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Microplastics Pollution - A Qualitative Material Flow Analysis

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Affidavit

I, **CONSTANTIN GRIGORE MURARU**, hereby declare

1. that I am the sole author of the present Master's Thesis, "A QUALITATIVE MATERIAL FLOW ANALYSIS OF THE MICROPLASTICS ", 71 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

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Abstract

The quantity of plastic released into the environment has grown considerably in the past decades. Small plastic fragments, found in cosmetics or resulted from friction and abrasion may percolate through the sludge of wastewater treatment plants and subsequently enter the hydrosphere. While the effects of plastic pollution on animals are becoming more evident, it is uncertain if the human health is affected by this phenomenon. In order to apply a precautionary approach, it is necessary to limit the quantity of such pollutants. It is therefore of utmost importance to identify the main direct and indirect sources. Also, a quantification would also be beneficial in order to classify these pollutants.

The literature confirms that microplastics may reside in the environment for very long periods of time. Using the STAN2 software, this study designed a Material Flow Analysis that illustrates the main pathways of microplastics. Thus, from source to sink, they can enter the biofuel plants and later enter the pedosphere if the digestate or the sewage sludge is used as fertilizer. The lighter particles may become airborne or can be washed by water overflow. Lastly, most of the microplastics are discharged into the hydrosphere. Even the most performant wastewater treatment plants are unable to capture all the microplastics. In regions where no water treatment is in place, these particles can directly enter the oceans. They can be accidentally ingested by biota. Significant quantities of microplastics were also found in food sources. Using data from international statistics, this thesis quantified the potential amount of microplastics ingested by a human during one year. More than 5800 microplastics may be ingested by one individual from beer, honey, sea salt and seafood only. Around 99% of this amount is excreted. In conclusion, humans may actively contribute not only to an increase in the amount of microplastics, but they also contribute to a recirculation of the particles found in food.

Key words: Material Flow Analysis, primary microplastics, secondary microplastics, plastic pollution.

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1.Introduction

Plastics are synthetic materials, produced by processing monomers extracted from fossil fuels (Derraik, 2002; Rios et al., 2007; Thompson et al., 2009). In the past decades, the growing demand for goods and services led to a rapid increase in the quantity of plastics produced worldwide. It is estimated that the global production accounts for more than 322 million tonnes of plastics (Plastics Europe, 2016).

These durable, corrosion-resistant, versatile goods have a plethora of applications. On the other hand, due to their characteristics[1] they are also an environmental concern (Barnes et al., 2009; Sivan, 2011). Up to 10% of the waste generated on global level contains plastic (Barnes et al., 2009). Only a small share is recycled or incinerated. Thus, in nature, landfills or waste deposits, plastics can remain intact for up to 500 years (Lapidos, 2007).

Improper waste management represents an issue that leads to high amounts of plastic waste in the environment. Large plastic debris, commonly referred to as 'macroplastics', not only represent an aesthetic issue, but also a threat for tourism, marine-industries or animal life (Gregory, 2009; Moore, 2008; Sivan, 2011).

In addition, plastic residues can be unintentionally discharged into rivers or directly into the sea by anthropogenic activities. Through friction and abrasion, tyres or textiles can produce microscopic particles called 'microplastics'.

Cosmetic products, paints or adhesives, may contain tiny plastic fragments which are directly released into sewer systems. Now, the average consumer uses products that include microplastics almost on a daily basis. Despite efforts on domestic level, there is no clear international legislation with regard to the label of products that have microplastics. Some producers may take advantage of the *non liquet*[2] , while customers are not aware of the goods they are using.

Microplastics were found in oceans in the 1970s (Carpenter and Smith, 1972), however, their potential impact was not completely understood. In the 1990s, they were classified as a *minor source of plastic pollution* (Zitko and Hanlon, 1991).

Presently, the oceanic gyres form large concentrations of solid pollutants that are continuously growing in size. It is estimated that by 2050 the oceans will contain more plastic than fish (World Economic Forum, 2016).

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[1] Most importantly the slow degradation rate and the content of additives.

[2] Term originating from the Roman law, meaning "it is not clear". It refers to a subject which is not properly addressed by the legislation.
Source:http://www.oxfordbibliographies.com/view/document/obo-9780199796953/obo-9780199796953-0130.xml

Thus, the scientific community has become more and more interested in the effect of microplastics on animals and humans as well as their transport from source to sink. The diversity of the microplastics, their small size and their ubiquitous presence are three major issues. Virtually any animal species on the planet can accidentally ingest such materials. Since microplastics have small dimensions, they are generally harmless. However, due to their large surface area, in aquatic environments they form small clusters bound together by the secretion of microorganisms. Such accumulations also attract toxic pollutants, including Persistent Organic Pollutants(POPs). Therefore, the ingestion of microplastics is likely to be a vector for harmful chemicals and may affect an entire food web (Teuten et al., 2009).

