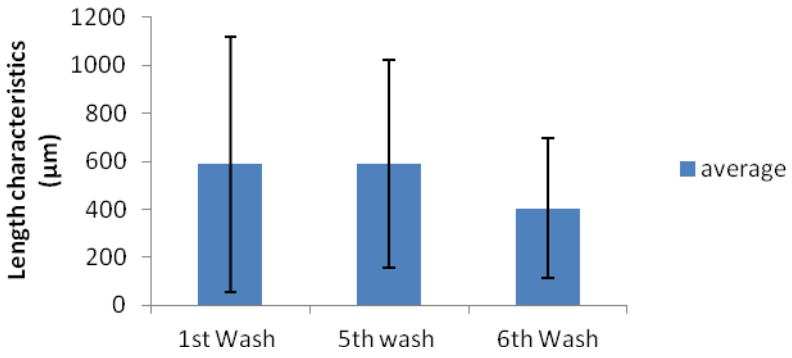


*Figure 25: Bar-graph showing the average **length** of fibers with their standard deviation through the different washes for the socks*

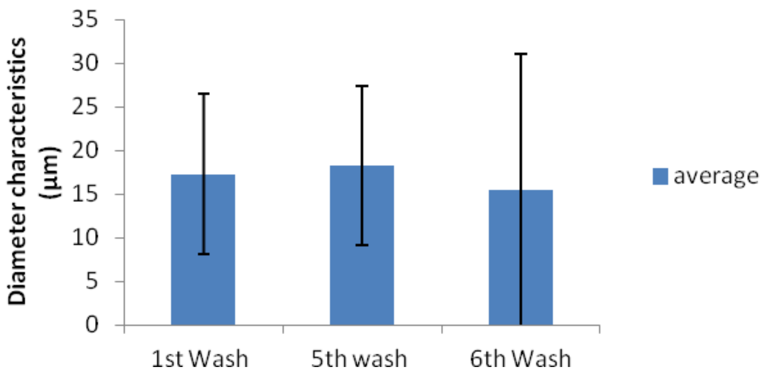


*Figure 26: Bar-graph showing the average **diameter** of fibers ranging and their standard deviation through the different washes for the socks*

Some actual clue of the changing shapes of the fibers was taken during the microscopy analysis. Their pictures are presented below in Figure 27.

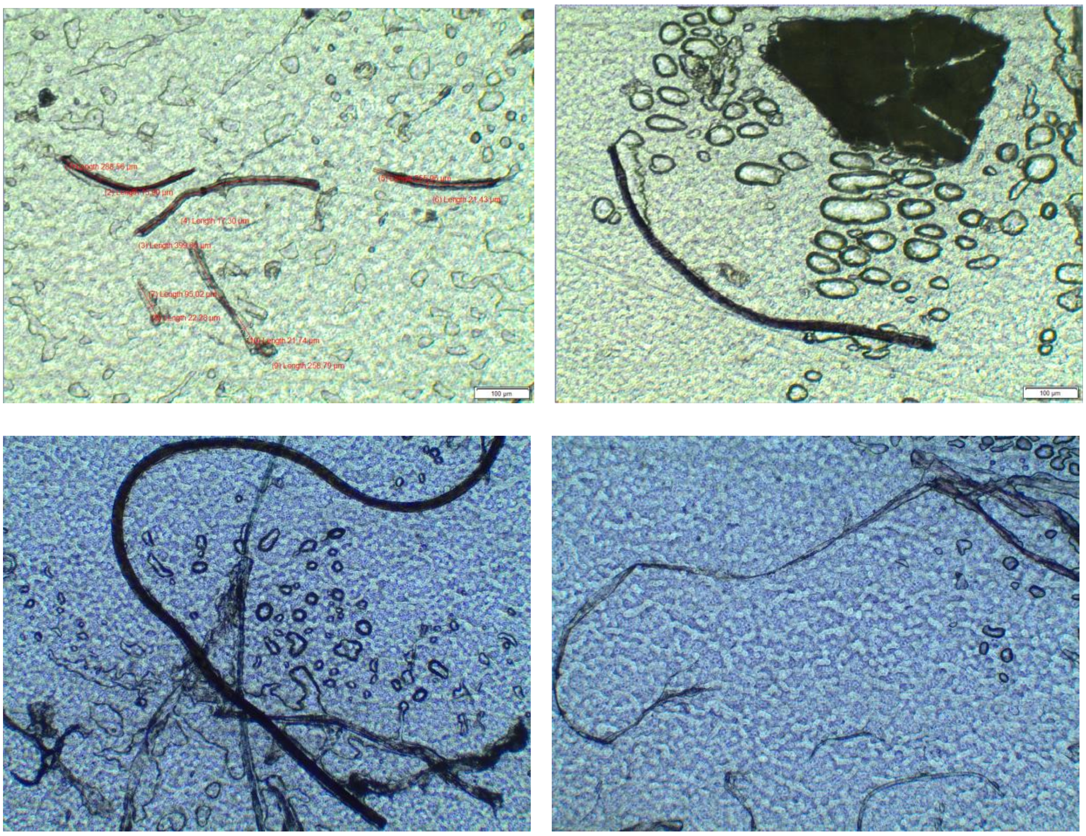


Figure 27: Pictures from optical microscopy of the socks' fibers in different lengths and diameters. (Upper left: from 5th wash), (Upper right: from 5th wash), (Bottom left: from 1st wash), (Bottom right: from 1st wash).

Finally after measuring the density which was 1.3377g/cm^3, an estimation of the number of fibers was attributed. The pattern was similar to Figure 24 which means that after the 1st wash the fiber release was moderately high, after 5th wash drops and finally after 6th wash it rockets to an extremely high value. According to Figure 28 below that number is estimated to roughly 2,500,000 fibers which is more than 10 times higher than the initial release.

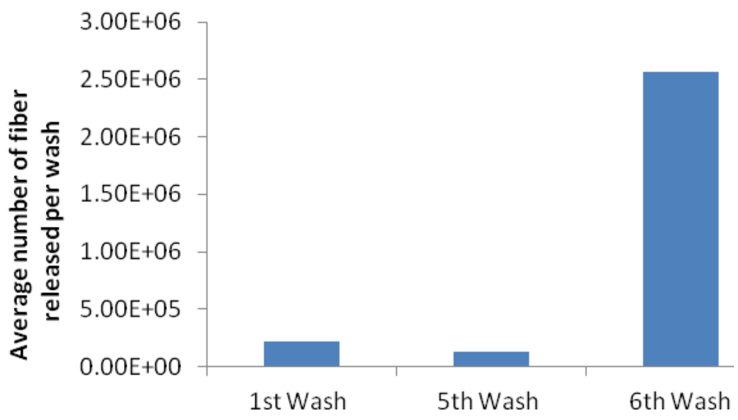


Figure 28: Average number of fibers released during the 1^{s} ,5th and 6th Wash for the socks.

4.4. Environmental Scanning Electron Microscopy analysis

Another part of the analysis was the ESE microscopy which was completed for all three garments (Fleece, T-shirt and Socks), unwashed, after the 5th wash and after the 6th wash. The results are presented below.

Beginning with the *Fleece*, there is no significant difference after assessing the Figures 29 and 30 visually. The unwashed fleece braids look almost the same between the unwashed garment and after the 5th washed ones. The situation though changes slightly after the 6th wash (Figure 31). There seem to be more fibers out of the braids which can be justified taking into account the friction the fibers experienced after use of 12 h.

