Microplastic in the Urban Environment

Concentrations and Sources in Streets and Sand Traps

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Environmental Toxicology
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List of Abbreviations

ABS	Acrylonitrile-butadiene-styrene
AR	Alkyd resin
ATR	Attenuated total reflectance
CleanGravel	Clean gravel without salt
CleanGravelw/salt	Clean gravel with salt
dw	Dry weight
EP	Epoxy resin
EVA	Ethylene-vinyl acetate
FTIR	Fourier transform infrared spectrometers
GF/C filter	Glass Fiber filter
HDPE	High-density polyethylene
IRP	Irregular particles
LDPE	Low-density polyethylene
LMP	Large microplastic particles
LOI	Loss on ignition
m/z	Mass to charge ratio
PA66	Polyamide
PC	Polycarbonate
PE	Polyethylene
PEA	Poly(ethyl acrylate)
PES	Polyester
PET	Polyethylene Terephthalate
PMMA	Poly(methyl methacrylate)
PP	Polypropylene
PS	Polystyrene
PTFE	Polytetrafluoroethylene
PTFE	Polytetrafluoroethylene
PUR	Polyurethane
PVA	Poly(vinyl acetate)
PVC	Polyvinyl Chloride
Pyr-GCMS	Pyrolysis–gas chromatography–mass spectrometry
S	Street sweeping
SBR	Styrene−butadiene rubber
S-F	Street sweeping fall
SMP	Small microplastic particles
S-Su	Street sweeping summer
Suburban1	Årstadgeilen
Suburban2	Landåssvingen
Suburban3	Bendixens vei
Suburban4	Wiers-Jenssens vei

TPE	Thermoplastic elastomer
TR	Sand Trap
TWP	Tire wear particles
Urban1	Strandgaten/Strandkaien
Urban2	Christies gate
Urban3	Lungegårdskaien/Østre Strømkaien
Urban4	Olaf Ryes vei/ Muséplassen
Urban5	Vaskerelven
WWTP	Wastewater treatment plant

Abstract

Microplastic pollution is an issue of emerging public concern. Despite the recent advances, there is still a substantial lack of knowledge regarding the sources, concentrations, and distribution of microplastic in urban areas, which are likely essential sources of microplastic dispersal to the ocean. Microplastic (here defined as < 1 mm) were extracted from 21 samples of sediment from street sweepings and sand traps, collected from nine locations in the urban and suburban area of Bergen, Norway. The extraction was performed by density separation with $ZnCl_2$ (1.7 g/cm^3) with a MicroPlastic Sediment Separator. Obtained samples were purified by enzymatic and strong oxidative treatments and size-fractioned ATR-FTIR identified large microplastic (500-1000 µm). Pyrolysis GC-MS identified small microplastic (50-500 µm).

The present study demonstrates that the urban environment was highly polluted by microplastics, both in the streets and sand traps. The microplastic concentrations were considerably higher in the urban streets during the summer. Indicating that dry, warm weather and more traffic influence the microplastic pollution in urban areas, especially the generation of tire wear particles. However, the quantification by this method is uncertain as tire wear particles are qualitatively extracted from the matrix as tire wear particles resulting density varies according to the extent of incorporated minerals. This study shows that the urban streets were generally more polluted by microplastic than suburban, even though they were cleaned with a higher frequency. Therefore, population density and traffic load are presumed to influence the microplastic concentrations. Again, supported by polymer identification showing that tire wear particles were dominant in the urban environment. In the suburban areas, the sand traps were more polluted by microplastic than the streets. Presenting that surface run-off water transport microplastic from the streets and into the sand traps. This study is the first to report microplastic concentrations from sand traps and street sweepings in a medium-sized city. The study adds valuable insight into microplastic concentrations and distribution in urban areas as hotspots, where microplastic is generated and may be accumulating or dispersed at high concentrations.

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Introduction

Background

First synthesized

The history of plastic can be dated back to 1855 when Alexander Parkes (England) invented Parkesine, which today is known as celluloid. The first fully synthetic polymer is Bakelite and was invented in 1907 by Leo Hendrick Baekeland (Belgium) (American Chemical Society National Historic Chemical Landmarks, n.d.). From 1928 to 1936, some of the most universally produced plastic types today were synthesized, e.g., polyvinyl chloride (PVC), polystyrene (PS), and polyethylene (PE). The production of synthetic polymers was blossoming by the 1980s, and the same plastic types produced then are also the ones most often found in the environment today (Crawford & Quinn, 2017).

What is plastic?

Plastic, as a group of materials, is composed of long-chained molecules known as polymers. A polymer consists of many repeating units of simple molecules with low molecular weight, i.e., monomers. Commercial plastic often consists of 10 000 to 100 000 monomers in each polymer (Crawford & Quinn, 2017). Only synthetic polymers and heavily altered natural polymers (e.g., rayon, cellophane) can be defined as plastic. Natural polymers e.g., sugar, hair, and DNA are not defined as plastic (Hartmann et al., 2019). Figure 1 shows the composition of a PE polymer, from monomers to a plastic bag.

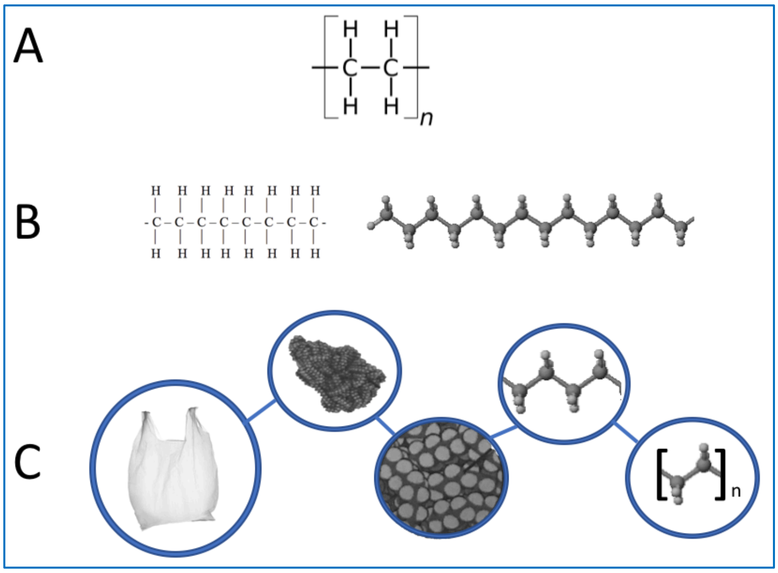


Figure 1: A) Ethylene monomer. B) PE polymer. C) A PE bag composition, from a mass of long polymer chains, consisting of many repeating ethylene monomers.

In some cases, synthetic polymers can consist of more than one type of monomer, called copolymers. To still be defined as plastic, the copolymer needs to be thermoplastic polymers, e.g., acrylonitrile-butadiene-styrene (ABS) and ethylene-vinyl acetate (EVA) (Hartmann et al., 2019). With this definition, styrene−butadiene rubber (SBR), an elastomer found in automotive vehicle tires, can be defined as plastic. However, some polymer chemistry definitions argue that rubber is not definable as plastic (Hartmann et al., 2019; International Organization for Standardization [ISO], 2013). Additives can be added to polymers in various quantities and are essential for the plastic formulation. They enhance the characteristics of the plastics and specify it for correct use (Hahladakis et al., 2018). Hartmann et al. (2019) propose to exclude the number of additives as a criterion for defining plastic, especially as this amount will continuously change after entering the environment due to various natural factors (see chapter ‘Definition of microplastic’).

The number of additives and copolymers are decided in the manufacturing of polymers, which are manufactured through a polycondensation process or a polymerization from various materials, providing the monomers, e.g., coal, salt, crude oil, cellulose, or natural gas (Bhat & Kandagor, 2014; Shrivastava, 2018). Synthetic polymers can be separated into two main groups, thermoplastic polymers and thermosets. Thermoplastic polymers, e.g., PE, polypropylene (PP), have considerably higher production rate than thermosets and, therefore, engage the most attention (SAPEA, 2019). Thermoplastics have reversible characteristics, as they have the ability to harden when cooled and melt when heated. Whereas thermosets, e.g., polyurethane (PUR) and epoxy resin (EP), can only be heated and formed once (Hale, 2002).

Plastic in society

Today, plastic production is a multibillion-euro industry, and plastics have become ubiquitous in modern society (Horton et al., 2016). Every year about 359 million metric tons of plastic is globally produced (2018) and increasing yearly (PlasticEurope, 2019). Plastics have unique properties, e.g., low cost, lightweight, chemical resistance, and long-life expectancy, that make them ideal for everyday use (Andrady and Neal, 2009; Vermeiren et al., 2016). Approximately 14 % of the global plastic production is applied and demanded in Europe (PlasticEurope, 2019). The highest demanded plastics are used for packaging (39.9 %), building and construction (19.8 %), and a category called ‘others’, which include, e.g., medical, appliances, furniture (16.7 %). This demand is reflected in the plastic polymers produced, where the seven most ubiquitous polymers contribute to 81 % of the total production (PP (19.3 %), low-density PE (LDPE, 17.5 %), high-density PE (HDPE, 12.2 %), PUR (7.9 %), PS (6.4 %), PVC (10 %), polyethylene terephthalate (PET 7.7 %)). The remaining 19 % of plastic production consist of the less popular polymers, e.g., poly(methyl methacrylate) (PMMA) and polyamide (PA66) (PlasticEurope, 2019).

Plastics have changed our modern society, as it provides us with benefits and necessary equipment. Single use plastic facilitates sterile and affordable healthcare products, e.g., plastic syringes, IV drips, surgical equipment, and aseptic medical packaging (Andrady & Neal, 2009). Plastics have increased safety in other areas of society, like helmets and seat belts for protection. By replacing heavier parts, e.g., in vehicles and packaging, with plastic parts the weight reduction contributes to considerable energy savings and reduced greenhouse emissions during transport (Andrady & Neal, 2009).

Introduction to the problem

While it may be true that plastic contributes to our society in many positive ways, plastic is often associated with problems due to high production volume and the properties that have made plastic so useful. Plastic products have a service life of anywhere from minutes (plastic straw and cutlery) to more than 50-100 years (water pipes and building materials). Irresponsible human behavior and incorrect or poor waste management have led to improper handling of plastic, which have resulted in tons of plastic ending up in the environment (Barnes et al., 2009). Due to the mass production of plastic, an increasing amount of it now ends up in the environment. Plastic waste has been detected in all environmental compartments, from urban cities to remote places in the Antarctic and Arctic (Bergmann et al., 2017; Dris et al., 2015; Munari et al., 2017; Waller et al., 2017). Plastic in the environment is a problem entirely caused by humans, and therefore the responsibility to correct this lies with us. With an increasing and uncontrollable amount of plastic released into the environment, it is now a global problem addressed by both the European Commission and the United Nations Environment Programme. Plastic debris is now declared an unnatural stressor to various organisms, an eyesore, and an immoral introduction to the environment, according to the SAPEA report (2019).

The fate of plastic products is determined based on their end point. Plastic products may be recycled at the end of their service life, end up in landfills or burnt for energy recovery (Barnes et al., 2009). Plastic pollution and mismanaged plastic have negative consequences for the environment and our society's economy and ethics (Koelmans et al., 2017). Industries such as aquaculture, fishing, and shipping, are areas vulnerable to marine plastic release (Beaumont et al., 2019). For instance, by considering the economic cost of plastic waste, causing damage to equipment, and reducing the quality and quantity of the goods (Mouat et al., 2010). The cost of continuously keeping affected areas and beaches clean of litter and plastic waste affects the municipality's economy and can affect recreational value and tourism (Newman et al., 2015).

Additives, monomers, and byproducts from the plastic production may have a toxicological relevance if leached out of the product after entering the environment, which again can affect the degradation of the polymer (Hartmann et al., 2019; Hermabessiere et al., 2017; Teuten et al., 2009). Halsband et al. (2020) observed leaching of heavy metals (e.g., copper, iron, zinc) and organic additives from tire wear particles (TWP) in seawater. Copper, iron, zinc, and benzothiazole were the most abundant chemicals observed. However, small amounts of polycyclic aromatic hydrocarbons were also detected. Plastic debris, like TWP and especially particles of a smaller size, are known to absorb hydrophobic organic chemicals (persistent organic pollutants (POPs) and metals) from the environment in the same way as organic matter or organisms do (Kleinteich et al., 2018; Ziccardi et al., 2016). This may result in the possibility for plastic debris to act as a vector for harmful chemicals when ingested by organisms. However, this is investigated and found to be a non-significant source of exposure to POPs (Koelmans et al., 2016). In fact, if small plastic particles absorb harmful chemicals (like POPs), they can, in some cases, make them less bioavailable (Kleinteich et al., 2018).

Ingestion and entanglement are the physical problems often associated with plastic waste in the environment (Ryan, 2015). If an organism ingests plastic, the consequences can be physical and physiological. Various species have been reported ingesting plastic debris in all size ranges, and over 700 animal species are negatively affected by plastic waste in the environment, ranging from large whales to smaller birds (Besseling et al., 2015; Crawford & Quinn, 2017; Lusher et al., 2015; Wilcox et al., 2015). An internal blockage could lead to a false sense of satiety, lacerations, or other wounds caused by sharp plastic debris. The physical effects can often lead to physiological effects, e.g., nutritional defects, hormonal disturbance, developmental or reproductive issues. The consequences of plastic waste entanglement could be death by strangulation, drowning, or suffocation and decreasing the affected organisms' life quality (Gregory, 2009; Laist, 1987; Ryan et al., 2009; Teuten et al., 2007, 2009; Thompson, Moore et al., 2009). Plastic waste in the ocean can also transfer foreign species to new locations. These species can be invasive and possibly threaten the local ecosystem (Barnes et al., 2009; Derraik, 2002; Ekanger, 2017).

With many alarming incidents involving plastic and marine organisms presented in the media, the media focus often lies on the marine environment. Plastic pollution is today a problem attracting much attention both in the media and amongst the general public. During recent years, the environmental focus and concern in society has increased tremendously. With the focus on the marine environment, there is a higher consciousness from the public regarding, e.g., beach and coast cleanups. 'The Plastic Whale' that stranded outside Bergen in 2017, and its legacy has continued to affect public opinion. More people now see plastic, especially non-recycled plastic, as an environmental issue and aim to change their consumption and lifestyle (Tvinnereim et al., 2017). Today, plastic pollution is a subject on the political and public agenda, undoubtedly pushed forward by high-profile media attention. However, we lack significant knowledge regarding the situation surrounding urban areas and how this may affect the plastic in the ocean, especially concerning the smaller particles known as microplastics.

Microplastic

The term microplastic was first used in 2004 by Richard Thompson. However, smaller debris of plastic has likely been present in the environment as long as larger plastic (Thompson et al., 2004). Microplastics can be classified as primary or secondary. Primary microplastics are defined as plastic intentionally manufactured in micro-size, e.g., used in cosmetics, facial scrubs, and toothpaste. In contrast, secondary microplastic is a result from fragmentation of larger plastic debris in the environment (Andrady, 2003; Cole et al., 2011; Thompson et al., 2004). An alternative approach is defining the byproducts from product usage as primary microplastics, e.g., TWP originating from abrasion of rubber tires due to driving, and microfiber from clothing. Secondary microplastics will then only represent fragmentation due to environmental causes (Hartmann et al., 2019). This could be challenging to separate in environmental samples. From a biological point of view, this definition will not make a difference. However, it may place the responsibility on the correct polluter for future regulatory measures when the source is identified (Hartmann et al., 2019). The determination of what action needs to be taken and what measures would be most efficient depends on locating if the pollution originates from, e.g., construction work or littering from the everyday person in the street.

Definition of microplastic

Even though microplastic pollution continues to receive much attention, the definition persists to be inconsistent and contradictory. In particular, size definitions range from a lower limit of 0.1 µm to an upper limit of 5000 µm (Hartmann et al., 2019). In this study, we adopt the definition of microplastic as < 1000 µm as proposed by Hartmann et al. (2019) based on six criteria (and one optional), shown below.

Criterion I – Chemical Composition

Based on "What is plastic?", the chemical composition of a microplastic particle consists mostly of synthetic or heavily modified natural polymers.

Criterion II – Solid-state

The general perception is that all plastic products are solid material; however, this is not necessarily the case for semisolid, liquid, or wax-like polymers. To set a definition regarding solid-state, all amorphous polymers with a glass transition temperature (T_g) of over 20 °C will be included, meaning polymers that are brittle and solid below their T_g and free-flowing when exceeding the T_g.

Criterion III – Solubility

The most ubiquitous polymers are insoluble in water; however, some plastic polymers, like poly(vinyl acetate) (PVA), are dissolvable in water. Hartmann et al. (2019) follow the definition provided by REACH that a polymer is insoluble in water at 20 °C.

Criterion IV – Size

Hartmann et al. (2019) propose the definition of microplastic size to range from 1 to < 1000 µm in consensus with the SI unit for 'micro' (Table 1). Additionally, defining the plastic particle is based on the largest dimension, as this will determine the potential for organisms to ingest the particle.

Table 1: An overview of plastic size definitions used in this study.

	Size	**Size in µm**
Nanoplastics	1 to < 1000 nm	0.001 - 1
Microplastics	1 to < 1000 µm	1 – 1000
Mesoplastics	1 to < 10 mm	1000 – 10000
Macroplastics	1 cm and larger	10000 +

Criterion V – Shape and Structure

Microplastics are often classified based on shape and structure. The four main classes of shapes are spheres, fibers, films, and irregular particles (IRP). Spheres will define particles with every border the same distance from the core (Biology Dictionary, 2017). A fiber particle is thin, long, and threadlike, meaning one dimension significantly longer than the two others. When a planar particle has one dimension significantly thinner than the two others, it is defined as a film. Irregular particles are often known as fragments with an irregular shape, implying that the particle originates from fragmentation, which is not always the case. The particles could also be primary microplastics in their original shape. The shape of small microplastic particles is hard to determine.

Criterion VI – Color

Color is a challenging aspect but could be an essential criterion in terms of determining potential sources. Weathering can cause discoloration, and brighter colors can be more noticeable; this could create bias during analysis.

Optional criterion VII – Origin

Microplastics are often categorized as primary or secondary microplastics, as mentioned above. Hartmann et al. (2019) recommend not to define plastic based on origin as it is troublesome to determine with certainty.

Microplastic behavior

After entering the environment, plastic in all sizes begins fragmenting into smaller and smaller particles, creating microplastics, but also microplastic particles (including primary microplastic) experience further fragmentation (Thompson, 2015). The process of fragmentation and degradation of plastic is not entirely understood. However, it depends on the specific polymer, available oxygen, and the additives present (Andrady, 2017; Avio et al., 2017). The fragmentation rate is also dependent on temperature, UV radiation, and physical abrasions, like weathering and sediment abrasion (Andrady, 2003, 2017; Browne, 2015; Ryan et al., 2009). These elements will affect the density, surface, brittleness, and size of the plastic (Andrady, 2015; Macleod et al., 2015). The alteration in properties will determine particle fate in the environment and its transportation (Bond et al., 2018; Waldschläger et al., 2020). Microplastic can also be affected by organism establishment or by biofouling on the particle, which can increase the weight of the particle and again affect its fate in the environment (Andrady, 2011; Avio et al., 2017; Li et al., 2020). However, it is documented that after 32 years in soil, no degradation of PVC and PS was observed (Otake et al., 1995), implying that the terrestrial environment can be an endpoint for microplastic where fewer factors affect fragmentation.

The environmental influence will continuously affect the properties of the particle and, therefore, the fate in the environment. The size, density, and weight are determining factors in the transportation routes for the particles (Kowalski et al., 2016). Low-density particles are prone to air transport, and their buoyancy in water makes the particles available to be transported over long geographical distances. Denser particles are more prone to be deposited in sediments (Li et al., 2020). Microplastics can be transported by, e.g., wind and rain (Waldschläger et al., 2020)

Microplastic in the urban environment

The focus within research and the knowledge concerning microplastic pollution has been mostly on the marine environment, as the ocean is recognized as an endpoint for litter, including plastic (Welden & Lusher, 2020). Microplastic pollution in the terrestrial environment is significantly less studied. Plastic will be generated, distributed, and may accumulate in the urban environment until it is removed or transported by natural weather incidences (e.g., rain, wind). It is natural to assume that there are numerous hotspots for microplastic pollution, especially in crowded areas with high population densities, much transportation, and industry that use plastic and generate waste (Lebreton & Andrady, 2019). Cities are of rising concern, especially as already about half of the world's population lives in cities. As the world's population is increasing, so is the pressure on the cities and their infrastructure. It is estimated that by 2050 68 % of the population will live in cities (George, 2020). With increasing population follows increasing amounts of plastic in the environment - if changes to our plastic-use or waste management are not made (Lebreton & Andrady, 2019). As a result, the potentially harmful effects on the environment and its organisms will consequently increase. There is limited knowledge, and relatively few studies focus on microplastic pollution in the terrestrial environment. Studies of urban environments show that this is a relevant area of concern. Several publications can conclude that anthropogenic activities significantly affect microplastic concentrations, such as in urban areas.

Pathways and transportation

Pathways and transportation of microplastic in the environment are complex and challenging to conclude firmly. There are still some major knowledge gaps concerning pathways for plastic waste, especially urban transportation routes (Birch et al., 2020; Koelmans et al., 2017). Microplastic particles can travel long geographical distances and through various pathways due to their small size. Birch et al. (2020) state that most plastic waste originates from urban environments, particularly in highly populated areas, but more knowledge is needed in terms of sources and pathways. The marine transportation routes are a more researched area than the terrestrial transportations routes, especially the urban environment (Waldschläger et al., 2020). However, the geographic location and features (e.g., building and vegetation) can contribute to the fate of the microplastic particles in nature (Vogelsang et al., 2019). In urban areas, the building density is higher, and the cities features can limit the microplastic dispersal to remain nearby the pollution source, e.g., TWP could remain near the streets.

Some known pathways transporting microplastic into the ocean, supported by research, are rivers, sewage, wastewater, surface run-off, and direct entry (Waldschläger et al., 2020). Rivers near urban areas can be seen as a pathway for microplastic particles traveling from terrestrial areas to the oceans (Dris et al., 2015). However, there are still knowledge gaps concerning these areas. Mani et al. (2015), McCormick et al. (2014), and Yonkos et al. (2014) all conclude that the highest concentrations of microplastics are identified in rivers or estuaries near urban areas. Urban lakes and fjords are also places affected by microplastic from urban areas. These areas are also understudied. Haave et al. (2019) observed twenty different plastic polymers in an urban fjord in Norway and high microplastic concentrations at sewage outlets and deep basins in the fjord that indicated deposition and accumulation in the area. Studies of urban lakes all identify microplastics in various concentrations (Ballent et al., 2016). Some studies regarding urban airborne street-dust pollution are published by Dehghani et al. (2017), Dris et al. (2015), Panko et al. (2013). These studies all identified microplastic particles in street-dust from urban cities.

Also, wastewater treatment plants (WWTP) are defined as a source of microplastic (Mintenig et al., 2017). In wastewater from urban Paris, microplastic particles were detected in high concentrations (Dris et al., 2015). Verschoor et al. (2016) state that microplastic particles are transported into the sewerage system with street-dust and surface run-off water in paved areas, especially in urban areas. Particles can be transported down the streets by, e.g., surface run-off and into a nearby sand trap. A preliminary study conducted by Haave (2017) (NORCE SAM e-report nr 07-2017) found that sand traps contain substantial amounts of anthropogenic particles. Liu et al. (2019) assessed urban and highway stormwater run-offs, and it indicated that industrial and commercial areas have a higher microplastic concentration than residential and highway areas. Vogelsang et al. (2019) assume the majority of street-dust particles could be located in sand traps and run-off from the streets, especially during rainfall. Sand traps are an interesting pathway for microplastics and a possible deposition point, especially in densely populated areas. Sand traps also offer insight into the distribution and sources of microplastic particles in surface run-off and help identify sources possibly transported to the sewage system. In some cases, the surface run-off water is directly deposited into the harbor. Any floating debris that escapes the sand trap, such as microplastics, can be released into the ocean as well. The microplastic sources identified in the sand traps could reflect on the sources in the streets. An assumption is that the street systems, especially in urban areas, are highly polluted by microplastic particles. Although there are few publications to back up this assumption, Lusher et al. (2018) observed the highest microplastic concentrations near urban areas and/or a street in samples collected from Lake Mjøsa, Norway. Previous investigations of WWTP, urban sediments, rivers, and air samples will be used as background for the project. However, very few similar studies have been conducted so far.

Sources

Plastic pollution originates from various sources both on land and sea, either by accidents and loss, mismanaged waste or intentional release. An estimate of 4.8 to 12.7 million metric tons of plastic enters the ocean every year (Jambeck et al., 2015). All plastic production and most plastic application are performed on land, hence, there is reason to conclude that most plastic in the marine environment has a terrestrial origin. It is broadly agreed that 80 % of marine waste originates from land-based sources, such as landfills or industry (Driedger et al., 2015; European Commission, 2019). Microplastic particles can originate from any plastic product, and it is crucial to determine the source to decrease the impact on the environment. There are still some major knowledge gaps regarding microplastic sources (Koelmans et al., 2017). Sundt et al. (2014) estimated the total microplastic release from primary sources in Norway to be approximately 8000 metric tons. With sources originating from, e.g., artificial sports turfs and rubber from sports fields (often made from tire particles) and plastic-based paint from buildings, ships, and streets (9.2 %). Abrasion of synthetic textiles is also a significant primary microplastics source (8.3 %) (Sundt et al., 2014, 2016). However, multiple publications agree that the dominating source of microplastic pollution is TWP (Kole et al., 2017; Siegfried et al., 2017; Verschoor et al., 2016; Vogelsang et al., 2019), representing 53.6 % of the Norwegian microplastic emissions (Sundt et al., 2014). There is currently no knowledge of how TWP behaves when accumulating in the environment. These particles have an intricate density and chemical make-up, containing various additives (e.g., carbon black, silica) and stabilizers (e.g., antiozonants, antioxidants), that makes them difficult to track and detect in environmental samples (Halsband et al., 2020; Vogelsang et al., 2019). The appearance of TWP can vary according to the materials incorporated from nature, e.g., organic matter and minerals, altering the density, color, and texture of the particle (Kole et al., 2017).

Aim of the study

This thesis is a part of the larger project named "Mapping of microplastics in urban environments - quantities, sources, and distribution - Urban Microplastics", owned by Bergen municipality and led by The Norwegian Research Centre (NORCE), and funded by Regional Research Fund West (RFFV #284827). The main goal of the project is to map and quantify sources and quantities of microplastic pollution in the urban environment in selected areas of Bergen, Norway, as a basis for management and risk assessment.

Bergen represents a medium-sized city in a western country with a regular to high standard renovation system. This is a regional as well as a national matter. Due to the lack of knowledge surrounding the urban system, there is an inadequate basis for implementing effective measures preventing pollution and dispersal of microplastics. The insight provided by this study could be communicated to other cities and relevant environmental authorities. The understanding we have regarding microplastic in urban environments today is mostly based on presumptions rather than environmental data and knowledge. It is crucial to determine the microplastic concentrations, sources, and pathways to find suitable solutions to limit the release into the urban environment. A broader understanding of sources and processes leading to microplastic generation and dispersal allow for an opportunity to deal with the problem most efficiently. This project will increase awareness regarding the plastic situation in the cities and possibly generate a change in behavior regarding our plastic usage and waste management.

This thesis aims to address the microplastic pollution in the urban environment, focusing on street sweepings and sand traps as likely areas of accumulation. The Microplastic concentrations in the streets need to be identified to analyze if the street cleaning measures are efficient and to know if it limits microplastic dispersal sufficiently. A comparison of suburban and urban environmental samples will aid our understanding of how population density and traffic will affect the microplastic concentrations. The possible seasonal effects on microplastic concentrations will also be investigated in this study. A focus will be on the major sources of microplastic in streets and sand traps, as well as the fragmentation of particles and some essential pathways that disperse microplastic in the urban environment.

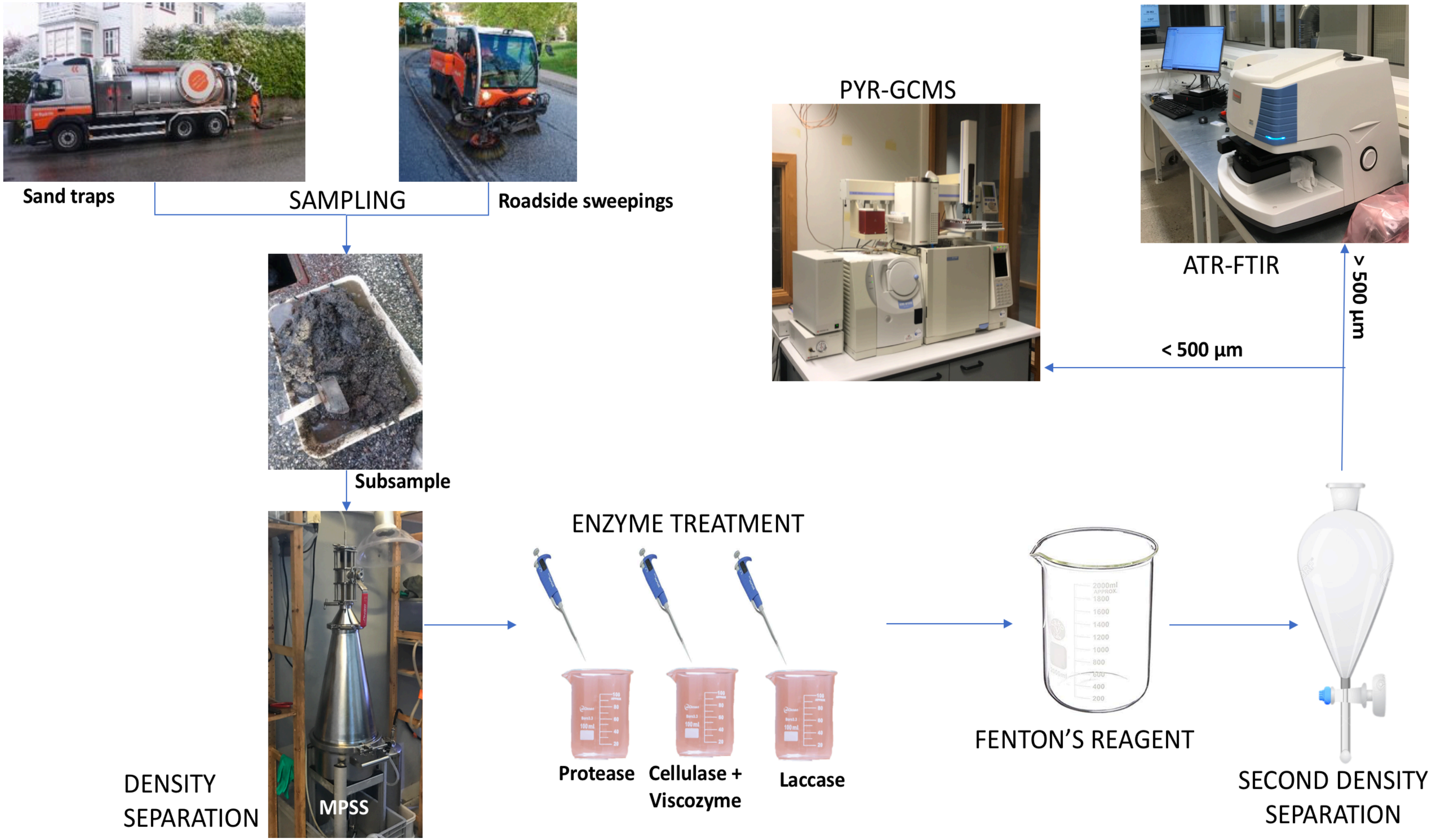
Research questions that will be addressed in this thesis

- What are the concentrations of microplastic in street sweepings and sand traps?
- To what extent does the population density affect the microplastic concentration in sand traps and street sweepings in a medium-sized city?
- To what extent is the microplastic concentration in street sweepings in a medium-sized city affected by alternate seasons and tourism?
- What are the dominant sources of microplastic in the urban environment in a medium-sized city?
- How are microplastic distributed in the environment in a medium-sized city?
- What are the major transportation routes?

This project could also contribute to a definition of microplastic as an environmental contaminant by increasing awareness regarding the microplastic concentrations and sources in the cities. Such a definition will limit further pollution, both regionally and nationally.

Methods

An outline of the workflow performed in this study:



Selected sites

The study area was located in Bergen city, Vestland, Norway. Bergen represents a medium-size city with ~ 280 000 inhabitants and an area of 462 km^2 (SSB, 2019a, 2019b). Nine locations were selected for the investigation of microplastic pollution in the area (Figure 2). Each location was represented with a sample from street sweepings and a sample from a corresponding sand trap. In total, 21 environmental samples were analyzed.

Urban samples

Urban areas have a complex infrastructure and commercial areas, substantial levels of tourism, and possibly affecting the littering situation in the area. The samples collected were chosen to represent different areas in a complex city center (Figure 3) and collected from five street locations once during the summer and once during the fall (ten in total). These streets are cleaned frequently with variations based on traffic and anthropogenic influence (Table 2). Urban5 is swept twice a day, Urban1 and Urban2 are swept daily as these are areas heavily influenced by people and traffic continuously. Urban4 is swept fortnightly as this is a less trafficked area in the city center. Three locations were represented with a corresponding sand trap sample (Urban 3, 4 and 5). The sand trap sample from Urban5 was collected from an adjacent street to where the sweeping sample was taken. The main sand trap in that street had been emptied outside the schedule, and no sediments could be collected. The urban sand traps are scheduled to be emptied once a year.

Suburban samples

The suburban study areas are located outside Bergen city center (Figure 4), selected to represent areas with fewer people and less traffic than in the urban city center. All the suburban streets and sand traps studied are cleaned or emptied once a year (Table 2). The sand trap correlated to the streets studied was found within a few meters from the sweeping area, in order to best represent run-off from the street in question.

Clean gravel

In addition to the samples collected from the nine locations in Bergen, clean gravel was collected from Løvaas Maskin in Rådalen, Vestland, Bergen. The gravel is mixed with salts to be dispersed in the streets for de-icing and to increase friction on the roads for the winter. Two samples of gravel were analyzed, one with salt added and one without. These samples will be considered control samples to investigate if the gravel contributes to the microplastic when dispersed in the streets (non-environmental samples).

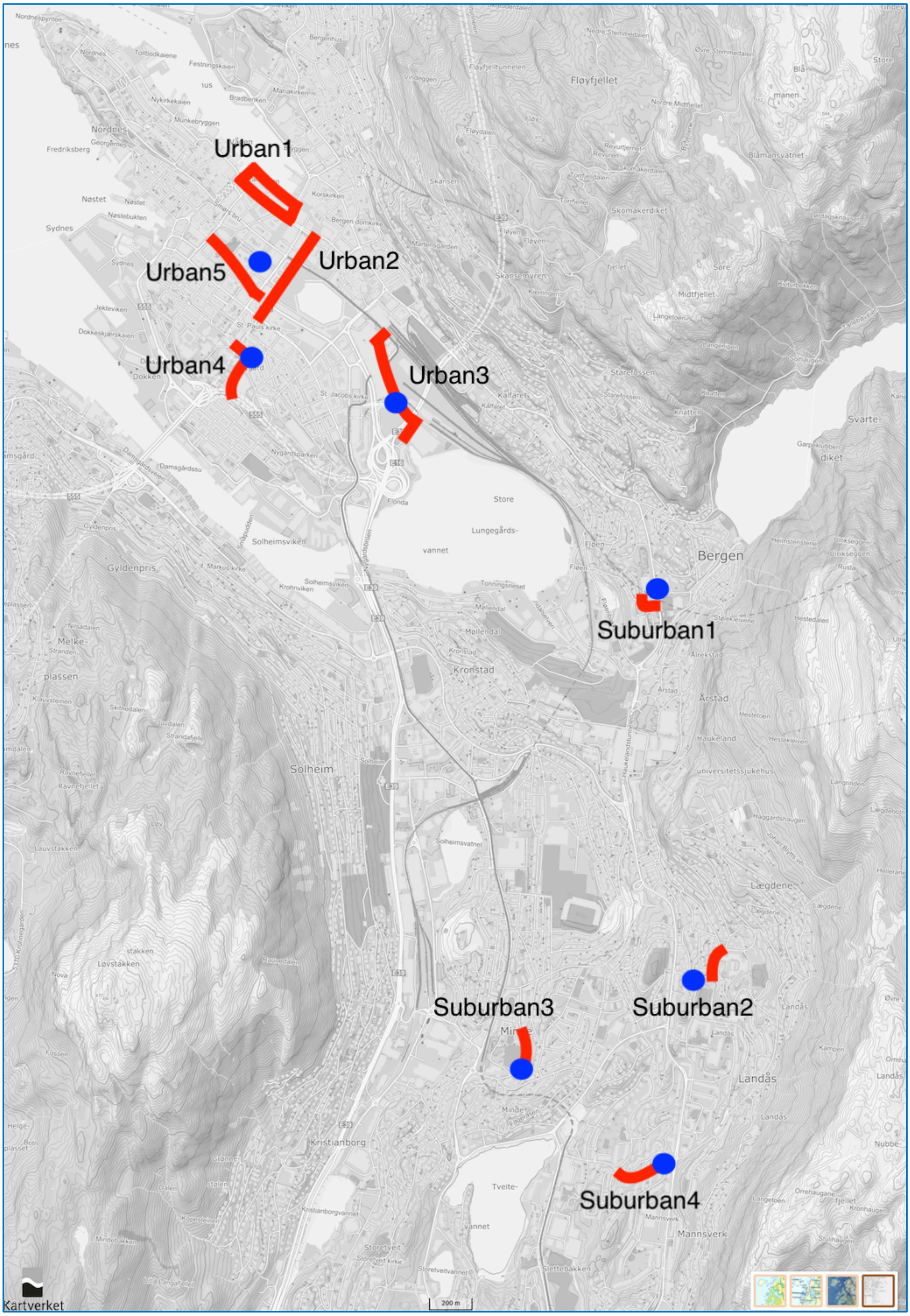


Figure 2: The nine sampled locations in Bergen. Red lines represent the distance covered for the street sweepings; the blue dots represent the sand traps.

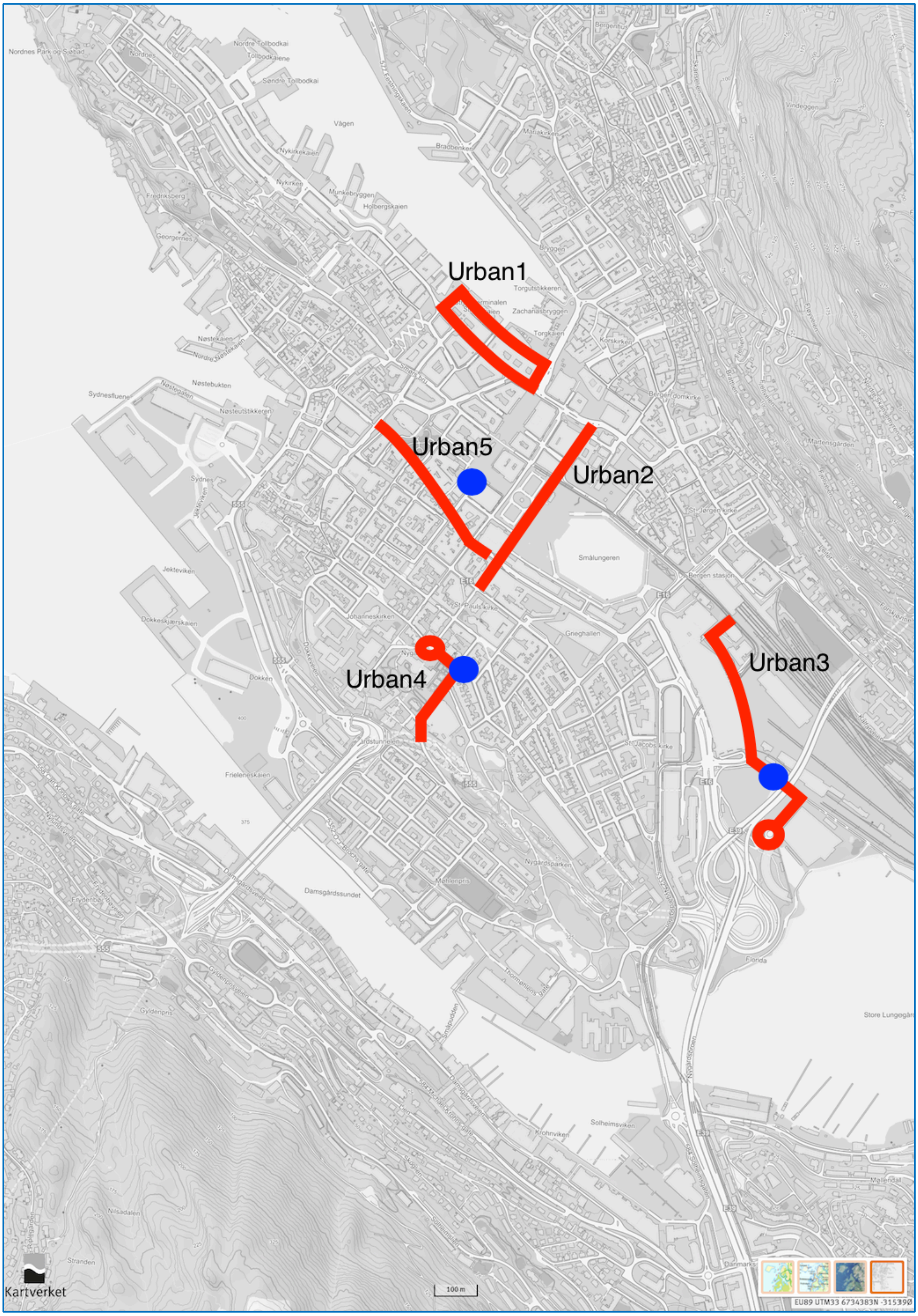


Figure 3: The samples collected in the urban city center of Bergen. Red lines represent the distance covered for the street sweepings; the blue dots represent the sand traps.