The consequences of microplastics for human and animal health shall remain a priority for the scientific community. Yet, this issue is not part of the main objectives of this paper. Instead, this thesis aims at designing a qualitative and a quantitative Material Flow Analysis of the main sources of microplastic pollution. An ample literature review will serve as the foundation of this thesis. Additionally, another section of the paper will evaluate the main pathways of the microplastics ingested by humans.

1.1.Aim of the paper

The subject of microplastic pollution is a relatively new field in the scientific world. The literature contains numerous articles on quantitative analyses, trophic interactions between species vulnerable to bioaccumulation and biomagnification or toxicology. However, there is little research on the exact pathways and flows of microplastics. Such a practical analysis would demonstrate that most probably plastic particles do not travel from source to sink directly, but instead, they go through a multitude of biological cycles, physical interactions and also chemical reactions. These processes allow them to travel large distances and reside in the environment for considerable periods of time. In addition, it would be more facile to find out a contamination source and additional reasons that could cause inaccurate sampling.

Which are the possible pathways of a microplastic from source to sink?
What is the origin of a microplastic particle found on the ocean’s shore?
How to quantify the abundance of microplastics in a sample?

In practice, it might be unreasonable and impractical to investigate every single particle from a specific sink and to identify its origin. Instead, this paper will use a top-down approach in order to answer the research questions from above.

The main aim of the paper is to design a qualitative Material Flow Analysis of primary microplastics and secondary microplastics directly derived from human activities[3]*.*

This assessment will present a theoretical analytical method that will evaluate the dominant pathways. While quantitative estimations are difficult to compute and could easily lead to erroneous results, additional sections will estimate the quantities of microplastics discharged by quantifiable anthropogenic activities. Statistical data will be used for a preliminary quantification of the most relevant flows of the microplastics mentioned above.

Additional sections of the article will examine:

(1) the main factors affecting the degradation of microplastic

(2) methods used to detect microplastics in the marine environment

(3) the spatial distribution of microplastic.

While practical data is not always available, an extensive literature review allows us to combine the knowledge of different research groups in order to connect the dots between the already documented facts and the realistic hypotheses.

1.2.Definitions.Assumptions.

It is commonly accepted that microplastics are plastic fragments that are smaller than 5 mm (Andrady, 2011; Barnes et al., 2009; Betts, 2008). The lower limit of the microplastics varies from study to study, depending on the objectives of the research project, but also on the laboratory equipment used[4]. While this study attempts to include all the microplastics larger than 50 micrometers, the quantitative estimations rely on data that do not always respect this inferior limit.

The general definition of microplastics includes two main sub-categories: primary and secondary microplastics. **The primary** particles are manufactured in order to perform a specific function. They can be found in different goods, such as personal care and cosmetic products (PCCPs), where their role is to enhance the cleaning

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[3] Secondary microplastics such as particles resulted from the degradation of macroplastics in natural environments are not included.

[4] Derraik, 2002 defined microplastics as particles with sizes between 2 and 6 mm, while Ryan et al., 2009 considered all the microplastics smaller than 2 mm as microplastics.

function. In adhesives or paints, microplastics increase the adhesion or the tensile strength. There are two main pathways that lead to the formation of **secondary microplastics**. Such fragments are the result of numerous chemical, physical or biological processes that alter the structure of either macroplastics or primary microplastics. Firstly, the deterioration of macroplastics[5] may produce particles that according to their dimensions are microplastics. In addition, the degradation of primary microplastics can have the same outcome. If the degradation product is smaller than the inferior size limit, that particle can also be a microplastic. Previously, it was erroneously believed that such fragments are nanoplastics. However, nanomaterials are generally considered to be smaller than 100 nm (Koelmans et al., 2015). Thus, a clear description shall be done while defining microplastics. It is also necessary to characterize the particles above and below the size limits.

A fundamental assumption of this study is related to the impact the processes have on the material which is analyzed. From the point of view of the definition, the distinction between primary and secondary microplastics remains clear. Yet, in reality, most of the synthetic goods are subject to stress factors that have the power to modify their chemical or physical properties. The alteration of their structure would automatically make any particle a secondary microplastic. As mentioned in the introduction, *there is no clear scientific agreement on when exactly does a primary microplastic become a secondary one.* This demarcation could take into account a difference in the mass, density, chemical structure, or even all three factors.

A distinction between primary and secondary microplastics is necessary because of the following reasons.*Firstly*, secondary microplastics are believed to have a higher degree of toxicity due to their previous exposure to abiotic and biotic factors.

Secondly, microscopic observation has shown that primary microplastics found in the hydrosphere have the same visual characteristics when compared with the microplastics found in PCCPs.

Such an evaluation could reveal that primary microplastics are more persistent in the environment. *Lastly*, while the total amount of plastic waste discharged into the environment is difficult to measure and to collect, the elimination of primary sources from goods is possible and achievable. For policy makers, it is therefore useful to know precise facts and figures on the abundance of primary microplastics.