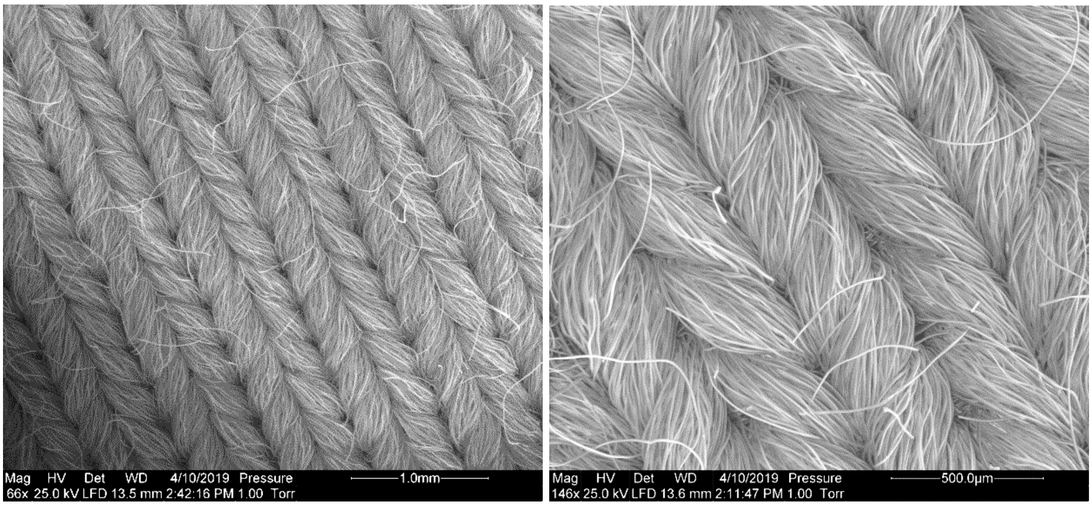


Figure 29: Fleece garment unwashed. (Left: x66 magnification, Right: x146 magnification)

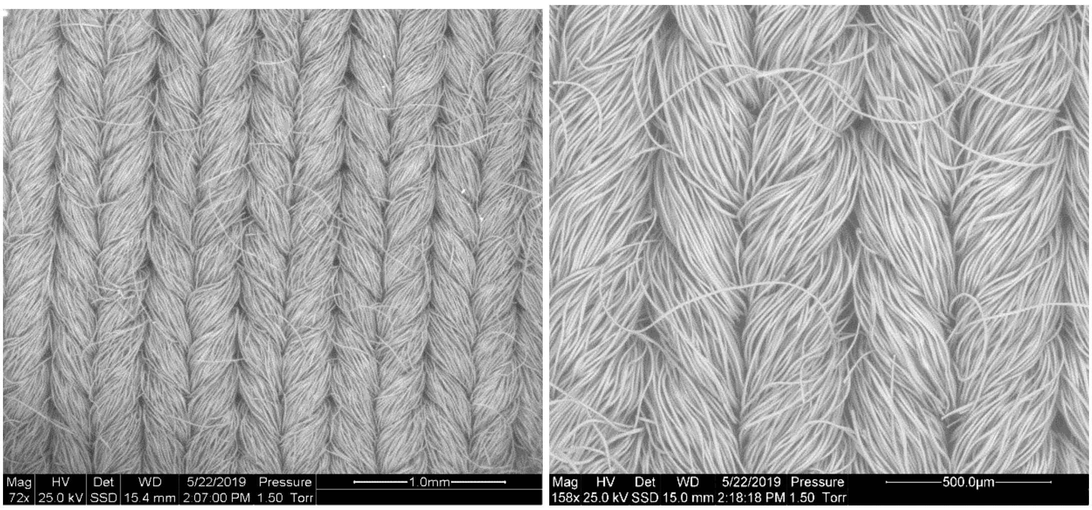


Figure 30: Fleece garment after 5th wash. (Left: x72 magnification, Right: x158 magnification)

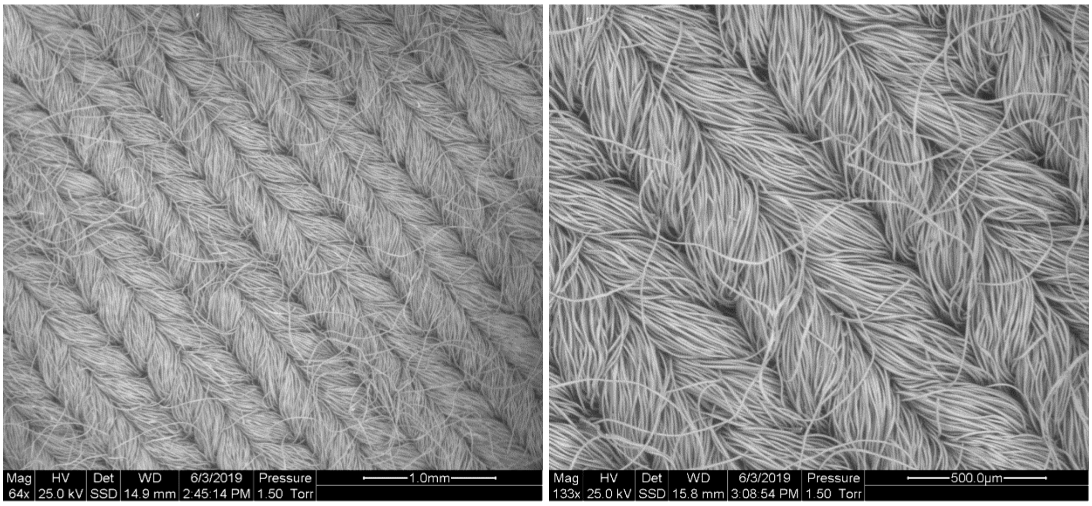


Figure 31: Fleece garment after 6^{th} wash. (Left: x64 magnification, Right: x133 magnification)

Continuing with the T-shirt, there is also major resemblance in terms of texture of the braids among the unwashed garment and after the 5^{th} washed one. (Figures 32, 33) Additionally, they look similar to the Fleeces one whose synthesis were also similar. The only difference is the appearance of the white spots after 5^{th} wash which were further analyzed to identify them with the help of EDAX analysis. The results of the latter showed high concentrations of phosphate, silicone and titanium which could all be ingredients of detergent. EDAX analysis can be found in Appendix V. Furthermore, after the 6^{th} wash there is a great difference compared to the unwashed and after the 5^{th} wash one (Figure 34). There seems that the fibers are more damaged compared to the other two figures and that their braids have almost a different shape.

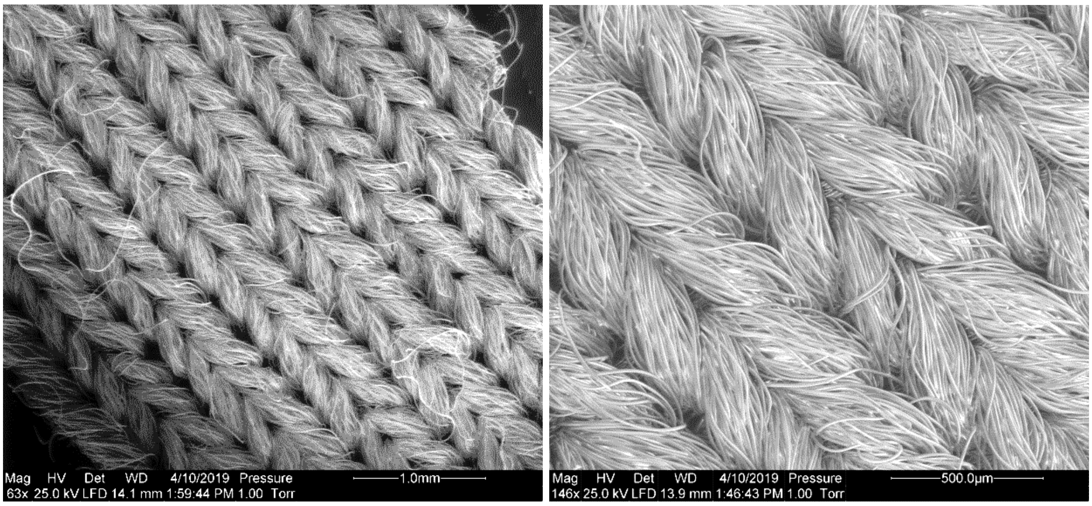


Figure 32: T-shirt garment unwashed. (Left: x63 magnification, Right: x146 magnification)