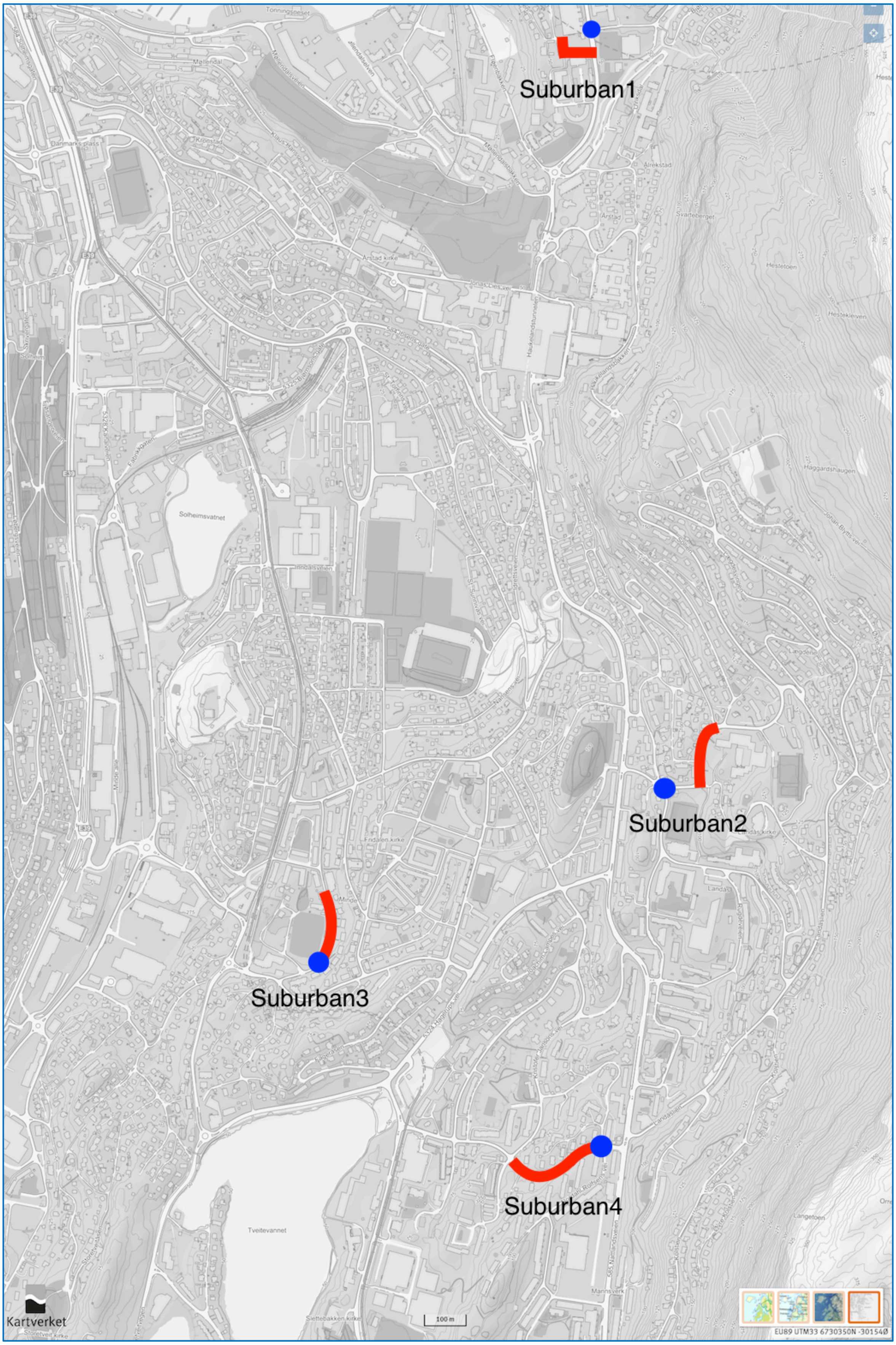


Figure 4: The samples collected in suburban Bergen. Red lines represent the distance covered for the street sweepings; the blue dots represent the sand trap

Table 2: Sample characterization for all street sweeping (S) and sand trap samples (TR) from urban and suburban Bergen collected in April – November 2019, Bergen. Street sweepings were collected in the spring (Sp), summer (Su) and fall (F). Sand trap samples (-TR) were taken throughout the year. The two clean gravel samples are also included.

Sample									**Sample for MPSS analysis**	
Location	*Abbreviation*	*Location*	*Sample type*	*Length of sweeping (m)*	*Sweeping and emptying frequency*	*Season*	Loss on ignition (%)	Dry matter (%)	*Volume (L)*	*dw (g)*
Strandgaten/Strandkaien	Urban1S-Su	Urban	S	1100	Daily	Su	1.11	93.18	0.46	630.4
	Urban1S-F					F	1.39	92.72	0.50	661.4
Christies gate	Urban2S-Su	Urban	S	900	Daily	Su	4.36	78.68	0.50	583.4
	Urban2S-F					F	8.38	69.58	0.53	403.2
Lungegårdskaien/Østre Strømkaien	Urban3S-Su	Urban	S	650	Weekly	Su	2.62	83.47	0.43	582.9
	Urban3S-F					F	1.18	91.07	0.50	567.5
	Urban3TR		TR	-	Yearly	F	7.84	72.01	0.47	576.9
Olaf Ryes vei/ Muséplassen	Urban4S-Su	Urban	S	600	Fortnightly	Su	1.11	76.30	0.56	499.3
	Urban4S-F					F	1.03	95.12	0.56	693.0
	Urban4TR		TR	-	Yearly	F	2.80	76.52	0.45	608.0
Vaskerelven	Urban5S-Su	Urban	S	400	Twice-daily	Su	1.40	92.00	0.50	702.0
	Urban5S-F					F	2.06	88.23	0.80⊕	512.2
Torggaten	Urban5TR	Urban	TR	-	Yearly	F	9.19	59.47	0.50	431.1
Årstadgeilen	Suburban1S-Sp	Suburban	S	240	Yearly	Sp	6.23	69.99	0.25∇	177.6
	Suburban1TR		TR	-	Yearly	Sp	8.79	79.83	0.35	441.3
Landåssvingen	Suburban2S-Sp	Suburban	S	280	Yearly	Sp	5.27	76.07	0.36	440.1
	Suburban2TR		TR	-	Yearly	Sp	3.93	79.23	0.35	453.8
Bendixens vei	Suburban3S-Sp	Suburban	S	150	Yearly	Sp	2.68	92.56	0.35	468.2
	Suburban3TR		TR	-	Yearly	Sp	18.32	52.23	0.45	285.2
Wiers-Jenssens vei	Suburban4S-Sp	Suburban	S	260	Yearly	Sp	3.63	81.79	0.35	473.4
	Suburban4TR		TR	-	Yearly	Sp	8.78	63.52	0.35	344.4
Clean gravel with salt□	CleanGravel w/Salt	-	-	-	-	-	0.15	98.77	0.50	781.9
Clean gravel without salt□	CleanGravel	-	-	-	-	-	0.04	99.61	0.50	766.3

dw: dry weight □ Defined as non-environmental samples /control sample ∇ The first sample analyzed with a small sample volume

⊕ Required a large sample volume due to high amount of lightweight material

Sampling

The sediment samples from street sweepings and sand traps were collected in collaboration with contractors to Bergen Municipality, Løvaas Maskin AS, and Bergen Bydrift AS. The urban street locations were sampled during the summer season (July 2019) and repeated during fall (September 2019), the urban sand trap samples were collected during the fall (November 2019). The suburban street sweeping samples and sand trap samples were collected in the spring (April/ May 2019).

Street sweepings

Weather, traffic, and people all influence the streets in a city, generating street-dust, organic matter, and litter. As part of maintenance, the areas are cleaned by sweeping the streets with intervals dictated by the traffic load. Street sweepings were collected with a specific sweeping vehicle (Figure 5) that arrived clean and was emptied between every sample. The sweepings were collected over a stretch of 150m to 1100m (depending on the amount of sediment on location) (Table 2). During sweeping, the street dust was sprayed with water to limit dust dispersal, the sample was then collected from the vehicle's collection chamber by use of a shovel and a stainless-steel sampling spoon. A sample of approximately 2 kg was collected and stored frozen in a sample bag at -18 °C until. A presumption was made that the samples were homogenized during collection, meaning it was not necessary to mix the sample further to achieve a representative result.

Figure 5: The vehicle collecting street sweeping masses. Photo: Einar Bye-Ingebrigtsen, NORCE

Sand traps

Sand traps collect run-off from the street and contain these masses in compartments located beneath the street (Figure 6). Here a sedimentation process prevents sand, sludge, and other material, with a density heavier than 1.0 g/cm³, from entering the drainage pipes. Water and floating debris will be flushed out when the sedimentation chamber reaches its capacity, while dense material such as sand will be deposited in the chamber, preventing downstream blocking of the sewage pipes. In some areas of Bergen, the run-off water is transported into the sewage system and to the nearest WWTP, where the microplastic will be removed during the treatment process. In other areas of Bergen, where the run-off water is presumed to be less polluted, the run-off has direct drainage into the ocean (Statens vegvesen, 2007). Løvaas Maskin AS or Bergen Bydrift AS opened the sand traps, and the overwater was removed by vacuum suction when necessary (Figure 7). Sediment was collected with a steel shovel from the sand traps. A sample of approximately 2 kg sediment was collected and frozen at -18 °C. Again, the presumption was made that the sample was already homogenized in the deposition chamber and in the collected sample.

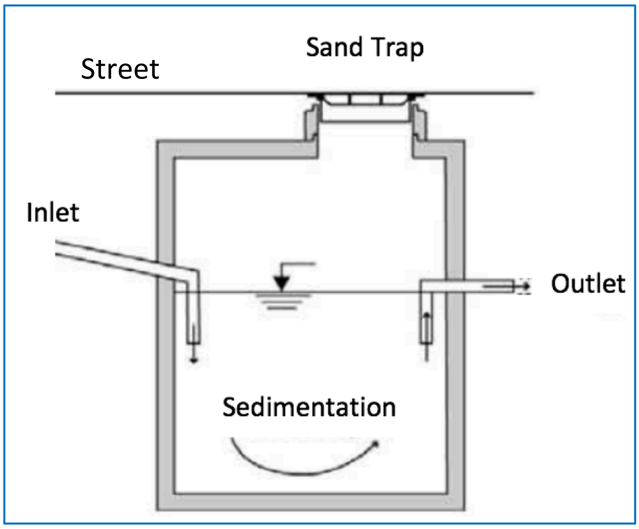


Figure 6: A technical display of a sand trap (illustration by Statens vegvesen). The sand trap collects surface run-off water from the street. The sedimentation process involved the heavy material to remain in the compartment while the lighter material exits the outlet pipe.

Figure 7: A) The vehicle removing overwater from sand traps. B) Sediment collected with a stainless-steel sampling spoon. Photo: Einar Bye-Ingebrigtsen, NORCE

Sample Characterization

Dry Matter

The water content of the sample was determined to standardize microplastic concentration to kg dry weight sediment. Two parallels of 30-50 g of the moist sediment were added into two pre-weighed ceramic beakers and dried overnight at 105 °C, cooled to room temperature in a desiccator, then weighed again, and the dry matter was calculated according to Equation 1.

$$\frac{Dry\ sample\ \text{weight}}{Wet\ sample\ \text{weight}} * 100 = Dry\ Matter\ (\%) \qquad \text{Equation 1}$$

Loss on ignition

The percentage of organic material is determined by loss on ignition (LOI). After the dry matter calculation, the same parallels were burned in a muffle furnace (L 3/12, Nabertherm GmbH, Germany) overnight with increasing heat (23-500 °C for 3h, 500 °C for 3h, 500-23 °C for 3h). When the subsamples reached room temperature, they were weighed, and the organic content was calculated according to Equation 2.

$$100 - \left(\frac{Burned\ sample\ weight * 100}{Dry\ sample\ weight}\right) = Loss\ on\ ignition\ (\%) \qquad \text{Equation 2}$$

Microplastic density separation

Density separation is an application often used in microplastic studies (Hidalgo-Ruz et al., 2012). By placing materials of diverse densities in a separating liquid, the denser materials will sink, and the less dense material will separate in the upper level of the liquid (Quinn et al., 2017). Plastic (Table 3) and organic material that have a lower density than inorganic material, e.g., sand and gravel, and will be separated with zinc chloride ($ZnCl_2$, density of 1.65-1.80 g/cm^3) as the separation liquid. The density separation was performed with a MicroPlastic Sediment Separator (Figure 8) (MPSS - Hydro-Bios GmbH). The efficiency of this extraction has been validated by Imhof et al. (2012), providing recovery rates of 95.5 % for microplastics (< 1 mm). Therefore, recovery was not repeated for this study. The density separation of microplastic particles was performed similarly to Haave et al. (2019) and Bergmann et al. (2017).

In short, the sample was weighed in a clean glass beaker, density separated over 12 hrs, and a separated sample of approximately 95 mL was isolated in the top chamber. The street sweeping sample from Suburban1 was the first sample processed on the MPSS, and a sample size of 0.25 L and 253.72 g was chosen. The separated volume in the sample chamber indicated that for future samples the volume for the MPSS could be increased to approximately 0.5L. Therefore, the chosen volume and mass of the wet samples was aimed to be similar to 0.5 L and approximately 600-700 g (Table 2). The extracted volume in the sample chamber should result in a half full sample chamber, as this allows the ball valve to be closed below the extracted sample. The street sweeping sampled from Urban5 (fall) needed a volume of 0.8 L to obtain a mass of 580.5 g, because of more lightweight material in the sample.

Table 3: The specific polymer density for polymers identified in this study, as well as the density for water and $ZnCl_2$

Polymer	**Density (g/cm³)**
EPS	0.02
PUR	0.03
PP	0.89
PE	0.96
PS	1.06
Water	1.00
PA	1.14
TPE	~1.16
PMMA	1.18
PVA	1.19
PEA	1.20
PC	1.21
EP	1.29
PES	1.38
PVC	1.39
PET	1.39
TWP	1.15-2.50
AR	1.68-1.80
$ZnCl_2$	1.65-1.80
PTFE	2.20
Silicone	2.30

Figure 8: The Micro-Plastic Sediment Separator (MPSS) consisting of the sample chamber (1), the top standpipe (2), the bottom standpipe (3), the sediment container (4), the trolley stand (5), motor unit (6), the operation unit (7), the ball valve (8), and the side drain valve (9). Photo: Hydro-Bios.

Preparation of $ZnCl_2$

The preparation of the $ZnCl_2$ solution was performed in a clean MPSS in a cold room (ca. 15°C). First, 5.5 L MilliQ water was added, then slowly adding 10 kg technical $ZnCl_2$ while the rotor was running (5.5 rpm), resulting in a stock solution of 64.30 % $ZnCl_2$. It is essential to slowly add the $ZnCl_2$ to dissolve the powder completely and avoid a drastic rise in temperature during this exothermic reaction. The density was then confirmed by weighing a known volume and adjusted. The density was continuously measured throughout the analysis and corrected if lower than 1.65 g/cm^3 by adding more $ZnCl_2$ powder.

Figure 9: The filtration process for reusing $ZnCl_2$. 1 – Sedimentation of $ZnCl_2$ after MPSS analysis. 2 – Manual pump for unclean $ZnCl_2$ filtered through two filters of 500 µm and 250 µm, respectively. 3 – Compressor (Chemical Duty Pump Model WP6111560, Millipore, USA). 4 – Pressure container for 250 µm filtered $ZnCl_2$, attached to pressure hose for compressed air from 3. 5 – Stainless steel cylinder filter containers, from right to left: 100 µm stainless-steel filter (Rolf Körner GmbH), 10 µm glass fiber filter (GF/C filter, Hytrex Catrige), 1 µm GF/C filter (Hytrex Catrige). These filters were clean or exchanged when the filtration process considerably slowed down. 6 – Clean $ZnCl_2$ (< 1 µm particle size) qualified for sample processing, stored in precleaned glass bottles.

Preparation of the MPSS before separation

Before extraction, the MPSS was cleaned with paper and EtOH:water (30 %), and the motor was connected to the sediment container. The sample chamber was plugged and filled with $ZnCl_2$. The ball valve was opened and closed multiple times to remove all air bubbles and fill the dead volume of the ball valve. If there is air left in the dead-space, particles in the separated sample could be pulled in when the air bubbles escape, potentially increasing sample loss and causing cross contamination of later samples. The main chamber of the MPSS (bottom standpipe and sediment container) (Figure 8) was filled with approximately 30 L of prefiltered (1 µm) $ZnCl_2$, filtration following the procedure from Figure 9.

Density separation of sample

The weighed sample was quantitatively transferred into the $ZnCl_2$ in the MPSS main chamber through the top of the bottom standpipe, and the sample container was rinsed several times with $ZnCl_2$ (Figure 8). The bottom standpipe was covered and the rotor on the MPSS ran for ~30 min (5.5 rpm). The system was then visually inspected. Large (> 3 cm) pieces of organic material and plastic floating to the top of the bottom standpipe were removed with forceps and either kept for documentation (plastic) or discarded (organic material). The removed pieces were thoroughly rinsed with $ZnCl_2$. The top standpipe and sample chamber were mounted, $ZnCl_2$ was filled through the top of the sample chamber to within 1-2 cm from the top. The rotor then ran for another ~30 min (5.5 rpm) before the sample was left to settle and separate overnight (min. 12 hrs). After 12 hrs, the ball valve was closed, isolating the extracted material in the sample chamber. The $ZnCl_2$ was drained off through the side drain valve on the sediment container. The sample was transferred to a clean beaker by thoroughly flushing the sample chamber with filtered $ZnCl_2$ to include all particles. The beaker with the sample was then further processed, following chapter 3.6. The drained $ZnCl_2$ was again recycled through the filtration process (Figure 9). All parts of the MPSS were dismounted and cleaned.

Purification of sample

Preparation of sample

After a density separation, the sample was filtered over a 50 µm stainless-steel mesh filter (diameter (⌀) 47 mm). The particles on the filter were cleaned with EtOH:water (70 %) and MilliQ to remove all traces of $ZnCl_2$. The stainless-steel filter with the sample were transferred into a clean beaker with approximately 100 mL 10 % sodium dodecyl sulfate solution (SDS) and ultrasonicated in MilliQ water (max. five min; B200, 117V, 60 Hz, Bransonic™ Ultrasonic Cleaner). The filter was flushed with MilliQ water to remove all particles from the filter, additionally diluting the SDS. However, the SDS concentration was preserved to remain ranging between 5-10 %. The sample was then left in SDS in the beaker overnight at 37 °C, covered with an aluminum lid. As an anionic surfactant, SDS denaturizes proteins and increases the surface for contact for the following enzyme treatments.

Enzyme degradation

In order to obtain a clean sample for ATR-FTIR and Pyr-GCMS, the organic material in the sample was degraded through a procedure with technical enzymes following Löder et al. (2017) with some modifications. All treatments were done in the same 250 mL beaker, if not stated otherwise, to limit loss of particles, and with an aluminum foil lid. The filtration process was performed with a vacuum flask, graduated funnel, and a glass funnel. All enzyme treatments followed the same laboratory procedure, changes were made only in type and amount of enzyme and buffers, and incubation time (Appendix A). The sample was vacuum filtrated over a 50 µm filter and rinsed with MilliQ water to remove all residue from previous purification solution. The filter was carefully transferred into the beaker with the particles facing down. The correct amount of the enzyme-specific buffer was added to the sample and ultrasonicated in MilliQ water. The filter was flushed with the correct buffer to remove all particles (and removed). The correct amount of enzyme was added and incubated the minimum time for the specific enzyme at 50 °C.

First, to degrade proteins, an enzyme treatment was conducted with 70 mL of 0.1 M glycine-buffer (pH 10.0) and one mL of protease concentrated enzyme (P3111, Sigma Aldrich, Germany), incubated for a minimum of 48 hrs (Gomiero, Strafella, et al., 2019). Second, to degrade cellulose from plants, an enzyme treatment was conducted with 70 mL of acetate buffer (pH 4.8), 0.5 mL of the cellulolytic enzyme mixture - Viscozyme L, and 0.5 mL cellulase enzyme, incubated for a minimum of 48 hrs. The final enzyme treatment was conducted for lignin degradation with 50 mL of Tartrate buffer and 1 mL of a mixture of Laccase and Lignin Peroxidase, with an incubation time of a minimum of 24h. The enzyme treatment steps were repeated if not a substantial amount of the targeted organic material was degraded. Figure 10 shows a flowchart of the enzyme treatments, and Figure 11 demonstrate an enzymatic degradation after each treatment.

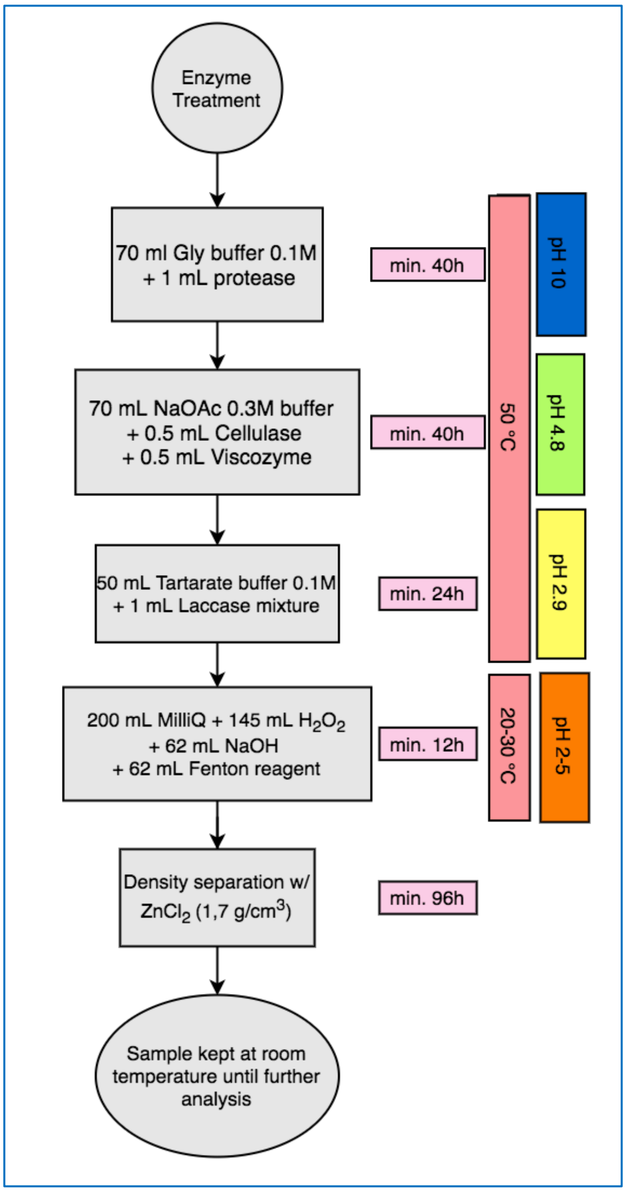


Figure 10: A flowchart showing the detailed enzyme treatment in the study.

Figure 11: An enzymatic digestion of a sample. A) Sample after 24h in SDS. B) After 48h of protease treatment. C) after 48h of cellulase and Viscozyme treatment. D) After 24h of laccase treatment (Sample: Urban5TR).

Further treatment

Fenton's reagent

To further degrade organic matter, the Fenton's reaction was performed (Appendix B). The sample was vacuum filtrated over a 50 µm filter and rinsed with MilliQ water to remove all the laccase solution. The beaker was thoroughly rinsed with MilliQ water to secure all particles transferred onto the filter. The filter was carefully transferred into the beaker with the particles facing down. 200 mL of MilliQ water was added to the beaker, and the sample was ultrasonicated in MilliQ water. The filter was then flushed with MilliQ water to transfer all the particles into the beaker and the filter was removed. The sample was transferred to a 2 L clean beaker, 62 mL of 0.1M NaOH, and 145 mL of hydrogen peroxide 30 % (H_2O_2) were added. A thermometer was rinsed and placed in the beaker. Sixty-two mL of 0.1M iron(II)sulfate heptahydrate ($FeSO_4 \cdot 7H_2O$) was added slowly while the temperature was kept between 20-30 °C. To ensure the correct temperature, the 2 L beaker was placed in an ice bath if the temperature exceeded 30 °C and removed before the temperature dropped below 20 °C. The sample was left overnight (min. 12h) at room temperature after the temperature stabilized at 23 °C and covered with an aluminum lid.

Second density separation

A second density separation with filtered $ZnCl_2$ was performed in a glass separation funnel to secure microplastic particles in the top layer and inorganic matter (e.g., sand) possibly attached to the synthetic polymers or the degraded organic matter in the bottom layer. The sample was vacuum filtrated over a 50 µm filter, and the 2 L beaker was thoroughly rinsed with MilliQ water to secure particle transfer onto the filter. The sample on the filter was first flushed thoroughly with 0.1 M hydrochloric acid (HCl) to remove all remains of iron sulfate, then rinsed with MilliQ water. The filter was carefully transferred back into the 250 mL beaker with the sample facing down. An appropriate amount of $ZnCl_2$ was added to the beaker, sufficient to cover the filter, and ultrasonicated in MilliQ water. The filter was flushed with $ZnCl_2$ to transfer all particles into the beaker (and removed). The sample was quantitatively transferred into the clean glass separation funnel, $ZnCl_2$ was filled until 3 cm from the top. The separation was considered complete when the top and bottom layers were entirely separated, and the $ZnCl_2$ was transparent with no visible particles (Figure 12). Separation time ranging from 4 days to 4 weeks, depending on the particle mass in the sample. After a complete separation, the precipitate was gently released through the separation valve. The precipitate from some randomly selected samples was examined under a microscope and analyzed on Pyr-GCMS to check for potential loss of plastic particles, particularly TWP which have a varying density due to incorporated minerals. The top layer of the sample should now contain non-degradable particles of a density below 1.65 g/cm^3, which is supposedly the plastic polymers. The top of the sample was collected in a beaker, and 150 mL EtOH:water (50 %) was used for flushing the separation funnel a minimum of three times to secure all particles transferred into the beaker efficiently. EtOH water breaks the surface tension of the water and efficiently washes away microplastic particles that otherwise would cling to the glass. The $ZnCl_2$ was filtered off using vacuum filtration and a 50 µm stainless-steel filter. The filter was carefully transferred into a clean beaker with the particles facing down. An adequate volume, sufficient to cover the filter, of EtOH:water (50 %) was added to the beaker, and the sample was ultrasonicated in MilliQ water. The filter was flushed with MilliQ water to transfer all particles (and removed). An aluminum lid was placed over the beaker with the sample in EtOH:water (50 %) water and kept at room temperature until further analysis.

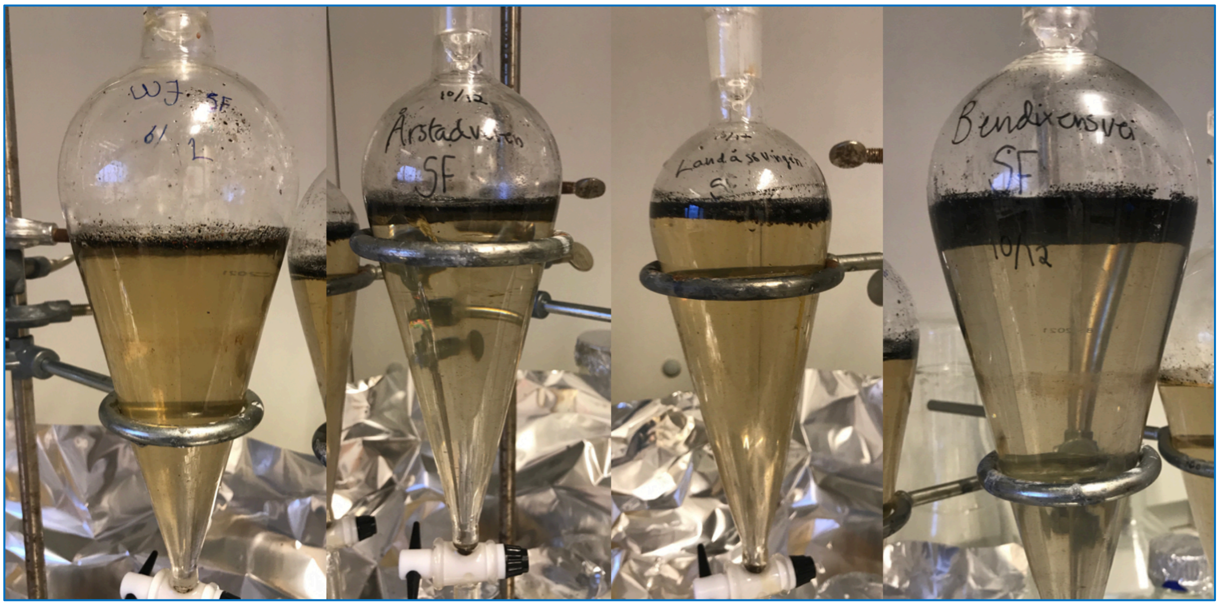


Figure 12: A selection of samples in glass separation funnels during the second density separation with $ZnCl_2$, showing abundant microplastic and TWP. From left to right: Suburban4TR, Suburban1TR, Suburban2TR, Suburban3TR.

Separating plastic particles into three size classes

Before identification of the extracted and purified plastic particles, the particles were separated into three main size classes (50-500 µm, 500-1000 µm, and > 1000 µm), following the procedure shown in Figure 13. To determine the total mass the three size classes were transferred quantitatively by vacuum filtration onto separate pre-weighted filters, dried overnight and weighed (± 0.15 mg, AT200 Mettler, Mettler Toledo). A manual sorting of the larges size-class was performed separating the particles into 1-5 mm and > 5 mm.

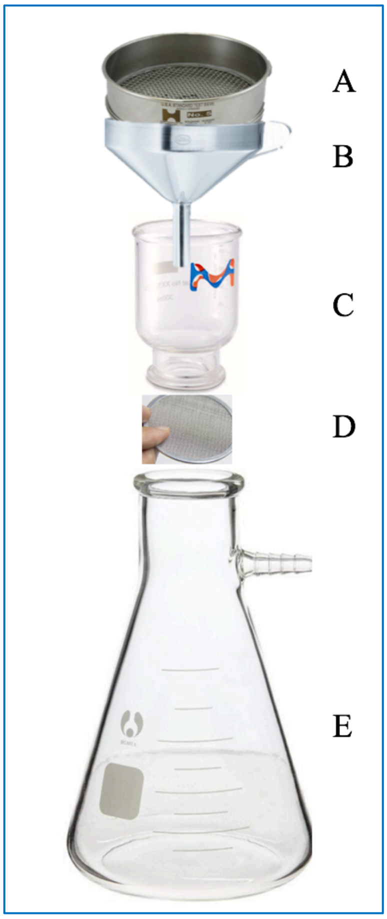


Figure 13: The setup for separating the particles into three size classes. A) The stainless-steel geological sieve with 1 mm pore size, ⌀ 100 mm. B) The stainless-steel funnel. C) The glass vacuum filtration funnel. D) The stainless-steel mesh filter with 500 µm pore size, ⌀ 47 mm. E) The glass vacuum filtration flask.

Analyzing the small microplastic particles (SMP, 50-500 µm) by Pyrolysis–gas chromatography–mass spectrometry (Pyr-GCMS)

Pyr-GCMS was used to identify the SMP below 500 µm. The particles were quantitatively transferred into a 100 mL glass bottle, and precisely 100 mL of EtOH:water (50 %) was added. Following the procedure by (Gomiero, Øysæd, et al., 2019), an appropriate amount (0.25-20 %) of the solution was transferred onto a pre-burned GF/C filter (1.2 µm pore size, ⌀ 25 mm). For samples with a high number of particles, analyzes of multiple replicates were performed, resulting in a minimum of 1 % of the total sample analyzed. A custom-made glass adaptor reduced the deposition area to ⌀ 10 mm. The filter was cut with a metal cylinder to obtain a ⌀ 15 mm. The filters were folded, securing the samples, and placed in pre-burned pyrolytic stainless-steel cups special for Pyr-GCMS analysis. The stainless-steel cups with the sample were added ten µL of tetramethylammonium hydroxide (TMAH, 25 % in water, Sigma Aldrich) to perform thermochemolysis. The cups were dried overnight (~17h) on a heating plate set to 40 °C. The sample in the pyrolytic stainless-steel cup was pyrolyzed at 590 °C, and a carrier gas transported the fragments into the chromatograph. The fragments were then chromatographically separated according to each specific boiling point. By mass spectrometry, as the detections technique, the substances were detected by the characteristic compound and their mass to charge ratio (m/z) (Kusch, 2018). Distinct indicator ions were chosen to identify and separate single polymers in complex environmental samples (Figure 14). From the pyrograms, the most polymer specific compounds were chosen as the indicators (Table 4). In environmental samples, the polymer origin is identified by a comparison of the pyrograms from the standard polymer and with the combustion product (chosen as the indicator) from the sample (Fries et al., 2013; Nuelle et al., 2014). The peak area of the indicator ion in the pyrogram was fitted in the standardized polymer calibration curve to calculate the correct amount of each polymer. Quantification and calibration curves were created from > 99 % pure polymers to calculate each specific polymer mass in the sample with Pyr-GCMS (Figure 15, Appendix C). To create the calibration curves, the specific polymer standards were analyzed on the pyrolysis in various exact weights.

The Pyr-GCMS analyzes were performed with a Shimadzu Optima 2010C GCMS controlled by GCMS solution V 4.45 equipped with a Rxi-5ms column (RESTEC, Bellefonte, PA) and coupled with Frontiers lab's Multi-Shot Pyrolizer EGA/PY-3030D with auto-shot sampler (BioNordika, Norway) (Table 5). The Pyr-GCMS used in this study was set to identify 9 of the most common synthetic polymers; PP, PE, PA66, PMMA, PS, PVC, PET, PC, and PES. To examine if car tire particles are present, the analysis tries to identify D-Limonene in the sample and is present in natural rubber and, hence, in all types of car tires. The calibration curve was created from a car tire used during the summer from one supplier. We have presumed that this do not to affect our results significantly, as the amounts of D-Limonene in different tires vary. The actual concentrations of TWP would be more accurate in these samples if all cars used this specific type of tire. The detector is sensitive and can detect masses down to 1 µg. However, due to the complex samples in this study, the minimum detection limit is set to 10 µg. Therefore, one cannot conclude whether or not there are polymers present in the sample with a weight of below 10 µg.

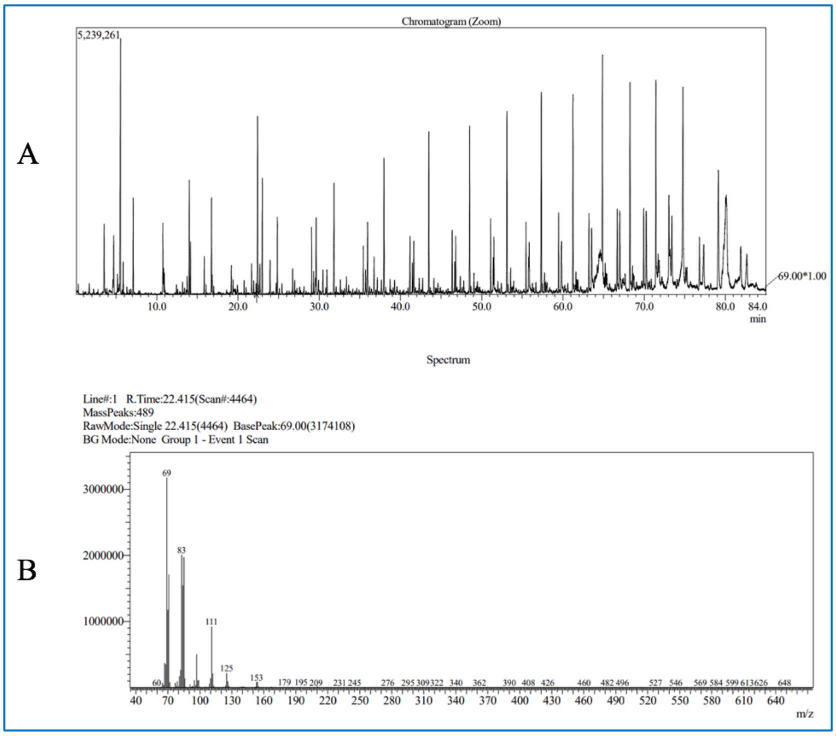


Figure 14: Pyrogram for an analyzed standard PP polymer (90 µg). A) The chromatogram. B) The mass spectroscopy, with the PP indicator ion peak at m/z 69.

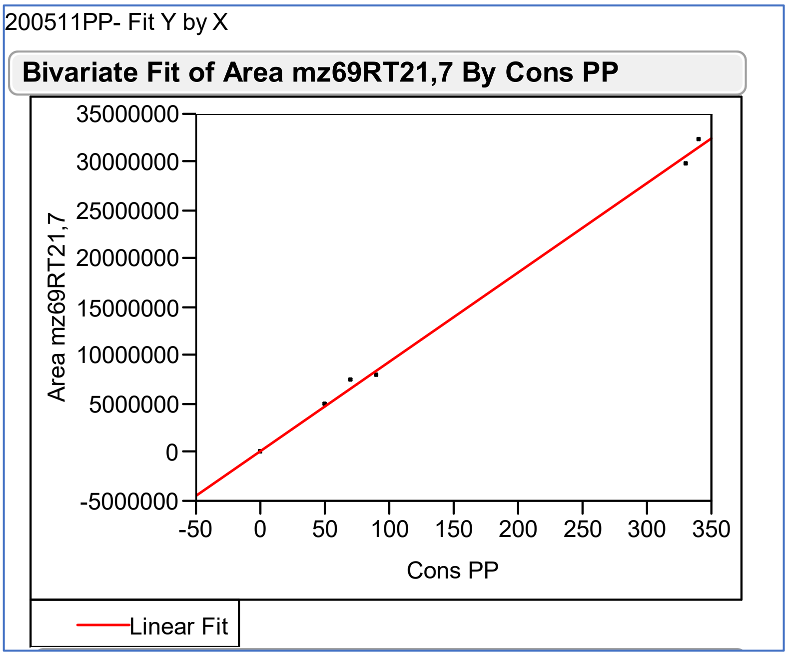


Figure 15: The quantification and calibration curve for PP, presenting the concentration of PP on the x-axis and the peak area on the y-axis.