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[5] Plastic fragments larger than 5mm.

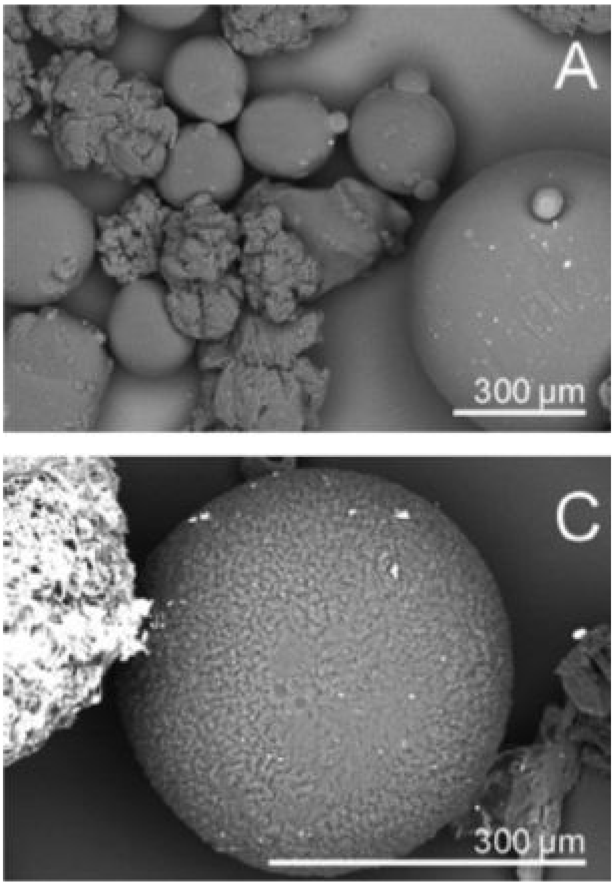

Figure 1. Visual comparison between polyethylene microbeads found in PCCPs (A) and a spherical microplastic found in Lake Erie (C).
Source: Eriksen et al. 2013.

1.4.The structure of the paper

This document is structured into six main chapters, each containing several additional sections. Firstly, the **2.Methodology** presents the characteristics of the instruments necessary to design a comprehensive quantitative and qualitative Material Flow Analysis. The summary of the literature review consists of fundamental theoretical information on the origin, uses and properties of microplastics and plastics in general. Also, the relevant findings include three illustrative studies (Desforges et al., 2014; Dubaish and Liebezeit, 2015; Eriksen et al, 2013) which offer complex answers to quantitative questions and elaborate on sampling techniques. Moreover, these studies also reflect the results of research projects which took place in different environments and conditions. Such a comparison is relevant for a possible assessment on global level, as well as regional trends. For a better understanding of the processes that affect the transport of microplastics from source to sinks, but also the stress factors that may have an impact on them, it is of utmost importance to have a minimum knowledge of the mechanisms taking place on macro and micro level. While biotic and abiotic degradation play a fundamental role, the properties of the polymer itself are also important.

The **5.Results** section presents the Material Flow Analysis. Concurrently, the detailed assessment of the transport of microplastics from source to sink is done taking into account the most probable intermediary sinks. Two of these sinks are the sewage sludge and the pedosphere. The potential uses of the sludge may modify the flows of microplastics. On the other hand, the absence of a wastewater treatment plant allows the pollutants to move directly from source to the hydrosphere. Lastly, the waste disposal method applied by a community can end the flows of microplastics[6], or may create an isolated sink[7].

It is also relevant to present potential impact of microplastics on biota on humans. Thus, the last section of chapter **6.Discussion** briefly presents a preliminary quantitative estimation of the microplastics ingested by an average citizen of the world.

2.Methodology.

2.1.MFA

An analysis of the sources and sinks of a specific pollutant is complete if and only if the pathways are thoroughly investigated. From production to discharge, there can also be numerous intermediate accumulations where the contaminant concentrates. On the other hand, there might be processes that have the potential to alter its properties or degrade it completely. It is therefore important to characterize not only the quantities of a pollutant that enter and leave a system but also its flows and sinks. Such a complex map can help specialists as well as ordinary citizens to have a better understanding of the flows and processes that have or may have an impact on this specific pollutant.

A Material flow analysis (MFA) serves as a very useful instrument to design the pathways of a substance or material[8]. It represents a comprehensive evaluation of

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[6] 6.4.2.Incineration

[7] 6.4.1.Landfilling

[8] Brunner, P. H, and Rechberger H. Practical Handbook Of Material Flow Analysis. 1st ed. Boca Raton, FL: CRC/Lewis, 2004.

the processes and flows that connect the sources, the stocks and the sinks. The limits of such a system can be temporally and spatially defined.

This paper will evaluate the flows of primary microplastics and the main flows of secondary microplastics derived from anthropogenic activities. Primary microplastics can enter the hydrosphere and the pedosphere directly from wastewater. Indirect sources, considered by scientists primary microplastics that are unintentionally discharged, will be considered secondary microplastics.