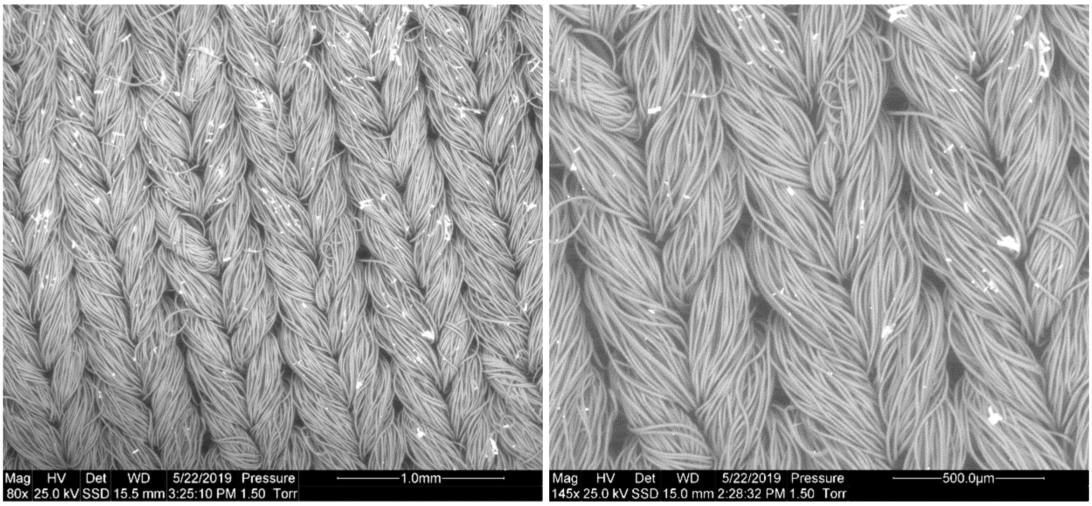


Figure 33: T-shirt garment after 5th wash. (Left: x80 magnification, Right: x145 magnification)

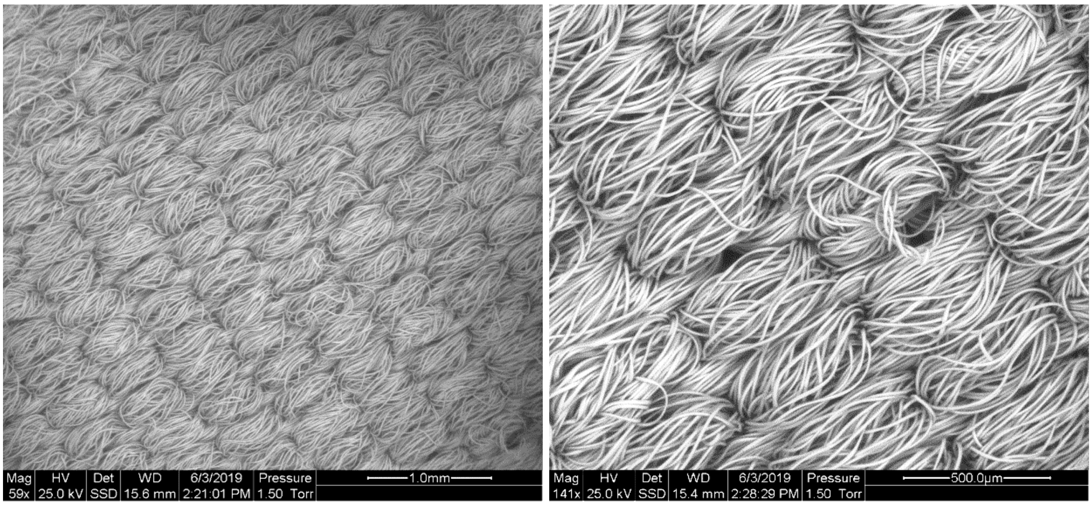


Figure 34: T-shirt garment after 6th wash. (Left: x59 magnification, Right: x141 magnification)

Finally, for the socks, there is also high affinity between the unwashed and after 5th wash garment (Figures 35 and 36). Their only difference is the presence of some white spots remainders of detergent as identified by EDAX analysis. Interestingly, their texture was completely different from the Fleeces and the T-shirts' ones which may be justified taking into account its completely different synthesis too. On the other hand, after the 6th wash, it appears that the garment's texture is transformed looking messier. Their fibers after the 6th wash seem to be more elongated compared to their previous more curly shape. That may be because of the high fiction loads after 12 h of use.

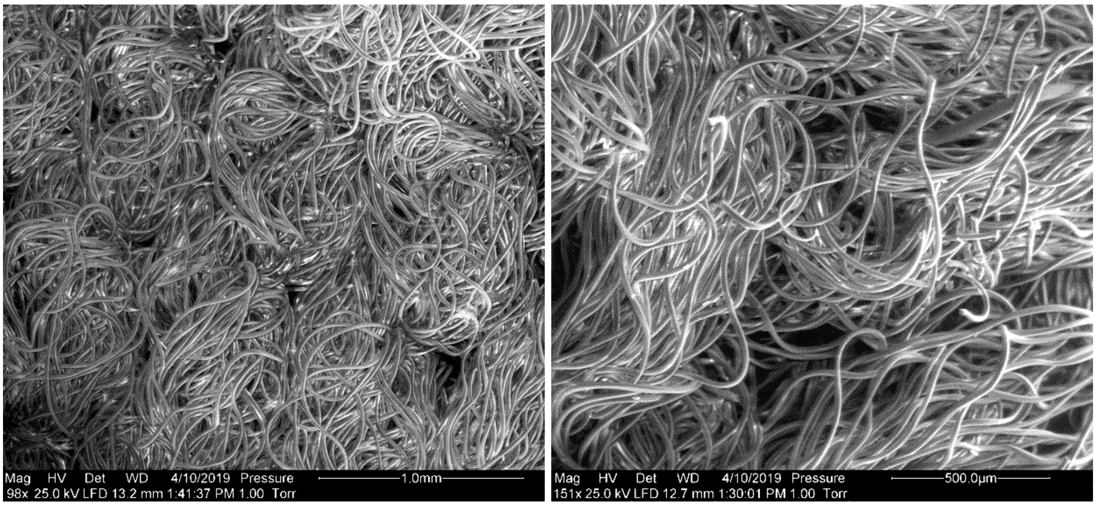


Figure 35: Socks garment unwashed. (Left: x98 magnification, Right: x151 magnification)

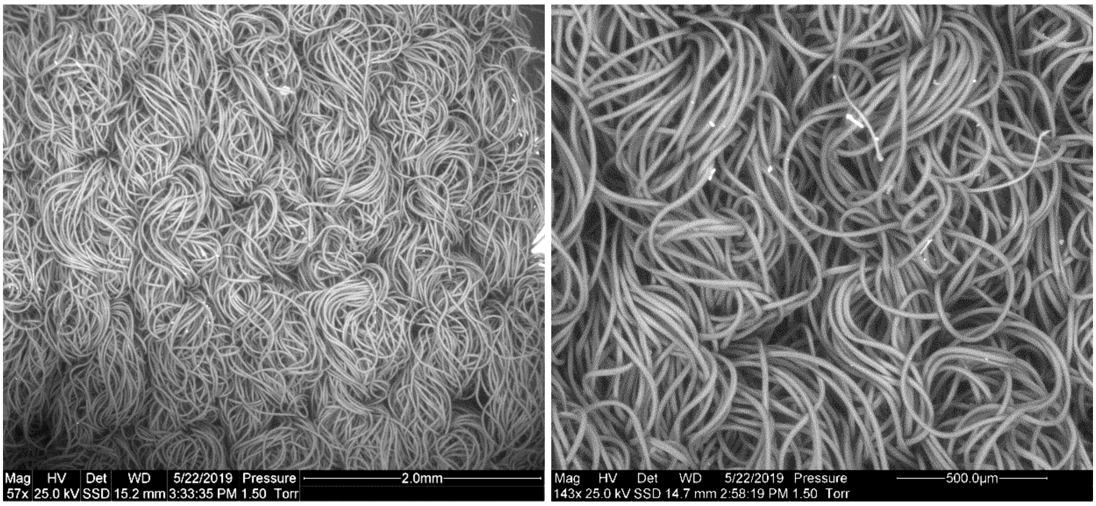


Figure 36: Socks garment after 5th wash. (Left: x52 magnification, Right: x143 magnification)