Table 4: The indicator ions and mass to charge ratio for the polymers identified with Pyr-GCMS.

Polymer	m/z	Characteristic compound
TWP	68	D-Limonene
PP	69	2,4,6,8-tetramethyl-1-undecene
PE	83	1-Tetradecene
PA66	84	hexene
PMMA	100	methyl methacrylate
PS	104	styrene
PVC	117	Benzen, 1-propenyl
PES	131	2-propionic acid
PET	135	dimethyl terephthalate
PC	149	p-methoxy-tert-butylbenzene

Table 5: The conditions applied to the Pyr-GSMS instrument used in this study.

Pyrolysis conditions	
Instrument:	EGA/PY-30300
Carrier gas:	Helium 6.0
Pyrolysis temperature:	590 ˚C
Thermolysis:	Single Shot analysis
Pyrolysis time:	1 min
Interface temperature:	300 ˚C
Gas chromatographic conditions	
Injector:	split/split less injection port
Mode:	Split (ratio 1:20)
Injector temperature:	300 ˚C
Column	Restex Rxi-5ms
Column length	30 m
Flow	3.0 mL/min
Temperature program:	40 ˚C in 2 min
	40 ˚C to 320 ˚C with 4˚C/min 320 ˚C in 20 min
Mass spectrometric conditions	
Detector voltage:	1.6 kV
Scan speed	2500 MAU/sec
Scan range	50 - 650

Analysis of the large microplastic particles (LMP, 500-1000 µm) and plastic particles above 1000 µm (ATR-FTIR)

Large microplastic particles

The LMP were first evenly distributed in a glass petri dish (Figure 16). A random section of the sample was drawn and all particles in the section analyzed to obtain approximately 40 particles to be identified (mean 40 particles, ranging from 19-69, from all to 1/16 of the total number of particles) (Figure 16). In samples with a low number of particles (≤ 36), all of them were analyzed. In Appendix D all samples with the chosen fraction, obtaining approximately 40 particles, are presented.

The selected particles were analyzed by Attenuated total reflectance-Fourier transform infrared spectrometers (ATR-FITR) on Nicolet™ iN10 MX Infrared Imaging Microscope (Thermo Fisher™) (iN10) (ATR-FTIR principle described in Appendix B. A germanium crystal at a 35° angle was used and the spectra were collected in absorbance mode. With an MCT detector requiring liquid nitrogen, 64 scans were collected per particle with a spectral range 4000-650 cm^{-1} (12 seconds) and a spectral resolution of 8 cm^{-1}. The germanium tip gives an aperture of 350 µm.

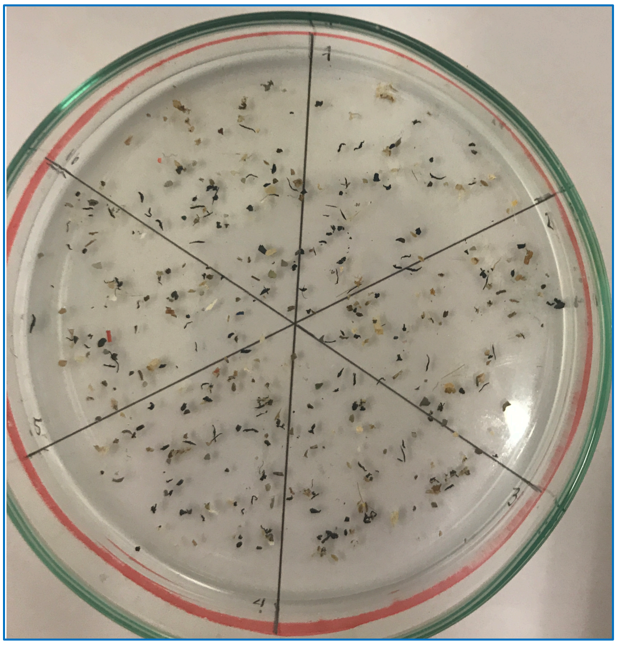


Figure 16: A sample randomly distributed into six fractions, where one was randomly selected, and all the particles in the fraction were analyzed (Sample: Urban1S-Su).

Plastic particles above one mm

Plastic particles > 1 mm was analyzed with ATR-FTIR on a Spectrum One FT-IR Spectrometer (PerkinElmer). A diamond crystal at a 45° angle was used and the spectra were collected in absorbance mode. A DTGS detector worked at room temperature, collecting 32 scans per particles with a spectral range 4000-650 cm^{-1} (70 seconds) and a spectral resolution of 8 cm^{-1}.

All particles > 5 mm was analyzed with ATR-FTIR. The particles < 5 mm were sorted into groups based on appearance and structure for each sample, a selection of particles in all groups were imaged and measured with a microscope with an attached imager. For instance, TWP have a recognizable appearance and structure, and could appear in substantial numbers. Therefore, only a representative number from each group per sample was analyzed with ATR-FTIR.

Spectra identification

All spectra collected were compared to the reference libraries (Hummel polymer library and HR Nicolet polymer library) and a minimum of two spectra were collected for every particle. Following Hanke et al. (2013), a match quality above 70 % was accepted as an approved polymer match. If the match qualities were below 70 %, the spectra were manually compared to find a possible identification. TWP > 500 µm were identified manually, as carbon-black presents a recognizable spectrum with ATR-FTIR, and an original TWP was analyzed for comparison (Figure 17). Some particles could not be identified with the reference library or by manual confirmation. These particles often gave an inconclusive spectrum and were excluded from the results. Organic particles were also excluded from the results after ATR-FTIR analysis. By appearance, these often have a recognizable brown/beige color, a soft texture and film-like structure sometimes with visible cellular structures.

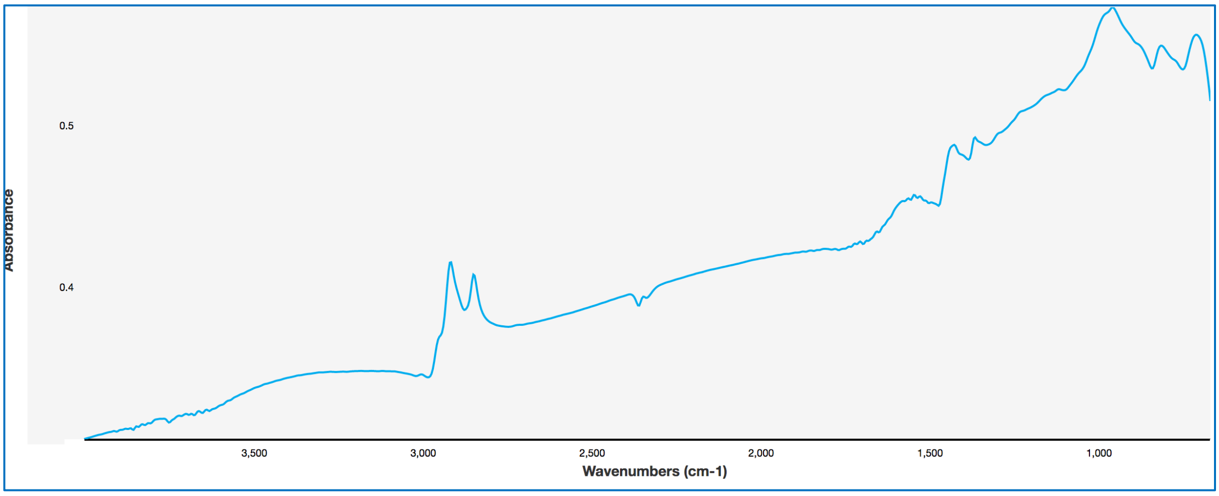


Figure 17: An absorbance spectrum for an example of a TWP from a sample.

Mass calculation

The mass of the LMP particles analyzed was calculated following Equation 3 (Simon et al., 2018). The size (length and width) of each particle was measured and imaged on the Nicolet™ iN10 MX Infrared Imaging Microscope (Thermo Fisher™) (iN10). The specific polymer density is listed in Table 3.

$$Particle\ length * Particle\ width * (0.6 * Particle\ width) *$$
$$Polymer\ spesific\ density = Mass\ per\ particle \qquad \text{Equation 3}$$

Prevention of contamination and quality control

In studies analyzing microplastics, prevention of contamination is an integral part of the procedure. All surfaces were wiped down with laboratory tissue and MilliQ water or filtered ethanol (Whatman GF/C: 0.7 µm). All equipment used was either burned in a muffle oven at 500 °C or rinsed repeatedly with MilliQ water (minimum three times). Samples were covered with aluminum foil or lids made of non-plastic materials at all times. Equipment with samples during analysis, e.g., part of the MPSS, were covered at all times. This was implemented to avoid possible air contamination. Care was taken not to lose any material or contaminate the sample with microplastic particles. In the laboratory, coats and clothing used were made of natural fibers to limit possible contamination. Chemicals delivered in plastic containers were filtered (Whatman GF/C: 0.7 µm) before use and stored in glass containers. All plastic equipment was replaced with non-plastic materials. Exceptions were squeezy-bottles for chemicals (Polytetrafluoroethylene (PTFE)), the valve in the separation funnel (PTFE), and silicone tubes for filtration of $ZnCl_2$. These polymers have a higher density than $ZnCl_2$ and, therefore, should not be separated in the MPSS. If these polymers are identified in the samples with the ATR-FTIR a contamination from one of the procedures have occurred. Plastic goggles and nitrile gloves had to be used for protection.

To secure reliable results, quality controls were implemented throughout the study. Wet traps were implemented to identify airborne contamination. Procedural blanks were used to identify likely contaminants from the procedure and reagents. In order to prepare a procedural blank from the MPSS density separation the procedure was performed only with filtered $ZnCl_2$ and left to settle for a few hours (2-4 h). The separated material in the sample chamber was analyzed with Pyr-GCMS for possible cross contamination of later samples. The filtered $ZnCl_2$ used for both density separations were regularly (every fifth sample) controlled for particles over > 1 µm. Although the focus in this study is particles over 50 µm and contamination below this will not affect our results. In highly plastic-rich samples, like in this study, a large sample size (> 800 g) processed with the MPSS could result in errors and issues with the sample chamber becoming overfilled with plastic and organic material. To dismiss contamination through the pyrolysis analyses, procedure blank controls were performed using MilliQ water. All control samples were visually inspected, and a random selection of the controls were analyzed on Pyr-GCMS.

Risk assessment and environmental consequences

As seen from an ethical research perspective, neither the completion nor the results from this study are considered problematic. Hazardous chemicals will be properly handled and disposed of according to the Material Safety Data Sheet (MSDS) to avoid environmental damage. The recycling and reusing of $ZnCl_2$ is both cost- and time-effective. This will also be environmentally beneficial, as $ZnCl_2$ is corrosive, irritating and hazardous to aquatic life (VWR Chemicals, 2014). When performing the Fenton's reaction, the temperature was kept below 30 °C (to ensure the H_2O_2 efficiency) this will limit the possibility of a violent reaction occurring, ensuring laboratory safety. Throughout this project, there were no other negative environmental consequences expected. On the other hand, this study could contribute to actions taken to prevent further dispersal of microplastic particles in the urban environment, and thus have a beneficial environmental effect.

Statistics and calculations

The statistical analyzes and calculations were performed with IBM SPSS Statistics (version 25.0) and Microsoft Excel. The SMP and LMP were converted to microplastic concentration per kg dry weight. The two microplastic size classes were combined prior to data analyses if not stated otherwise, and reported masses indicate the sum of SMP and LMP. The mass calculations for the LMP followed the calculations shown in chapter 'Mass calculation'. The mass of the microplastic particles were presented in µg from the Pyr-GCMS and due to uncertainties in the method, the when calculating to mg we decided that two decimals would be sufficient and limit uncertainty. To obtain the correct concentration unit, first the total mass of each polymer was calculated from the fraction analyzed to a 100 % of the sample. The calculation then followed Equation 4, resulting in the polymer mg per kg dw.

$$\frac{Polymer\ Weight\ (mg)\ in\ 100\ \%\ of\ the\ Sample\ /\ the\ Wet\ Weight\ of\ the\ Sample}{Dry\ Matter\ \%\ /\ 100} = Polymer\ mg\ /\ kg\ dw$$

Equation 4

The total mass-estimate of street sweepings from Bergen (2000-2500 metric tons wet matter) was obtained from the head of the Agency for Urban Environment in Bergen. The dry matter of the total street sweeping mass used in the calculations is based on the average dry matter percentage from our street sweeping samples (84.34 %). The calculations to find the presumed total microplastic contamination in the total street sweepings were calculated following Equation 5.

$$Total\ Yearly\ Street\ Sweeping\ Mass\ (kg) * \ Microplastic\ \left(\frac{g}{kg}dw\right) = Microplastic\ in\ the\ Total\ Sweeping\ Mass$$

Equation 5

The sample size in this study is small and the results show large variation. The Levene's test of normality showed non-normal distribution in the data. Therefore, parametric tests would not be suitable. A Mann-Whitney U test was determined to be suitable for our dataset and used to test the difference between two independent variables. The non-parametric Spearman Rho correlation test was used to find relevant correlations between samples. Both SPSS (IBM Statistics, v. 25.0 for Mac) and Excel were used to design graphs presenting the results. The statistical significance level was set to α = 0.05.

Results

Sample characterization

Dry matter and organic content percentage per sample were calculated and shown in Table 2. Dry matter content varied between 95.12 and 52.23 % in the 21 environmental samples analyzed. The organic content from sand trap samples had a higher mean (8.52 %) than the sediment samples from street sweepings (mean = 3.03 %). The organic content was below 10 % for all samples tested, except for one sand trap sample (Suburban3) that demonstrated an 18.32 % organic content. In addition, the latter sample had the lowest dry matter content (52.23 %).

Microplastic separation and sample purification

The 23 sediment and sand trap samples were all successfully separated with the MPSS. The volume and mass of the samples processed are listed in Table 2. Organic matter and low-density synthetic polymers were isolated in the sample chamber (Figure 18), while the high-density (> 1.7 g/cm^3) materials were left in the sediment container. Presumed synthetic particles were also observed in the sediment container, presumably with a higher density than the separation liquid. The inspected precipitate from the second density separation showed PVC in all the analyzed samples, showing that PVC was not fully recovered using density separation with $ZnCl_2$. TWP was observed in 80 % of the tested samples, indicating that TWP was not fully recovered. Two samples (Urban3S-Su and Urban5TR) also contained the low-density polymers PE and PS in the remaining precipitate. The identified concentration from the precipitate is shown in Table 6.

Table 6: The detected polymers (µg) from the precipitate from the density separation in the glass funnels, analyzed with Pyr-GCMS.

	Polymers			
	TWP	PE	PS	PVC
Urban3S-Su	717	33	20	113
Urban1S-F	25	< 10	< 10	71
Urban5TR	< 10	25	25	49
Suburban4S-Sp	22	< 10	< 10	22
Suburban4TR	13	< 10	< 10	51

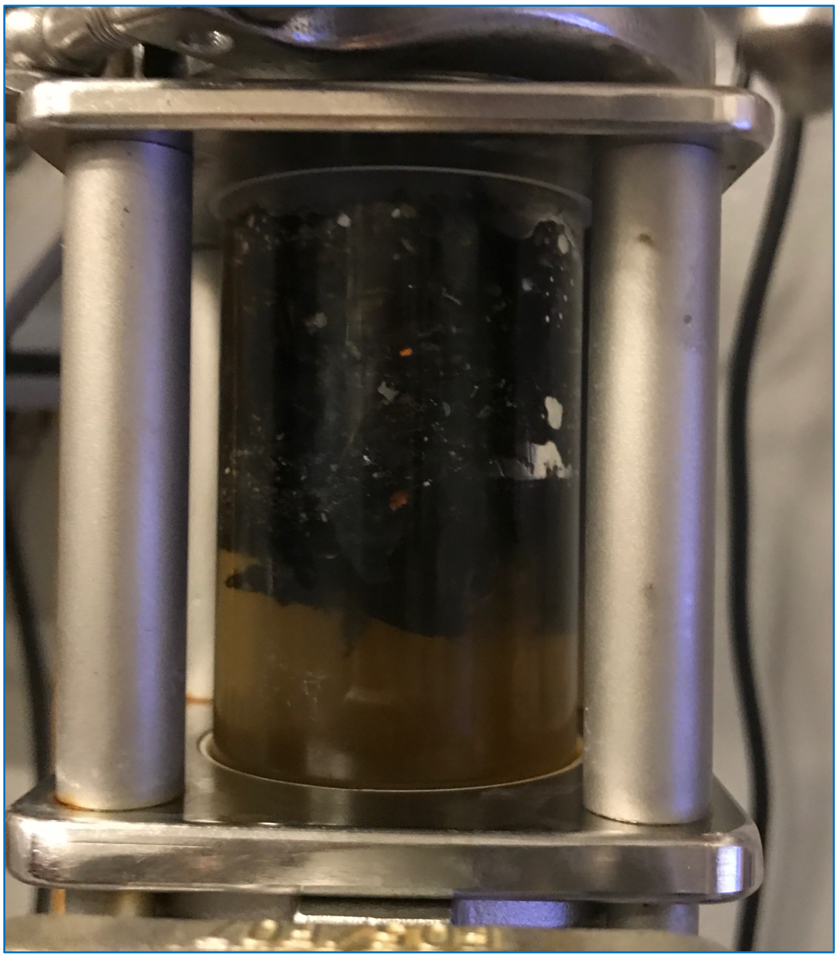


Figure 18: The top chamber of the MPSS with a separated sample with isolated low-density material (< 1.7 g/cm^3) (including synthetic and organic material) for further processing (sample: Urban5TR).

Total microplastic concentration

The total microplastic concentrations (SMP and LMP) from each location and season for both urban and suburban areas are shown in Table 8, Figure 19, and Figure 22. The mean microplastic concentration for the suburban and urban areas for both street sweepings and sand traps are listed in (Table 7). There were large variations between samples from the urban environment (summer and fall) and the suburban environment, including street sweeping and sand trap samples (Table 8). The lowest concentration (4.58 mg/ kg dw) was detected at Urban4 (from the fall), while the highest concentration (666.58 mg/ kg dw) from street sweepings was located at Urban3S-Su. The lowest sand trap concentration (22.72 mg/ kg dw) was located at Urban4, and the highest microplastic concentration (808.63 mg/ kg dw) was found at Suburban4. The street sweepings from Urban4 also had a low microplastic concentration as this is an urban location less influenced by traffic or people. Moreover, all the sand traps had a microplastic concentration higher than the corresponding street sweeping sample. The two clean gravel samples had a significantly lower microplastic concentration than street sweeping samples from urban and suburban Bergen (Mann-Whitney U test, U = 0, p = 0.034).

Table 7: The mean microplastic concentration (mg/ kg dw) from the urban and suburban areas, represented by street sweepings and sand traps, including the clean gravel samples. Presented with mean microplastic concentration (mg/ kg dw), standard deviation, minimum and maximum value (mg/ kg dw).

	Street Sweepings		**Sand Traps**	
	Mean ± SD	Min-Max	Mean ± SD	Min-Max
Urban summer	196.63 ± 275.98 (n = 5)	5.04 – 666.58	432.19 ± 366.36 (n = 3)	22.73 – 728.96
Urban fall	69.75 ± 63.08 (n = 5)	4.58 – 172.72		
Suburban (n = 4)	24.77*⊗ ± 22.54	5.74 – 56.23	607.67 ± 198.07	377.98 – 808.65
Clean gravel (n = 2)	1.84• ± 0.32	1.61 – 2.06	-	-

⊗ Statistically significantly lower than corresponding sand traps

•Statistically significantly lower than the street sweepings from urban and suburban areas

Table 8: The total microplastic concentration (SMP+LMP) (mg/ kg dw) from street sweepings and sand traps from urban and suburban areas.

Location	**Total microplastic concentration from street sweepings (mg/ kg dw)**		**Total microplastic concentration from sand traps (mg/ kg dw)**
	Summer	Fall	
Strandgaten/Strandkaien **Urban1**	211.34*	43.99	-
Christies gate **Urban2**	94.52	50.86	-
Lungegårdskaien/Østre Strømkaien **Urban3**	666.58*	172.72*	728.96*
Olaf Ryes vei/ Muséplassen **Urban4**	5.67	4.58	22.72
Vaskerelven **Urban5**	5.04	76.63	544.88*
	Spring		
Årstadgeilen **Suburban1**	56.23		512.18*
Landåssvingen **Suburban2**	11.65		731.89*
Bendixens vei **Suburban3**	25.43		377.98*
Wiers-Jenssens vei **Suburban4**	5.74		808.63*
Clean gravel with salt	1.61		-
Clean gravel without salt	2.06		-

* The concentration is based on multiple parallels.

Differences in microplastic concentration from urban to suburban areas

The samples from the urban and suburban street sweepings showed large differences in microplastic concentration (Figure 19). The suburban street sweepings had less variation between samples than the urban (summer and fall) samples. There was no statistically significant difference in total microplastic concentration from urban (summer) and suburban street sweepings (Mann-Whitney U test, U = 8, p = 0.624). However, the street sweepings from the urban areas (summer) had almost seven times higher (693.82 %) average microplastic concentration in comparison to the street sweeping sampled in the suburban areas. No significant difference was observed between urban (fall) and suburban street sweepings (U = 6, p = 0.327), but 181.61 % higher mean microplastic concentration in the urban fall street sweepings was revealed. The high average microplastic concentration from the urban samples (summer and fall) was heavily influenced by the concentration at the highly trafficked Urban3 (a statistical outlier) (Figure 20). This location also affected the differences in microplastic concentration between urban and suburban areas. Urban4 was the location with the lowest microplastic concentration (from summer and fall season) of all the urban and suburban samples.

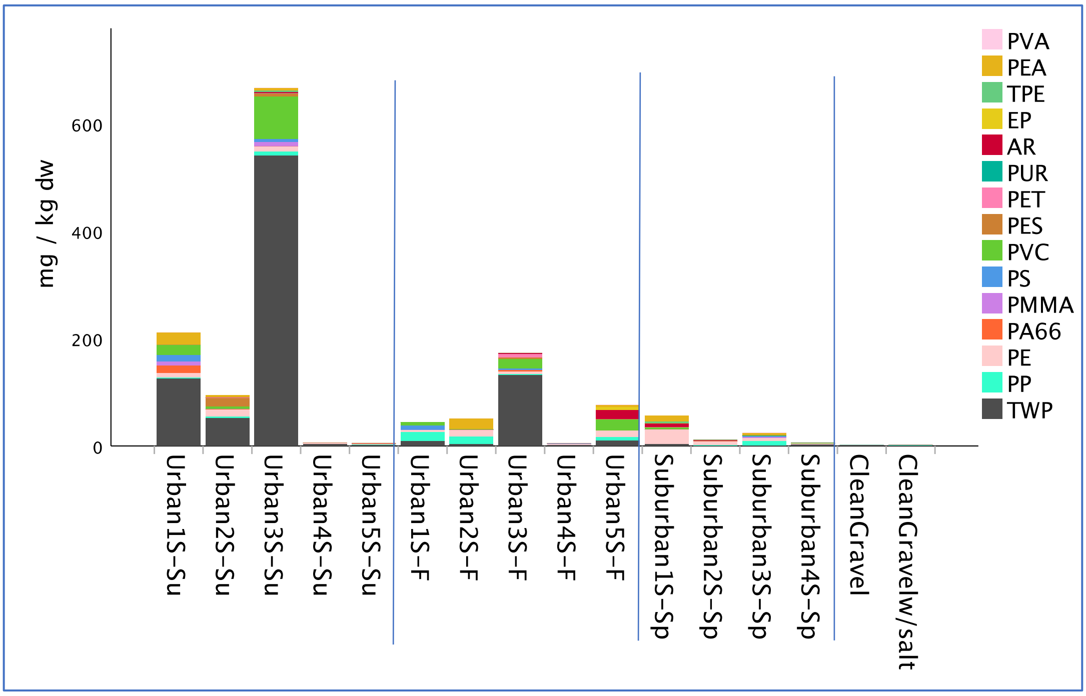


Figure 19: The total microplastic concentration (mg/ kg dw) and the polymer types from street sweeping samples from urban areas (including the summer and the fall season) and the suburban areas, and the concentration from the clean gravel samples.

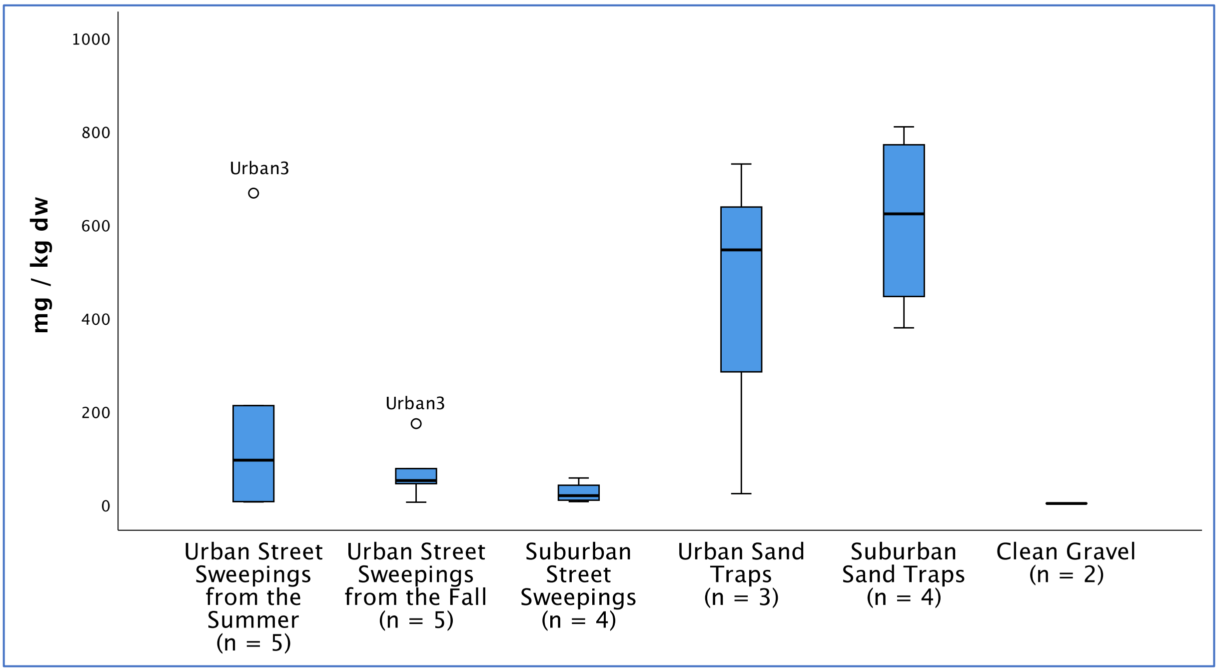


Figure 20: Box plot of the microplastic distribution (mg/ kg dw) from street sweepings and sand traps from urban (summer and fall) and suburban areas. Including the clean gravel samples. The line in the box represents the median, the box represents the 25th - 75th percentile, and the whiskers represent the 95 % confidence interval. The outliers are represented by the circles (Urban3).

A simple scatter plot (Figure 21) shows a weak correlation between the street sweepings and the sand traps from all urban and suburban locations ($r_{sq} = 0.105$). Indicating high microplastic concentrations in the sand traps were not necessarily associated with high microplastic concentrations in the street sweepings in any significant way. This was strengthened by a Spearman rank correlation test that indicates no correlation between street sweepings and sand traps ($r_s = 0.071$, $p = 0.879$). However, when only testing correlation between the suburban street sweepings (with a generally low microplastic concentration) and sand traps (with a generally high microplastic concentration) (Table 8), a Spearman rank correlation test indicated a strong negative correlation ($r_s = -0.800$, $p = 0.200$). Indicating that low microplastic concentrations in suburban street sweepings are associated with high microplastic concentrations in corresponding sand traps. The results indicate that the overall microplastic concentrations in street sweepings do not reflect the overall concentration in the sand traps, so that one sample cannot be replaced by the other.

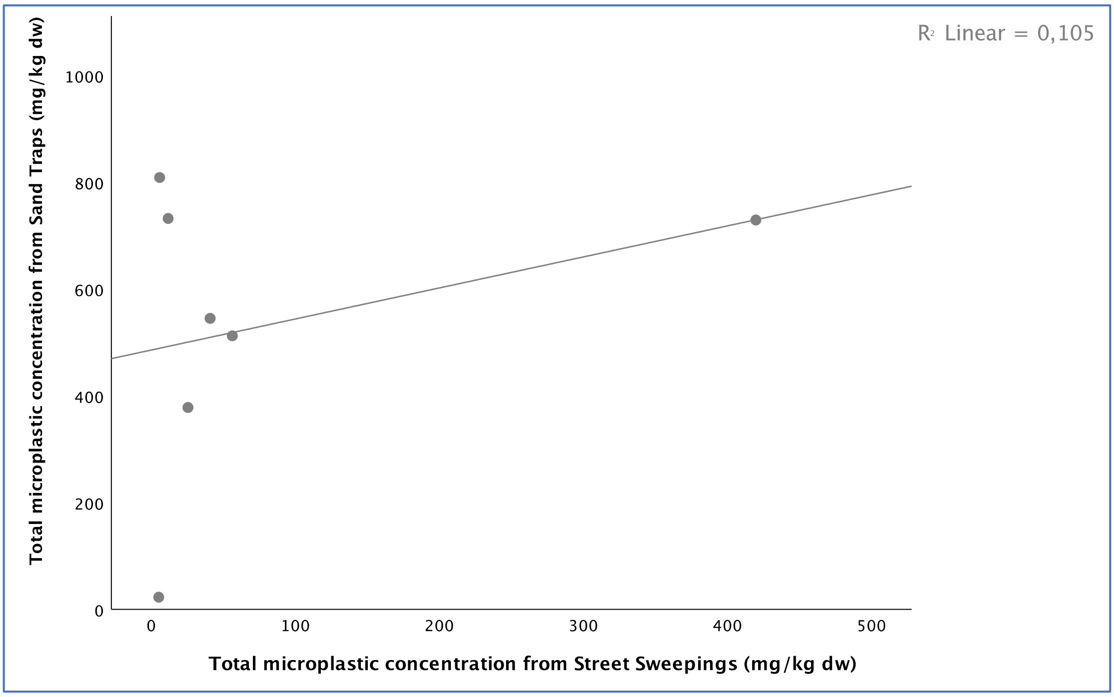


Figure 21: A simple scatter plot with the total microplastic concentration (mg/ kg dw) from the street sweepings and the sand traps (including the outlier in Urban3).

In contrast to the street sweeping samples, the sand traps presented a 40.62 % higher microplastic concentration in the suburban samples than in the urban (Figure 22). The difference was, however, not statistically different (Mann-Whitney U test, U = 4, p = 0.480). The urban and suburban sand traps showed a large variation between the individual samples. Suburban4 had the highest microplastic concentration in all sand trap samples and had the lowest concentration from the suburban street sweepings. The sand trap with the lowest microplastic concentration was located at Suburban3.

All urban sand trap samples had a higher microplastic concentration than the corresponding street sweeping sample (for both the summer and fall street sweeping samples), but the difference was not significant (Mann-Whitney U test, U = 4, p = 0.197). In suburban samples, there was a significant difference between the mean microplastic concentrations from street sweepings and corresponding sand traps (Mann-Whitney U test, U = 2, p = 0.05), where suburban sand trap samples all had high microplastic concentrations, compared to the corresponding street sample. The urban sand traps are only represented by three samples in this study, where Urban4 had a considerably lower concentration than the two other sand traps.

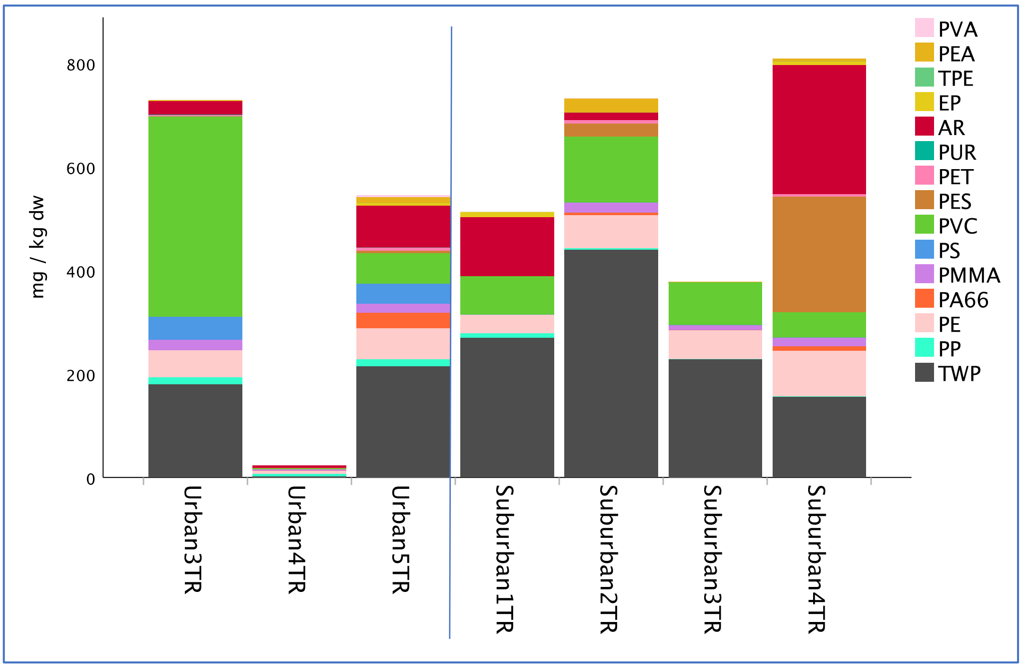


Figure 22: The total microplastic concentration (mg/ kg dw) and the polymer types from the urban and suburban sand traps.

Seasonal differences in microplastic concentration from urban street sweepings

The investigation of the seasonal differences in microplastic concentration from the urban street sweepings samples collected at the five locations showed a 180.91 % higher mean microplastic concentration in summer than in fall samples (Figure 23). However, a Mann-Whitney U test indicated no statistically significant difference in microplastic concentration between the two seasons (U = 9, p = 0.465). All locations had a higher microplastic concentration during the summer, except Urban5, which had a higher concentration from the fall (Figure 23). Both seasons had a large variation between samples, especially the summer samples with a low minimum concentration from Urban4 and a high maximum concentration from Urban3. Urban3 heavily influenced the difference between seasons, however, it also had the highest concentration in both seasons.

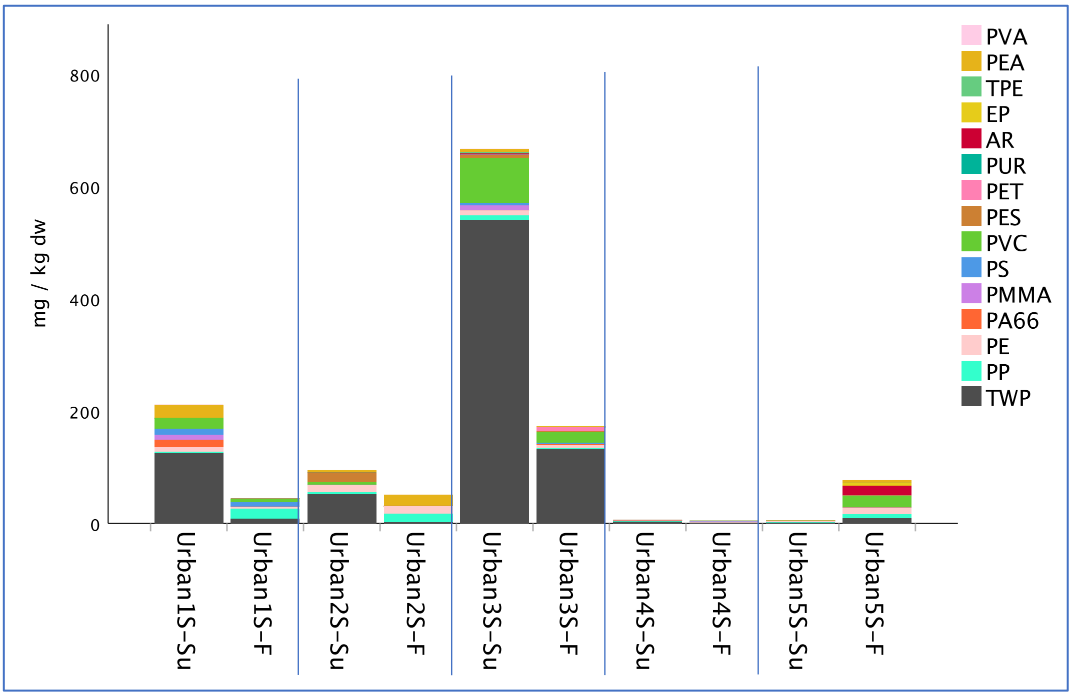


Figure 23: The total microplastic concentration (mg/ kg dw) and the polymer types in the summer and fall street sweeping samples from urban areas.

Total Microplastic Polymer Distribution

In the 21 environmental samples, 15 different polymers were identified and found to be above the LOQ (10 µg/ kg). The mean, SD, minimum, and maximum concentration of each polymer are listed in Table 9. The sand trap samples had a slightly higher average number of polymers (mean = 9) identified than the street sweepings (mean = 8).

The most common polymers detected in all environmental samples (including street sweepings and sand traps) were TWP, PE, and PVC, making up 76.29 % of the total microplastic concentration. The most dominating polymer in both street sweepings and sand traps was TWP, accounting for 45.97 % of the total. TWP generally showed great variation between samples. The highest TWP concentrations were found in Urban3 in both summer and fall street sweeping samples, while the lowest concentration was detected in the street sweeping from less trafficked Suburban2. PVC accounted for 18.24 % of the total microplastic concentrations and presented less variation between the samples, except for sand trap Urban3, where PVC accounted for 53.03 % of the total concentration. Paint particles (alkyd resin) were identified in 13 out of 21 street sweeping and sand trap samples. The paint concentrations demonstrated large variations between samples but accounted for 10.09 % of the total microplastic concentrations. PE particles were identified with a generally low concentration but accounted for 9.08 % of the total microplastic concentrations. The less frequently identified polymers that contributed to < 6.00 % of the total microplastic concentration were the remaining eleven polymers (PES > PEA > PS ~ PP > PMMA > PA66 > PET ~ EP > TEP ~ PVA > PUR).

In the clean gravel samples, TWP accounted for 66.54 % of the mean microplastic concentration. The other polymers detected in the clean gravel samples and their relative abundances were PP > PE >PVC > PET.

Table 9: The mean polymer concentration (mg/ kg dw) with standard derivation, maximum and minimum values for urban (summer and fall) and suburban street sweepings, and urban and suburban sand traps. And values from the clean gravel.