There are four essential terms which have to be defined. Firstly, a **stock** represents the accumulation of a quantity following the transition to a process. It is generally defined in kilograms, however, a generic analysis does not require a specific unit. The input and the output are connected by **flows**. The matter that enters the system is also called **imports**, while the substances leaving the diagram are **exports**. The impact a specific action has on the flows is called **process.** A process is generally defined as mass per time, yet it can also describe a phenomenon that creates one or more additional flows, as well as supplementary sinks. Lastly,the whole system is enclosed by the **system boundary**. This frontier represents the temporal and spatial limits.

While the qualitative analysis does not require a specific unit or a temporal boundary, the qualitative analysis will be done using values expressed in tons/year. The preliminary MFA on the microplastics ingested by humans will analyse the units of [microplastic particles] that enter the human body per year.

To design the MFA, the STAN 2 software will be used[9].

2.1.1.The boundaries of the analysis

Despite general agreement on the description of microplastics, there is no standardized definition (EFSA CONTAM Panel, 2016). This issue makes quantitative comparisons difficult. Also, it has consequences on the accuracy of a Material Flow Analysis that uses data from various sources. The controversies come from the different sizes and types of synthetic polymers that belong to this category. A more broad definition could lead to an overestimation, while a limitation of the general description might reveal an undercount. A disadvantage of the present estimations is that the inferior size limit of microplastics varies. Additionally, there are studies that include all the microsized plastic fragments derived from human activities in the category of primary microplastics. This controversy stems from the fact that microplastics resulting from

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[9] Stan2web.Net. Last modified 2017. Accessed May 31, 2017. http://www.stan2web.net/.

wear and tear are neither specifically produced to perform a function, nor the product of degradation processes in natural environments per se. Such a classification would include textile particles, degraded tyre rubber or urban dust. Nonetheless, this categorisation is inconsistent with the common definition of primary microplastics, which states that the particles have to be produced in order to carry out a concrete role, as individual particles and not as part of a different item. Since the wear and tear particles are unintentionally released into the environment, they do not belong to the class of primary microplastics. Indeed, the definition of primary pollutants underlines that these chemicals are emitted directly from a source and enter the environment in the form they are produced.

On the other hand, secondary pollutants develop as a result of environmental stress applied on a primary pollutant. Thus, a microplastic which is derived from a larger object and it is not precisely produced in order to perform a particular function can not be a primary microplastic per se and shall be therefore considered a secondary microplastic. Nonetheless, there are four main reasons why it is important to use an inclusive and flexible approach.

Firstly, it is almost impossible to decide whether a primary microplastic remains intact or undergoes degradation as it enters the environment. Studies acknowledge that the deterioration takes place at a very slow rate, yet, it is difficult to conclude if a primary microplastic remains undamaged after a specific period of time or not.

Second of all, if a primary microplastic is subject to stress factors that cause a slight change in its properties, that particle will theoretically become a secondary microplastic. Yet, it would be a laborious process to distinguish between two identical secondary particles, one of them derived from a primary microplastic, while the other is the result of wear and tear.

Thirdly, both primary and secondary microplastics are likely to end up being degraded, thus from the toxicological point of view, they will a similar behaviour. The main concern is that once microplastics enter the hydrosphere, they form small clusters which are bound together by the secretion of microorganisms. Such aggregates act like a sponge and have the potential to attract high quantities of persistent organic pollutants (POPs), aromatic compounds and many other harmful chemicals. Once formed, these fragments can be eaten by biota. The plastics can temporarily reside in the body of the animal, while the other toxic chemicals can biomagnify in the trophic web. Thus, it is already known that POPs have detrimental consequences for the human and animal health (WHO, 2006). On the other hand, small quantities of microplastics can be excreted without causing significant harm. The individual impact of primary and secondary microplastics on health remains subject to further research.

Last but not least, the majority of the secondary plastics are the direct consequence of improper waste management strategies. By definition, most of these actions represent illegal activities and they occur due to poor law enforcement or deficient environmental education. It is expected that rigorous and inclusive policies could increase environmental awareness. The consequence should be a sharp decrease in the quantity of macroplastics discharged into the environment and implicitly less secondary microplastics derived from these sources. On the other hand, diminishing the volume of synthetic textile fibers or urban dust[10] requires drastic behavioural changes. Textiles should be produced exclusively from biodegradable sources, while the entire tyre industry should be reformed.

2.2.The methodology of the literature review

In the absence of practical measurements, this paper uses data from the present literature on microplastics, as well as national and international databases.

Three main types of literature review were carried out. Firstly, an exploratory literature review was done in order to identify the state of the art. Such a technique is necessary to find out the potential research gaps. Secondly, the evaluative review aimed at collecting the current data on the content of microplastics in goods, potential secondary sources and the abundance of microplastics in sinks. Lastly, the instrumental review laid the foundation for the Material Flow Analysis. Using the knowledge from the evaluative review, the instrumental analysis comes up with a series of techniques employed for quantitative estimations.