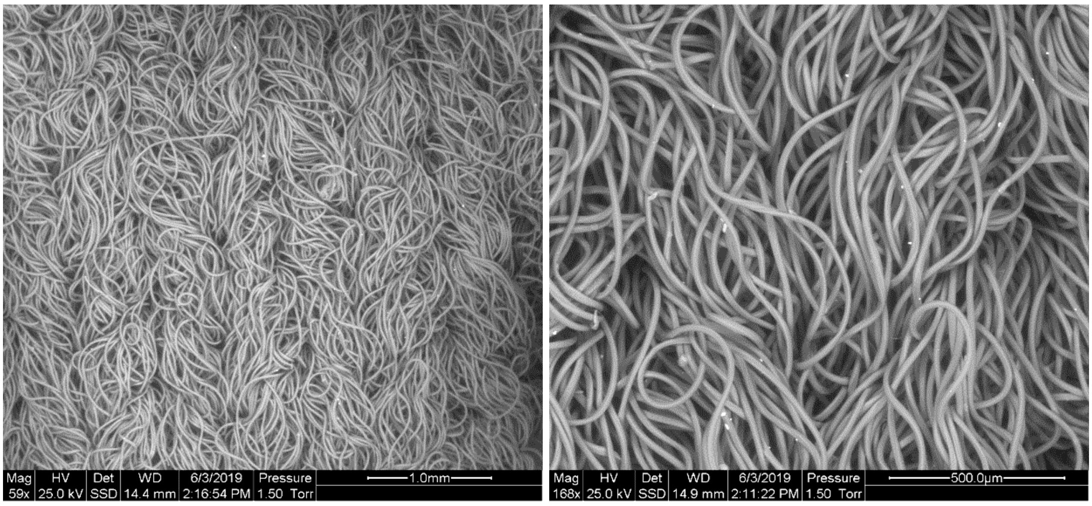


Figure 37 Socks garment after 6th wash. (Left: x52 magnification, Right: x143 magnification)

4.5. Summary of all results

To sum up all the results retrieved from the measurements, it can be said that the highest fiber release per wash was for the socks after the use of 12h. Interesting is also the fact that the T-shirt taking into account the fibers per wash are higher than the fleece proportionally. A possible reason would be that particles smaller than 50 microns departed through the filter's pores. Another assumption would be that remainder detergent on T-shirt was also counted together with the fibers although the filter was washed out with water. What may finally have an impact on the release would be the different synthesis of the garments. Fleece had more elastane than the T-shirt so that could possibly "hold" better fleeces' fibers together. See Figure 38 below for more details:

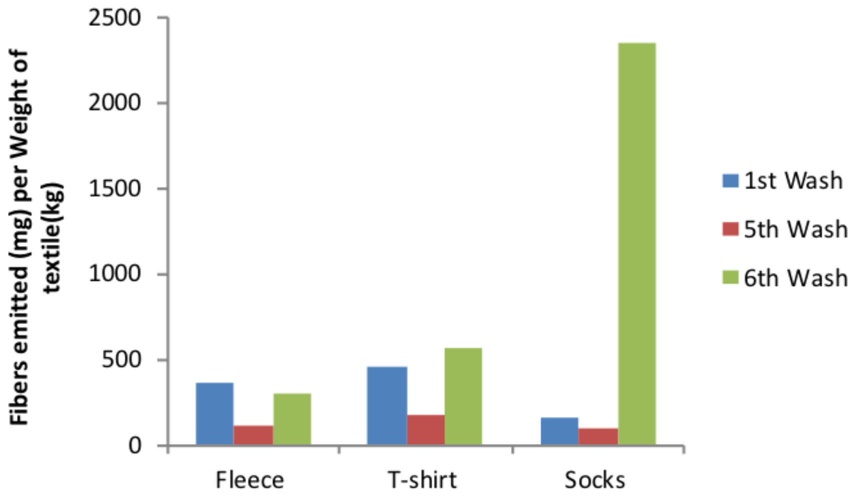


Figure 38: Fiber release (in mg) per wash (in kg) for all garments and for all different washes

Moreover, the number of fibers was calculated in a summary for all the garments during their different washes. Their number was calculated both using their average number and their median as seen in Figures 39 and 40. Their differences are a result of the different shapes in fibers met during the optical microscopy analysis. In more details, as already mentioned their length and diameter were ranging a lot between the different fibers in each garment. In Appendix VI it can be found the average length, together with their average diameters and their varying standard deviation in a summary table for all garments, which in some cases is as high as the average values.

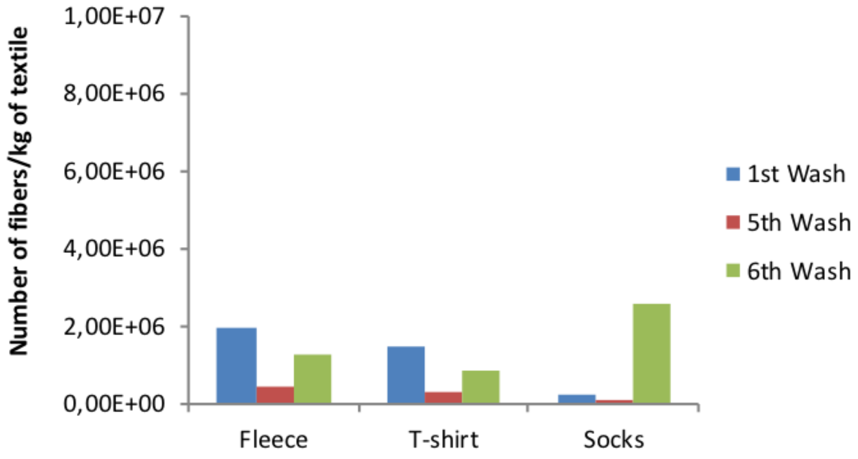


Figure 39: Average fiber release per kg of textile for all garments and for all their different washes

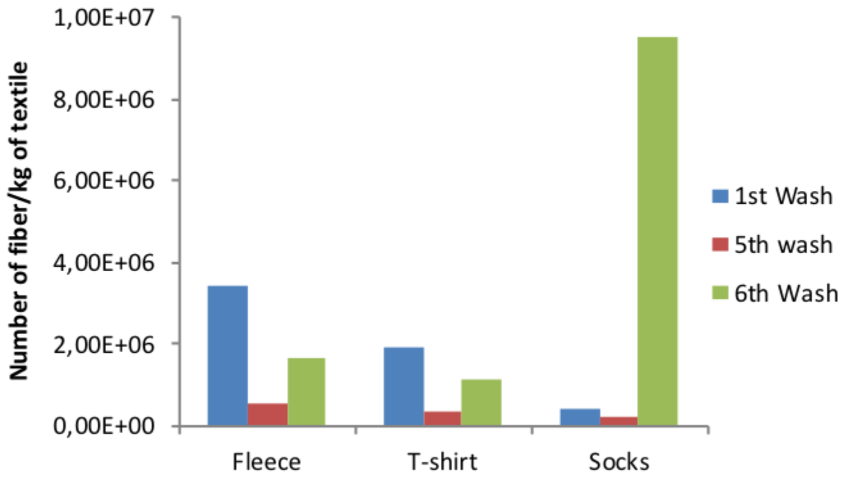


Figure 40: Median fiber release per kg of textile for all garments and for all their different washes

4.6. Density

In terms of the density, the experimental values were estimated accordingly (Table 18):

Table 17: Experimental Density values for all the garments used (in g/cm³).