		Street Sweepings (mg/ kg dw)			**Sand Traps (mg/ kg dw)**		
		Urban Summer	Urban Fall	Suburban	Urban	Suburban	Clean Gravel
TWP	Mean	144.34	30.84	1.43	132.26	273.15	1.22
	SD	227.16	56.67	1.23	113.92	120.66	0.52
	Maximum	540.65	132.02	2.83	214.81	439.62	1.59
	Minimum	1.45	1.19	0.13	2.30	155.02	0.85
PVC	Mean	21.05	9.56	1.63	149.74	83.04	0.10
	SD	33.77	9.91	1.32	207.08	32.78	0.10
	Maximum	79.97	21.55	3.57	386.55	127.26	0.10
	Minimum	0.55	0.57	0.68	2.72	48.61	0.10
PE	Mean	6.68	6.77	10.28	39.50	60.37	0.22
	SD	4.86	5.29	11.54	29.25	21.80	0.17
	Maximum	12.25	12.70	27.22	60.06	87.56	0.34
	Minimum	1.44	1.21	1.48	6.01	34.79	0.10
AR	Mean	0.43	3.79	2.13	37.32	94.74	< LOQ
	SD	0.76	7.53	3.35	39.31	114.74	< LOQ
	Maximum	1.75	17.20	7.04	81.01	249.15	< LOQ
	Minimum	< LOQ	< LOQ	< LOQ	4.82	0.00	< LOQ
PES	Mean	4.19	0.40	< LOQ	1.34	62.23	< LOQ
	SD	6.80	0.89	< LOQ	2.33	108.11	< LOQ
	Maximum	15.63	2.00	< LOQ	4.03	223.39	< LOQ
	Minimum	< LOQ	< LOQ	< LOQ	< LOQ	< LOQ	< LOQ
PEA	Mean	6.56	4.94	4.05	4.67	8.42	< LOQ
	SD	9.87	8.64	5.14	5.88	12.41	< LOQ
	Maximum	23.75	19.94	11.24	11.27	26.74	< LOQ
	Minimum	< LOQ	< LOQ	0.33	< LOQ	< LOQ	< LOQ
PS	Mean	3.36	2.36	0.34	27.71	< LOQ	< LOQ
	SD	5.13	3.53	0.51	24.21	< LOQ	< LOQ
	Maximum	11.60	8.31	1.09	44.81	< LOQ	< LOQ
	Minimum	< LOQ	< LOQ	< LOQ	< LOQ	< LOQ	< LOQ
PP	Mean	2.97	8.06	2.64	9.99	3.67	0.28
	SD	2.76	7.43	3.80	4.95	3.98	0.04
	Maximum	7.33	17.03	8.33	13.09	9.27	0.30
	Minimum	0.47	0.44	0.52	4.28	< LOQ	0.25
PMMA	Mean	3.30	< LOQ	0.62	13.49	11.48	< LOQ
	SD	4.52	< LOQ	1.23	9.62	8.24	< LOQ
	Maximum	8.47	< LOQ	2.47	20.47	19.00	< LOQ
	Minimum	< LOQ	< LOQ	0.00	2.52	0.51	< LOQ
PA66	Mean	2.81	0.64	< LOQ	10.15	3.47	< LOQ
	SD	5.74	0.89	< LOQ	17.57	4.27	< LOQ

	Maximum	13.06	2.17	< LOQ	30.44	8.75	< LOQ
	Minimum	< LOQ	< LOQ	< LOQ	< LOQ	< LOQ	< LOQ
PET	Mean	0.10	1.33	0.24	2.97	2.81	0.02
	SD	0.23	2.98	0.21	3.04	3.28	0.00
	Maximum	0.52	6.65	0.48	6.08	6.17	0.02
	Minimum	< LOQ	< LOQ	< LOQ	< LOQ	< LOQ	0.02
EP	Mean	< LOQ	1.07	0.14	1.60	4.21	< LOQ
	SD	< LOQ	2.26	0.28	2.77	4.97	< LOQ
	Maximum	< LOQ	5.10	0.57	4.80	9.70	< LOQ
	Minimum	< LOQ	< LOQ	< LOQ	< LOQ	< LOQ	< LOQ
TPE	Mean	0.74	< LOQ	0.80	< LOQ	< LOQ	< LOQ
	SD	1.65	< LOQ	1.60	< LOQ	< LOQ	< LOQ
	Maximum	3.70	< LOQ	3.19	< LOQ	< LOQ	< LOQ
	Minimum	< LOQ	< LOQ	< LOQ	< LOQ	< LOQ	< LOQ
PVA	Mean	< LOQ	< LOQ	0.47	1.32	< LOQ	< LOQ
	SD	< LOQ	< LOQ	0.94	2.29	< LOQ	< LOQ
	Maximum	< LOQ	< LOQ	1.89	3.97	< LOQ	< LOQ
	Minimum	< LOQ	< LOQ	< LOQ	< LOQ	< LOQ	< LOQ
PUR	Mean	0.10	< LOQ	< LOQ	0.11	< LOQ	< LOQ
	SD	0.14	< LOQ	< LOQ	0.09	< LOQ	< LOQ
	Maximum	0.32	< LOQ	< LOQ	0.21	0.15	< LOQ
	Minimum	< LOQ	< LOQ	< LOQ	0.06	< LOQ	< LOQ

LOQ = 0.01 mg/ kg dw

Difference in polymer distribution from urban to suburban areas (street sweepings and sand traps)

The relative polymer distribution from urban and suburban street sweepings is shown in Figure 24. The number of different polymers detected in the suburban streets (mean different polymers = 9) was higher than the urban streets (mean different polymers = 7). TWP dominated the urban street sweepings and accounted for 41.75 % of the total microplastic concentration, whereas in the suburban street sweepings TWP only accounted for 11.08 %. TWP generally had a higher presence in street sweeping samples with more traffic (Urban1, 2, and 3) compared to the locations with less traffic (Urban 4, 5 and Suburban1, 2, 3, and 4). In the urban street sweepings, PE, PVC, and PP were the other common polymers and found in all samples (15.49-11.64 %). The dominating polymer in the suburban streets sweepings was PE, accounting for 39.10 % of the microplastic. Other common polymers found in all the suburban street sweepings were PP, PEA, and PVC (13.31-8.70 %). Paint particles were identified in half of the urban and half for the suburban street sweepings; however, there was 54.70 % more paint in the suburban streets. The less frequent polymers observed in both urban and suburban street sweepings and their relative abundances were PMMA ~ PS > PET ~ TPE > PES > PUR > EP (> 3.96 %).

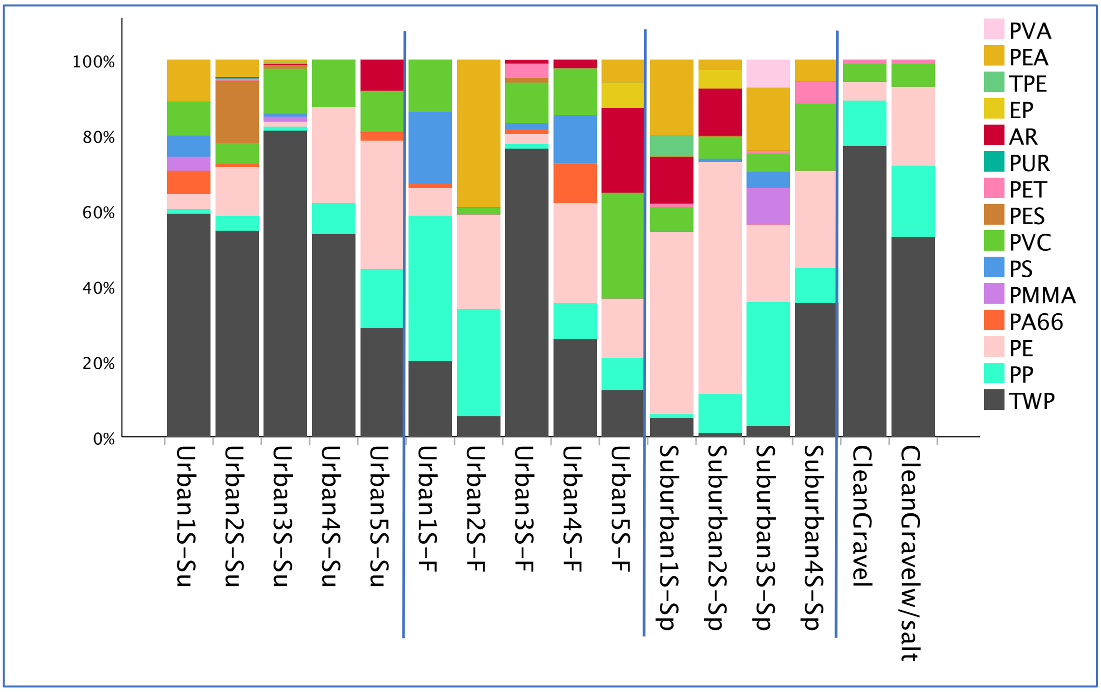


Figure 24: The relative polymer distribution for street sweepings from urban (including the summer and the fall season) and the suburban areas, and clean gravel, presented as 100 % concentration.

The sand trap samples all had a generally high count of different polymers. The difference in microplastic concentration between urban and suburban sand traps was considerably influenced by the high concentrations of TWP in the suburban (Figure 25). The suburban sand traps were dominated by TWP, accounting for 48.07 % of the microplastic. The urban sand traps were dominated by PVC (25.33 % of the total) and TWP (24.73 %). PMMA was identified in all suburban sand traps but only to account for 1.84 %. Paint particles accounted for 13-14 % of the microplastic from both urban and suburban sand traps. If paint particles were found in a street sweeping sample, there were also paint particles in the connecting sand trap (except Suburban4, where paint only was identified in the sand trap). In the three urban sand traps, different polymers dominated the total concentration. TWP dominated Urban5, as it is located in a highly trafficked area. Urban3 was substantially dominated by PVC. The sand trap Urban3 is located in a highly trafficked area and an area with considerable construction work when the sampling was conducted. Urban4 was, however, dominated by microplastic originating from PE and PP. Three of the four suburban sand traps samples were dominated by TWP, while paint particles dominated Suburban4.

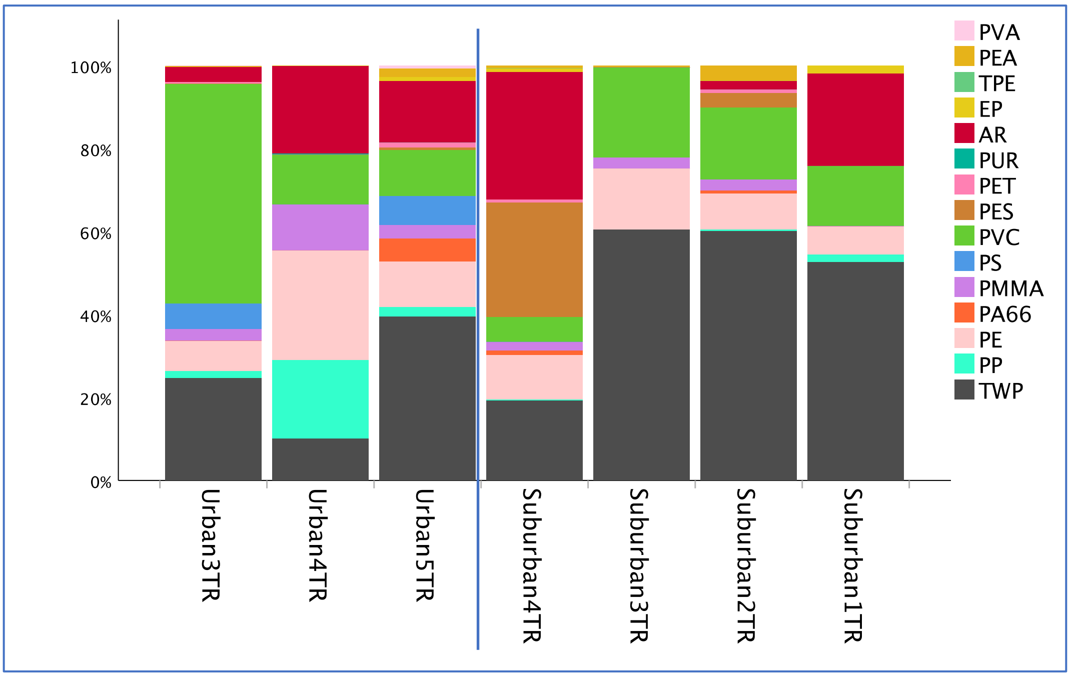


Figure 25: The relative polymer distribution for sand traps from urban and suburban areas, presented as 100 % concentration.

Seasonal differences in polymer distribution from urban street sweepings

The seasonal differences in polymer distribution from the urban street sweeping samples showed differences and similarities. Both summer and fall seasons was dominated by TWP, accounting for 55.46 % and 28.03 %, respectively (Figure 26). Highly trafficked Urban3 contributed strongly to the high concentrations of TWP in both seasons. Other common polymers found in all summer and fall samples were PE, PP, and PVC. As TWP dominated the total concentration from the summer season, the fall samples showed a higher variation in the polymers and a higher count of single-use plastic types. The less frequently detected polymer found in the frequently cleaned urban streets were PES, PA66, PEA, AR, PS, PMMA, EP, and PET.

The streets swept once or twice a day (Urban1, Urban2, and Urban5) can provide information on which polymers generally could be generated daily (Figure 26). TWP dominates the daily microplastic pollution during the summer season, accounting for 57.26 % from these locations. The daily microplastic pollution from the fall samples was here dominated by PP, accounting for 22.15 %. PE and PVC were polymers found in all the samples from the areas that were swept daily regardless of the season. Paint particles were identified in the Urban5 samples from both seasons. At the same time, PS was found in both Urban1 samples. Other polymers were not identified or identified in small concentrations, like PMMA, PES, and PET.

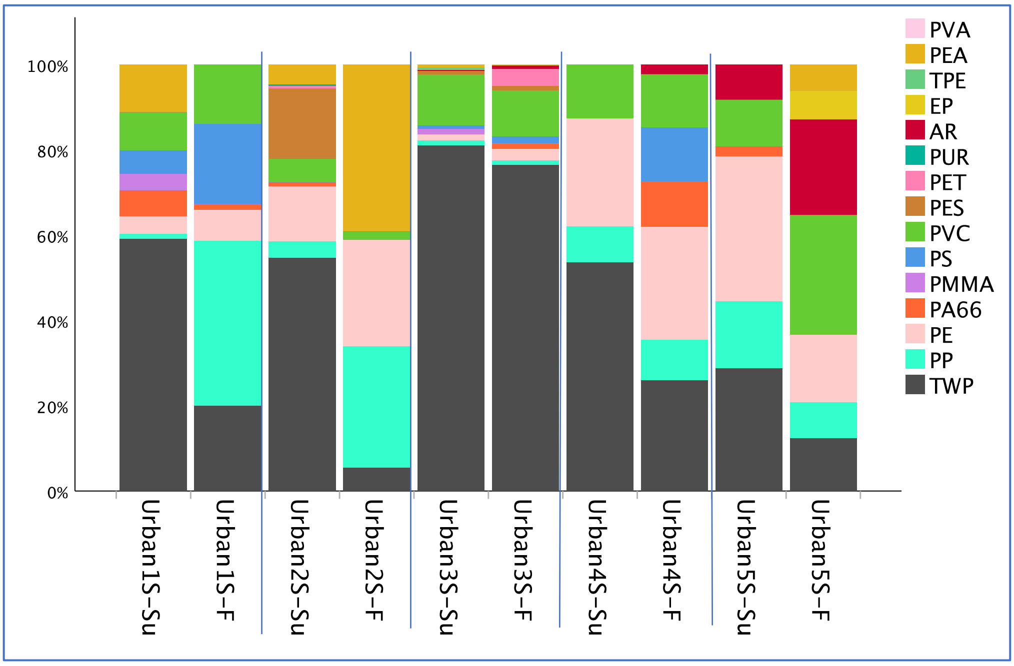


Figure 26: The relative polymer distribution for street sweepings from the summer and fall season in the urban areas, presented as 100 % concentration.

Low- and high-density polymers sorted in street sweepings and sand traps

To investigate if deposition in sand traps lead to a sorting of the plastic, possibly leading to a loss of low-density polymers, we looked at the difference between the relative contribution of low- and high-density polymers in street sweepings versus sand traps. Polymers denser than 1.0 g/cm^3 will sink in water (Table 3), while low-density materials that float in the water may be released into the waterways. As sand traps represent a year of microplastic accumulation, a comparison was made between the average concentration from all the street sweeping samples and all the sand trap samples. Only the street sweeping samples with a corresponding sand trap sample were included (i.e., excluding Urban1 and Urban2). In the street sweeping samples, 42.53 % of the microplastic were low-density polymers, compared to 17.81 % in the sand traps, but with the low number of samples, the difference was not statistically significant (Mann-Whitney U test, $U = 10$, $p = 0.064$). This still indicates a notable separation between low- and high-density polymers in sand traps, compared to the street sweepings (Figure 27), and support the suggestion that sand traps lead to a sorting of the polymers with loss of lightweight material in the discharged water.

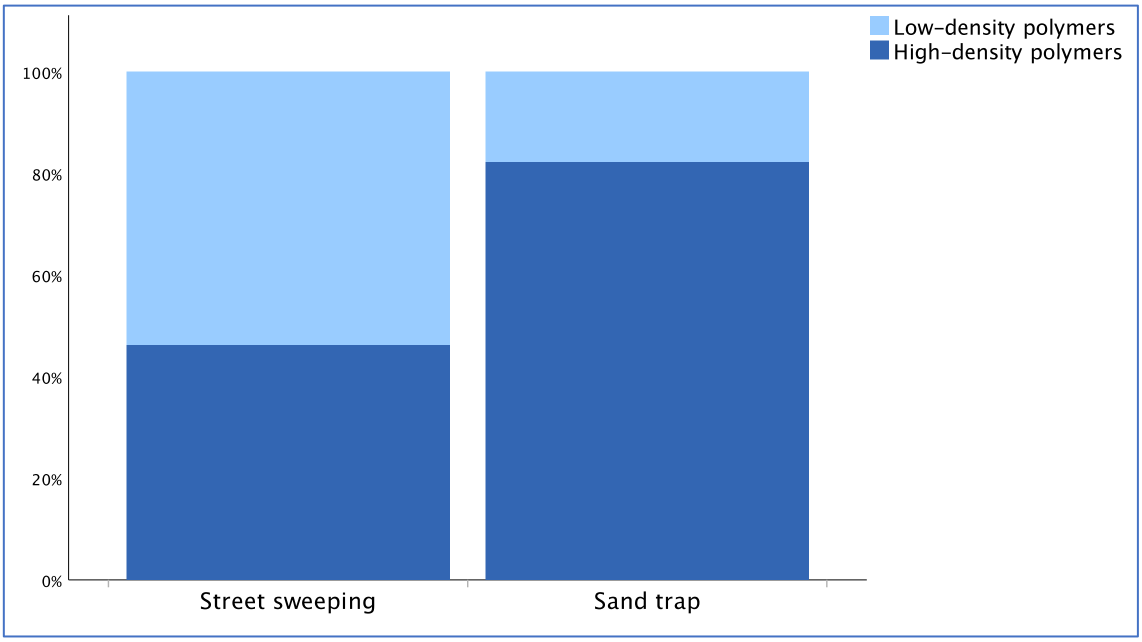


Figure 27: The relative distribution between low-density polymers (< 1.0 g/cm^3) and high-density polymers from street sweepings and sand traps, combining urban and suburban locations, presented as 100 % concentration.

Fragmentation of plastic in the streets

SMP and LMP – Concentration

The relative percentage of microplastic concentration between large and small microplastic particles are shown in Figure 28. The sand traps from urban and suburban areas and the urban street sweepings from the fall show an approximately equal distribution of SMP and LMP based on the concentration (Table 10). SMP made up 71.61 % of the total concentration in the urban street sweeping sample collected during the summer season. However, the difference was not statistically significant (Mann-Whitney U test, U = 12, p = 0.170). In the suburban street sweeping samples LMP made up 85.61 % of the total concentration, the difference was not statistically significant (Mann-Whitney U test, U = 2, p = 0.083). The largest difference between LMP and SMP concentration was observed in Urban2, a street sweeping from the fall, where LMP made up 93.26 % of the total concentration.

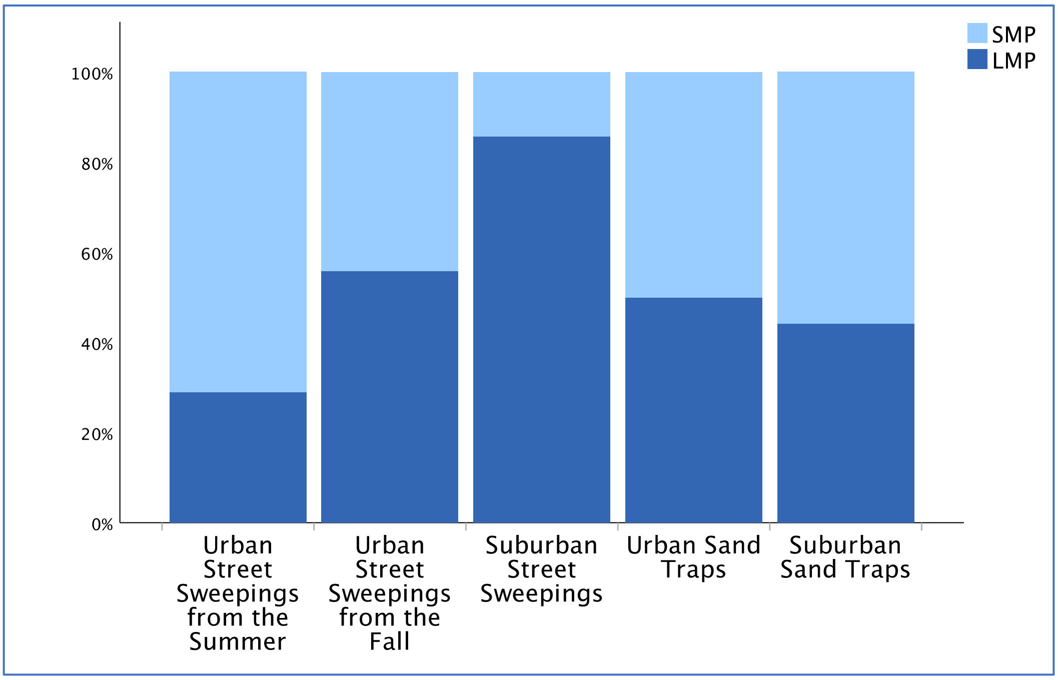


Figure 28: The relative contribution of SMP (50-500 µm) and LMP (500-1000 µm) to the total microplastic concentrations from street sweepings and sand traps, including urban (summer and fall) and suburban locations, presented as 100 % concentration.

Table 10: The total concentrations (mg/ kg dw) for the SMP and LMP size-classes, for all street sweepings from urban (summer and fall) and suburban, and for urban and suburban sand traps.

Location	**Total concentration from STREET SWEEPINGS (mg/ kg dw)**				**Total concentration from SAND TRAPS (mg/ kg dw)**	
	Summer		Fall			
Urban	SMP	LMP	SMP	LMP	SMP	LMP
Strandgaten/Strandkaien **Urban1**	85.69*	125.65	13.77	30.21	-	-
Christies gate **Urban2**	58.83	35.69	3.43	47.43	-	-
Lungegårdskaien/Østre Strømkaien **Urban3**	553.22*	113.36	126.20*	46.52	471.65*	257.31
Olaf Ryes vei/ Muséplassen **Urban4**	3.88	1.79	2.63	1.95	7.49	15.23
Vaskerelven **Urban5**	2.51	2.54	8.37	68.26	170.99*	373.89
	Spring					
Suburban	SMP		LMP		SMP	LMP
Årstadgeilen **Suburban1**	5.33		50.90		339.35*	172.83
Landåssvingen **Suburban2**	1.13		10.53		597.72*	134.18
Bendixens vei **Suburban3**	5.24		20.19		223.97*	154.01
Wiers-Jenssens vei **Suburban4**	2.56		3.18		196.92*	611.71
	-					
Clean Gravel	1.06		0.56		-	-
Clean Gravel w/ salt	1.12		0.94		-	-

* Based on multiple analysis parallels

Large plastic items in the streets and sand traps

The mass per size class for the whole sample separated into microplastic (SMP and LMP) and large plastic (meso- and marcoplastic) is listed in Table 11. The general observation was, as expected that the large plastic dominated the mass in the samples. In the urban street sweeping samples (from both seasons), the mass of large plastic (89.11 % of the total mass) was dominating compared to the microplastic mass. In the urban sand traps, the mass distribution between size-classes was approximately equal (57.52 % large plastic of the total mass). The street sweepings and sand traps from suburban areas contained a higher mass of microplastics (85.16 %) than large plastic.

Table 11: The total mass (mg) of microplastic and large plastic (meso- and macro-plastic), for all street sweepings from urban (summer and fall) and suburban, and for urban and suburban sand traps.

Location	**Total measured mass from STREET SWEEPINGS (mg/)**				**Total measured mass from SAND TRAPS (mg)**	
	Summer		Fall			
Urban	MP	Large	MP	Large	MP	Large
Strandgaten/Strandkaien **Urban1**	200.03	7328.68	64.26	99.49		-
Christies gate **Urban2**	91.19	891.30	139.38	4166.57		-
Lungegårdskaien/Østre Strømkaien **Urban3**	552.94	1887.18	155.43	863.47	2350.00	402.53
Olaf Ryes vei/ Muséplassen **Urban4**	27.04	79.32	27.13	5.77	130.91	2664.94
Vaskerelven **Urban5**	901.05	856.74	81.60	2158.16	1624.22	2490.62
	Spring					
Suburban	MP		Large		MP	Large
Årstadgeilen **Suburban1**	624.51		257.35		718.58	140.05
Landåssvingen **Suburban2**	49.99		5.91		866.34	74.27
Bendixens vei **Suburban3**	55.96		5.55		2064.23	140.96
Wiers-Jenssens vei **Suburban4**	59.78		119.98		679.19	147.62

MP: Microplastic (< 1 mm)
Large: Meso- and marco-plastic (> 1 mm)

Polymers in SMP, LMP and large plastic

TWP dominated the masses in SMP (55.52 %) and LMP (33.91 %). In the LMP size-class, the other most frequently identified particles were paint (22.84 %). Other LMP polymers identified and their abundant size were PES > PE > PEA > PS > PMMA > PVC (12.11 - 1.73 %). Less common LMP polymers were EP > PA66 > TPE > PET > PVA > PUR (1.21 - 0.05 %). The colors in the LMP size-class were dominated by black particles, accounting for 53.74 % of the polymers, followed by grey (16.00 %) and red (7.18 %). Other colors represented were blue, green, pink, white, yellow, transparent, purple, silver, orange, glitter, and turquoise. The dominating shape of the LMP was IRP, followed by films. Less observed shapes were spheres and fibers. The polymer resulting in high concentrations of LMP in the suburban street sweepings were PE, especially in Suburban1. SMP concentrations had a high content of PVC (31.28 %). Small TWP and PVC particles were also dominating polymers that resulted in the uneven distribution of large and small particles in the urban summer street sweepings. As PVC and TWP dominate the total SMP concentration in all samples (86.79 %) other polymer were identified in smaller amounts, including PE > PP > PA66 > PMMA > PES > PET (7.12-0.78 %).

Among the large plastic found in the samples, TWP was the dominating polymer, being the most abundant in the samples from the urban areas (Table 12). Common large particles also identified were PES > PE > PEA > PS > PMMA > PVC > EP > PA66 (12.11-0.96 %). Some had easily detectable sources, for example, food wrappings and bottle caps. Other large particles had less recognizable sources, same as the microplastic particles, however, could be classified as tearing/fragmentation from larger plastic products (see pictures in Figure 29).

Table 12: The number of large plastic particles identified in the samples from urban (summer and fall) and suburban areas from street sweepings and sand traps.

1 – 5 mm	**n**	**Total**	**TWP**	**PP**	**PE**	**PA66**	**PMMA**	**PS**	**PVC**	**PES**	**PET**	**PUR**	**AR**	**EP**	**PEA**	**PVA**
UrbanS-Su	3 of 5	**122**	91	1	13	-	-	4	2	3	2	3	2	1	-	-
UrbanS-F	4 of 5	**66**	36	3	17	-	1	2	-	3	1	2	1	-	-	-
SuburbanS-Sp	1 of 4	**2**	-	-	2	-	-	-	-	-	-	-	-	-	-	-
UrbanTR	3 of 3	**111**	53	2	18	-	8	9	2	-	9	2	4	4	-	-
SuburbanTR	4 of 4	**31**	14	-	4	-	1	1	2	1	-	-	6	-	2	-
> 5 mm		**Total**	**TWP**	**PP**	**PE**	**PA66**	**PMMA**	**PS**	**PVC**	**PES**	**PET**	**PUR**	**AR**	**EP**	**PEA**	**PVA**
UrbanS-Su	2 of 5	**22**	2	2	8	1	-	5	2	2	-	-	-	-	-	-
UrbanS-F	4 of 5	**19**	-	5	6	-	-	2	-	-	1	1	2	-	1	1
SuburbanS-Sp	0 of 4	**0**	-	-	-	-	-	-	-	-	-	-	-	-	-	-
UrbanTR	3 of 3	**18**	1	3	3	-	1	2	3	-	2	1	-	1	1	-
SuburbanTR	4 of 4	**24**	11	1	-	-	1	-	-	-	-	-	11	-	-	-

UrbanS-Su: Urban summer street sweepings
UrbanS-F: Urban fall street sweepings
SuburbanS-Sp: Suburban street sweepings
UrbanTR: Urban sand traps
SuburbanTR: Suburban sand traps

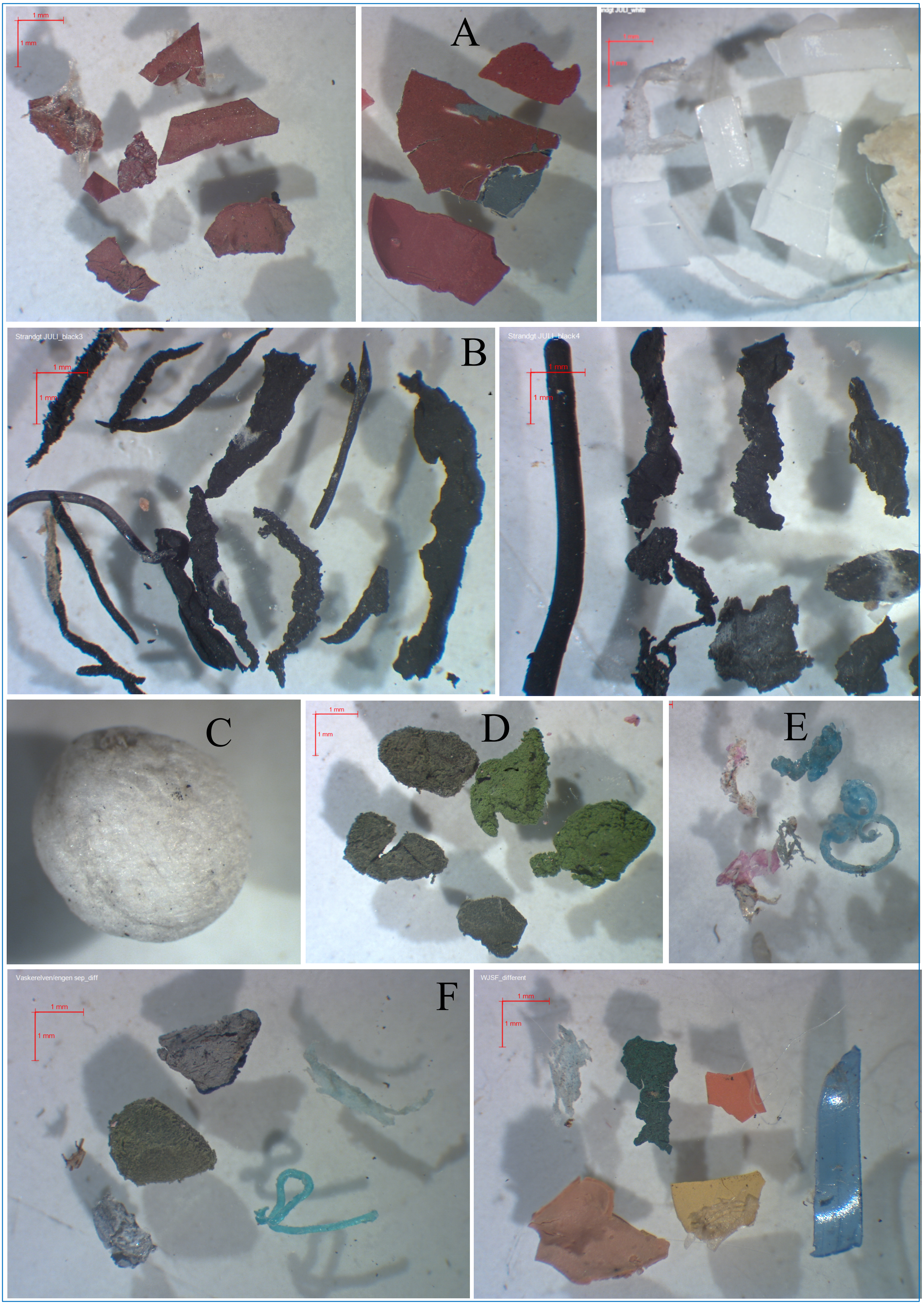

1 mm
1 mm
A
Strandgt JULI_black3
1 mm
1 mm
B
Strandgt JULI_black4
1 mm
1 mm
C
1 mm
1 mm
D
E
Vaskerelven/engen sep_diff
1 mm
1 mm
F
WJSF_different
1 mm
1 mm

Figure 29: Picture of various particles from the samples collected, chosen to represent the different shapes and structures identified. A) Particles classifies as films; the red films are often paint particles. B) Particles classified as IRP. These are TWP particles with recognizable shape, structure and color. C) Particles classified as sphere. This is a particle from EPS (PS). D) Examples of particles classified as IRP. Particles with this recognizable shape are often granules from artificial football fields. E) Particles classified as IRP. The source of these particles could be tearing from large plastic pieces. F) Other particles classified as IRP from various sources.

Microplastic in Total Street Sweeping Masses

The calculations of the total microplastic and TWP amount in the street sweeping samples are based on the data collected throughout this study from both urban and suburban street sweepings. The amounts of presumed microplastic in the total street sweeping mass are shown in Table 13.

Table 13: The concentration (mg/ kg dw), total mass of microplastic (kg) and mass per capita (g) for microplastic and TWP in the urban and suburban street sweeping samples.

	Concentration in the sample (mg/ kg dw)	Total particle mass in the total street sweeping mass (kg/ 1898 metric tons)	Particle mass per capita (g/ 280 000)
	Microplastic		
Average	666.58	194	1
Maximum	4.58	1265	5
Minimum	102.21	9	0
	TWP		
Average	62.97	120	0.4
Maximum	540.65	1026	4
Minimum	0.13	0.2	0

The worst-case scenario was based on the most polluted street in this study (Urban3). It resulted in approximately 1.3 metric tons of microplastic in the 1898 metric tons dry total street sweeping masses yearly. The minimum yearly microplastic pollution from the streets resulted in considerably less pollution of microplastic and was based on Urban4. The average microplastic release (194 kg) in the streets was based on all street sweeping samples collected in this study. Based on the inhabitants in Bergen (ca. 280 000 people), the microplastic release per capita yearly resulted in some unsecure numbers, however, the worst-case scenario from this study can show 5 g microplastic per person.

TWP was the most dominating source of microplastic in Bergen street sweepings. The worst-case scenario was based on the most TWP polluted street (Urban3) and calculated to 1.0 metric tons TWP yearly. The minimum yearly microplastic pollution from the streets results in 0.3 kg TWP in the 1898 metric tons street sweeping masses, based on Suburban2. The average TWP calculated was substantially lower than the worst-case scenario. When calculating the total TWP release per capita yearly, there are also high levels of uncertainty, the worst-case scenario can, however, be 3 g TWP in the streets per person yearly.

Quality Assurance/ Quality Control

All quality controls were first visually inspected, showing no visible particles. The blank control samples and the procedural blanks analyzed on Pyr-GCMS had no contamination above the detection limit. In general, we believe that the Pyr-GCMS will not pick up single fibers since the LOQ was ten µg/ kg. Therefore, small fragments of contamination will make a relatively small contribution, especially in samples with high plastic content, such as urban street samples.

Discussion

Summary of the study

This study aimed to provide greater knowledge of microplastic in the urban environment. Sediment samples were collected from nine urban and suburban locations from street sweepings and sand traps. The sources and concentrations of microplastic in these samples were assessed. Results show microplastic pollution at considerable concentrations mainly dominated by tire wear particles. The microplastic concentrations showed to be affected by population density as higher concentrations were found in the urban samples compared to the suburban. The present study showed sand traps to be more polluted by microplastic than the streets. Seasonal differences indicated a higher generation in urban microplastic during the summer compared to the fall.

Microplastic isolation methods

The methods used in this study are previously tested with satisfactory results (Berg et al., 2017; Gomiero, Strafella, et al., 2019; Haave et al., 2019; Imhof et al., 2012; Löder et al., 2017). The MPSS density separation, although efficient, was a heavy and time-consuming method. The MPSS worked with high volumes of $ZnCl_2$ for a small sample size, and the preparations were extensive. Since $ZnCl_2$ is a corrosive chemical, adequate filtration equipment was hard to locate for the correct usage and needed replacements throughout the project. The purification methods demonstrated degradation of organic material as presumed. The precipitate from the second density separation was analyzed to confirm the possible loss of polymer, like TWP. The precipitate from the MPSS density separation could also have been tested, as presumed synthetic polymers were observed in the precipitate. However, this analysis was not performed, as the same polymers were assumed to be detected as in the precipitate from the second density separation. The precipitate analysis detected four polymers in relatively small amounts. TWP was identified in four of five precipitate samples, presumably due to density differences in TWP (see chapter 'TWP as a dominating source of microplastic'). The more surprising polymers found to be incompletely extracted were PVC, PE, and PS. The blank controls for the Pyr-GCMS did not show any contamination, so the identified polymers did not originate from contamination. Low-density polymers could be incorporated with the high-density polymers, like sand, and therefore be found in the precipitate. PVC was identified in all the precipitate samples analyzed and have a higher density than PE and PS. PVC polymers consist of considerably high amounts of additives and plasticizers, which could account for up to half of the total PVC plastics weight (Rochman, 2018). A possible leaching of these additives could alter the density and be a reason for PVC to be found in the precipitate. We know that density can change by environmental factors, and perhaps also the sample preparation methods result in the density alterations. However, all the samples were analyzed using the same method with very few differences in sample treatment. The enzymes used in the purifications should not increase the density and rather remove possible biofilms. Since biofilms on a particle could increase the density, making the particle sink instead of float (Andrady, 2011; Nerland et al., 2014). The temperature could affect polymer density and $ZnCl_2$ density, however, the temperature remained at room temperature throughout the purification of the sample.

According to the PYR-GCMS analysis of the precipitate, the loss of microplastics by density separation made up a very low mass and, therefore, lead to a negligible loss in these complex environmental samples.

Microplastic analysis with Pyr-GCMS

Microplastic analysis with Pyr-GCMS is a time-effective and reliable method. However, there were some error sources with this method. Especially with intricate environmental samples as analyzed here, and only a fraction of the sample was analyzed. Pyr-GCMS could not detect paint particles at the time of analysis. When generating quantification and calibration curves, a small amount of the specific polymer needs to be weighed prior to the analysis. Qualitatively weighting these small amounts is not 100 % reliable. Some samples had polymer in significant amounts creating out of scale numbers. The out of scale mass was the minimum of the maximum mass, as the peak in the pyrogram could be higher than the areas of detection. Meaning that there were most likely slightly more of these polymers in the samples than our results show. TWP was the polymer most frequently detected out of scale.

Microplastic analysis with ATR-FTIR

Microplastic analysis with ATR-FTIR was time-consuming, and therefore only a fraction of the sample was chosen to be analyzed. The polymers identified with ATR-FTIR were quickly matched with the correct polymer or concluded as unknown or organic. As TWP gives a spectrum with low absorbance due to carbon-black, an original particle from a tire was used for comparison.

The locations sampled

As the samples needed to be collected in collaboration with external contractors, the communication made it hard to achieve samples from all the planned sites. Nevertheless, the locations sampled in this study were suitable for our analysis. The urban samples represent the urban environment well, with samples collected from places with much traffic and less trafficked areas. This gives us results to further understand the microplastic pollution in the urban environment. The suburban areas were also chosen to give a representative image of the suburban environment, with locations with similar suburban topography and traffic influence. One urban sand trap sample needed to be collected from a connecting street rather than from the same street as the sweeping sample. However, this is presumed not to influence the results. The stretch of the sweeping samples varied substantially between urban and suburban areas. The planned stretch where approximately 100-200m, which were appropriate in the suburban areas as they are swept once a year. In the urban areas, the sweeping stretch needed to be longer to achieve a sufficient sediment amount.

The microplastic concentrations and sources

The total microplastic concentration

The total microplastic concentration (SMP and LMP) from the different locations had a high variation, as some samples had close to one gram (1000 mg) microplastic/ kg dw, and some had five mg microplastic/ kg dw. The sediment from the sand traps had the highest total microplastic concentrations and the results indicate that microplastic accumulate in sand traps. Sand traps are emptied once a year and represent a yearly accumulation. Street sweepings had a lower average microplastic concentration as much microplastic is presumed to be transported into a nearby sand trap. Comparing the concentrations achieved in this study with other relevant studies can only be partially done due to variations in microplastic size-definition, methods, and reported concentration units. Nevertheless, multiple studies agree that urban areas are locations significantly polluted by microplastic (Birch et al., 2020; Dris et al., 2015; Haave et al., 2019; Liu et al., 2019; Lusher et al., 2018).