3.Current knowledge about the main sources of microplastics

A recently published IUCN report includes seven main sources of primary microplastics, arranged in two classes depending on how anthropogenic activities release these particles. The first category includes plastic microbeads, which are considered to be intentionally discharged into the environment (Boucher and Friot, 2017).

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[10] Primary microplastics discharged unintentionally, as defined by the IUCN.

On the other hand, the other six sources refer to synthetic fibers, plastic pellets and other microplastics that result from abrasion, weathering or involuntary actions. These pollutants are seen as primary microplastics that are unintentionally discharged. It is noticeable that some of the sources included in the second class of primary microplastics as defined by the IUCN report should have been considered secondary microplastics. As mentioned above, most of the particles which are subject to physical, chemical or biological stress might change their structure and implicitly their properties. In reality, the biotic or abiotic interactions have the capacity to shape a primary microplastic without significantly changing its molecular mass or observable characteristics. However, according to theoretical considerations, a chemical reaction of a microplastic could mean the loss of one single monomer, which would make the particle a secondary microplastic.

Taking into account the facts mentioned in above, a complete analysis of the flows of primary microplastics shall be done in parallel with a study on secondary microplastics directly derived from anthropogenic activities. This approach would clarify some of the uncertainties regarding the origin of the diverse family of secondary microplastics.

3.1.Microplastics intentionally released into the environment

3.1.1.Personal care and cosmetic products (PCCPs)

PCCPs represent the main category of primary microplastics that are intentionally released into the environment. There are two key issues related to the microplastics found in PCCPs. Firstly, the diversity of such goods makes them appropriate for a wide range of uses in households, hospitals or tourism activities. Hence the challenge of identifying the exact pathways of these chemicals. Secondly, the complicated scientific names written on the labels of these products can easily mislead the customer. So far, despite efforts on domestic level, there are no clear international standards with regards to the products which contain primary microplastics.

Depending on their end use, some products contain circa 10% microbeads or up to thousand particles per gram (Lassen et al., 2015). It was estimated that in Germany, the per capita emissions of microplastics originating from PCCPs is 6.2 g/year (Essel et al., 2015). An Euromonitor came up with a similar per capita value: 6.4 g/year (Lassen et.al., 2015). A different study concluded that in the US, every citizen emits less than 1 g/year (Gouin et al., 2011).

Not all the microplastics found in PCCPs are released to sewage. Around 5-10% remains in the package, which subsequently ends up in the municipal solid waste (Lassen et al., 2015). The rest is discharged into the waste water. A negligible percentage used in products such as sun creams may enter the hydrosphere or the pedosphere (Lassen et al., 2015).

3.1.2.Microplastics unintentionally released into the environment

3.1.2.1.Plastic pellets

Many plastic polymers are fabricated in the form of pellets or powders, having a diameter of 5mm or less. Subsequently, they are traded, transported and processed accordingly. During this entire chain, the pellets can be accidentally discharged into the environment (Essel et al., 2015).

A study done in Norway concluded that the emission factors of plastic powders and pellets is 0.04% of the quantity produced (Sundt et al., 2014). In Germany, between 0.1 and 1% of the pellets are believed to be lost (Essel et al., 2015). An OECD emission scenario document (ESD) from 2004 estimate that the default emission factor for plastic powders larger than 40 μm is 0.25% (OECD, 2004).

3.1.2.2. Synthetic textiles

Synthetic textiles can release a high amount of fibers due to abrasion and shedding. These materials can easily penetrate most of the filters of a wastewater treatment plant (Browne et al., 2011), entering the rivers and the oceans. To determine the quantity of fibers that enter are discharged into the environment from washing textile clothes, it is necessary to have a rough estimation of the total mass of the clothes. These assumptions are very variable.

It is nonetheless known that synthetic fibers cover almost half of the total production of textiles (WRAP,2012). Sundt et al., 2014 estimates that more than half of the textiles from Norway are derived from plastics. Thus, it is reasonable to assume that around half of the textiles are made of synthetic products.

Another possibility would be to calculate the mass of fibers released by washing machines. It was found that after washing a polyester product with a mass of 660g, up to 260 mg fibers were released (Dubaish and Liebezeit, 2013). Depending on how often such a good is washed, up to 0.74% of its weight can be transferred to wastewater (Dubaish and Liebezeit, 2013)[11].

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[11] 19 washing cycles per lifetime were assumed.

Knowing the total number of washing machines in operation and how frequently a person uses one would lead to more realistic results. On the other hand, the number of washing machines in the world is not a perfect indicator for a global estimation, since in the developing world not every family uses one.