	Density (g/cm³)
Fleece	1.184
T-shirt	1.015
Socks	1.338

Relevant values were unfortunately not available in the papers used as literature review. Nevertheless, H. Ejhed et al. (2018) provided some values related to the material's density. Specifically, the density of the polyester was 1.37 g/cm^3 but also, polyamide, elastane and elastodiene were not available. As a result, the comparisons will be more relevant for the fleece and the T-shirt. Indicatively, the fleece and t-shirt's density is lower than the one found in H. Ejhed et al.'s work (Table 19). That can be since there is also 16% and 13% of elastane in the garments' synthesis.

Table 18: Comparative table of experimental values of density and polyester density by H. Ejhed et al. (2018) both in g/cm^3.

	Experimental Density (g/cm^3)	Polyester Density (g/cm^3)
Fleece (84%polyester, 16% elastane)	1.18	1.37
T-shirt (87% polyester 13% elastane)	1.02	1.37
Socks (75% polyamide 17% polyester 7% elastodiene 1% elastane)	1.34	-

5. Discussion

5.1. Fiber release from literature review

After comparing the current thesis results to the literature review results, it seems that there are several differences (Table 17). In the part of fibers (in mg) per textile (in kg), there seems that the results from the literature are in the same range with the current thesis. That is because the range of the current thesis is formed by the minimum and maximum average values recorded in the measurements during all different washes and all the garments which is rather wide. In the number of fibers per kg of textile part, there are even more differences. That can be associated with the slightly different conditions the each ones' experiments both in terms of washing machines used, the washing temperatures and the washing durations and counting methods. The number of the fibers from the current thesis in table 17 is also presented for two situations: for the after 5th wash and the after use one.

Table 19: Comparative table of current thesis results to the literature results both for the part of the fibers (in mg) per textile (in kg) and the number of fibers per textile (in kg)

Sources	Fibers (in mg) per textile (in kg)	Number of fibers per textile (in kg)
I.E. Napper et al. (2016)	-	22,991 - 121,466
F.D. Falco et al. (2018)	86-254	1,200,000 - 3,540,000
C. Jönsson et al. (2018)	-	7,571 – 75,462
E. Hernandez et al. (2017)	250-1500	-
B.M.C. Almroth et al. (2018)	-	110,000
M.A. Browne et al. (2011)	-	>1900
A. Gkirini-Current thesis (2019)	96.85-2,347	132,918.57 – 416,966.79*1 848,190.10-2,560,798.85*2

*1: After the 5th wash   *2: After the 12 hours of use

In general since there is no standard method applied for the quantification of fibers, the results are very difficult to be compared to each other. In some experiments already completed domestic mashing machines were used, while in others professional ones or pilot small scale ones. In our research, it was used a common washing machine used is a low-energy professional one.

Another parameter that should be taken into account is that in terms of how the textile reacts after the use where there no experiments done so far. Thus, there is no picture of how would the pieces of clothing could respond after several times of use.

A limiting factor of this thesis is also the amount of particles deriving from the outer environment which are also difficult to approach. Additionally, the detergent remainders in the filter, if any, were not examined due to time limitation. However, in order to have a complete picture of if there is any left microscopy is suggested.

5.2. Fibers released yearly in Sweden

Finally, the amount of fibers was calculated that are estimated to be released both in Göteborg and in the whole Sweden during 1 year (Figure 38). In more detail, in Göteborg nearly are released 35 tons annually which is 10 times less than the amount expected from the whole Sweden. These values however were calculated taking into account the fibers released after the 5th wash which was relatively low compared to other two washes.

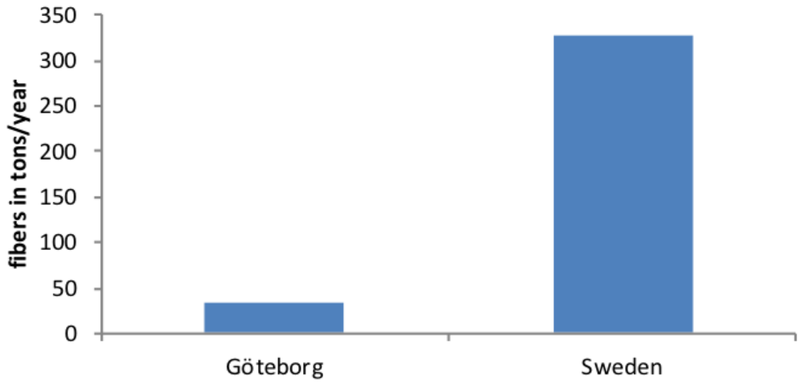


Figure 41: Fibers released both in Göteborg and in Sweden annually.

A higher fiber release was found when taking into account used textiles (Figure 42). The fiber release is almost 8.5 times higher reaching about 330 tons/year in Göteborg and 3000 tons/year in whole Sweden.

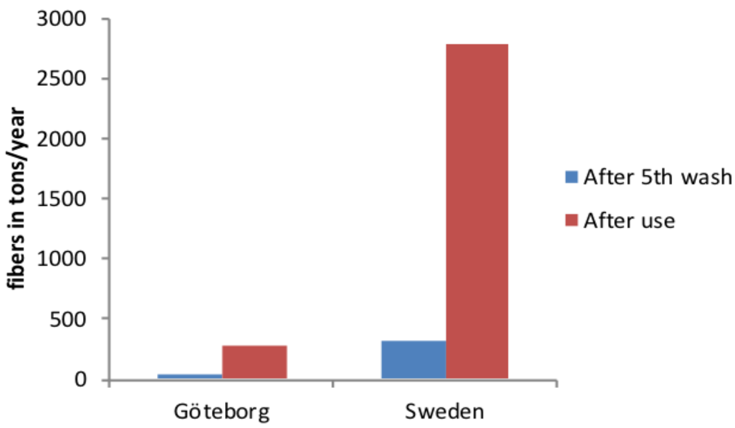


Figure 42: Fibers released both in Göteborg and in Sweden annually. Comparison of 5th wash and after use release.

5.3. Challenges during measuring microplastics

Throughout the measuring of microplastics, different challenges were faced that could also have potential impact on the results. To begin with, the presence of soluble additive in the textile (e.g. oils and waxes) makes it difficult to estimate the fiber loss as they interfere in the weight measurements. Also another parameter is the presence of particles larger than 5mm. As only 100 individual fibers were examined under the microscope there is a possibility that there could be larger particles in the filter. What is more, a possible presence of detergent on the washed textile or also on the filter raises the uncertainty of the attained results. Apart from the detergent, particles from the external environment are possible to be also present on the filter and on the clothes, when it comes to the after use of clothes situation, which also obstruct the microplastics estimation. Finally, the estimation of emission of microplastics in order to be more accurate may need more data on textile consumption in Göteborg or Sweden.

6. Conclusion and suggestions

This study provides evidence that fibers are released from the laundry of synthetic textiles, including fleeces, T-shirts and socks. The release of fibers was found to decrease from the 1st to the 5th wash. However, a higher release was found after use, reaching the initial release levels for the fleeces and T-shirts, and higher levels for the socks. The higher release after use is attributed to the deterioration of the materials, as supported by ESEM observation of the textiles.

The quantification of microplastics derived from synthetic textile is a challenging task. Without the presence of a standard method to count the fibers, researchers conducting experiments are facing difficulty to compare their results. Their experiments have differences not only in the quantification method but also in the washing procedure. The weight of emitted fibers might be affected by the presence of particles from the detergent or from the environment. In addition, because the large number of particles, it is not possible to count them all and the estimation of particle number is based on extrapolation.

Finally, for future research there are several parameters that can be investigated. To begin with, the effects of different temperatures during use, the adding of softener or even the use of different materials would be interesting to explore. Also, further use of the clothes would be noteworthy especially since there are not investigated in the literature or even use of already used clothes to see their effect. What's more, in terms of methodology it would be interesting to use a smaller pore size filter to see if there are more particles trapped. Finally, counting them with an automated method and compare those afterwards with the current thesis' results would also be interesting.