The microplastic concentrations found in the clean gravel used for slippery roads in the winter in Norway contain significantly lower microplastic concentrations than the environmental samples. Therefore, clean gravel used during the winter will not be a massive contributor to the microplastic concentration found in the environment, especially in the urban areas. No other studies have analyzed this type of clean gravel. However, Rødland et al. (2020) found microplastic particles in road salt used for the same purpose during the icy winters. The study showed similar results as the clean gravel investigated in our study. The dominating source was black rubber particles in both studies, which we have defined as TWP, accounting for 96 % (Rødland) and 66 % (our study). The TWP most likely originates from the vehicles used to transport or move the gravel. The concentrations found from other polymers were also low in Rødlands study. These low total microplastic concentrations will be a negligible microplastic pollution source found in urban and suburban areas.

Difference in microplastic concentration from urban to suburban areas

The suburban street sweeping samples present less variation in total concentration between samples in comparison to the urban streets. This could be due to the sampled suburban areas being more similar than the urban areas, having approximately the same topography, amount of traffic, and sweeping length. A short sweeping length was sufficient for the suburban areas as they represent yearly accumulation, and the streets collect more sediment and organic matter during that time. The urban areas are swept frequently and needed longer sweeping stretches to achieve a sufficient sediment mass. With this in mind, the urban sediment was presumed to be more concentrated by microplastic, while in the suburban samples the microplastic would be more diluted by sand, gravel, and organic matter. The urban samples contained approximately half of the organic content as the suburban areas. The results present some uncertainties as the samples were not collected during the same season.

Urban3 has considerably high microplastic concentrations from both the summer and the fall season. Location Urban3 is an area influenced by more heavy transportation than the other urban areas and located close to a large shopping center, the railway, and the central bus station.

With this location included, the difference in microplastic concentrations between urban and suburban areas was very high but not statistically different. As the results show, the urban samples have almost 700 % (summer) and 180 % (fall) higher average microplastic concentration than the suburban areas. This shows that the population and traffic density affect microplastic concentration. Vogelsang et al. (2019) presented a suggestion of how particles will behave in urban and rural settings. Even though the suburban areas in this study are not defined as rural, having more buildings and vegetation, the illustration could be a fitting description of the microplastic distribution in the environments. The main idea is that the particles are more dispersed in less populated areas, as there are fewer ‘obstacles’ (buildings and vegetation) containing the particles near the streets in these areas (Vogelsang et al., 2019). The results from this study support that this is a fitting description, with higher urban concentrations. The microplastic in the suburban areas also has a year to disperse away from the streets and is influenced by all seasons. Windy and rainy weather disperse particles away from the road in a higher volume than dry still weather, especially in less populated areas (Vogelsang et al., 2019).

The microplastic particles from urban areas often remain closer to the streets as more buildings limit the dispersal routes and the influence from wind. Streets located near water could have a higher chance of direct release of microplastic into the waterways. Urban areas are swept clean more frequently. This limits the dispersal time and accumulation of sediments, hence fewer particles might end up in the sand traps. At the location Urban4, the lowest street sweeping concentrations were detected, the sand trap concentration was also considerably lower than the other sand traps. Urban4 is located near the University Museum in Bergen. This is a popular attraction, however closed during the time of sampling. Therefore, this is an urban location less influenced by traffic and people, in similarity to the suburban areas. The street sweeping from Urban5 has a lower concentration than the sand trap, this could most likely be because the street is swept twice a day and consequently limits the possible microplastic release and accumulation. The sand trap was not sampled from the same street as the sweeping sample, possibly affecting the results, however, both areas are highly trafficked by cars and people.

The sand traps in the suburban areas have a higher concentration than the urban sand traps. This could also be a supportive argument for the description above. Microplastic in the suburban areas presumably travel away from the street and can end up in a nearby sand trap. Our results supported this as the concentrations were significantly higher in the suburban sand traps compared to the street sweepings, and both represent yearly accumulation. The sand trap samples from the suburban areas were also overall the most microplastic polluted samples. The highest microplastic concentration from a suburban sand trap and the lowest microplastic concentration from a suburban street sweeping were found at the same location, Suburban4. This could result from of the sand trap being located in an intersection with moderate traffic amounts and was located in a hill draining from both streets in the intersection. The street sweeping sample was collected from the less trafficked part of the intersection, which was located on a hillside. Here the surface run-off water can transport the particles away from the street and into the sand trap. The lowest sand trap concentration was found at Suburban3, presumably as the sand trap is located at the beginning of a hill and might avoid microplastic drainage from the street.

Our results show no correlation between all the street sweepings and all the sand trap samples. Therefore, we cannot conclude that the microplastic concentrations in street sweepings reflect the sand trap concentrations. Future studies cannot conclude that analyzing one of the pathways will give representative date for the other to receive an understanding of the microplastic pollution in the samples area. However, a strong correlation was observed for only the suburban street sweepings and sand traps. As the suburban sample size is considerably low, the correlation is not representative for a whole suburban area. Sand traps collect surface run-off from a duration of a year, including possible meltwater in the spring and heavy rainfall. So, the results showing higher concentrations in the sand traps compared to the street sweepings, especially in suburban areas, were not surprising.

Other studies investigating urban areas also conclude that these are areas highly contaminated by microplastic. In agreement with our results, higher microplastic concentrations were observed near urban streets by Lake Mjøsa, Norway. The sites with the highest concentrations were located near industry, car, and boat traffic (Lusher et al., 2018). A study assessing the fjord surrounding Bergen, Norway, reported high microplastic concentrations presumed to originate from the harbor activities, urban surface run-off, and wastewater discharges (Haave et al., 2019). River studies near urban areas often conclude that microplastic concentration increases near more populated areas (Lin et al., 2018; McCormick et al., 2014; Moore et al., 2011; Yonkos et al., 2014; Zhang et al., 2020). Other studies of urban WWTP, urban wastewater, and stormwater drains find microplastic in high concentrations (Bayo et al., 2020; Dris et al., 2015; Liu et al., 2019; Mintenig et al., 2017). In similarity with our results, they show that urban surface run-off, and presumed discharge from sand traps, are highly polluted by microplastic. Based on the results from these urban and suburban areas, we can conclude that more densely populated areas are more polluted by microplastic particles. Confirmed by Battulga et al. (2019), which found a positive correlation between population density and plastic release. Chen et al. (2020) identified that suburban streets are also polluted by microplastic, especially by TWP, in similarity with our results, demonstrating that urban streets are hotspots for microplastic pollution, and suburban streets are affected but in a smaller scale. The sand trap samples imply sand traps to be a highly microplastic polluted space in both suburban and urban areas, presumed to retain microplastic from a yearly accumulation. The fact that the street sweepings from the urban areas show considerably lower microplastic concentrations than the sand traps (however, not statistically significant) also indicates that the street cleaning conducted by the municipality is an effective way of limiting microplastic distribution in the urban environment.

Seasonal differences in microplastic concentration from urban street sweepings

The seasonal variation in the microplastic concentration found in this study showed an average concentration much higher during the summer compared to the fall, however, not statistically significant. The samples used for this comparison were only collected once during each season. However, it still gives a small representative result as the areas are cleaned frequently. The stretches swept were identical, and the amounts of organic content in the samples from the two seasons were approximately similar. Still, all the samples demonstrated a higher microplastic concentration during the summer, except Urban5. Urban5 had a considerably higher microplastic concentration in the fall sample. This area is swept twice a day during both sampling seasons, so this difference could be a random incident. This area was presumed to have no massive seasonal variation, and no apparent reason for this variation was observed during the sampling. Location Urban3 dominated the seasonal difference in microplastic concentration and contained the highest concentration in both seasons as the area is continuously influenced by much traffic. Even though the regular traffic from the bus station is lower during the summer, the concentration is here close to three times as high. There could be more heavy traffic during the summer or more construction work, but this is not known. From the results, we observe that urban areas with more traffic generally have a higher microplastic concentration, regardless of the season (Urban 1,2, and 3).

The summer season is affected by tourism and dry weather. Approximately 2.30 million tourists visit Bergen from May to October, with a clear peak in July (when our samples were collected) (Menon Economics, 2019). This could be a significant factor for the seasonal difference in microplastic concentrations. Tourists in the cities can increase the microplastic pollution by littering and increase the pressure on the cities renovation system. Numerous buses follow increasing tourism in the city center during the summer. This will additionally increase the microplastic pollution, as our results show that traffic load in an area affects the microplastic concentration. All the urban locations sampled here are usually popular areas for tourists. However, as the museum near Urban4 was closed, this area was presumably less affected by tourism, supported by the low microplastic concentrations from both seasons. A WWF report (2018) states that tourism can cause a close to 40 % increase in plastic entering the Mediterranean Sea. The results here show a much higher increase in microplastic release, however, influenced by other factors as well as tourism. The summer season is more dominated by warm, dry, and still weather compared to the fall. Dry weather contributes to containing the particles near the streets, while wind and rain conditions could transport particles away from the streets (Vogelsang et al., 2019). This could possibly contribute to why more microplastics are found in the street sweepings during the summer season. Bayo et al. (2020) observe, in agreement with our results, an increase in microplastic during the warmer season.

Total Microplastic Polymer Distribution

Of the 15 identified polymers identified in this study, the seven most globally produced were found. Furthermore, also less produced polymers like PA66 and PMMA were identified. With a more conflicting definition of plastic, some polymers, like paint particles and TWP, were found in substantial amounts. TWP was found in all the samples and was the dominating microplastic source (see chapter ‘TWP as a dominating source of microplastic’).

The other most dominating source was PVC, and this is a polymer globally produced in smaller numbers. PVC was found in all urban and suburban samples in varying concentrations, but generally higher in the urban areas. Some likely sources of PVC are from construction work, as PVC is used in wall coverings, window frames, pipes, and other building materials (Magnusson et al., 2016; Sundt et al., 2014). PVC particles can also originate from gutters or traffic cones near the streets (Dehghani et al., 2017; Sundt et al., 2014). Even though we cannot conclude what exact source the PVC originates from, it is more likely to come from industrial- or construction work rather than littering from the everyday man in the street. A concern in relation to finding high PVC concentrations is that this is a polymer consisting of substantial amounts of additives. These additives could leak out, causing toxicity, as well as the PVC monomer itself, is considered toxic and carcinogenic to humans (Bergmann et al., 2015).

Paint particles were identified in approximately half of the sampled locations but often in relatively large concentrations. Paint particles could end up near the road and in the sand traps through the removal of old paint or natural weathering (Verschoor et al., 2016). The most observed paint color was red, but yellow, orange, blue, green, and grey were also observed. Of the total microplastic pollution in Norway, outdoor house and building paint are calculated to contribute to 1.5 % (Sundt et al., 2016). In our samples, the overall paint contribution was 10.09%. This indicates that urban and suburban areas contribute to the total microplastic paint pollution in Norway in a significant way. However, only recently was paint considered to be a contributor to microplastic pollution, and in Norway, the ambition to have stricter guidelines regarding paint spill is increasing.

PE was also identified in all the samples and was the fourth most dominating polymer in these samples. PE particles were also often identified in the large plastic particles (> 1 mm). This is in similarity to PE (LD and HD) being the globally most produced polymer. Common sources of PE are more single-use plastic, like plastic bags or food containers. PE is the most frequently detected polymer in previous studies of microplastic in the marine environment (GESAMP, 2015).

The other eleven polymers identified were found in lower microplastic concentrations than TWP, PVC, paint, and PE. To find suitable actions to limit the release of these less common polymers, the source needs to be identified. Polymers with a globally high production rate make products that are popular in use. PP can originate from food packaging and wrapping, and PS often originate from Styrofoam (often a recognizable shape). PP is also a polymer often found in high concentrations in other studies, as well as PVC and PS (Liu et al., 2019; Rodrigues et al., 2018; Wagner et al., 2014). PP and PS are polymers less dominating the microplastic concentrations in our study, however, found in a large number in the large plastic. So, that PP, PS, and PE were the most frequently detected polymer in the large plastic indicate that the microplastic from these polymers originates from fragmentation of the large plastic. A common source of PET can be drinking bottles, while PES and PA66 often come from textiles. PUR can originate from construction, and PMMA is used as acrylic glass (PlasticEurope, 2019). PVA is a polymer used in various types of adhesives and road markings (Kaboorani & Riedl, 2015; Sundt et al., 2014). TPE near streets can originate from road marking paint (Sundt et al., 2016), but all the TPE found in these samples were black particles. A possibility could be the road paint was incorporated with asphalt. Epoxy resins are applied in different construction applications (Hale, 2002). If these sources are the correct ones for the particle found in our study are not possible to firmly conclude, with the exception of the PS particles large enough to identify the recognizable shape of Styrofoam.

The difference in polymer distribution from urban to suburban areas

The difference in polymer distribution from urban to suburban areas was mainly dominated by the high TWP concentrations in the urban street sweepings. The suburban streets also had TWP present but accounting for less of the total concentration. The results show that TWP is of higher abundance in more trafficked areas with cars, busses, and heavy transportation (Urban1, 2, and 3).

A low microplastic concentration in the suburban street sweeping samples can indicate that suburban areas are less influenced by irresponsible human behavior, like littering. However, this could also suggest that during the one year between the street cleanings, the larger plastic has more time to fragment into microplastic, influenced by seasonal weathering and UV-radiation. Supported by the most common polymers found in the suburban street sweeping samples were polymers often found in single-use plastic, like PE and PP. The results from the suburban sand trap samples also show TWP to be a dominating microplastic polymer, dominating in three of the four sand traps. As stated previously, the suburban areas allow for more particle transportation than urban areas, as the particles in these areas have more time to travel into the nearby environment. In the suburban areas, traffic amount is lower, however not insignificant from the locations sampled. So, the results showing low concentrations of TWP in the street sweepings and high concentrations in the sand traps demonstrate that TWP is, in fact, transported by run-off water from the streets and into the sand traps over the course of a year. In the sand traps, the high-density particles are involved in a sedimentation process and remain there until they are removed. The paint concentrations found in the suburban areas were also higher than in the urban, usually found in both street sweepings and sand traps from the same locations. However, Suburban4 only had paint in the sand trap, which was the dominating polymer in this sample. The reason for this is hard to conclude; however, it could be that a building or house nearby had been painted, and run-off water transported the particles into the sand trap and away from the street.

Based on the percentage, the urban areas showed TWP to be the more dominating polymer in the street sweepings compared to the sand traps. Possibly indicating that the street cleaning process being a beneficial way of limiting the dispersal of TWP. When we look at TWP concentrations (and other polymers), the concentrations were all higher in the urban sand traps compared to the street sweepings. Therefore, we know that microplastic particles do escape the sweeping process and are transported into sand traps. Nevertheless, since the sand traps represent a yearly microplastic accumulation, microplastic particles could also enter the sand traps during the winter and be transported from the streets with meltwater. The generation of TWP is much higher in the densely populated urban areas, even though the suburban streets are only swept once a year, and the urban areas have a much higher cleaning frequency. The results from the urban sand traps showed greater polymer variation than the suburban. The sand trap from Urban4, which had the overall lowest concentration from both street sweepings and sand traps, was dominated by single-use plastic (PP and PE), agreeing with this being an area where high concentrations of TWP were not suspected. The sand traps from Urban5 were, on the other hand, an area presumed to have high concentrations of TWP, which also the results demonstrated. However, not influenced by bus traffic, this is an area with much taxi traffic at all hours. Over 50 % of the microplastic found in the sand trap at Urban3 was PVC. This is in an area with much construction work conducted at the time of sampling, and the PVC is presumed to originate from this. Liu et al. (2019) also identified PVC, presumably from drainage pipes, as a major source of microplastic in an urban environment focusing on stormwater drains.

Again, the results show that the difference in urban and suburban areas is notable also regarding the polymers identified. However, proving that TWP was the overall dominating source of microplastic particles. Urban streets and sand traps both had high TWP concentrations, which showed that more traffic increases TWP pollution. Suburban streets contained lower concentrations of TWP, whereas the high TWP concentrations were found in the sand traps, thus indicating that TWP is transported from the pollution site (the streets) into an accumulation site (sand traps).

Seasonal differences in polymer distribution

TWP dominated the seasonal difference in urban street sweepings. The concentration of TWP from all five urban street samples showed an almost five times as high amount during the summer. Still, TWP was the dominating polymer found in both seasons. TWP was a significant microplastic source in the urban environment. Again, the location Urban3 stands out as a location with high polymer concentrations, especially of TWP. The other polymers' seasonal differences showed higher percentages of the more single-use plastic types in the fall samples since TWP was less dominating. PVC had a higher concentration during the summer season, which could be due to more construction work conducted during that period. The one location with more microplastics found during the fall was Urban5, where PP, PVC, and paint accounted for the difference. The frequent cleaning of the urban streets can limit the more rear polymer from less common plastic products to accumulate in these areas. When excluding TWP (and PVC) from the total microplastic concentration, the seasonal difference was considerably less extensive. Indicating that irresponsible littering in urban areas is not significantly affected by altering seasons in the same way as TWP. Showing that tourists might not contribute to microplastic pollution during the summer themselves. However, the traffic increase that follows the high levels of tourism could contribute to the observed TWP increase during the summer.

The major seasonal difference in TWP concentration was not affected by tire type as both sampling periods happed during the use of summer-tires. No other studies have looked at the variation of the microplastic concentrations between these two seasons. However, Vogelsang et al. (2019) state that TWP is generated in a higher frequency with light summer tires compared to studded winter tires. The study also indicates that local TWP distribution can have major variations between seasons. It is also shown that the abrasion of tires increases with higher temperatures, like during the summer (Klüppel, 2014; Korsvoll, 2017). Multiple tire tests show that wet asphalt decreases the abrasion of tires (Korsvoll, 2017). There is a generally higher amount of rain during the fall (CustomWeather, 2020). Dry weather, additionally, contributes to containing TWP (and other particles) near the streets, while rain and wind can further transport the particles. All these factors additionally increase the amount of TWP found in the urban areas during the summer and limit the TWP pollution during the fall.

The streets that are swept once or twice a day (Urban1, 2, and 5) could give us an insight into which polymers are generated at a high rate. During both seasons, all three areas have relatively high microplastic concentrations to originate from one day, displaying that these are areas highly polluted by microplastic. Compared to Urban4, an area swept every fortnight, and the variation was considerable, showing that also locations within the urban city center have notable microplastic pollution variations. TWP dominated the daily microplastic content during the summer sampling. In comparison, PP was the dominating polymer found in the fall samples from the daily swept areas. These results could be coincidental as the samples were only collected from each station one time during each season (two samples in total). However, street cleaning was not conducted any differently during the sampling days than on any other day. So, the other polymer found, excluding TWP, can originate from littering in the street, which implies a more coincidental process of what was used and thrown away at the sampling time. The large particles from these locations also support this statement as PP, PE, and PS particles were identified in moderate volumes, with a high number of particles above 5mm. The less coincidental findings are in regard to TWP, as the traffic load has less day-to-day variations. This indicates that TWP is generated continuously and in relatively high concentrations every day, especially during the warmer summer season.

Low- and high-density polymers sorted in street sweepings and sand traps

The difference in low- and high-density polymers in the sand traps compared to the street sweepings was considerable, however not statistically significant. Low-density polymers will be buoyant in run-off water and, therefore, might be easier transported into the sand traps and with the overwater out of the sand traps. As the results show, the street sweeping concentrations did not adequately reflect the sand trap concentrations. We found more than twice as high percentage of low-density polymers in the street sweepings than in the sand traps, indicating a sorting of polymers in the sand traps. The heavy particles will sink in the sediment, consisting of sand and sludge in the sand trap container (the sediment we have sampled). The run-off water will eventually be transported out of the sand trap and into the sewage system, possibly also transporting the lighter particles. Of the 15 polymers identified in this study, only four are defined as low-density polymers, including PP, PE, PS, and PUR. Regardless, these polymers account for more than 60 % of all plastic produced globally. Studies show that the density of a polymer can change after entering the environment. However, the definition of low-density polymers here has not taken this into account since the processes of altering densities are not entirely known and varying depending on other environmental factors. Therefore, we cannot conclude with certainty that the polymers we defined as low-density in this investigation are the same polymers that actually have a lower density than the run-off water in nature. With more urbanization and more pressure on our cities, the run-off water from the streets could increasingly be polluted by microplastic. Climate change can increase rainfall and, thereby, the pressure on the sand traps. These results enlighten the importance of having adequate measures to clean the run-off water from the streets.

Fragmentation of plastic in the streets

The overall microplastic concentrations from the areas investigated in this study generally showed a similar variation between SMP and LMP. However, when considering the individual polymer concentration, significant differences indicated that the size-classes do not represent each other well. For future studies, it would not be adequate only to analyze one size-class. The results show that the suburban street sweepings had higher concentrations of LMP, with PE dominating. As mentioned, PE is a common polymer found in single-use plastic and could originate from the fragmentation of large PE products that have entered the suburban streets by, e.g., irresponsible littering. Some studies argue that microplastic larger than 500 µm are located in fewer numbers than the particles smaller than 500 µm. We reported the concentration based on mass and not numbers, however as the concentrations are similarly distributed between size-classes, this could support the findings from Bergmann et al. (2017) and Haave et al. (2019).

Urban summer street sweepings were dominated by SMP from TWP and PVC, with Urban3 highly influencing this difference. The other urban areas that were swept daily or twice a day all had a higher content of the LMP. Presumably because the plastic in the environment at these locations did not have the time to fragment into SMP before the streets were cleaned. TWP is originating from tire abrasion and therefore does not break down from larger plastic products in the same way as other polymers. This means that the particles can fragment directly into SMP, as the results from this study indicate. Studies agree that TWP are most often found in sizes ranging from 50-350 µm, with no exact mean diameter, in consensus with our results (Kreider et al., 2010; Vogelsang et al., 2019). Paint could not be identified in the SMP size-class, and our study cannot give quantitative concentrations of this microplastic source. However, paint is presumed to be present in the SMP size-class.

Irregular particles dominated the shapes identified in the LMP size-class and the meso-and macro-plastic size-class, indicating fragmentation, films were also frequently detected. The only spheres identified were from Styrofoam (PS) and hard transparent spheres. These transparent spheres were found in considerable volumes in the sand trap at Urban3 and identified as PS, presumably PS resin pellets for plastic production. Fibers were less frequently identified in this study. A reason for this could be that the dominating part of microplastic fiber release originates from the washing of synthetic fibers entering the environment via wastewater (Sundt et al., 2016). A study focusing on the urban environment in Paris found high concentrations of fibers in atmospheric fallout and urban run-off water (Dris et al., 2015). As this contradicts our result, it could be reasoned to indicate that most fibers are smaller in size than detectable in this study (> 50 µm). Fibers might remain in the run-off water in the sand traps, which were not analyzed in this study. In addition, the methods applied in this study did not limit the loss of fiber, as the application of 50 µm filters might increase the loss by the smallest dimension through the filter pores.

The colors in the LMP-size class was dominated by black particles, in agreement with TWP being the dominating polymer. Red was identified in relatively high volumes, as most paint particles found in these samples were red. Multiple other colors were identified (e.g., green, blue, pink). However, as stated, can color as a source of identification bring bias into the results.

Sample preparations and weathering in the environment can cause discoloration of the particle (Hartmann et al., 2019; Hidalgo-Ruz et al., 2012), presumably why grey was the second most dominating color. Microplastic color is not defined as an important factor in determining sources in this study.

The mass distribution of microplastic and large plastic in the samples show, as excepted, generally a higher mass of the large particles. The high mass of large plastic in the urban samples shows that urban areas are more subjected to irresponsible littering, with a higher population density. The streets swept once a day present high numbers of large plastic pieces presumed generated throughout one day. The sand trap samples contained high masses of large plastic, collected throughout a year. In the suburban street sweeping and sand trap samples, the mass of microplastic particles was higher than the large plastic at almost all four locations (except the street sweeping sample from Suburban4). As suburban areas represent yearly accumulation, the large plastic pieces have more time to be exposed to UV and weathering in the streets. Presumably causing them to fragment into microplastic in nature and irresponsible littering could, in addition, be lower in these areas. Notably, the mass of microplastic here includes organic particles and unknown particles before identification.

Microplastic in Total Street Sweeping Masses

The total microplastic amount in the streets of Bergen calculated are estimations with a high degree of uncertainty and based on a limited number of samples for a small selection of streets in Bergen. Assuming that dry matter from the streets sampled in this study was representative of the total mass, we calculated the total amount of microplastic in the street sweepings in Bergen. Still, the worst-case scenario makes for a frightening estimate of the microplastic pollution in a medium-sized city. Especially since these collected street sweeping masses are washed and redistributed in the streets to limit slippery roads during the winter, in the same matter as the clean gravel samples. If the washing process of these masses is insufficiently removing microplastic particles, these concentrations will continuously be dispersed in the environment. The microplastic amount in the street sweepings is likely underestimated compared to the actual environmental data, presumably as the estimations only representing a small section of the whole city system, the streets. Our result shows that the highest concentrations of microplastic are found in the sand trap sample, and the total mass from the sand traps is unknown. Therefore, were these concentrations not included in the total microplastic mass calculations from the streets. The presumption that the total microplastic amount estimated in the cities is considerably higher than our estimations is supported as urban areas are cleaned more frequently, thereby collecting more street sweeping mass to the total and is shown to be areas more polluted by microplastic. This presumption indicates that the average microplastic estimation is an underestimated conclusion, with a limited number of samples and therefore not representative of the whole city. The minimum microplastic estimate in the streets is based on the concentrations from Urban4. Urban4 is shown to be a location with less traffic and people than other streets and, therefore, the best-case scenario will highly be inaccurate to represent the city of Bergen.

In contrast, the worst-case scenario was based on the highly trafficked Urban3 and will nightery represent the whole city. However, as the calculations here are presumed to be highly underestimated, the likelihood of this being more accurate than the average amount is considerable. In the worst-case scenario estimated here, TWP account for 81.11 % of the total microplastic in the street sweepings. As TWP is documented having higher toxicity than other microplastic polymers organisms (Adachi & Tainosho, 2004; Halle et al., 2020; Halsband et al., 2020; Hwang et al., 2016), actions to limit these releases should be considered.

Microplastic per capita estimations are also numbers with a high degree of uncertainty and presumably underestimated, with an estimated worst-case scenario of 5 g per person. However, all these estimations show that there is, presumably, high dispersion in the total microplastic content in the streets of Bergen and that traffic load influence this dispersion. With increasing populations and urbanization, the pressure on the cities is already high. With more people follow more traffic, littering, and construction, which are all sources of microplastic pollution in the cities. These numbers calculated here are likely to increase, as our results demonstrate that population density and traffic load heavily affect microplastic concentrations. The municipality needs sufficient cleaning and collection methods to limit microplastic dispersal in the streets if these worst-case estimations calculated here are accurate (or underestimated) and presumed to increase.

TWP as a dominating source of microplastic

As the results show, TWP is the dominating microplastic polymer found in the areas sampled and the decisive polymer in the difference between urban and suburban areas. Meso-sized TWP were also found in all the urban samples, except the less trafficked Urban4. The pathways and transportation routes the particles follow in urban and suburban areas can also affect the high concentrations found in the urban areas, as TWP tend to remain closer to the streets in urban areas. As stated, the concentrations of TWP found here are not quantitively reliable, and the concentrations are presumed to be even higher than stated here, supported by the identification of TWP in all precipitate samples from the density separations. TWP can originate from tire abrasion and rubber used at artificial sports turfs and separating these two sources can be difficult. TWP are more often found in rolls, shown in Figure 29. TWP has a complex chemistry, and the density varies based on the minerals and possible organic matter incorporated in the particle (Kole et al., 2017). Observed densities range from 1.15-2.50 g/cm^3 (Grigoratos & Martini, 2015; Kayhanian et al., 2012; Snilsberg, 2008). The incorporated mineral also alters the appearance of the particle. The colors observed for TWP particles were from dark black to grey, and the texture hardened with more minerals present. TWP can be subject to massive alterations after entering nature and makes the pathways and distribution hard to determine. Other studies also support our findings stating that TWP is a significant source of microplastic. There is, however, a lack of environmental data for comparison. TWP is determined to be the biggest microplastic source in Norway, presumed to account for 53.6 % of the total microplastic pollution (Sundt et al., 2014). The same conclusion was made for the microplastic release in Denmark (55.8 % of emissions) (Lassen et al., 2015). This is in similarity to our results, where TWP accounted for 45.97 % of the total microplastic pollution. It is notable that Sundt et al. (2014) and Lassen et al. (2015) define microplastic as < 5 mm, while we define microplastic as < 1 mm. This would mean that the TWP percentage in our studies will presumably decrease, as most TWP are smaller than 1 mm (Kreider et al., 2010; Vogelsang et al., 2019). These total estimations indicate that the high amounts of TWP pollution originate from urban (and suburban) areas.

Kole et al. (2017) state that TWP count for 5-10 % of all plastic ending up in the ocean. Highly trafficked streets located near water, like Urban1, could be reasons for more TWP ending up in the ocean. Studies from Verschoor et al. (2016) and Vogelsang et al. (2019) support our findings and agree that street-dust consists of substantial TWP amounts and that they are transported with run-off water from the streets and possibly into a nearby sand trap. The toxicity of TWP is relevant to know as TWP is a significant source of microplastic, especially in the urban environment. Halsband et al. (2020) discovered leaching of heavy metals and additives from TWP in seawater and, therefore, we should aim to limit the release of TWP in the terrestrial environment, thereby limiting the release into the ocean. Studies agree that TWP are sources of, e.g., heavy metals, polycyclic aromatic hydrocarbon (PAHs), and benzothiazoles released into the environment, which can cause severe toxicity or death to organisms (Adachi & Tainosho, 2004; Halle et al., 2020; Hwang et al., 2016). By knowing the possible consequences of TWP and the high amounts found in the environment, there should be more measures to limit the release.

Quality Assurance / Quality control

The quality controls of reagents and air-contamination applied throughout the study showed no visual or measurable contamination had happened. This proves that the measures to prevent contamination applied were effective. The $ZnCl_2$ density was tested and corrected as the density needed to be consistent to assure that the same polymers were extracted from all samples. We know that TWP and paint particles have varying densities and can be heavier than the $ZnCl_2$ density. Due to this, the TWP and paint concentrations were not quantifiable in this study.

Limitations to the study

There were some limitations to the study that needed to be considered. The detection size limit for this study was set at 50 µm, and particles below this size were not analyzed. The limit was chosen as our environmental samples were presumed to be highly contaminated by microplastic. The Pyr-GCMS has a detection limit of 10 µg in this study due to the complexity of the samples. We cannot conclude that there are no polymer traces in masses lower than 10 µg, however, these would not affect our results significantly. The environmental samples in this study had such high microplastic content that only a fraction of the samples could be analyzed on ATR-FTIR and Pyr-GCMS. Subsampling and standardization imply propagation errors in the estimate of concentrations, as is always the case when using small sample volumes. Multiple parallels had to be analyzed on PYR-GCMS to get a representative result, and even with these small percentages used here, some detected masses were out of scale.

Moreover, the methods chosen could not separate between LDPE and HDPE, making source identification harder. A µ-FTIR analysis method was tested for the SMP size-class, however, it did not present reliable results at the time. The mass calculation is a published method of calculating the mass from particles (Equation 3) (Primpke et al., 2020; Simon et al., 2018), however, it resulted in some uncertainty in the confirmed and calculated mass. The microplastic mass and percent contribution per polymer could have been used to calculate the total polymer mass, but with the low weight and number of organic particles, the mass equation was used instead.

The lack of standardizations within microplastic studies and a low number of studies focusing on the urban environment limits a comparison of concentrations with other studies. It followed great difficulty as sampling methods, and concentration units reported vary, and many reports in particle numbers. The size of microplastics has many definitions, and the concentrations can vary according to this definition. Due to the relatively small sample size, the statistical calculations were hampered. We used non-parametric tests since the concentrations were not normally distributed. In addition, to the low sample size, the presented outliers could not be removed.

Microplastic Restrictions

There are few regulations regarding microplastic pollution in the environment today, meaning the specific responsibility that needs to be taken to clean up or limit release. Plastic is a product with the ability to persist in the environment over the decades, and microplastics have been proven harmful when ingested by organisms (Barnes et al., 2009; Crawford & Quinn, 2017; Ryan, 2015; Thompson, Swan, et al., 2009). Microplastic could also possibly act as vectors for other contaminants or leak out harmful chemicals (Halsband et al., 2020; Kleinteich et al., 2018; Koelmans et al., 2016). Still, microplastic is not defined as an environmental pollutant today. A wide restriction is proposed by the European Chemical Agency regarding intentionally added microplastic and is set to be ready in 2021 (ECHA, 2020). However, unintentional microplastic entering the environment has yet no restrictions and the Norwegian pollution law has no mentioning of microplastics (Klima- og miljødepartementet, 2019). A perhaps unintentional limitation to microplastic dispersal today is the road cleaning. This study shows that road cleaning is a way to collect microplastic and limit the particles to become airborne or transported by run-off water. The sand traps collect a lot of the microplastic transported by the run-off water; however, our results indicate that the lighter particles most likely are transported through the sewage system and towards the ocean as an endpoint.

Bergen municipality is a part of this project and wants to identify the local microplastic sources to find suitable measures to limit distribution. As demonstrated by our results, the large plastic in the urban environment does fragment into smaller microplastic particles, which are harder to remove effectively. Therefore, limitations should prevent the plastic from entering the environment and then fragmenting into microplastic. Hopefully, the information from this study could contribute to people changing their irresponsible behavior regarding littering. People will easier change their habits if they have a better understanding of why and receive easy and concrete instructions to improve the situation in their city. Release of TWP will be harder to limit in the same way as other polymers. Some areas of the urban city center of Bergen was this year (2020) closed for car traffic to prioritize pedestrians, people traveling on public transport, and cyclists (Matre, 2020). This could also be a suitable measure to possibly reduce TWP emissions in these areas.

Conclusion

The present study quantifies microplastic in street sweepings and sand traps in a medium-sized city and demonstrates that the urban environment is a hotspot for microplastic pollution. In addition, the study indicates that microplastic concentrations increase with high population densities and traffic. The urban street sweeping samples indicated that seasonal changes, possibly enhanced by increased traffic and tourism, considerably affect the microplastic concentration. Temperature and dry weather seem to increase microplastic pollution in the streets during the summer season. As expected, the suburban areas had lower microplastic concentrations in the streets compared to the urban areas.

On the other hand, the suburban sand traps contained higher microplastic concentrations than the urban sand traps. Our results suggest that in the suburban areas, low microplastic concentrations in the streets are correlated with high concentrations ending up in a nearby sand trap, presumably transported by run-off water due to infrequent street sweeping. As sand traps represented yearly microplastic accumulation, the sand traps in this study had high microplastic concentrations and demonstrate the process of microplastic deposition in sand traps. According to our results, the sedimentation process in the sand traps separates low-density and high-density polymers, resulting in a higher proportion of high-density polymers than in the street sweepings. This demonstrates that there might be a significant loss of low-density polymer into the sewage system and further into the ocean.

Our results show that the dominating source of microplastic is abrasion from car tires, in agreement with the total estimated microplastic release in Norway by the Norwegian Environment Agency (Sundt et al., 2014). The results from this study showed that the sources of large and small microplastic particles did not represent each other well. However, the results indicate that TWP in the urban environment is most often detected in sizes below 500 µm. TWP concentrations are higher in areas with more traffic and higher population densities. Seasonal changes also seem to affect TWP pollution. Other dominating sources of microplastic were PVC and paints. PVC from construction work is a likely source, and the release and distribution can be hard to control. However, considering the potential toxicity of PVC, this may be a necessary topic to address. The method of extraction of paints is today considered inefficient and incomplete, and our data are not quantitative, observed by detection of paint in the precipitate from density separations. However, the results clearly show that paint is an important source of synthetic polymers in the urban environment and that measures to reduce the distribution of paint in the environment may be considered necessary.

Microplastic research has been advancing in recent years, yet the regulations to limit microplastic pollution remain few. Our results established that streets are a significant pathway for microplastic distribution, transporting particles with surface run-off water into sand traps. Sand traps are here shown to be accumulation sites for microplastic, and presumably a pathway for the lighter particles into the waterways in the city. In cases where the wastewater is released untreated into the ocean, this may be conceded as a direct route of microplastic release into the ocean. The street cleaning implemented by the municipality can be considered to limit microplastic dispersal in areas with high sweeping frequency. However, the highly trafficked areas in the urban environment might need a higher cleaning frequency or other restrictions to limit microplastic dispersal in these areas. The extent of microplastic pollution in the cities, demonstrated by this study, will be communicated to the municipality in order to address the processes leading to the generation of microplastic and the possible abatement and mitigation of the problem. Restriction placed on the public with regards to the microplastic situation, must also be communicated raising awareness and ensuring engagement to limit further pollution by sources of microplastic that likely stem from personal use and poor waste management related to single-use plastic. Although the number of samples was limited, this is the first study of its kind to provide detailed quantification of sources and distribution of microplastics in an urban environment. The study provides a basis for future actions, mitigating actions, environmental monitoring, and offers an opportunity to evaluate any actions taken by providing a baseline for comparison.

The large total amounts of microplastics estimated in our worst-case scenario may be dispersed in the streets with the washed and presumably clean gravel during the following winter. This potential redistribution of microplastic in the city is especially interesting as our mass calculations are presumably highly underestimated. A study to investigate the process of washing and locate the final fate of the particles is therefore necessary.

With the massive amounts of plastic produced and used daily, microplastic is shown to contaminate the urban environment profoundly. Urbanization and increasing populations consequently increase the pressure on our cities. Demonstrated through this study, microplastic concentrations will increase with increasing population density. Therefore, presumed future microplastic pollution is thought to be severe.

Future perspectives

This thesis is a part of the larger project “Mapping of microplastics in urban environments - quantities, sources, and distribution - Urban Microplastics” (RFFV #284827). The results from the remaining locations in the urban and suburban Bergen will give the data stronger reliability. The project will also investigate further if the washing of total street sweeping masses collected adequately removes microplastic particles or if the particles, in fact, are redispersed in the streets during the winter. In line with the current research on microplastic, these results highlight the necessity for further research and limitations in knowledge concerning microplastic pollution in the urban environment. Throughout this study, other areas of the urban and suburban environment have become interesting potential pathways for microplastic in need of more research. Since less microplastic was found in the suburban streets, the question of where the particles end up have arisen. There is a possibility that yearly street cleaning has allowed the microplastic particles to be transported into other nearby areas in nature, as well as sand traps, or that less microplastic was produced there. The high concentrations in sand traps and the indication of possible loss of low-density polymers increase the need for further research on the run-off water transported from the sand traps. As our results indicate, this can confirm, if the lightweight polymers are transported with the water, to what extent, and the polymers endpoint. The study shows that TWP is a dominating microplastic in the urban environment. Future research should focus on how these particles move in the environment and try to locate the best solution for limiting its dispersal. The daily rate of microplastic generation would be interesting to further investigate, as well as to get a better understanding of the fragmentation of microplastics to be able to see the final fate of microplastic. An investigation of the potential consequences for humans at the documented concentrations needs to be conducted to further understand and determine the environmental threshold of effect for microplastic.

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Appendices

Appendix A - Material and Suppliers

Chemicals and Enzymes

Table S 1: List of chemicals used throughout the study.