3.1.2.3. Tyre dust

Most of the tyres consist of synthetic rubber, natural rubber, metal wires and shock absorbing chemicals. The most common synthetic rubber found in tyres is Styrene Butadiene Rubber (SBR), a copolymer that represents around 50% of the tyre mass (Evans and Evans, 2006). Generally, the elastomer is part of the tread, covering and protecting the metal cords from abrasion. Thus, this segment of the tyre is the most vulnerable to friction forces.

The global demand for tyres was 3.3 billion units in 2015 (The Freedonia Group, 2015). Additional data is needed in order to estimate the average weight of one unit. However, for simplicity, one can estimate that a new tyre weights 10 kg. Retreaded tyres weight 10-15% less than the original product (Sundt et al.,2014). This means that this quantity is lost when the vehicle is used. For an annual estimation, it is also necessary to know the lifetime of a tyre. Sundt et.al., 2014 estimated that this varies between 2 and 4 years. The amount of tyre dust generated depends on the quality of the tyres, the road surface as well as the driving style. Once generated, these fragments can be washed off by precipitations or dispersed by wind (Lassen et al., 2015). Thus, not all of them end up in the wastewater.

3.1.2.4. Road markings

Road markings are subject to mechanical stress, but also to chemical degradation if certain deicing fluids or salts are applied. Most of these resistant paint mixtures contain various polymers or thermoplastics (Lassen et al., 2015). Once removed from the road surface, the microplastics from road markings follow the pathways of tyre dust. The exception is that a low amount of the particles found in road markings are blown by the wind.

The composition of the road markings varies. In Denmark, almost 99% of the road markings contain thermoplastics (Lassen et al., 2015). Plastic polymers represent between 0.5% and 2% (Lassen et al., 2015). In the case of water-based paints, acrylic polymers can weight up to 40% of the solution that is applied on roads (Lassen et al., 2015). A global estimation of the quantity of road marking material used has to take into account the different climatic conditions. In colder regions, such material is damaged faster due to the use of deicing fluids.

3.1.2.5. Marine coatings

Watercrafts are generally protected with special coatings which cover the hull as well as other parts. There are different types of coatings which play particular roles, such as anticorrosive paint or antifouling agent. Microplastics found in these coatings can be accidentally released during application, reparation or when the aged cover starts to exfoliate. Also, the air-blasting technology uses microplastics in order to remove old paint or biota that is attached to the surface of a ship.

The paint of a ship can be removed several times during its lifetime. It is estimated that in average, this process happens every 10-20 years (Højenvang, 2003). Most of the old paint is released into the environment. Sundt et al., 2014 reported that the removed cover is collected by less than 10% of the boat owners. Thus, the majority is discharged into waters. Also, approximately 10% of the new paint is lost during application (Lassen et al., 2015). It is nonetheless challenging to estimate the microplastics released by such activities. The quantity depends on the paint used, the frequency of the application but also on the technique.

3.1.2.6. City dust

This category includes nine main sources that are found preponderantly in urban areas (Boucher and Friot, 2017). Microplastics from city dust are caused by abrasion of goods[12], infrastructure[13], paints, abrasives or detergents. In comparison to the other sources, these plastic pollutants are grouped together because their emissions are considered low.

3.1.2.7.Others

There are many other potential sources of microplastics. However, from the quantitative point of view they have a low contribution. This category includes biodegradable items, dust from 3D printing, microplastics from the paper recycling industry and others.

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[12] Synthetic soles of footwear, synthetic cooking utensils etc.

[13] Household dust, artificial turfs, harbours, building coating etc.

3.2.The most common plastic polymers

3.2.1.Polyethylene (PE)

Polyethylene is the most widespread plastic. It is estimated that 80 million tonnes are produced annually (Piringer and Baner, 2008). It is also a versatile product, being used in packaging, furniture or cosmetics. It is inert at room temperatures, however, oxidizing agents and specific solvents may induce swelling. Low-density polyethylene can endure temperatures of up to 80 °C, yet, higher temperatures can weaken the structure of the polymer (Piringer and Baner, 2008). In contrast, high-density polyethylene can withstand even higher temperatures. The main difference between these two similar polymers is their molecular branching. LDPE has weaker intermolecular forces and a lower tensile strength. In contrast, HDPE is less resilient (Piringer and Baner, 2008). Polyethylene is also one of the main exfoliating agent found in microbeads.

3.2.2.Polypropylene (PP)

Polypropylene is a thermoplastic that also has numerous applications. Around 55 million tonnes are produced every year (Kuehner, 2014), being the second most common plastic. It is found in packages, textiles automotive components and cosmetics. Polypropylene has a low energy surface, which makes the polymer very resistant. It is more rigid and robust than polyethylene and can also withstand higher temperatures than both LDPE and HDPE (Piringer and Baner, 2008).

3.2.3.Polyvinylchloride (PVC)

Polyvinylchloride is third most manufactured plastic. Like PE, there are also two types of PVC. The rigid PVC is preponderantly used in construction and plastic containers. The more flexible type contains additives and is used as imitation leather, cable insulation or rubber substitute (Titow, 1986).