7. Reference list

1) A. Anastasopoulou et al. (2013). Plastic debris ingested by deep-water fish of the Ionian Sea (Eastern Mediterranean). Deep Sea Research I 74, 11-13.
2) B.M.C.Almroth, et al. (2018). Quantifying shedding of synthetic fibers from textiles; a source of microplastics released into the environment. Environmental Science Pollution Research 25, 1191-1199.
3) C. Jönsson, et al. (2018). Microplastic shedding from textiles-Developing analytical method for measurements of shed material representing release during domestic washing. Sustainability, 10, 2457.
4) C. Völker et al. (2017). More than a potential hazard-Approaching risks from a social-ecological perspective. Sustainability 2017, 9, 1039
5) E. Hernandez, et al. (2017). Polyester textiles as a source of microplastics from households: A mechanistic study to understand microfiber release during washing.Environmental Science & Technology, 51, 7036-7046.
6) Electrolux, n.d., Professional Laundry, <http://tools.professional.electrolux.com/Mirror/Doc/ELS/PDS/PS_438919550SE_TS5140LE_SE.pdf>
7) F.D. Falco, et al. (2018). Evaluation of microplastic release caused by textile washing processes of synthetic fabrics. Environmental Pollution, 916-925.
8) FEI Quanta200 ESEM, n.d., Chalmers, Chalmers Material Analysis Laboratory, Instruments, Scanning Electron Microscopy (SEM), <https://www.chalmers.se/en/researchinfrastructure/CMAL/instruments/SEM/Pages/FEI-Quanta200-ESEM.aspx>.
9) GESAMP (2015). Sources, fate and effects of microplastics in the marine environment: a global assessment. (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep. Stud. P. J. Kershaw, ed. GESAMP No 90: 96.

10) H. Ejhed et al. (2018). Mikroplast i Stockholms stad. Källor, spridningsvägar och förslag till åtgärder för att skydda Stockholms stads vattenförekomster. Number C 334. IVL Svenska Miljöinstitutet.
11) I.E.Napper, et al. (2016). Release of synthetic microplastic plastic fibers from domestic washing machines: Effects of fabric type and washing conditions. Marine Pollution Bulletin 112, 39-45.
12) Introduction to Energy Dispersive X-ray Spectrometry (EDS).
13) K. Magnusson et al. (2016). Swedish sources and pathways for microplastics to the marine environment. A review of existing data. Number C183, IVL's Report.
14) M. A. Browne et al. (2011). Accumulation of Microplastics on Shorelines Worldwide: Sources and Sinks. Environmental Science and Technology, 45, 9175-9179
15) M. Choudhari, (2018). Microfiber pollution in environment and its impact. Environment and pollution, Popular Plastics & Packaging, 23-28.
16) M. Wagner et al. (2014). Microplastics in freshwater ecosystems: what we know and what we need to know. Environmental Sciences Europe, 26:12
17) R. Dris et al. (2016). Synthetic fibers in atmospheric fallout: A source of microplastics in the environment? Marine Pollution Bulletin, , <http://dx.doi.org/10.1016/j.marpolbul.2016.01.006>
18) S. Raju et al. (2018). Transport and fate of microplastics in wastewater treatment plants: implications to environmental health. Reviews in Environmental Science and Biotechnology, 17, 637-653.
19) S. Rist et al. (2018). A critical perspective on early concerning human aspects of microplastics. Sci. Total Environ., 626, 720-726.
20) S.C. Gall and R.C. Thompson. (2015). The impact of debris on marine life. Marine Pollution Bulletin, 92, 170–179
21) The Research Hub by Electrolux ™ Professionals, n.d., HSB Living Lab, <https://theresearchhub.electrolux.com/hsb-living-lab-05-09-2016/>.
22) Weillie Zhou et al. Fundamentals of Scanning Electron Microscopy.

8. Appendix

Appendix I

The analytical washing durations per garment are presented below:

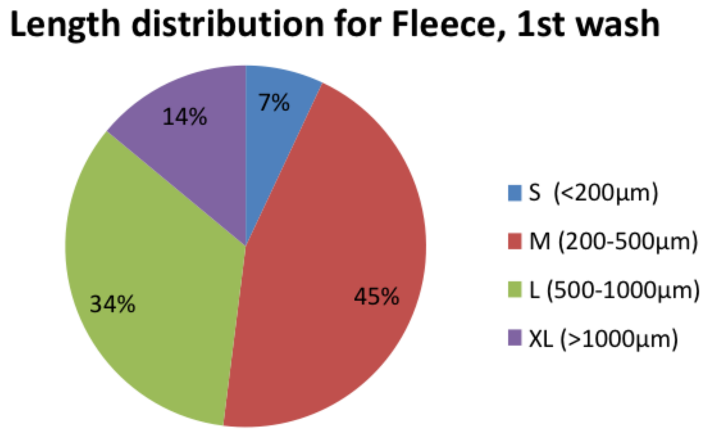
Durations (min)	Fleece 1	Fleece 2	Fleece 3
#1st wash	47	47	46
#2nd wash	47	46	46
#3rd wash	47	46	48
#4th wash	47	46	47
#5th wash	45	44	46
#6th wash	-	44	-

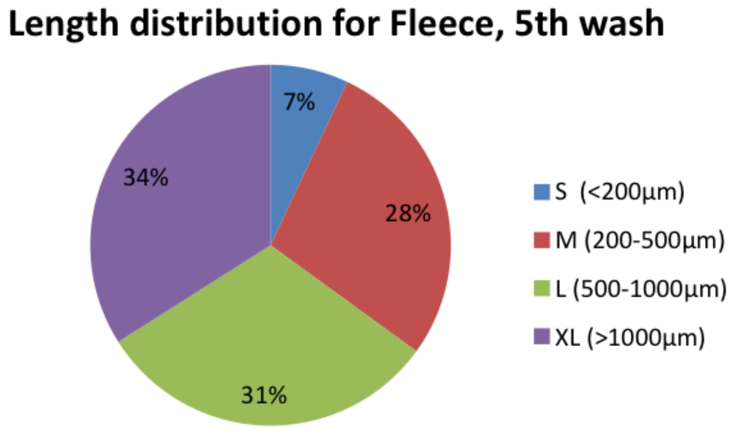
Durations (min)	T-shirt 1	T-shirt 2	T-shirt 3
#1st wash	47	46	46
#2nd wash	47	43	45
#3rd wash	47	47	47
#4th wash	47	43	47
#5th wash	46	47	47
#6th wash	-	41	-

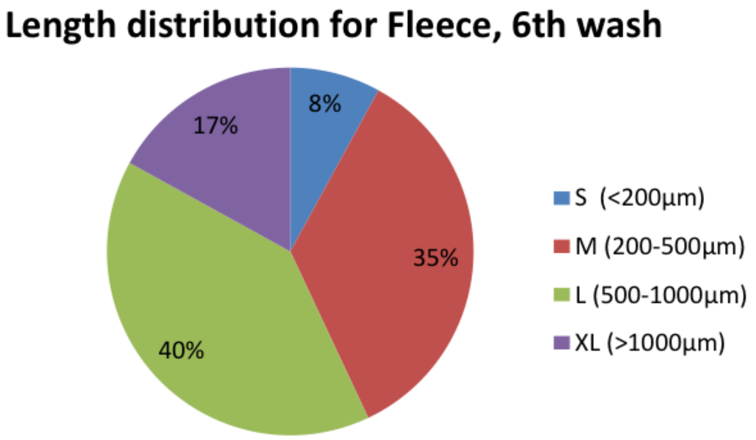
Durations (min)	Pack of socks 1	Pack of socks 2	Pack of socks 3
#1st wash	47	46	46
#2nd wash	46	46	47
#3rd wash	47	46	47
#4th wash	46	46	47
#5th wash	45	46	44
#6th wash	-	46	-

Appendix II

The length distribution of the fibers during different washes for the fleece is presented in the pie charts below:

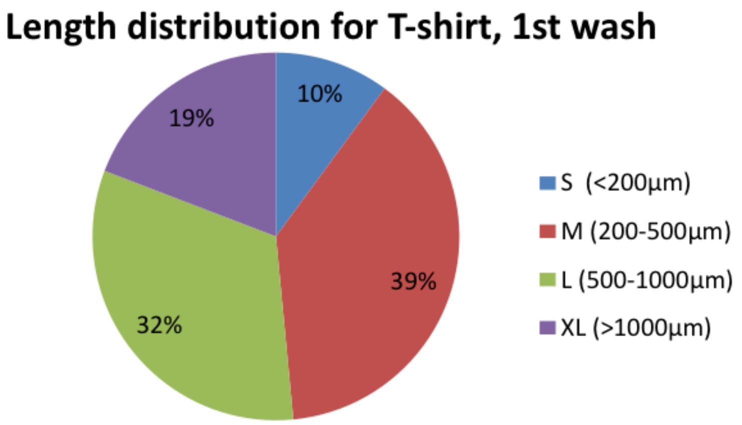


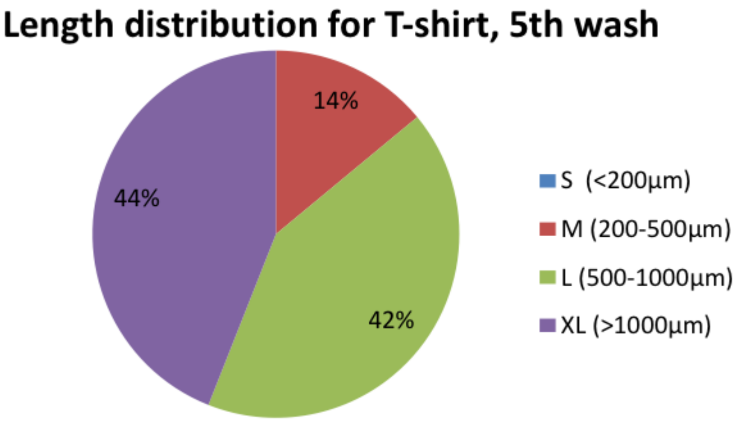


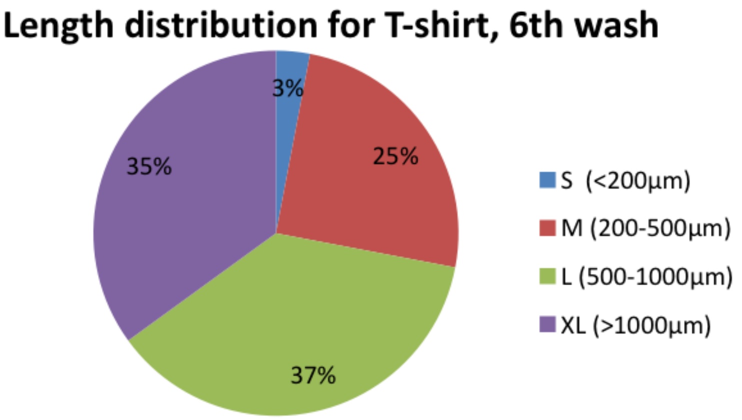


Appendix III

The length distribution of the fibers during different washes for the T-shirt is presented in the pie charts below:

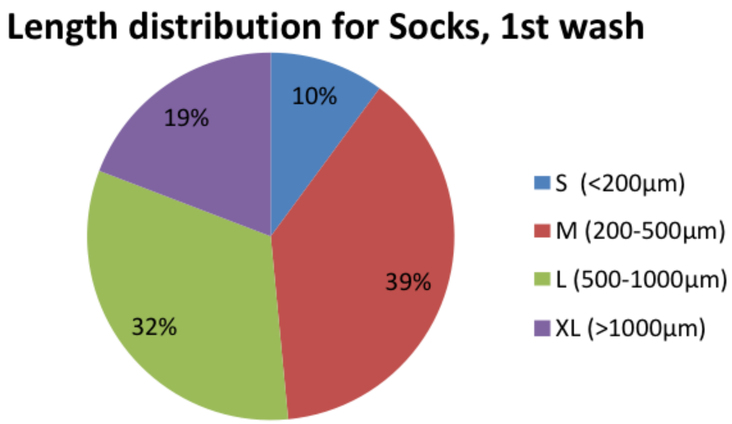


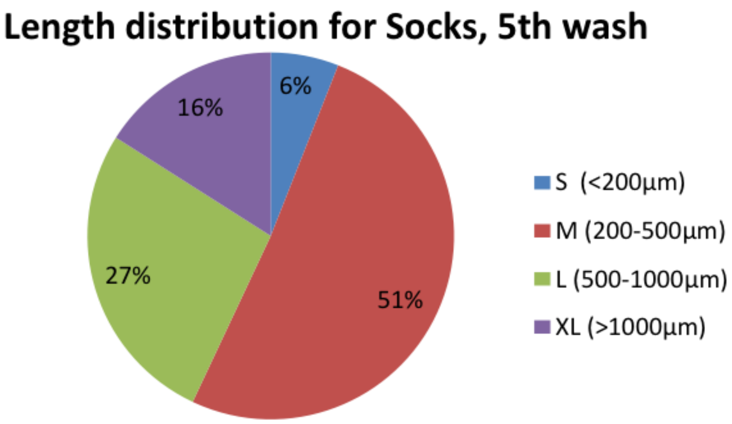


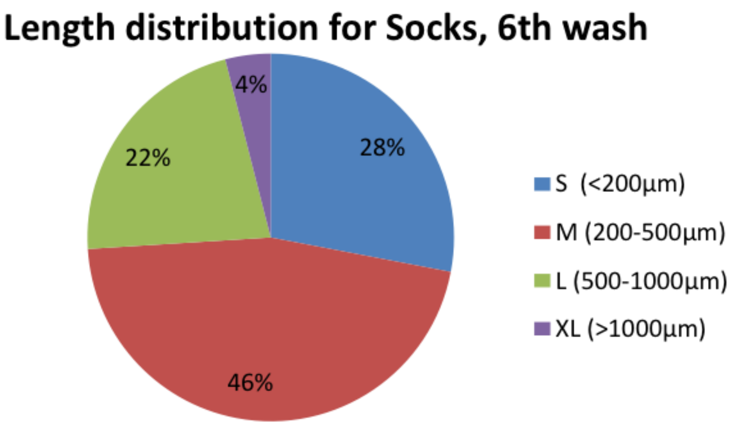


Appendix IV

The length distribution of the fibers during different washes for the Socks is presented in the pie charts below:

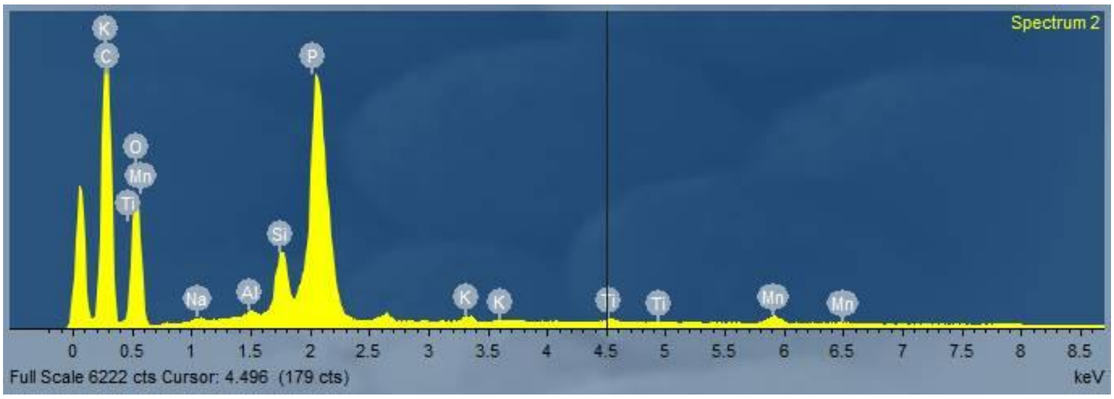






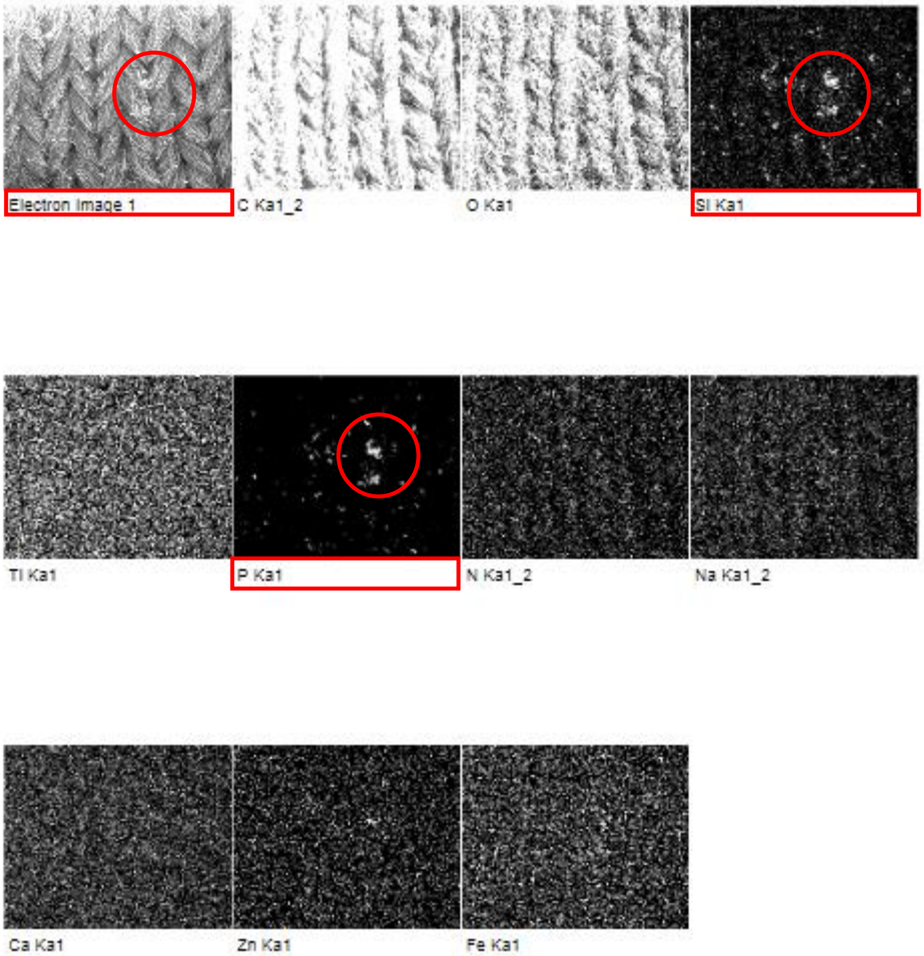
Appendix V

EDAX analysis results are presented below. The first graph is the result of pointing one white spot, while the rest is by analyzing of a whole electron image inserted in the system. The white spots are pointed out in the red circle above the electron image and also pointed out in the relevant concentrations (Si and P).

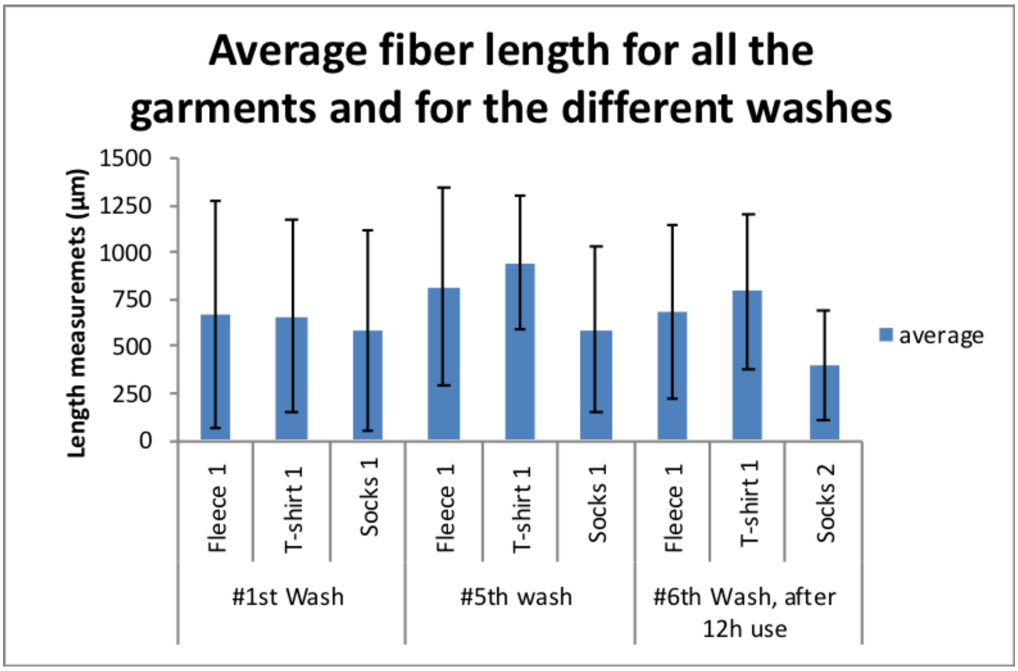


Tshirt_5th wash

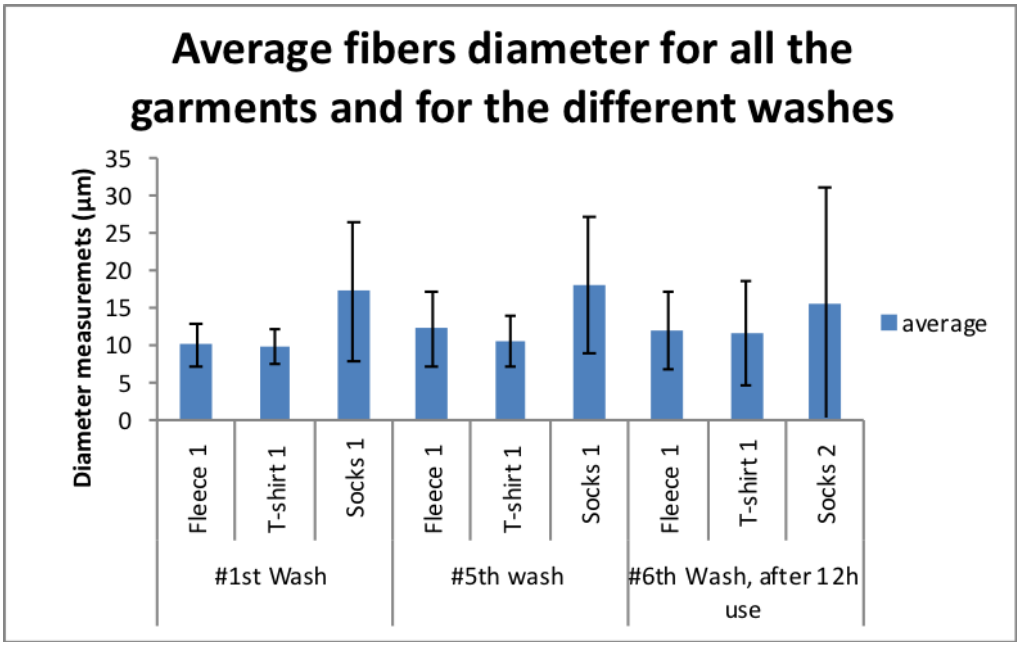
5/22/2019 3:27:31 PM



Appendix VI



Average fiber length for all the garments and for the different washes
Length measuremets (µm)
1500
1250
1000
750
500
250
0
Fleece 1
T-shirt 1
Socks 1
Fleece 1
T-shirt 1
Socks 1
Fleece 1
T-shirt 1
Socks 2
#1st Wash
#5th wash
#6th Wash, after 12h use
average



Average fibers diameter for all the garments and for the different washes
Diameter measuremets (µm)
35
30
25
20
15
10
5
0
Fleece 1
T-shirt 1
Socks 1
Fleece 1
T-shirt 1
Socks 1
Fleece 1
T-shirt 1
Socks 2
#1st Wash
#5th wash
#6th Wash, after 12h use
average