Name	Chemical formula	CAS #	Supplier
Ethanol	C_2H_6O	-	Antibac
Glacial acetic acid	$C_2H_4O_2$	64-19-7	VWR Chemicals
Glycine	$C_2H_5NO_2$	56-40-6	Sigma Aldrich
Hydrochloric acid **37%**	HCl	7647-01-0	Sigma Aldrich
Hydrogen peroxide 30%	H_2O_2	7722-84-1	VWR Chemicals
Iron(II)sulfate	$FeSO_4 \cdot 7H_2O$	7782-63-0	Merck KGaA
MilliQ water	H_2O	-	Q-POD Purelab Prima
Sodium-acetate trihydrate	$CH_3COONa \cdot 3H_2O$	6131-90-4	Sigma Aldrich
Sodium dodecyl sulfate (SDS)	$NaC_{12}H_{25}SO_4$	200-578-6	ACROS ORGANICS
Sodium hydroxide pellets	NaOH	1310-73-2	Merck KGaA
Sodium tartrate dihydrate	$C_4H_4Na_2O_6 \cdot 2H_2O$	6106-24-7	Sigma Aldrich,
Tartaric acid	$C_4H_6O_6$	87-69-4	Sigma Aldrich
Tetramethylammonium hydroxide solution 25 wt.% in H_2O	$(CH_3)_4N(OH)$	75-59-2	Sigma Aldrich
Zinc Chloride (Technical)	$ZnCl_2$	7646-85-7	VWR Chemicals
4% Sodium Chloride water	NaCl H_2O	-	Sigma Aldrich

Table S 2: List of enzymes used in the study.

Enzyme	**Synonym**	**Code**	**EC number**	**Application/ degrading**	**Supplier**
Protease from Bacillus sp.	Savinase® 16.0L	P3111	232-752-2	Proteins	Sigma Aldrich
Cellulase from Trichoderma reesei	Celluclast® 1.5L	C2730	232-734-4	Cellulase, cell walls	Sigma Aldrich
Viscozyme L - cellulolytic enzyme mixture	Cell Wall Degrading Enzyme Complex from Aspergillus sp., Lysing Enzyme from Aspergillus sp.	V2010	-	Cell walls	Sigma Aldrich
Laccase from Aspergillus sp.	*	*	*	Lignin	Sigma Aldrich
Lignin Peroxidase	*	*	*	Lignin	Sigma Aldrich

* Unpublished confidential method by Gomiero, A.

List of buffers

Table S 3: 0.1 M Glycine buffer (pH 10.0)

Component	**Concentration**
Glycine	7.5 g
NaOH pellets	3.7 g

Add MilliQ to make 1 L
pH adjusted to 10.0 using 5 M HCl

Table S 4: 0.3 M Sodium-acetate buffer (pH 4.8)

Component	**Concentration**
Sodium-acetate trihydrate	4.8 g
MilliQ	100 mL

pH adjusted to 4.8 using Glacial acetic acid

Table S 5: Tartrate buffer

Component	**Concentration**
Tartaric acid	*
Sodium tartrate dihydrate	*

* Unpublished confidential method by Gomiero, A.

List of instruments and equipment

Table S 6: List of instruments used in the study

Instrument	**Application**	**Supplier**
Oven	Dry matter calculation	Termaks
Muffel Furnace	Organic matter calculation	L 3/12, Nabertherm GmbH
Mettler AT200 weight	Milligram weight	Mettler Toledo
Mettler PB3002 weight	Gram weight	Mettler Toledo
MicroPlastic Sediment Separator	Density separation	Hydro-Bios Apparatebau GmbH
VacUum filtration	Pressure for filtration	Millipore
$ZnCl_2$ filtration	Compressor	Millipore
Shake “n” Stack Oven	Sample preparation	Hybaid
Pyrolysis	Microplastic analyze	Bionordica
Nicolet™ iN10 MX Infrared Imaging Microscope	ATR-FTIR particle analysis	Thermo Scientific
Q-POD	MilliQ water	Millipak Express 40
Branson 200	Ultrasonic cleaner	Branson
Multisizer 3	Particle counter	Beckman

Table S 7: List of equipment used in the study.

Instrument/Equipment	Application	Supplier
Stainless steel filter	Filtration of $ZnCl_2$, 100 µm	Rolf Körner GmbH
Glass fiber filter	Filtration of $ZnCl_2$ (1 and 10 µm)	Hytrex Catrige filters
Finnpipette Digital ACL 200-1000 µm	Pipette	Labsystems Finland
Stainless steel filter, 50 and 500 µm	Separation	Whatman
Separation funnel	Density separation	BS 2021
RET control-visc	Magnetic stirrer	IKA
Model 250A	pH measurement	Orion
Glass fiber filter	Filtration	Whatman
Integra Flameboy	Equipment preparation, burner	Integra
Glass wear	Sample preparation	Schott Duran and VWR
Glass wear	Filtration equipment	Millipore

Table S 8: List of software and online tools used in the study.

Name	Application	Provider
Excel, 16.30	Calculations, Statistical analysis	Microsoft
PowerPoint, 16.30	Figures	Microsoft
SPSS Statistics 25	Statistical analysis	IBM
OMNIC Picta	FTIR spectra analysis	ThermoFisher Sience
OMNIC Spectra	FTIR spectra analysis	ThermoFisher Sience
ThermoFisher Connect	FTIR spectra analysis	ThermoFisher Sience
Pyrolysis data program	Pyrogram analysis	Frontiers Lab

Appendix B - Theoretical principle for methods

Fenton's Reagent

Fenton's reagent is a procedure for removing organic compounds in an environmental microplastic sample. This reaction uses hydrogen peroxide (H_2O_2) as an oxidizing agent in the presence of Fe^{2+} or Fe^{3+} ions as a catalyst (Hurley et al., 2018). In this study, ferrous sulfate ($FeSO_4 \cdot 7H_2O$) was used as the iron catalyst (Fe^{2+}). Iron sulphate ($FeSO_4$) catalyzes the decomposition of two hydroperoxides (H_2O_2) producing oxygen-radicals (a hydroxyl radical and a hydroperoxyl radical) and water. The produced and highly reactive oxygen radicals react and destructs the organic matter in the sample. To achieve an optimal degradation of organic material and ensure a total dissolution of the ferrous sulfate the pH of the reactions needs to remain acidic (levels near pH 3). An iron hydroxide precipitate will form if the pH increases above 5 (Hurley et al., 2018; Neyens & Baeyens, 2003). The pH is adjusted with NaOH (alkaline) or sulfuric acid (acidic). According to Tagg et al. (2017), the oxidation process with Fenton’s reagent and the acidic conditions do not have any visible effect on the microplastic particles, neither the size nor the chemistry. The four different polymers tested by Tagg et al. (2017) were PE, PP, PVC, and PA66. Hurley et al. (2018) neither observed any changes in size or mass of eight polymers tested with Fenton’s reagent (PP, LDPE, HDPE, PS, PET, PA66, PC, PMMA). As an exothermic reaction organic matter removal with Fenton’s reagent can reach temperatures of 89 °C (Munno et al., 2018). Degradation of polymers is observed at temperatures above 70 °C (Hurley et al., 2018). The optimal temperature for this reaction should not exceed 40 °C, as the H_2O_2 efficiency will decline above this temperature (USP Technologies, n.d.).

Attenuated total reflectance Fourier-transform infrared spectroscopy (ATR-FTIR)

Vibrational spectroscopy by ATR-FTIR was used to quantify possible plastic particles > 500 µm. ATR-FTIR is an effective and non-destructive method. When using ATR, a total internal reflection of an infrared beam occurs when in contact with the sample. An optical crystal has a high refractive index at a specific angle (θ), depending on the crystal type, and the infrared beam interacts accordingly. The internal reflection generates an evanescent wave penetrating the sample in contact with the crystal. The sample analyzed absorbs energy at specific wavelengths for specific functional groups in the infrared light region, resulting in the evanescent wave to be attenuated. This attenuated energy returns to the infrared beam, and a detector collects the beam as it leaves the crystal (Figure S 1). Resulting in a sample-specific infrared spectrum for comparison with a reference spectrum (Figure S 2) (Bradley, n.d.). The depth of penetration into the sample is depending on different factors. The wavelength of the light, where a shorter wavelength equals shallower penetration. Another factor is the angle at which the infrared light hits the crystal, where a less steep angle corresponds to deeper penetration. A third factor is the refractive index of the specific crystal. For a diamond crystal, the refractive index is 2.4, leading to approximately 2 µm penetration. For a germanium crystal, the refractive index is 4, giving a penetration of 0.7 µm (PerkinElmer, 2007).

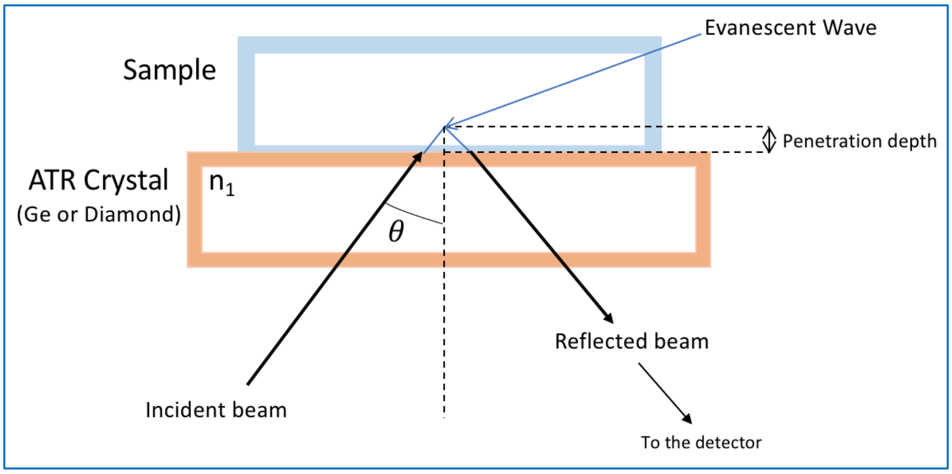


Figure S 1: A simple display of the ATR-FTIR principle. The infrared beam interacts with the sample at a specific angle (θ) depending on the crystals refractive index (n1). The internal reflection generates an evanescent wave that penetrates the sample. The returned reflected beam is collected by the detector, resulting in a sample-specific spectrum.

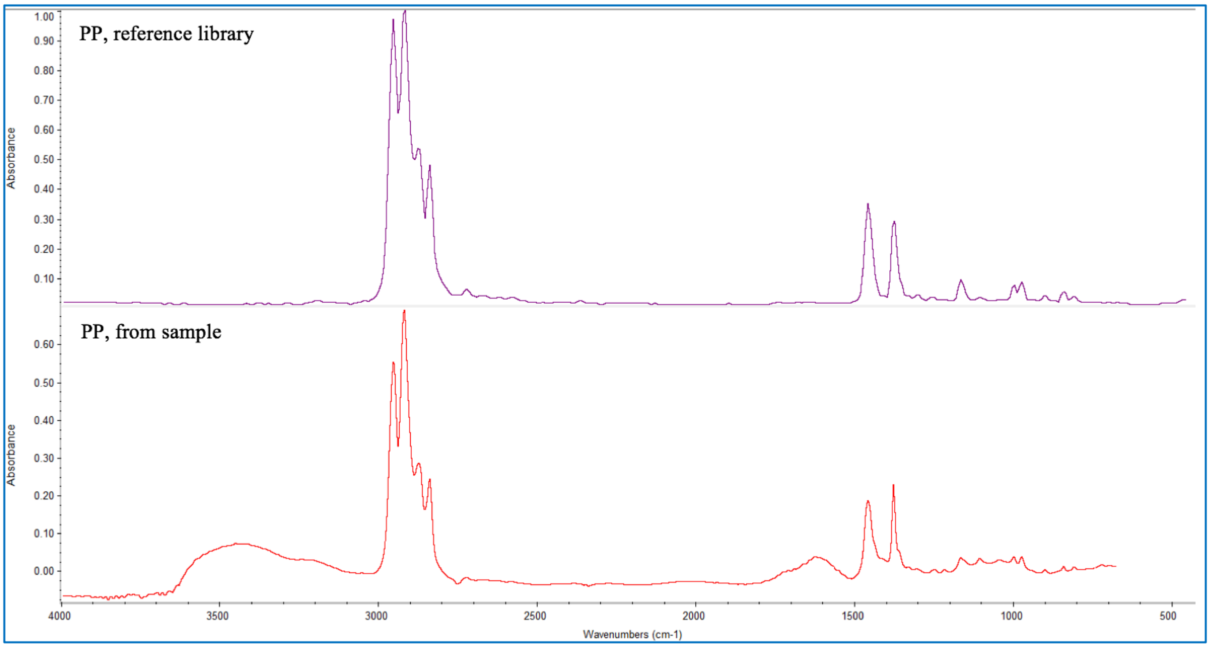
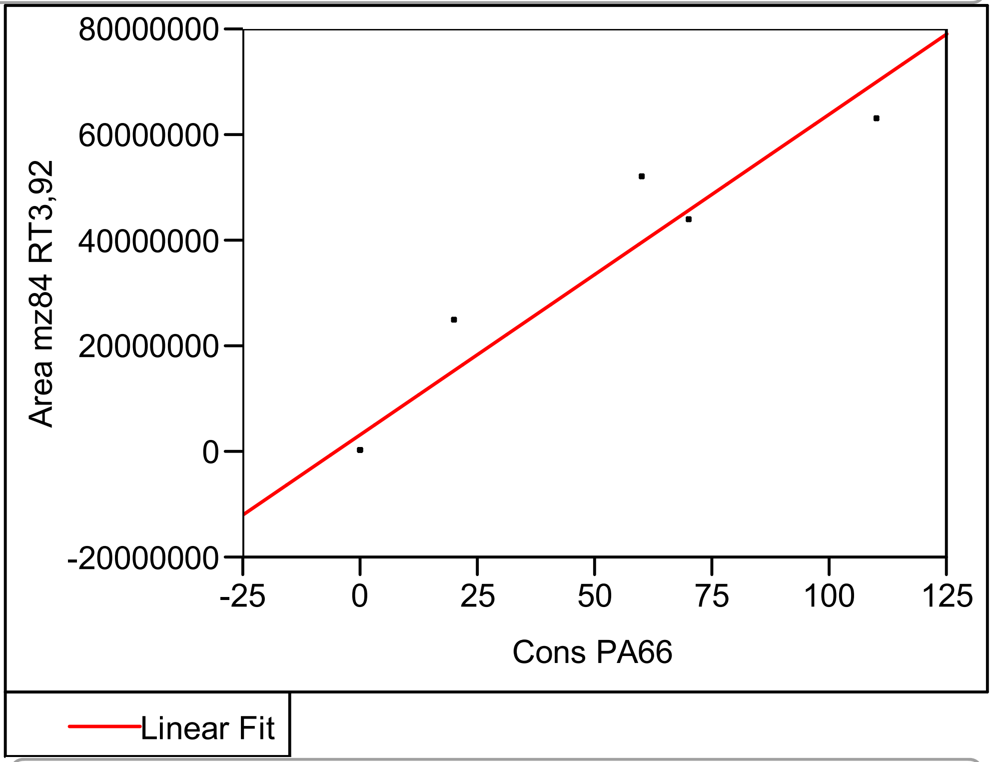


Figure S 2: A PP spectrum from the reference library stacked on a PP spectrum from a particle from a sample with a 96.56 % match. Presenting higher absorbance at specific functional groups. Reference spectrum: OMNIC Picta.

Appendix C - The quantification and calibration curves for all ten polymers identified by Pyr-GCMS.

200511PA66- Fit Y by X

Bivariate Fit of Area mz84 RT3,92 By Cons PA66



Linear Fit

Area mz84 RT3,92 = 3133904,6 + 607649,47 Cons PA66

Summary of Fit

RSquare	0,933091
RSquare Adj	0,921939
Root Mean Square Error	7441838
Mean of Response	22882512
Observations (or Sum Wgts)	8

Analysis of Variance

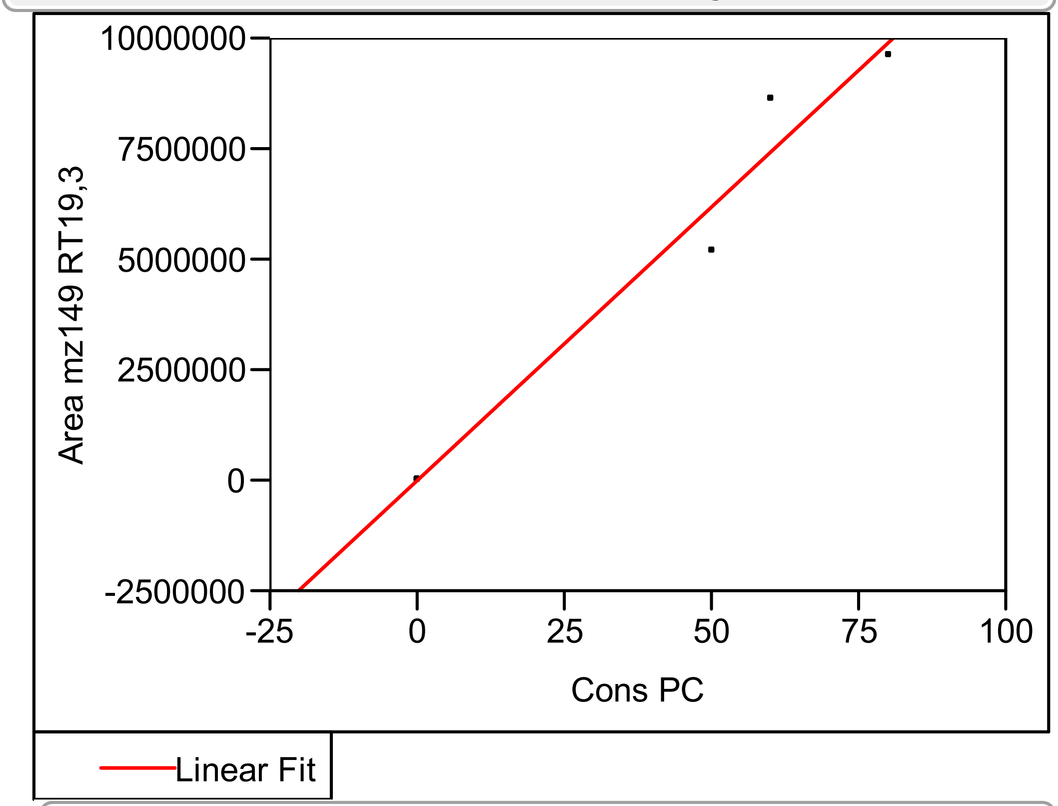
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	4,63394e15	4,6339e15	83,6738
Error	6	3,32286e14	5,5381e13	Prob > F
C. Total	7	4,96622e15		<,0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	3133904,6	3403478	0,92	0,3927
Cons PA66	607649,47	66429,09	9,15	<,0001

200511PC- Fit Y by X

Bivariate Fit of Area mz149 RT19,3 By Cons PC



Linear Fit

Area mz149 RT19,3 = -17621,07 + 123868,25 Cons PC

Summary of Fit

```
RSquare                          0,978097
RSquare Adj                      0,973717
Root Mean Square Error           710338,9
Mean of Response                  3344517
Observations (or Sum Wgts)              7
```

Analysis of Variance

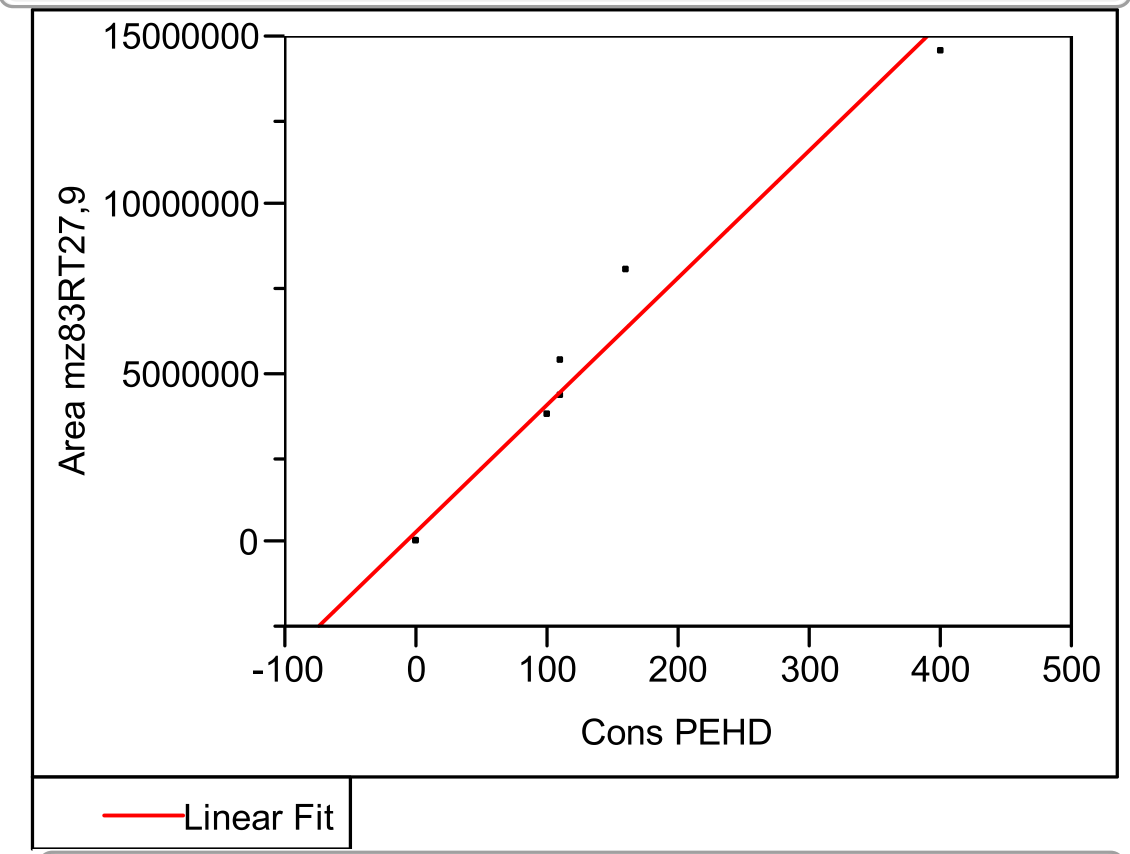
```
Source      DF   Sum of Squares   Mean Square     F Ratio
Model        1       1,12664e14     1,1266e14    223,2821
Error        5       2,52291e12     5,0458e11    Prob > F
C. Total     6       1,15187e14                   <,0001
```

Parameter Estimates

```
Term          Estimate    Std Error   t Ratio   Prob>|t|
Intercept    -17621,07     350299,1     -0,05     0,9618
Cons PC      123868,25      8289,59     14,94     <,0001
```

200511PEHD- Fit Y by X

Bivariate Fit of Area mz83RT27,9 By Cons PEHD



Linear Fit

Area mz83RT27,9 = 280290,98 + 37743,568 Cons PEHD

Summary of Fit

RSquare	0,975709
RSquare Adj	0,972672
Root Mean Square Error	794434,8
Mean of Response	3601725
Observations (or Sum Wgts)	10

Analysis of Variance

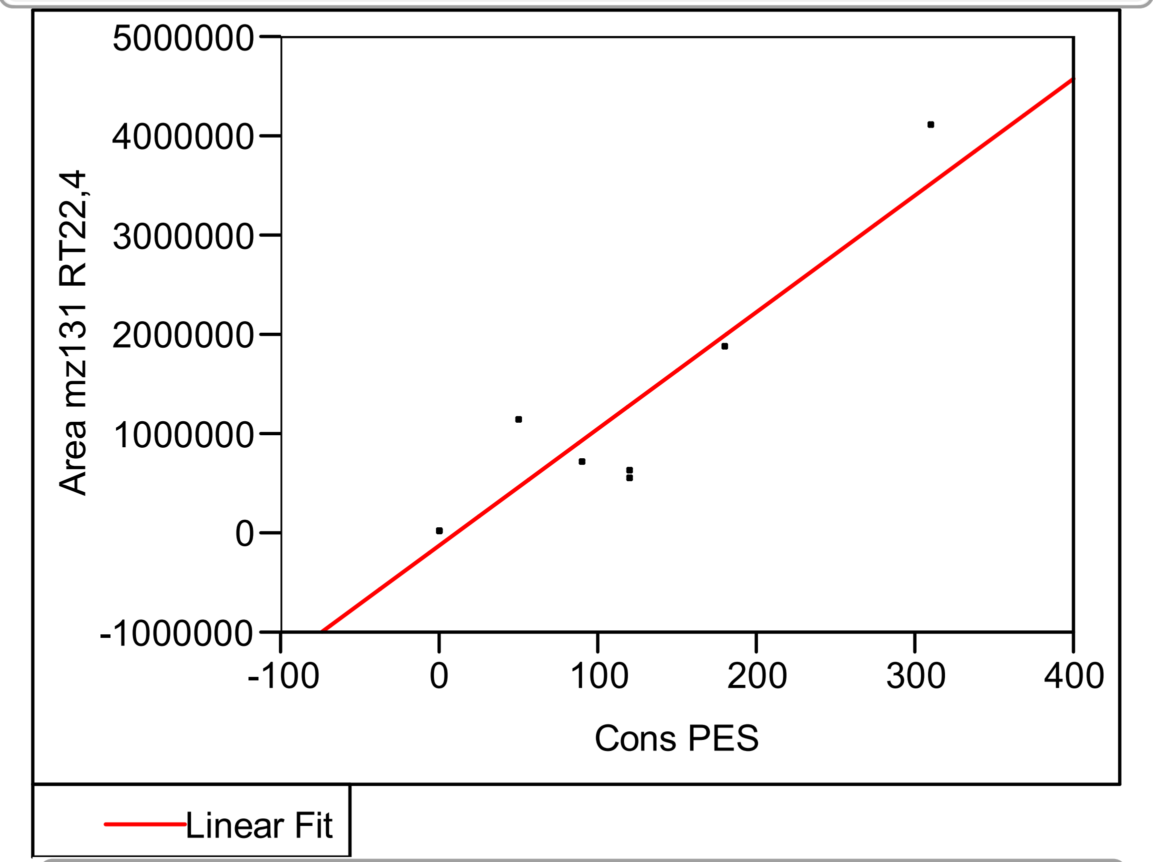
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	2,02803e14	2,028e+14	321,3345
Error	8	5,04901e12	6,3113e11	Prob > F
C. Total	9	2,07852e14		<,0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	280290,98	312160,6	0,90	0,3955
Cons PEHD	37743,568	2105,544	17,93	<,0001

200511PES- Fit Y by X

Bivariate Fit of Area mz131 RT22,4 By Cons PES



Linear Fit

Area mz131 RT22,4 = -131205,3 + 11757,669 Cons PES

Summary of Fit

RSquare	0,86899
RSquare Adj	0,852613
Root Mean Square Error	490129,3
Mean of Response	891711,9
Observations (or Sum Wgts)	10

Analysis of Variance

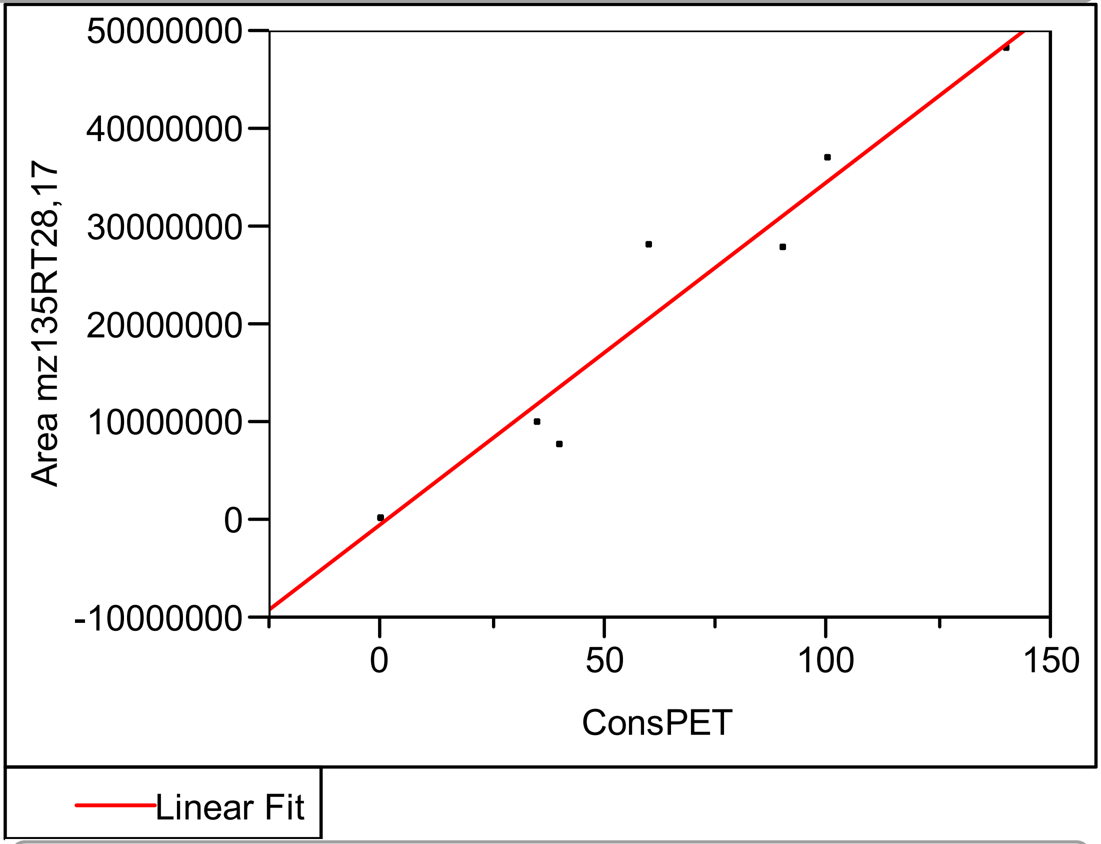
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	1,27474e13	1,2747e13	53,0639
Error	8	1,92181e12	2,4023e11	Prob > F
C. Total	9	1,46692e13		<,0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-131205,3	209144,8	-0,63	0,5479
Cons PES	11757,669	1614,067	7,28	<,0001

200511PET- Fit Y by X

Bivariate Fit of Area mz135RT28,17 By ConsPET



Linear Fit

Area mz135RT28,17 = -502825,5 + 350763,57 ConsPET

Summary of Fit

RSquare	0,96086
RSquare Adj	0,955968
Root Mean Square Error	3754611
Mean of Response	15807681
Observations (or Sum Wgts)	10

Analysis of Variance

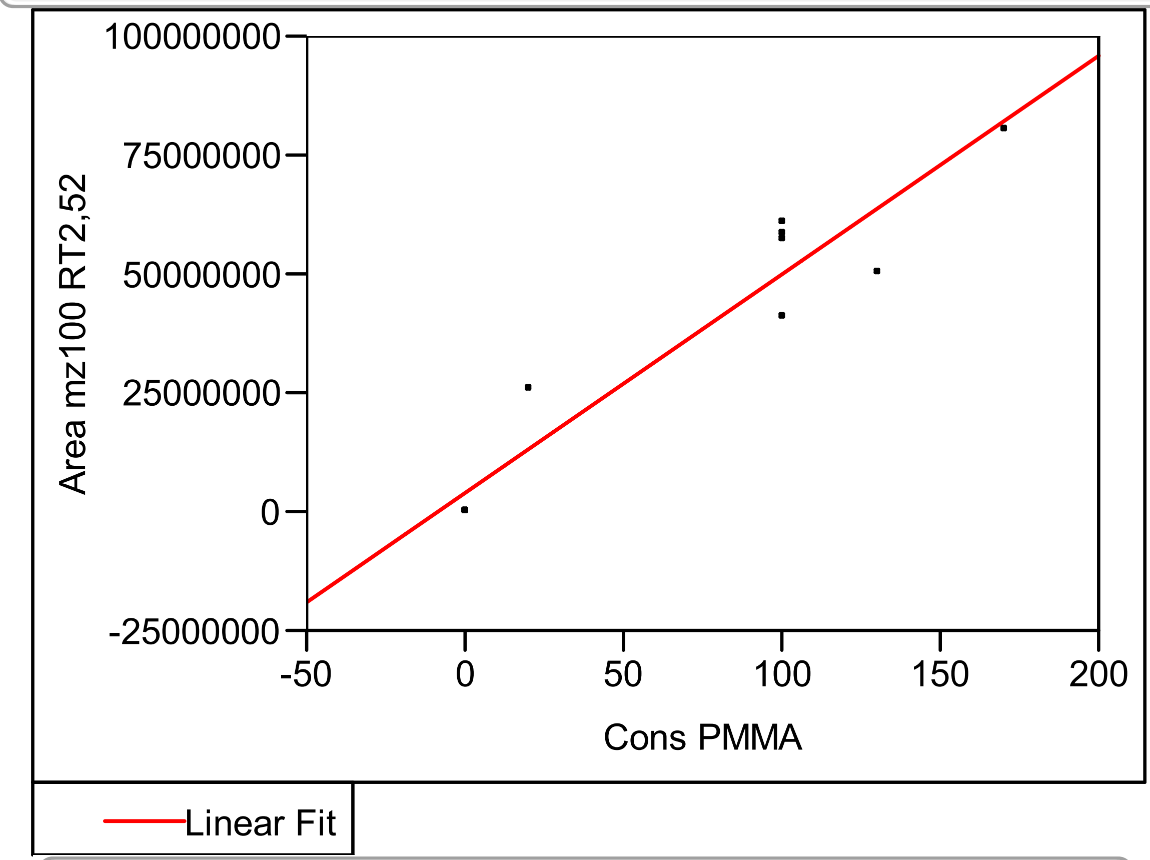
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	2,7686e+15	2,7686e15	196,3947
Error	8	1,12777e14	1,4097e13	Prob > F
C. Total	9	2,88137e15		<,0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-502825,5	1662616	-0,30	0,7700
ConsPET	350763,57	25029,35	14,01	<,0001

200511PMMA- Fit Y by X

Bivariate Fit of Area mz100 RT2,52 By Cons PMMA



Linear Fit

Area mz100 RT2,52 = 3859082,9 + 460344,79 Cons PMMA

Summary of Fit

RSquare	0,918787
RSquare Adj	0,909764
Root Mean Square Error	9017849
Mean of Response	33990742
Observations (or Sum Wgts)	11

Analysis of Variance

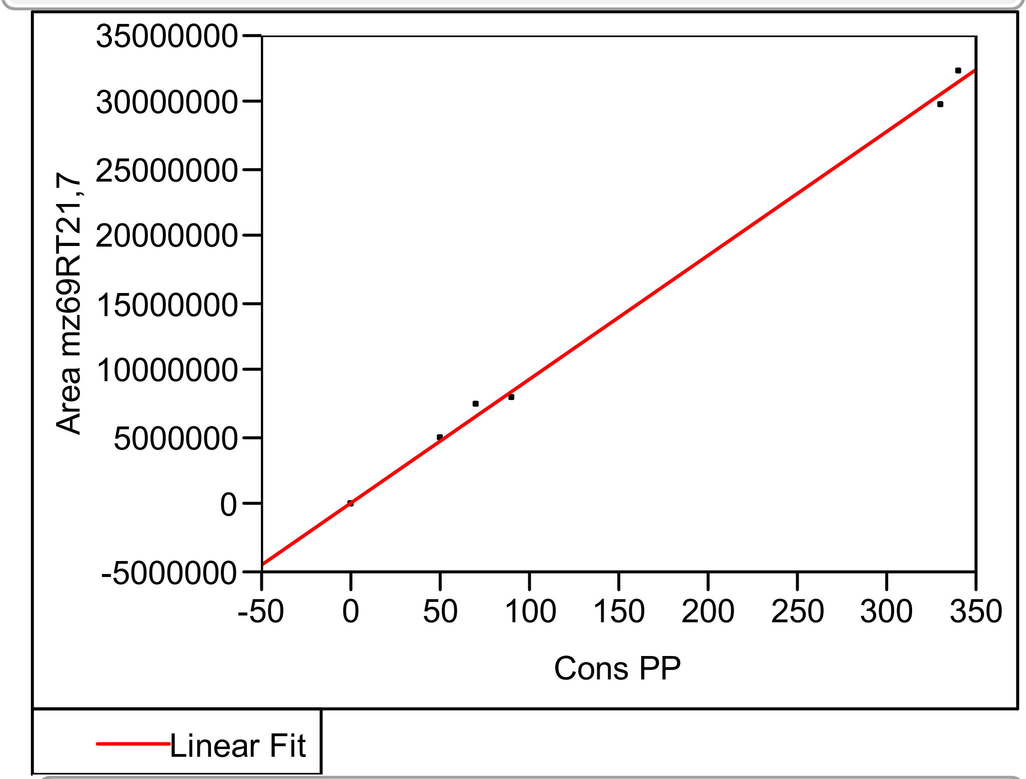
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	8,28019e15	8,2802e15	101,8203
Error	9	7,31894e14	8,1322e13	Prob > F
C. Total	10	9,01208e15		<,0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	3859082,9	4038531	0,96	0,3643
Cons PMMA	460344,79	45621,14	10,09	<,0001

200511PP- Fit Y by X

Bivariate Fit of Area mz69RT21,7 By Cons PP



Linear Fit

Area mz69RT21,7 = 110267,45 + 92475,959 Cons PP

Summary of Fit

RSquare	0,998237
RSquare Adj	0,997986
Root Mean Square Error	576286,1
Mean of Response	9152361
Observations (or Sum Wgts)	9

Analysis of Variance

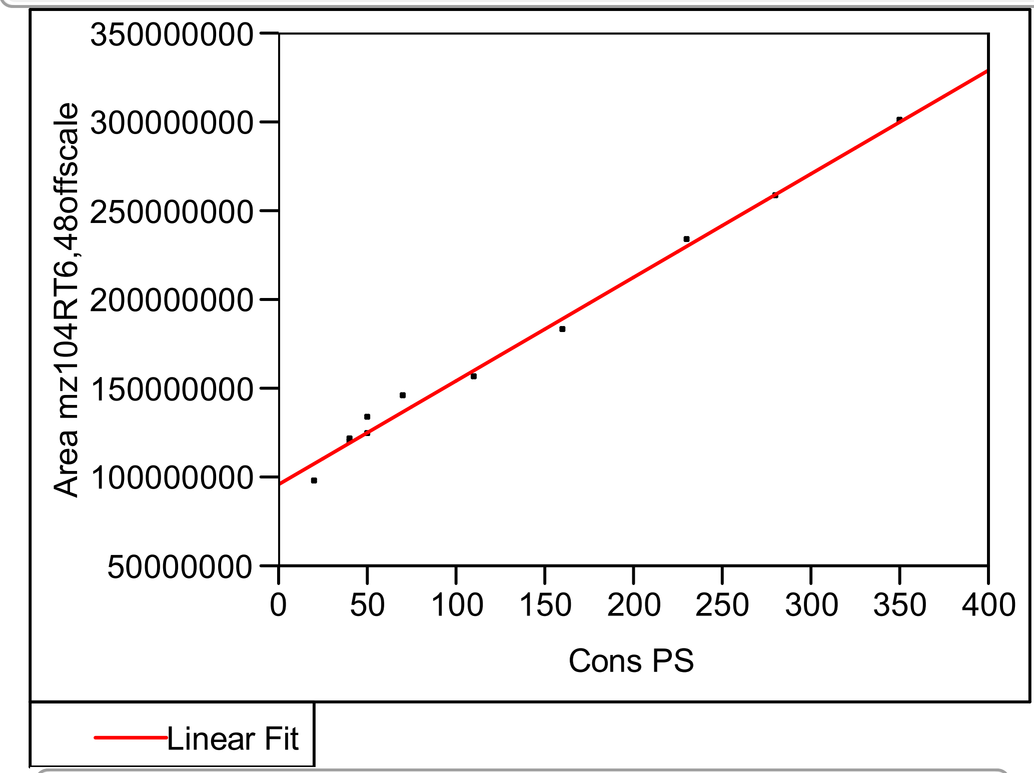
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	1,3166e+15	1,3166e15	3964,393
Error	7	2,32474e12	3,3211e11	Prob > F
C. Total	8	1,31892e15		<,0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	110267,45	239841,8	0,46	0,6596
Cons PP	92475,959	1468,725	62,96	<,0001

200511PS- Fit Y by X 2

Bivariate Fit of Area mz104RT6,48offscale By Cons PS



Linear Fit

Area mz104RT6,48offscale = 95562911 + 583181,49 Cons PS

Summary of Fit

```
RSquare                         0,992572
RSquare Adj                     0,991747
Root Mean Square Error           5988468
Mean of Response                1,6979e8
Observations (or Sum Wgts)            11
```