Table 1.The main classes of plastic polymers

Source: Andrady 2011.

Plastic polymer	Abbreviation	Percentage production	Uses
Polypropylene	PP	24%	Rope, bottle caps, netting
Low-density polyethylene	LDPE / LLDPE	21%	Plastic bags, six-pack rings, bottles, netting, drinking straws
Poly(vinyl chloride)	PVC	19%	Plastic film, bottles, cups
High-density polyethylene	HDPE	17%	Milk and juice jugs
Thermoplastic Polyester	PET	7%	Plastic beverage bottle
Polystyrene	PS	6%	Plastic utensils, food containers, foam cups
Nylon	PA	<3%	Netting and traps
Cellulose Acetate	CA	NA	Cigarette filters

3.2.4.Polystyrene (PS)

The global production of polystyrene, another widespread plastic, is around 14 million tonnes per year (Canada.com, 2017)[14]. In contrast to the other plastics, it is a cheaper alternative. Despite the fact that in comparison with the previous polymers it has a higher melting point, it becomes malleable at lower temperatures (Piringer and Baner,

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[14] Canada.com (2017); Now And Forever: The Styrofoam Dilemma. Www.Canada.Com. Last modified 2017. Accessed May 31, 2017. http://www.canada.com/life/forever+Styrofoam+dilemma/1522634/story.html.

2008). It is found in disposable cutlery, bottles or insulation material[15]. The latter also has a smaller density and can be easily dispersed by wind. Polystyrene generally degrades at very slow rates.

3.3.Fabrication

The plastic industry produces a diverse range of polymers with various applications, including packaging material, electronic components or even equipment used in the aerospace industry. Six main classes of plastics dominate the global production, as mentioned in the **Table 1**.

Fossil fuels remain the fundamental ingredient for the production of plastics, however, for the fabrication of bioplastics, biomass sources such as starches or cellulose are also used (Chanda and Roy, 2008). The raw materials go through a series of chemical and physical processes in order to produce the end product, plastic. Firstly, naphtha is treated in a steam cracker, where it is heated up to 800 °C in the presence of water vapour (Angyal et al., 2010). It splits into light hydrocarbons, alkenes and arenes. Among the alkenes, there are chains of two carbons (ethene), three carbons (propene), or four carbons (butene or butadiene). The arenes consist of benzene, toluene and xylene.

Furthermore, the alkenes go through a process called polymerisation, which produces repeating chains of small molecules out of monomers like ethene or propene (Chanda and Roy, 2008). The end product can be a polymer like low density polyethylene (LDPE), the polymer of ethene. Subsequently, the powder or the plastic granules of such a polymer go through a series of process that model their structure, color and implicitly their properties. These processes use a change in temperature and pressure or the addition of additives, such as flame retardants.

The size interval of the powders and the granules varies depending on the end use of the product. For example, plastic granules containing polycarbonate, urea, melamine and acrylic resins, measure between 0.10 and 1.7 mm (Kuhmichel.com, 2009)[16]. Such particles are used for deburring, paint-stripping or micro-blasting. On the other hand, selective laser sintering (SLS) uses powders with sizes between 20

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[15] In the form of a foam, called Styrofoam.

[16] Kuhmichel.Com (2009).Plastic Granules. Last modified 2017. Accessed May 31, 2017. http://www.kuhmichel.com/files/datasheet_plastic_granules.pdf.

µm and 80 µm (Schmid et al., 2015). According to the definition adopted by this paper, all the microplastics having dimensions larger than 50 µm are microplastics.

Losses can occur at virtually every stage of the fabrication process. Accidents may happen when the powders or the granules are transported, discharged or even processed (Lassen et al., 2015). When the equipment used to refine or transform these particles is washed, tiny fragments can flow away together with the liquid used. In most of the cases, the fluid is discharged into the drainage pipe and end up in the sewage. Alternatively, powders and small granules can be blown away by wind, high indoor air velocity or even attach to the equipment of the workers. The microplastics can be therefore dispersed not only in the vicinity of the facility but also at greater distances (Lassen et al., 2015).

4.The degradation of plastic polymers

Plastic polymers are by definition resistant chemicals, which under normal conditions and within moderate periods of time do not suffer visible changes. The justification is their inertness, which translates into negligible degradation rates. In natural environments, abiotic or biotic factors have the potential to speed up the deterioration of plastic particles, but also to immobilize a plastic fragment for long time frames. This immobilization does not necessarily imply that the polymer becomes chemically inactive. Yet, the number of stress factor can be considerably limited. Generally, the reason for an increase in the degradation rate is the fact that in nature a plastic fragment interacts with more stress factors than it was designed to withstand. Alternating temperatures, higher UV radiation and a fluctuating pH can break down a microplastic into fragmented polymers and leached additives, or even degrade it completely (Lassen et al., 2015).