Analysis of Variance

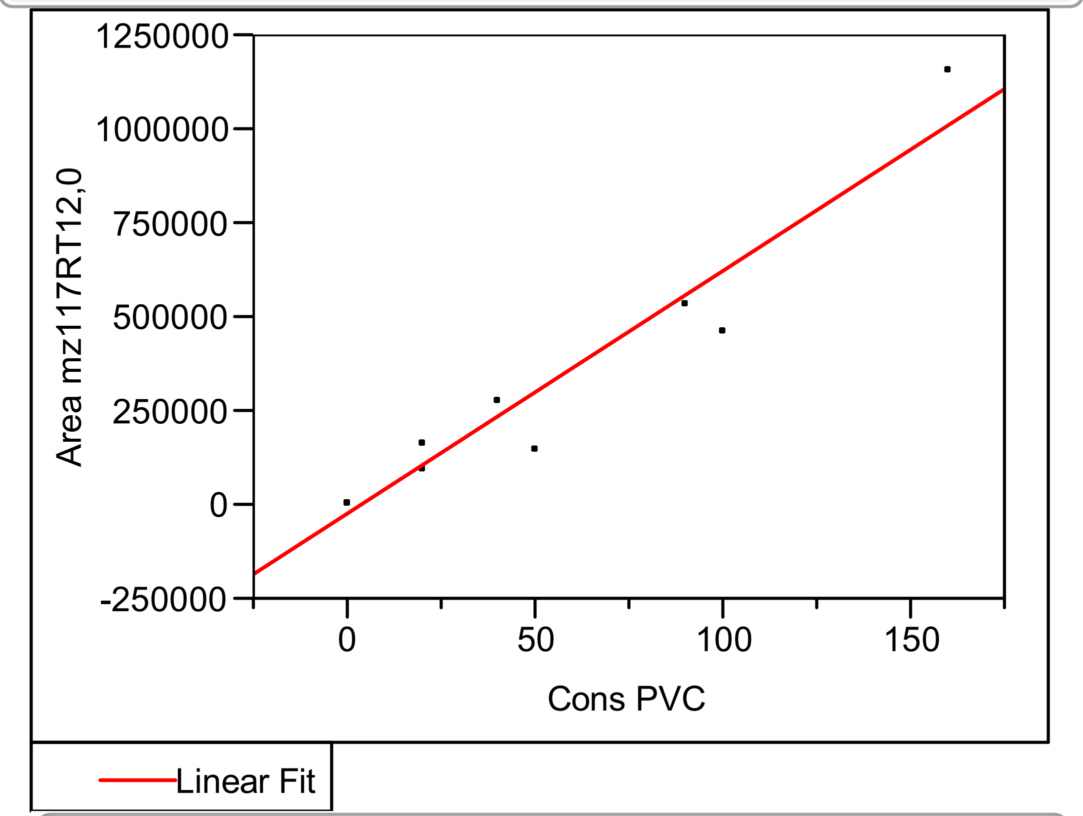
```
Source      DF   Sum of Squares   Mean Square     F Ratio
Model        1       4,31309e16     4,3131e16    1202,701
Error        9       3,22756e14     3,5862e13    Prob > F
C. Total    10       4,34537e16                   <,0001
```

Parameter Estimates

```
Term          Estimate   Std Error   t Ratio   Prob>|t|
Intercept     95562911     2800132     34,13    <,0001
Cons PS      583181,49    16816,09     34,68    <,0001
```

200109PVC- Fit Y by X

Bivariate Fit of Area mz117RT12,0 By Cons PVC



Linear Fit

```
Area mz117RT12,0 = -26533,28 + 6459,4398 Cons PVC
```

Summary of Fit

```
RSquare                          0,935666
RSquare Adj                      0,928518
Root Mean Square Error           93889,17
Mean of Response                 255333,2
Observations (or Sum Wgts)             11
```

Analysis of Variance

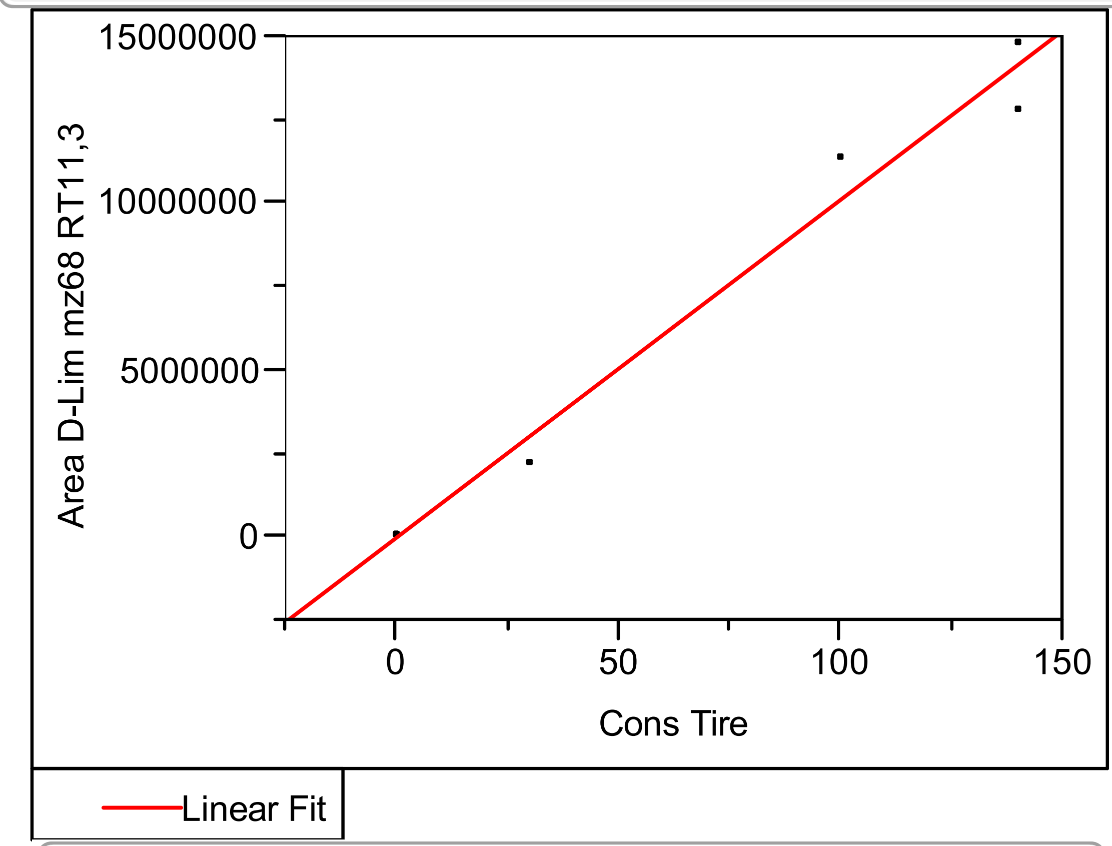
```
Source      DF   Sum of Squares   Mean Square     F Ratio
Model        1      1,15387e12     1,1539e12    130,8957
Error        9      7,93366e10     8,81518e9    Prob > F
C. Total    10      1,2332e+12                   <,0001
```

Parameter Estimates

```
Term          Estimate   Std Error   t Ratio   Prob>|t|
Intercept    -26533,28    37527,88     -0,71     0,4974
Cons PVC     6459,4398    564,5888     11,44     <,0001
```

200511Tire_D_limon- Fit Y by X

Bivariate Fit of Area D-Lim mz68 RT11,3 By Cons Tire



Linear Fit

Area D-Lim mz68 RT11,3 = -70058,93 + 101332,44 Cons Tire

Summary of Fit

RSquare	0,985043
RSquare Adj	0,98255
Root Mean Square Error	869411,6
Mean of Response	5123229
Observations (or Sum Wgts)	8

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	2,98678e14	2,9868e14	395,1414
Error	6	4,53526e12	7,5588e11	Prob > F
C. Total	7	3,03213e14		<,0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-70058,93	403409,5	-0,17	0,8678
Cons Tire	101332,44	5097,676	19,88	<,0001

Appendix D – ATR-FTIR fractions

All fractions for LMP (500-1000 µm) to be analyzed by ATR-FTIR. One fraction per petri dish was randomly selected, and all particles in the fraction were analyzed by ATR-FTIR.

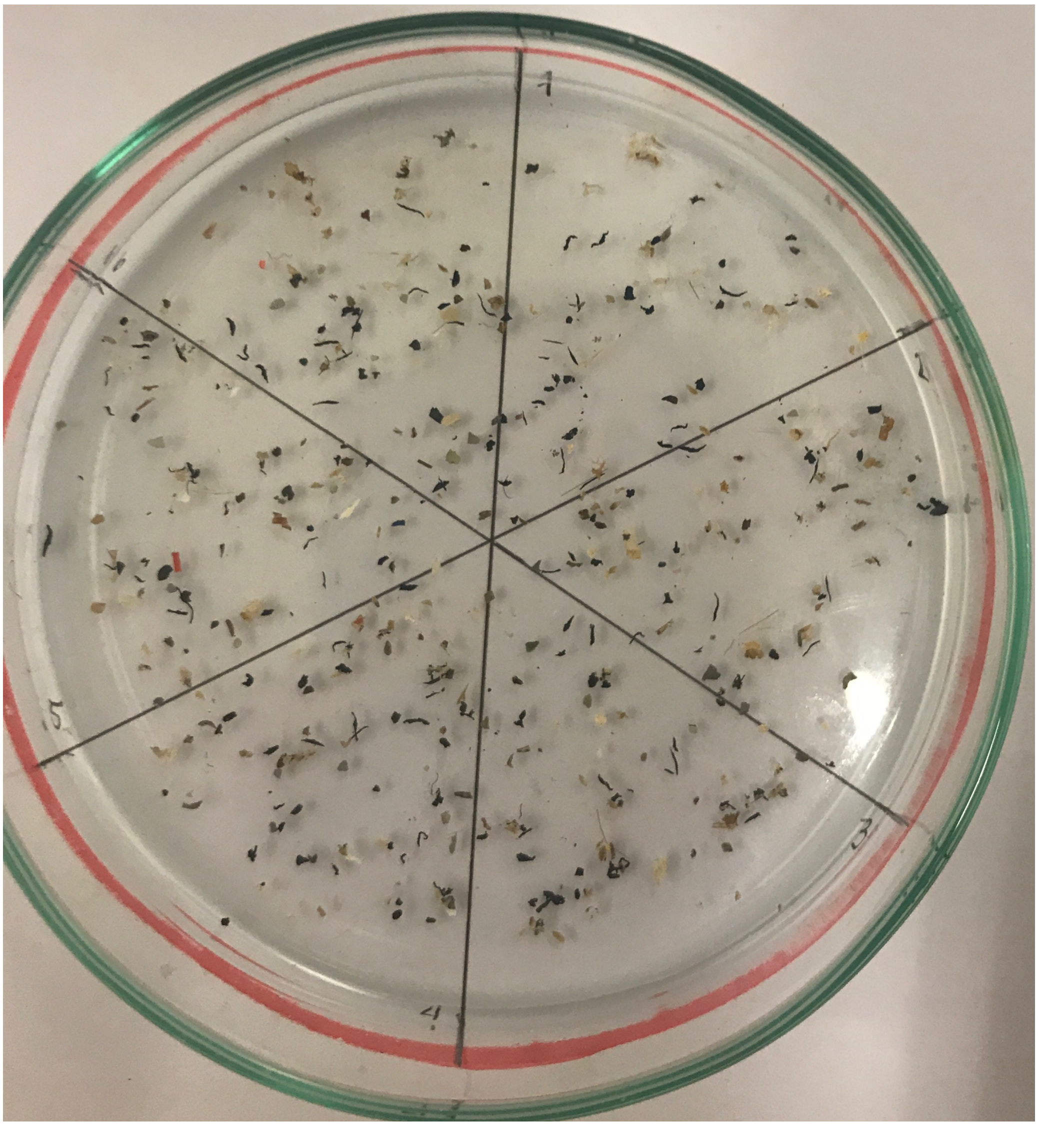


Figure S 3: The 1/6 size-fraction for Urban1S-Su.

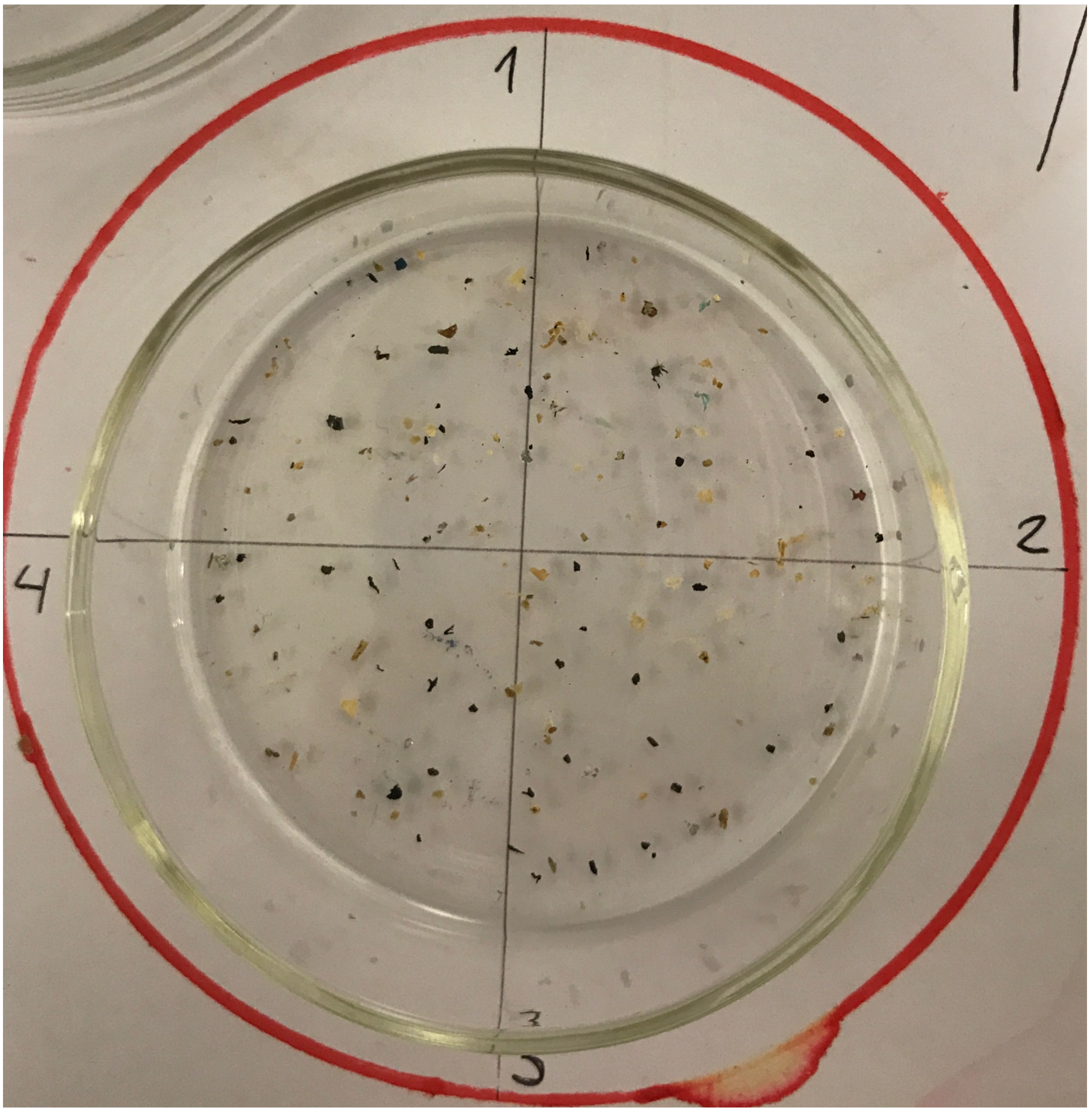


Figure S 4: The 1/4 size-fraction for Urban1S-F.

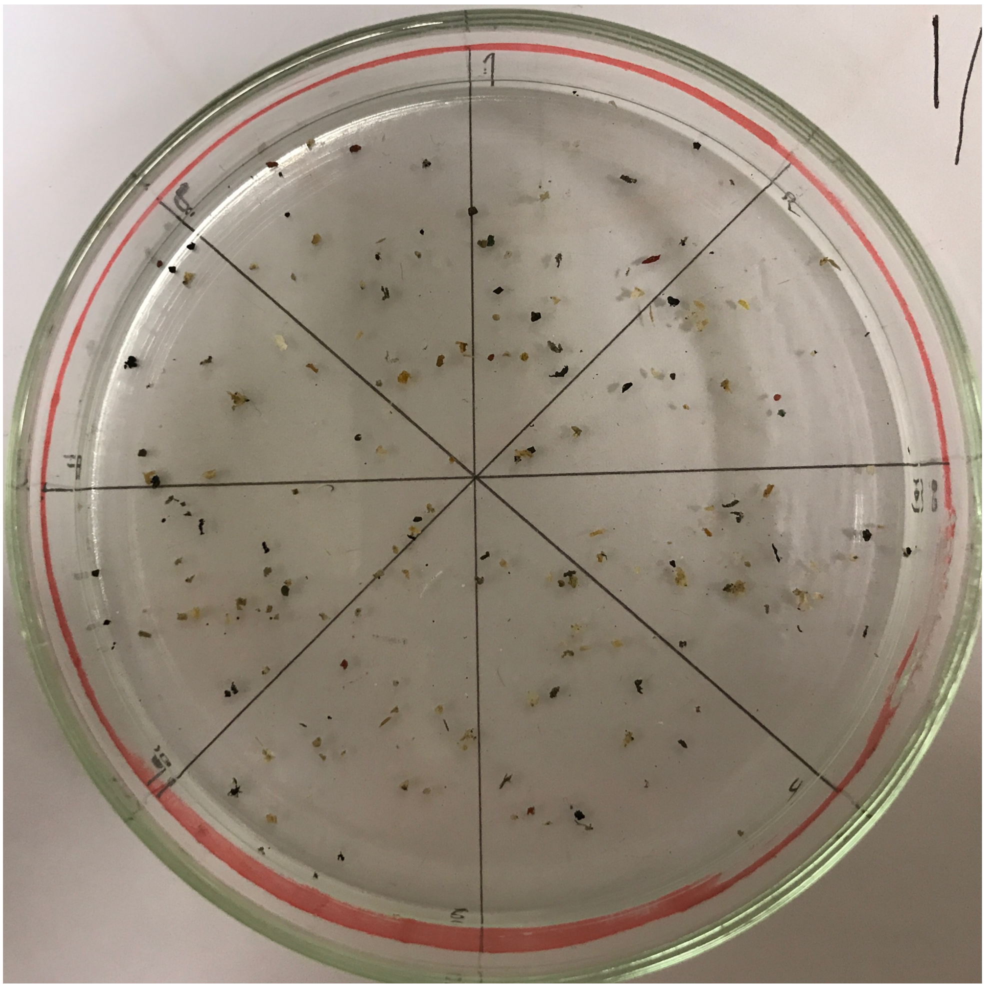


Figure S 5: The 1/8 size-fraction for Urban2S-Su.

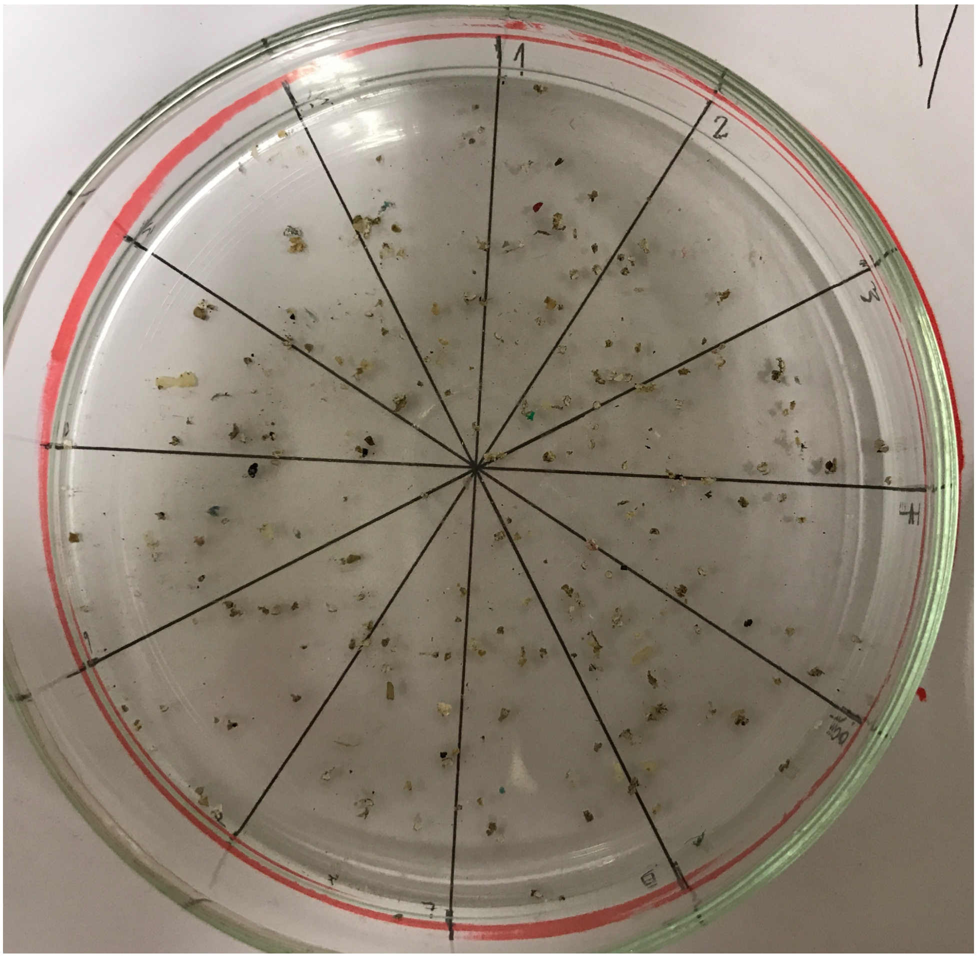


Figure S 6: The 1/12 size-fraction for Urban2S-F.

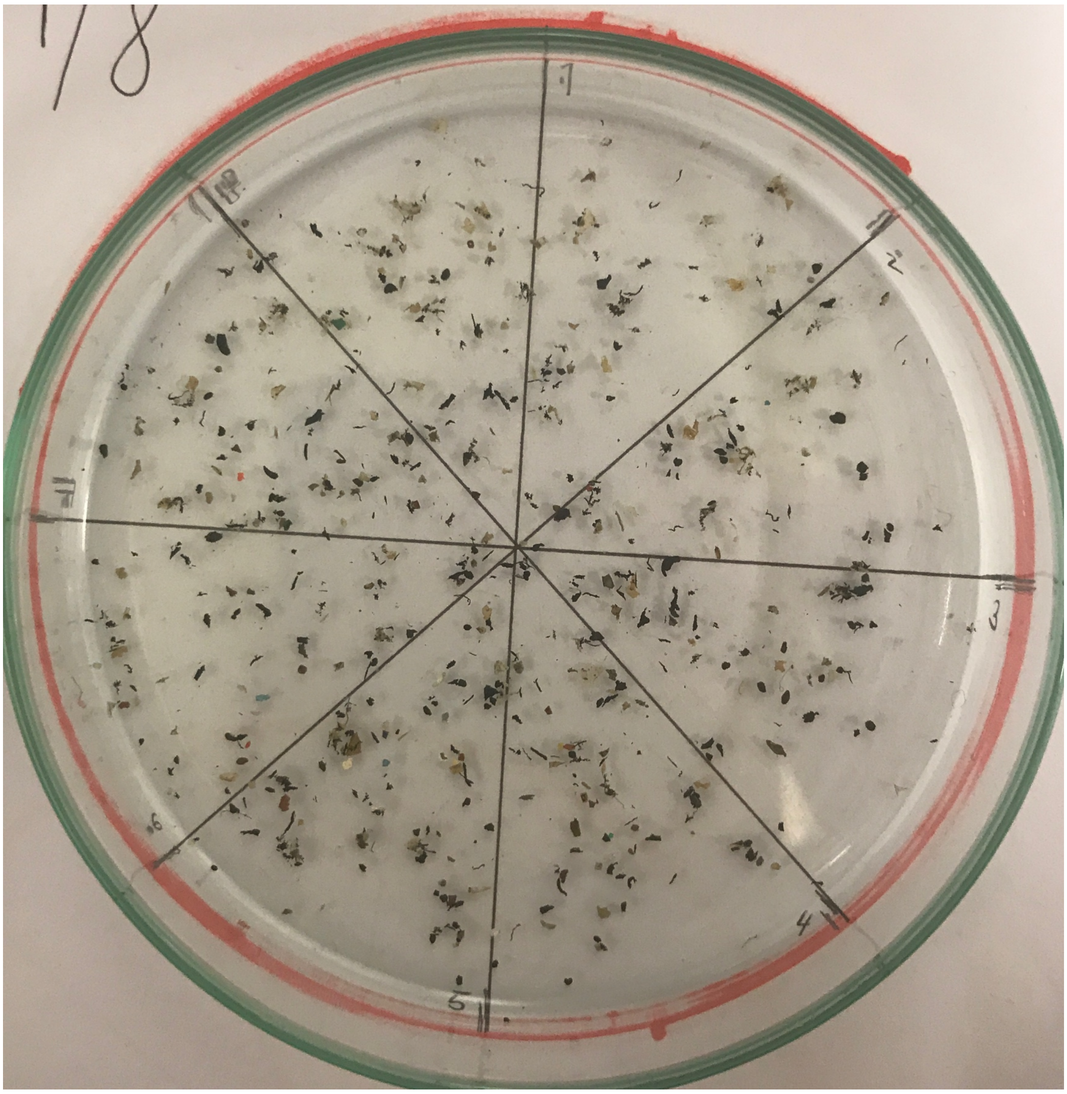


Figure S 7: The 1/8 size-fraction for Urban3S-Su.

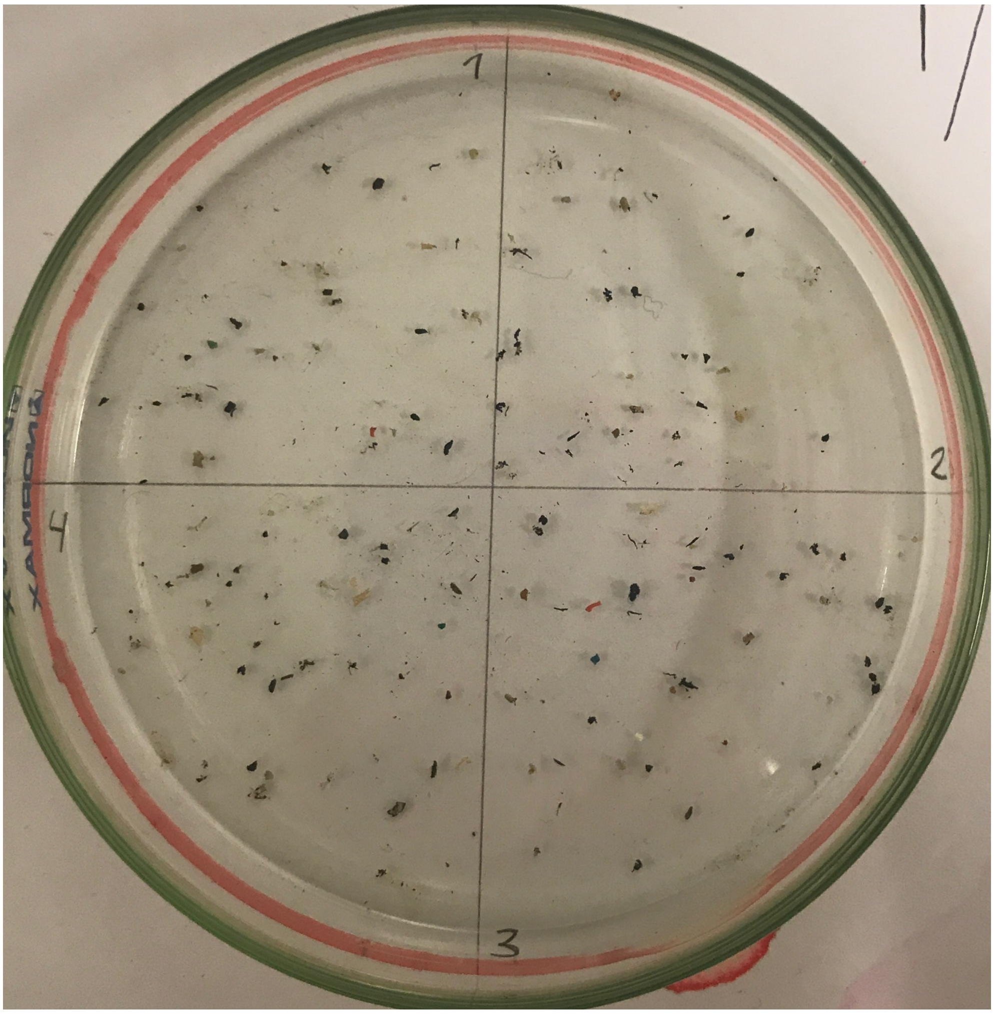


Figure S 8: The ¼ size-fraction for Urban3S-F.

Figure S 9: The 1/16 size-fraction for Urban3TR.

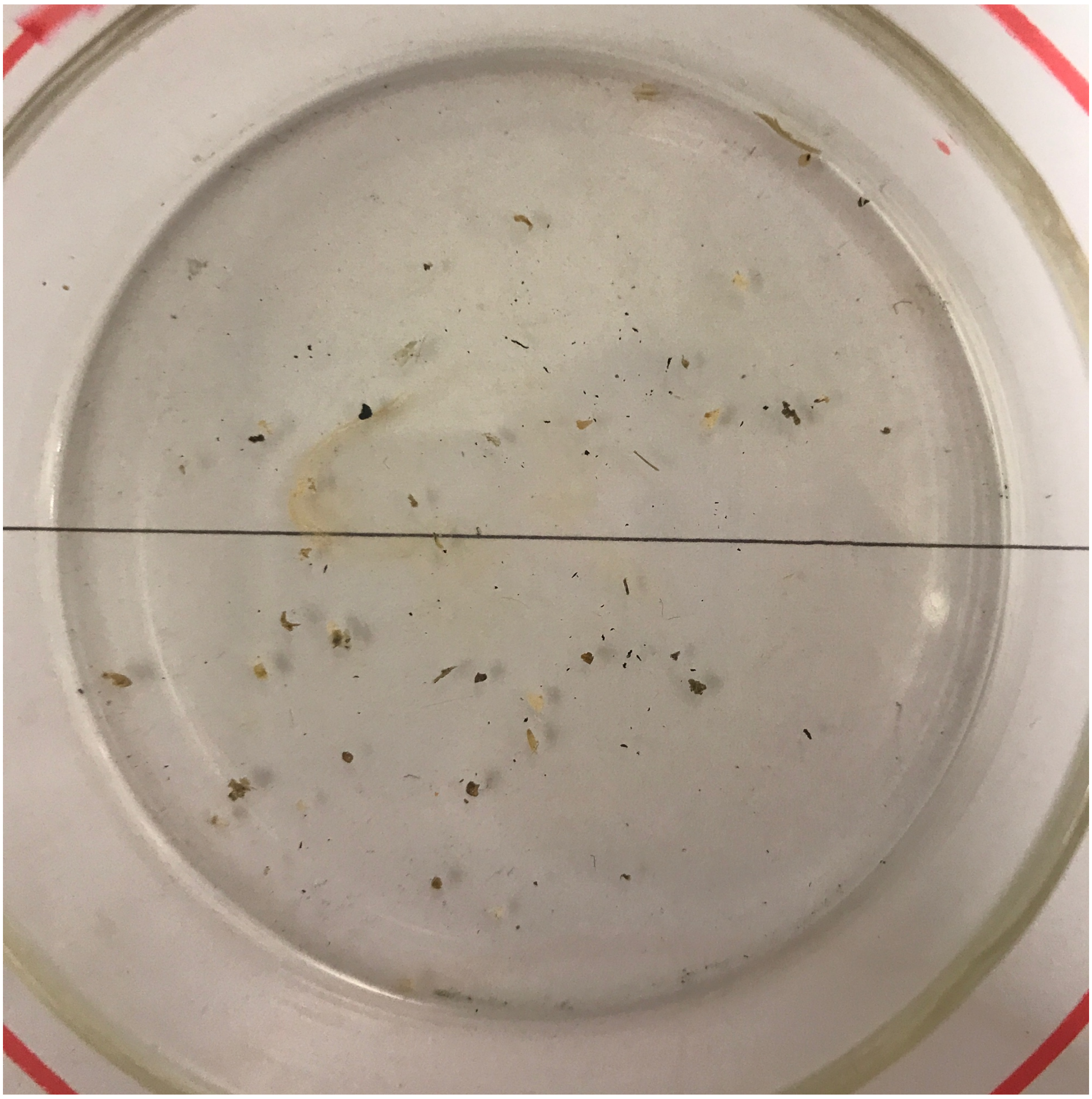


Figure S 10: The 1/2 size-fraction for Urban4S-Su.

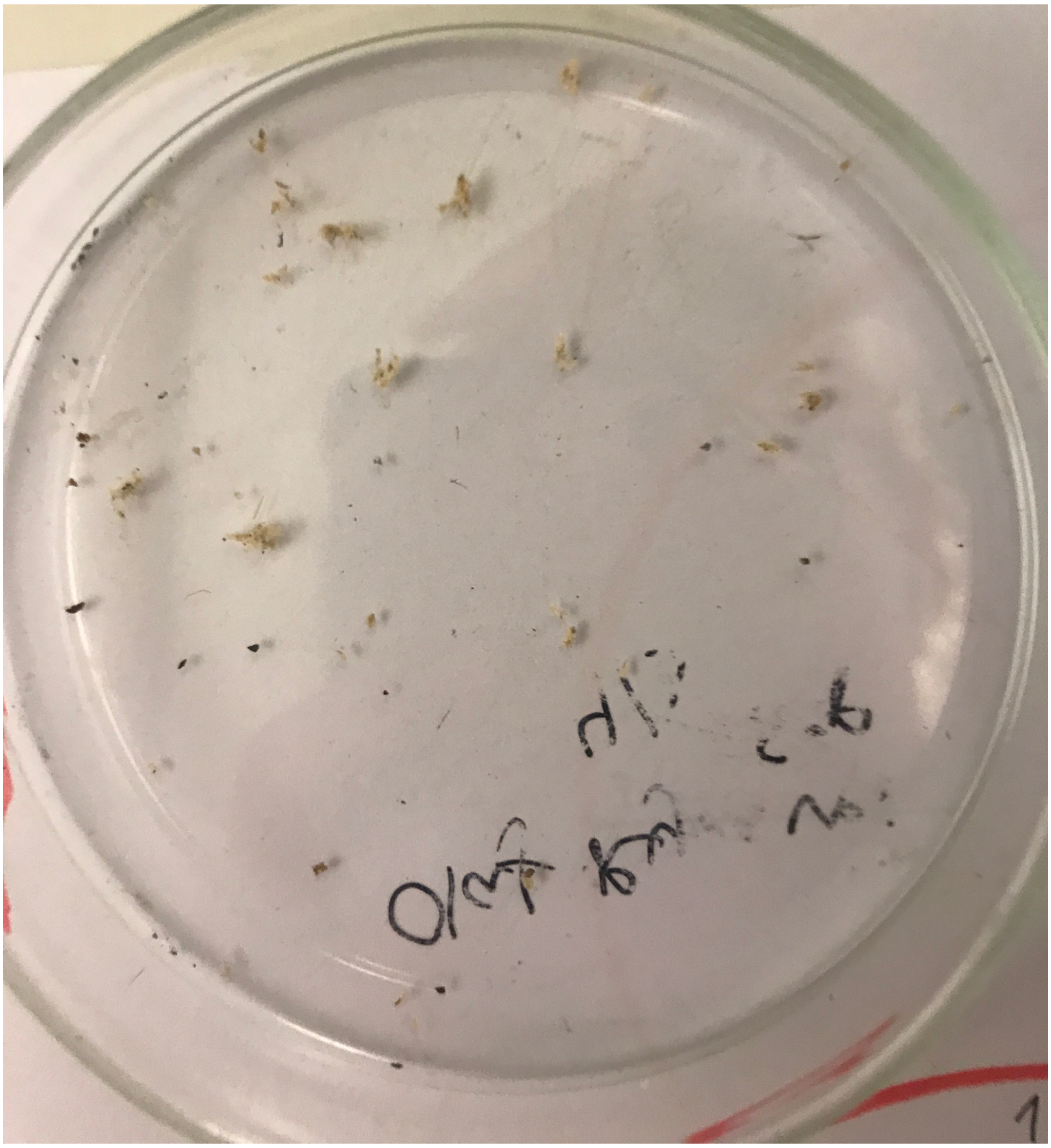


Figure S 11: The whole Urban4S-F analyzed.

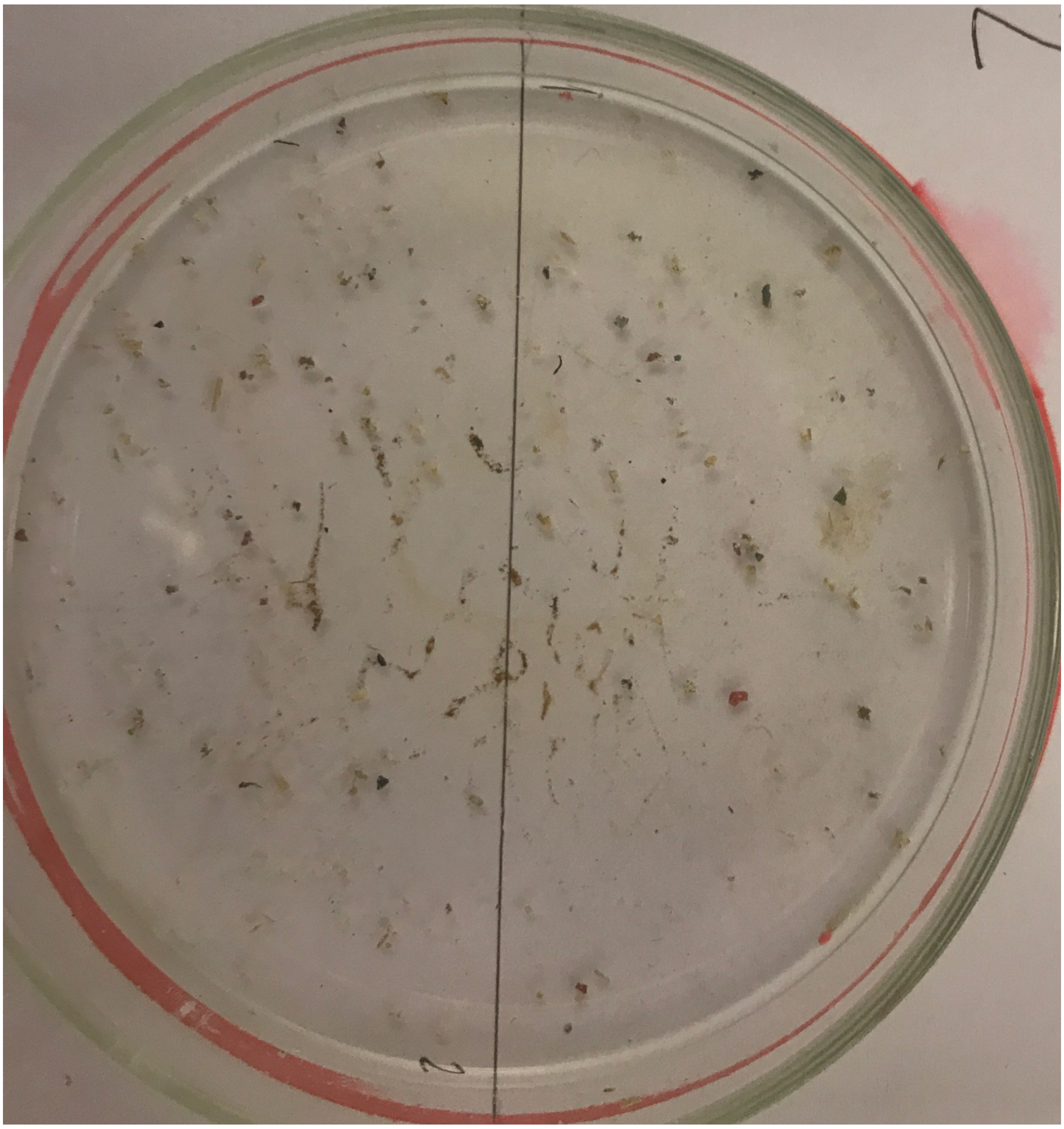


Figure S 12: The 1/2 size-fraction for Urban4TR.

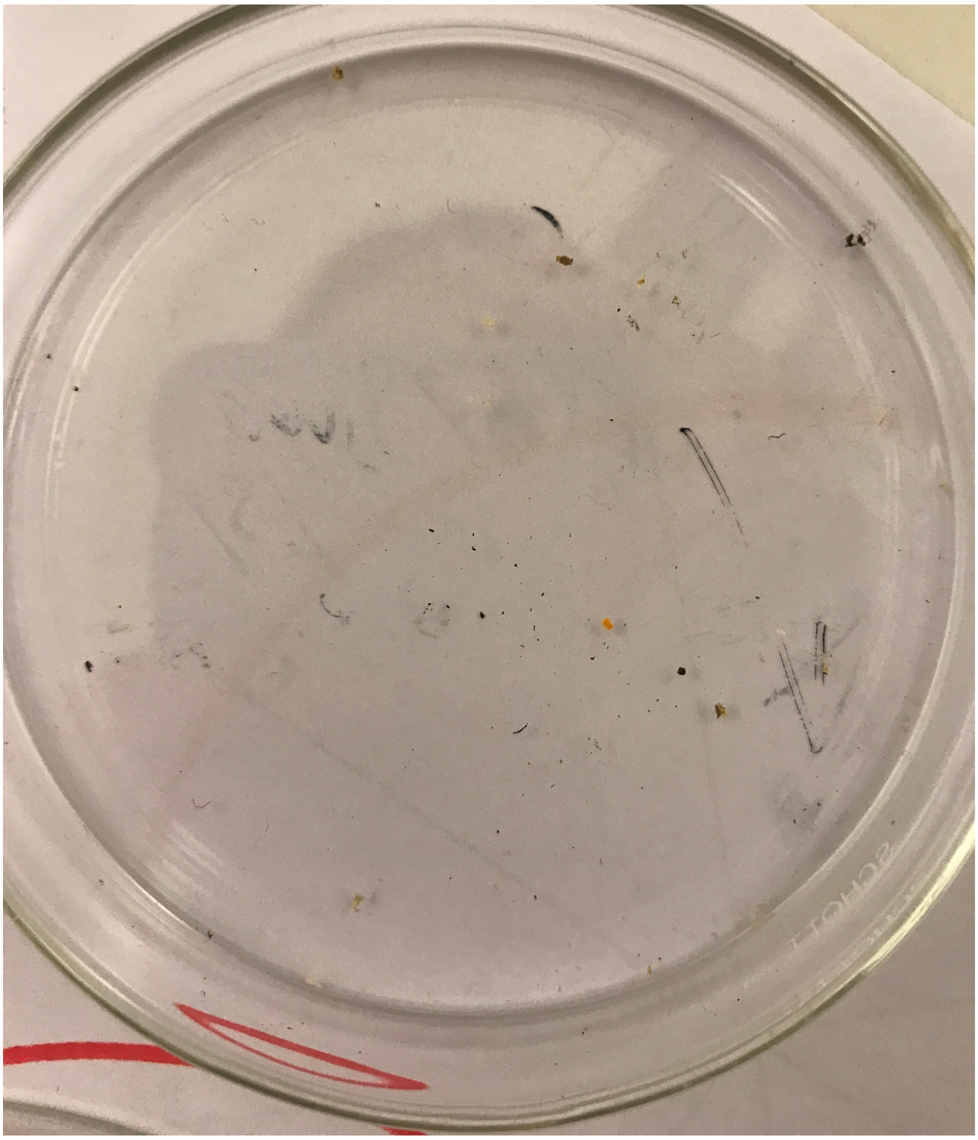


Figure S 13: The whole Urban5S-Su analyzed.

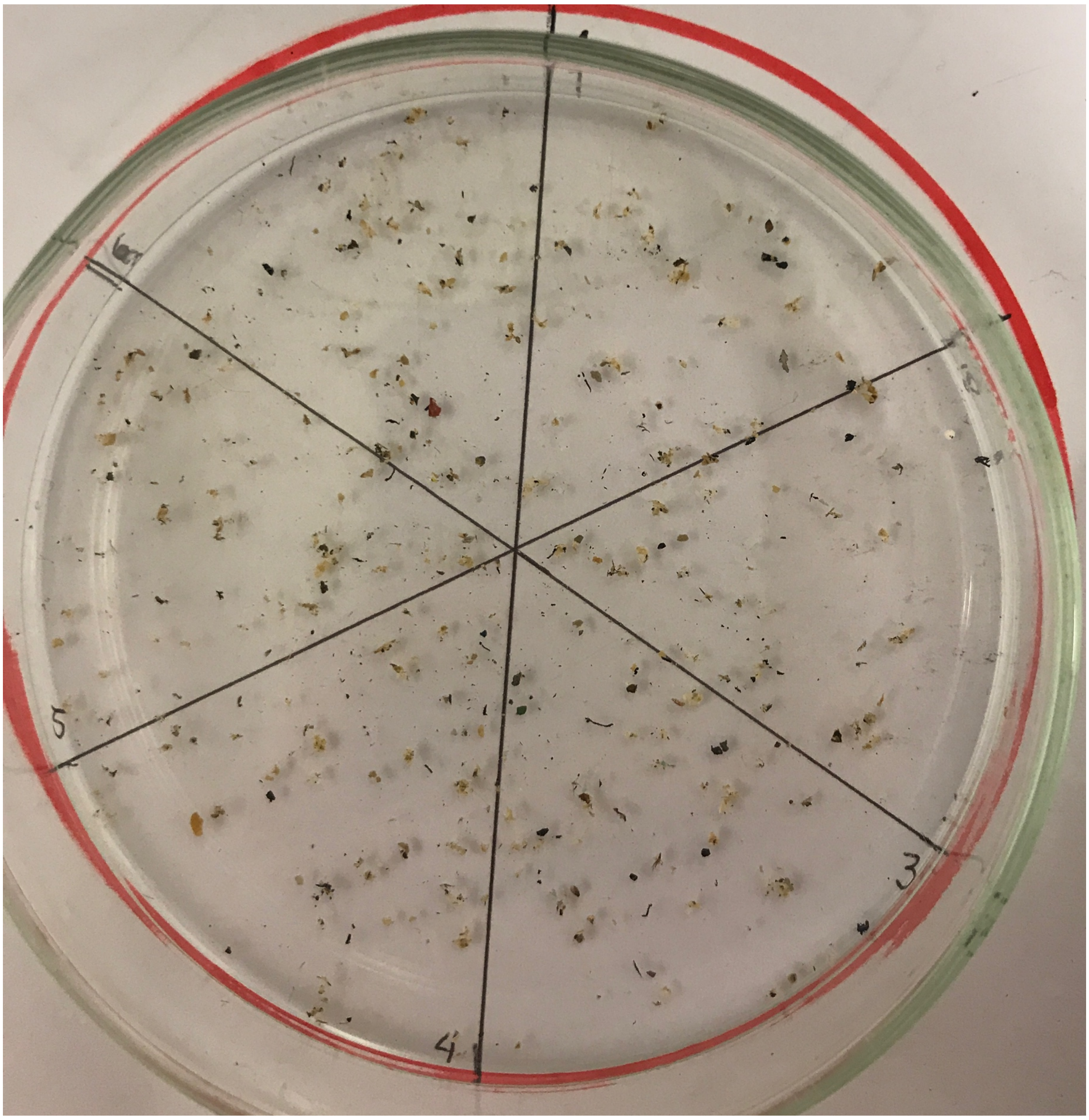


Figure S 14: The 1/6 size-fraction for Urban5S-F.

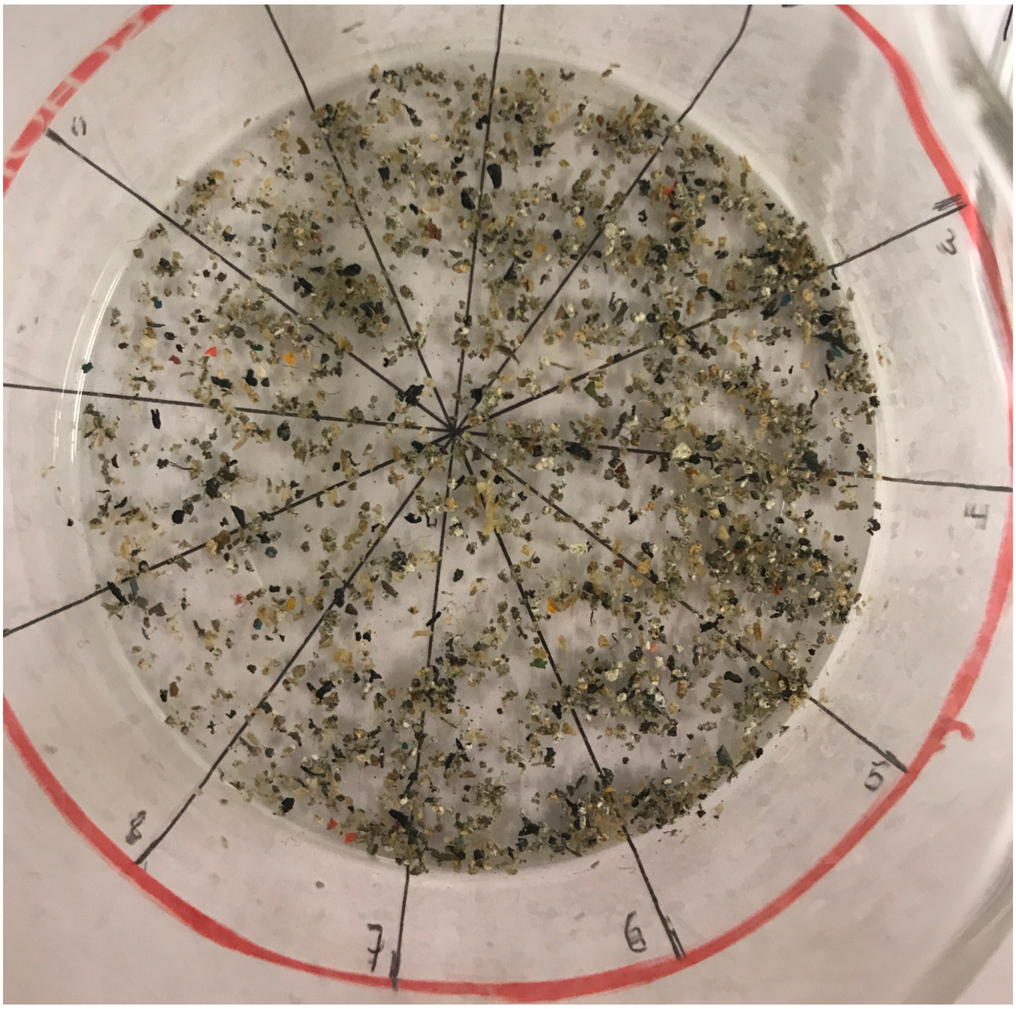


Figure S 15: The 1/12 size-fraction for Urban5TR.

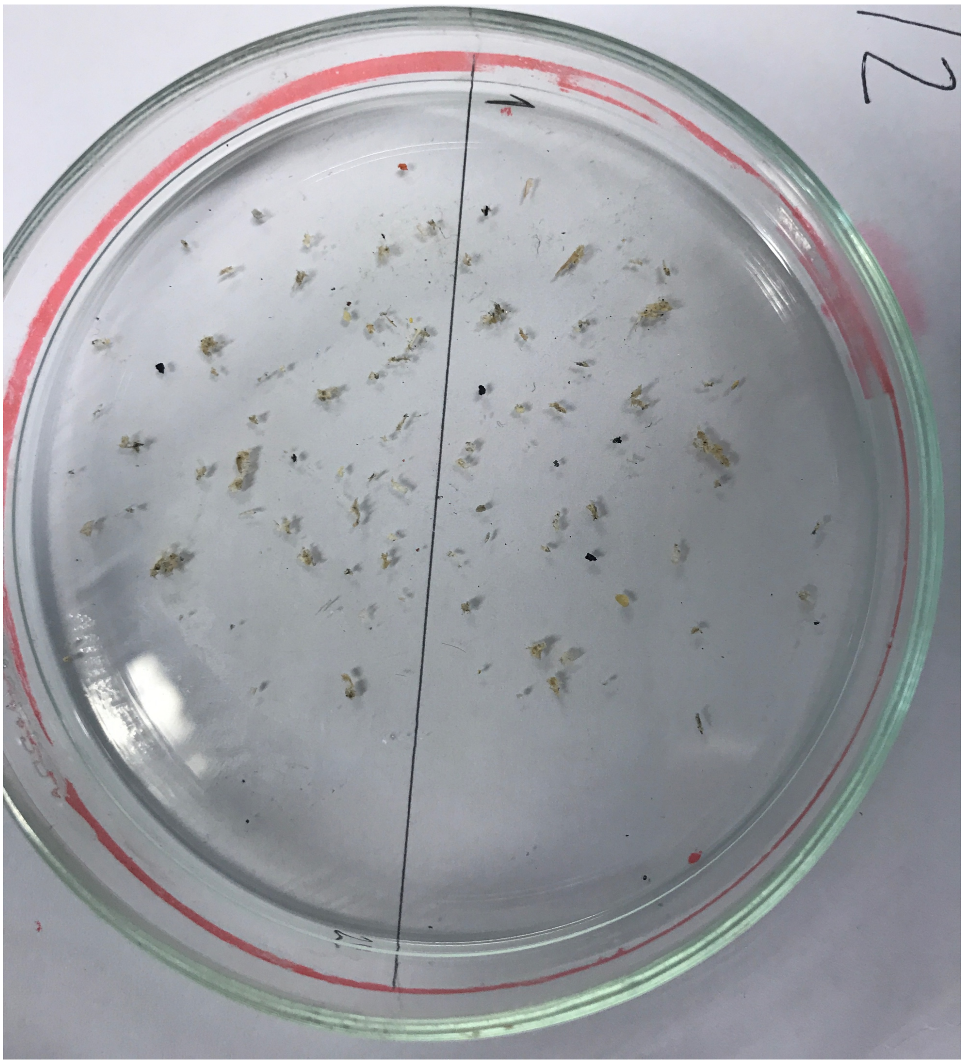


Figure S 16: The 1/2 size-fraction for Suburban1S-Sp.

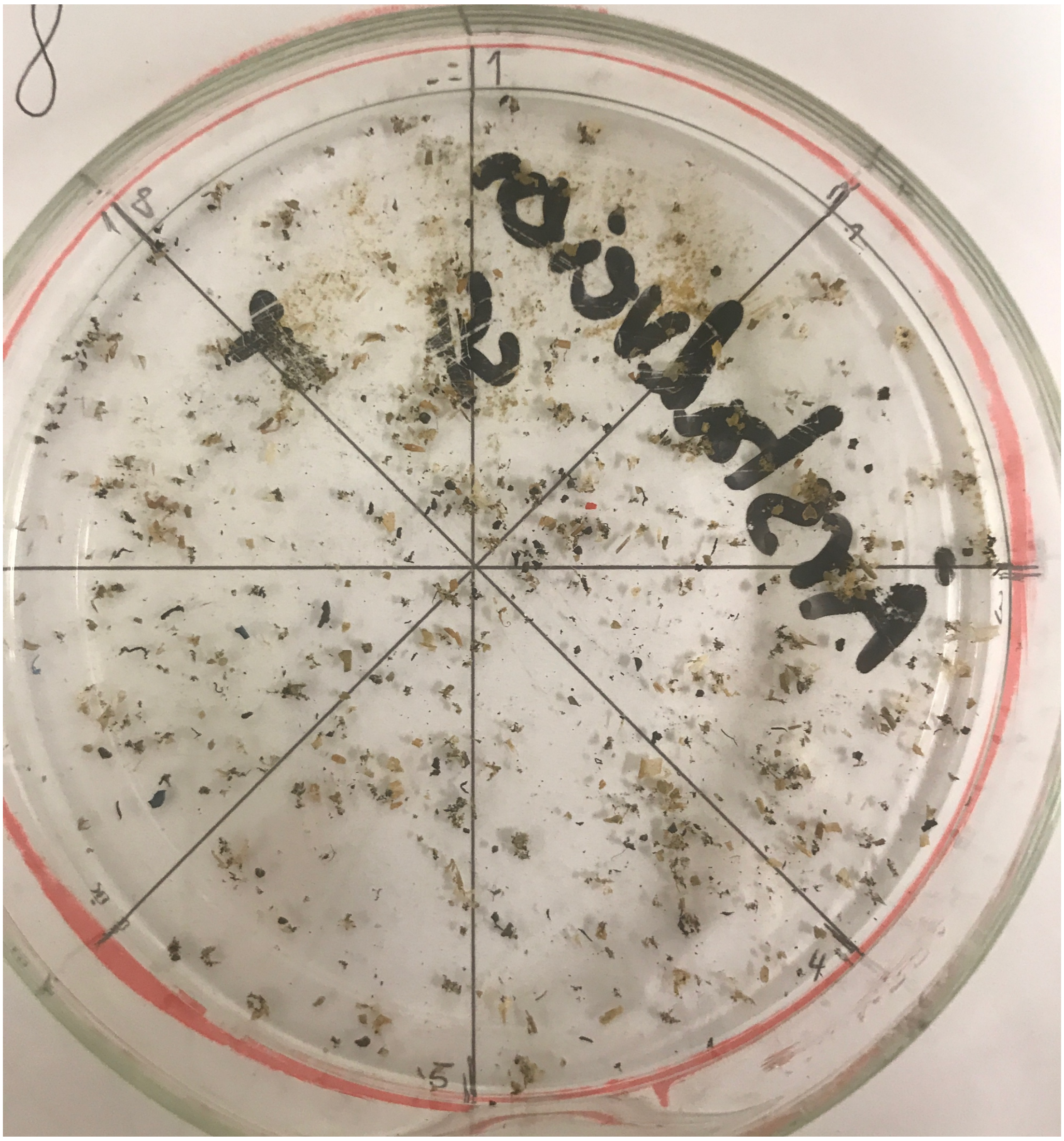


Figure S 17: The 1/8 size-fraction for Suburban1TR.

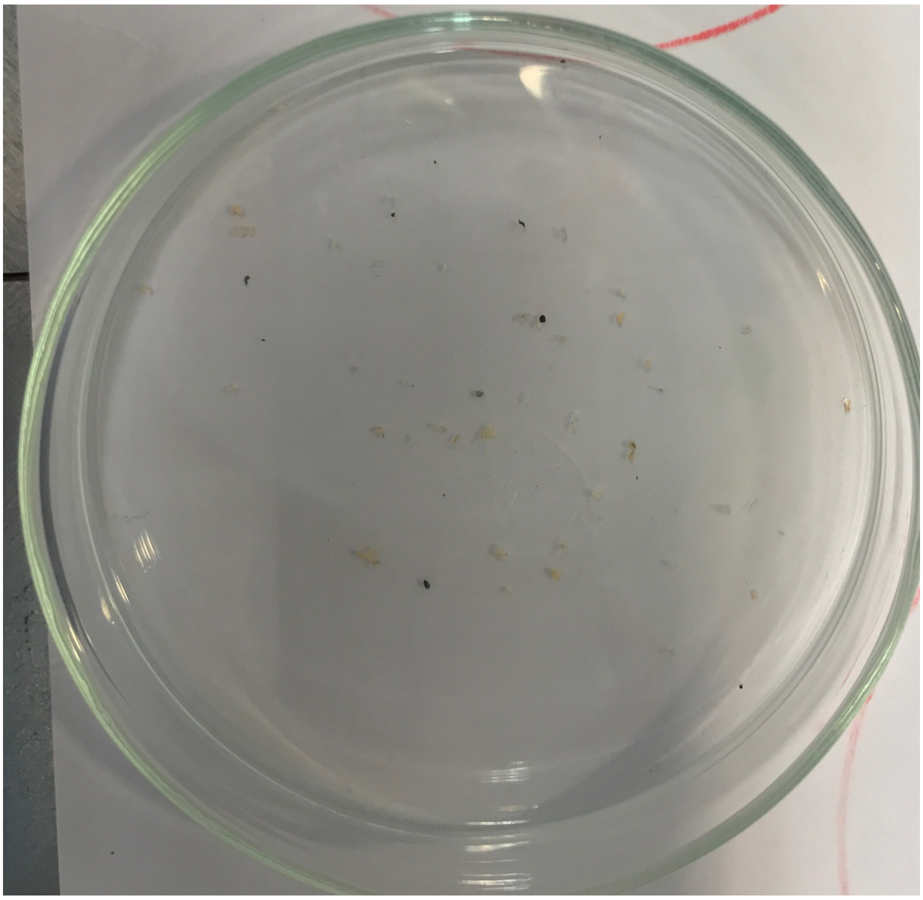


Figure S 18: The whole Suburban2S-Sp analyzed.

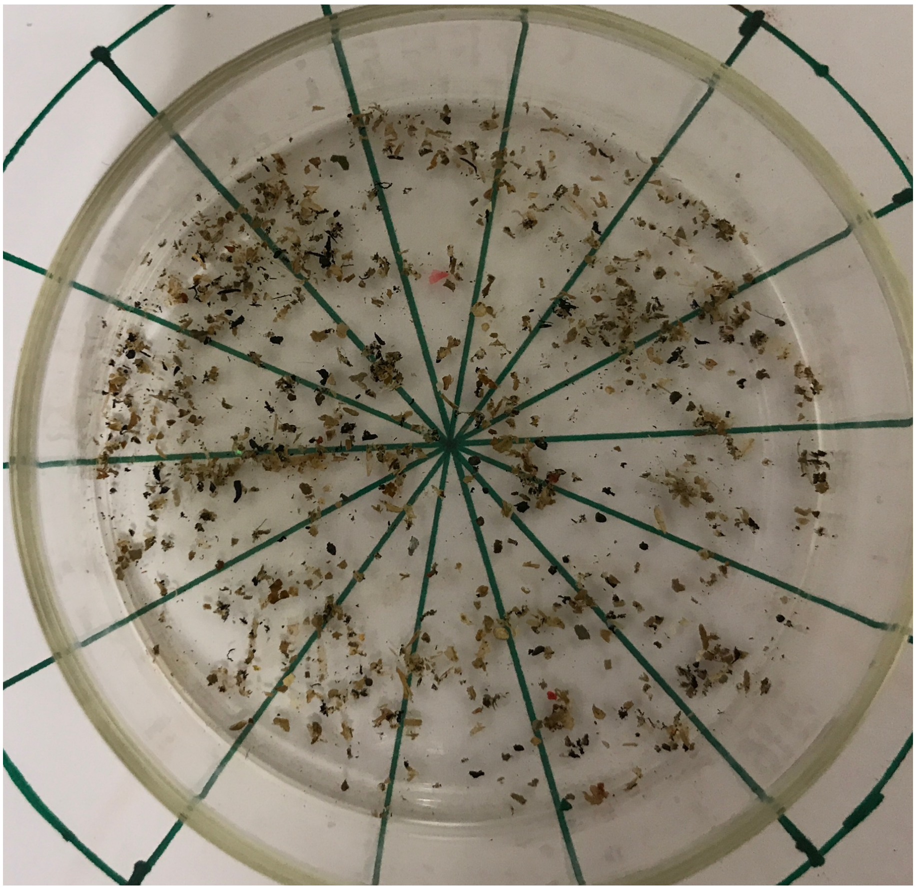


Figure S 19: The 1/16 size-fraction for Suburban2TR.

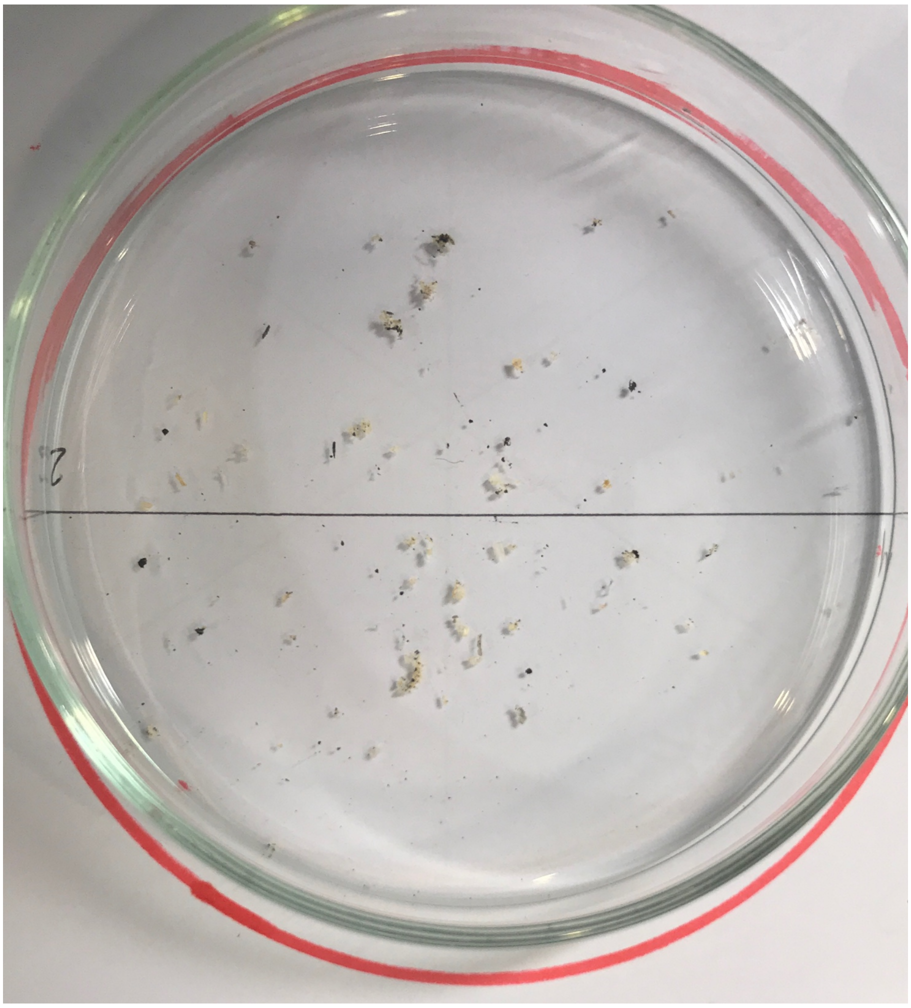


Figure S 20: The 1/2 size-fraction for Suburban3S-Sp.

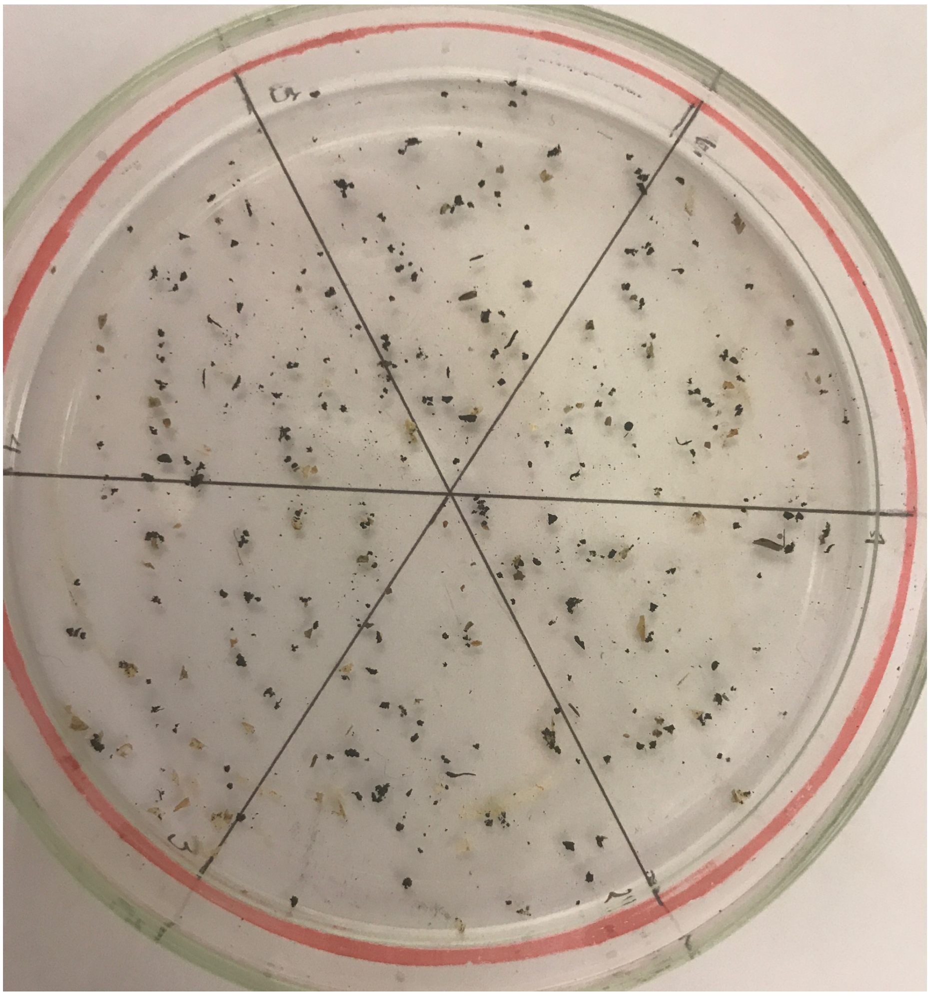


Figure S 21: The 1/6 size-fraction for Suburban3TR.

Figure S 22: The whole Suburban4S-Sp analyzed.

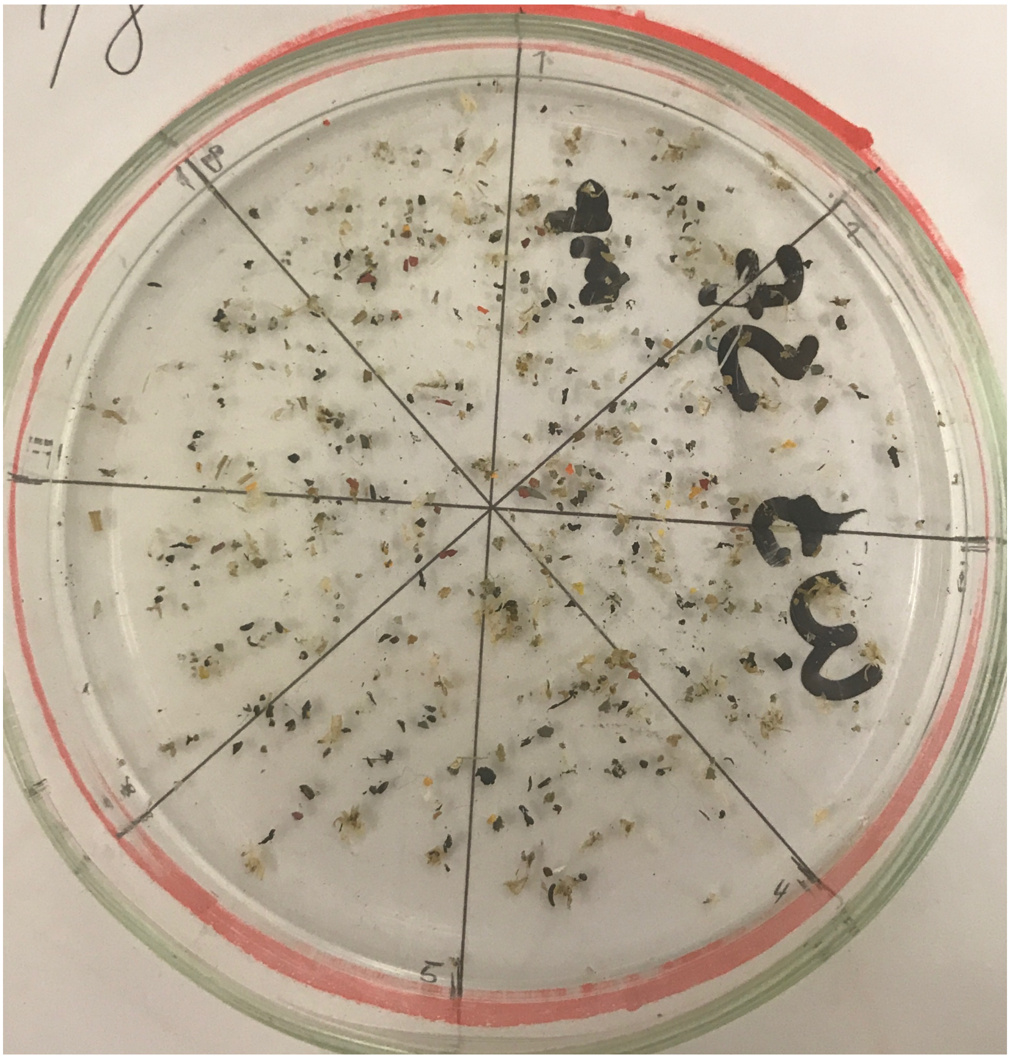


Figure S 23: The 1/8 size-fractions for Suburban4TR.

Appendix E - NETS2020 Poster

MICROPLASTIC IN THE CITIES - WHERE DOES IT COME FROM, WHERE DOES IT GO?

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The microplastic concentration in the urban environment is affected by seasonal variations and population density and quantifies the significance of cities as a hotspot for microplastic.

We studied microplastic (MP) (here defined as <1mm) concentrations from street sweepings (SS) and sand traps (ST) at nine different locations in urban and suburban Bergen (Vestland, Norway), 23 samples in total.

The MP extraction was performed by density separation with $ZnCl_2$ (1.7 g/cm^3) with a MicroPlastic Sediment Separator.

Obtained samples were purified by enzymatic and strong oxidative treatments and size-fractionated before identification.

Large MP (LMP: 500-1000 µm) were identified by ATR-FTIR, and the mass was calculated from the particle dimensions and specific density of the polymer. Small MP (SMP: 50-500 µm) were identified by Pyrolysis GC-MS.

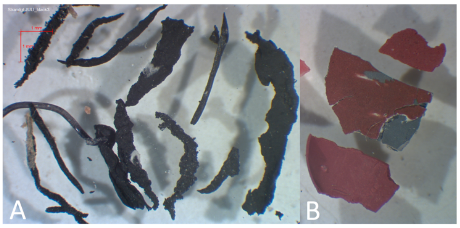
TWP dominated

Tire Wear Particles (TWP) dominated in numbers in both size-classes.

Paint particles were the second most dominant source of microplastic in the LMP size-class, identified by FTIR. Other frequent polymers were: PES > PE > PEA > PS > PMMA > PP > PVC > EP > PA66 > TPE ~ PET ~ PVA > PUR (all sites combined)

Relative polymer concentrations detected with Pyrolysis GC-MS in the SMP size-class were:

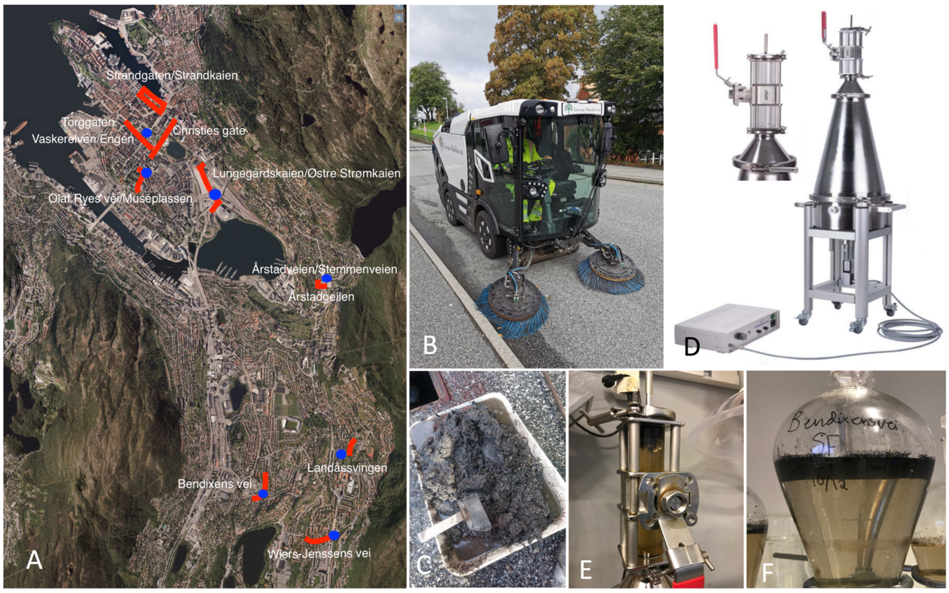
TWP > PVC > PE > PP > PA66 ~ PMMA > PS > PET in SS and ST (all sites combined).



Pictures show examples of the recognizable shape of TWP (A) and paint flakes (B)

HIGHLIGHTS

- There is more microplastic in street sweepings from the urban areas during the summer (Fig. 2)
- Sand traps may be a deposition site for dense microplastic particles
- TWP are a dominant source of microplastic in both urban and suburban areas, especially in places with much traffic.
- Blanks and controls show low contamination during analyses



Pictures show the sample locations (red lines = SS, blue dots = ST) (A), the vehicles assisting in the sampling of SS (B), a sediment sample from ST prior to analysis (C), the MPSS (Hydro-Bios) used for MP extraction (D) a sample during the second density separation, showing abundant MP and TWP particles (F)

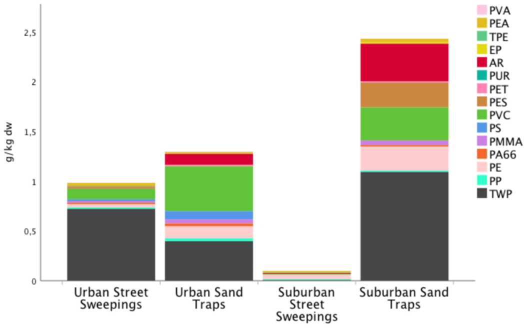


Fig. 1: Concentration of large and small MP in urban and suburban samples (µg/kg dw)

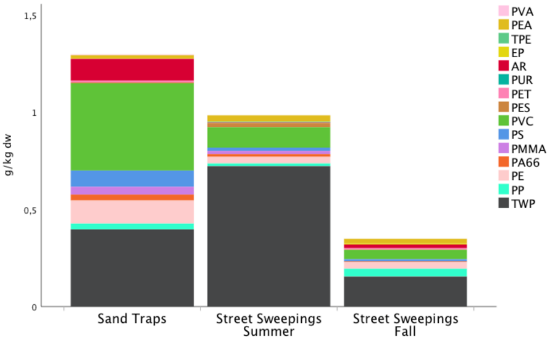


Fig. 2: Total concentration and relative abundance of synthetic polymers from urban areas in ST and SS from urban areas during summer and fall (µg/kg dw)

Microplastic concentrations were higher in urban areas

SS from urban areas had a microplastic concentration of up to 1 g/kg dw, which was higher than SS from suburban areas.

Microplastic concentrations in ST in suburban areas were, on the contrary, higher than urban areas: up 2.5 g/kg dw (Fig. 1).

The MP concentration from the summer showed a 180.9% higher average in SS compared to the fall (Fig. 2). The levels of MP in SS may be influenced by more traffic and dry weather with less run-off during the tourist season.

CONCLUSIONS

- The study adds valuable insight into sources, levels, and distribution of MP in urban areas as hotspots
- Sand traps and street sweepings contain up to 2.5 gram MP /kg dw
- Sand traps may retain the dense polymers and release lightweight particles through the discharge water
- More research is needed to conclude how microplastic and TWP behave and affect the environment

AR=alkyd resin, EP=epoxy resin, PA66=polyamide66, PE=polyethylene, PEA=poly(ethyl acrylate), PES=polyester, PET=polyethylene terephthalate, PMMA=poly(methyl methacrylate), PP=polypropylene, PS=polystyrene, PUR=Polyurethane, PVA=poly(vinyl acetate), PVC=polyvinyl chloride, TPE=thermoplastic elastomer

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