It is important to mention that the impact of stress factors depends on the physical and the chemical properties of the material, as well as on whether or not these biotic or abiotic elements act simultaneously or sequentially. While this section of the paper aims at investigating the impact of stress factors on microplastics, further research is needed in order to evaluate how different polymers respond to such interactions.

4.1.Factors affecting degradation

4.1.1.The characteristics of microplastics

There are numerous factors that influence the lifetime of plastic polymers. In addition to ordinary physical, chemical or biological interactions, moisture, light, radiation or microorganisms acting simultaneously or independently can transform a primary microplastic into a secondary one.

In general, chemical and physical degradation happen at higher rates in comparison to biodegradation. Moreover, physical and chemical processes facilitate the biodegradation, given the fact that through fragmentation the surface area of a particle is increased.This section will present the main factors which influence the degradation rate of microplastics.

4.1.1.1.Size

The mobility of a plastic fragment depends primarily on its density and size. A large particle can be trapped in the drainage pipe, removed by the mechanical filters of a wastewater treatment plant or if it enters the environment, it can sediment faster[17]. On the other hand, microscopic fragments are more mobile. They can escape from a wastewater treatment plant and can be ingested by biota. Some of this organisms may be misled by the accumulation of microorganisms on the outer layer of a microplastic and feed on it. It was found that the common mussel (*M. edulis*) is able to ingest microplastics measuring between 2 and 10 µm (Browne et al., 2008; Ward et al., 2003; Ward and Targett, 1989).

Animals from most of the trophic levels are unable to pick individual food fragments and instead they ingest large quantities, including synthetic chemicals. While some species are able to eliminate such foreign items, others accumulate into their body. Therefore, size represents an essential factor that influences not only the transport of microplastics, but also the absorption of such small items by biota.

4.1.1.2.Color

The visual perception of a plastic is relevant given the fact that animals potentially ingest only food items that have a specific color. Pelagic invertebrates are visual predators and select their prey depending on its color (EFSA CONTAM Panel,

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[17] Assuming that biofouling occurs if the density of the fragment is less than the water density.

2016). Microplastics that resemble the food of some organisms may transport additional pollutants to the entire food web.

Table 2. An analysis of the dimensions of microplastic particles found in four PCCPs.

Source: Fendall and Sewell, 2009

Brand	Median size(µm)	Size range(µm)	Shape
A	196.81	10.2 - 1075.0	Variable, includes ellipses, rods, threads
B	375.00	52.5 - 847.5	Uniform, granular
C	247.50	4.1 - 1240.0	Variable, irregular, rounded to thread-like
D	196.94	31.6 - 418.4	Uniform, elliptical, slightly granular

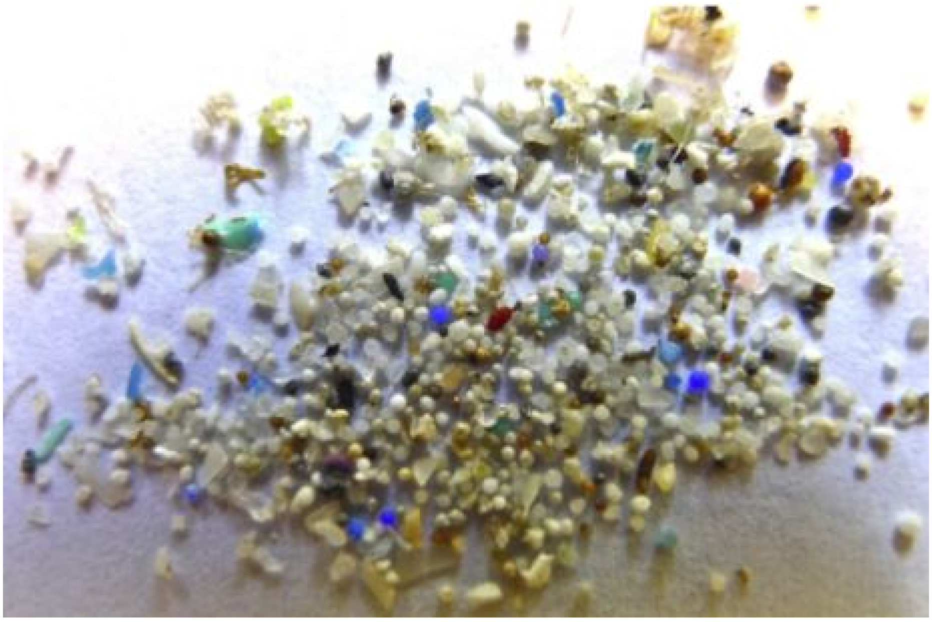

Figure 2. Visual differences between microplastics <1 mm.

Source: Eriksen et al. 2013.

4.1.1.3.Abundance

While color is a relevant factor for organisms that are actively looking for food, passive animals are more likely to accidentally absorb non-food particles.

Currently, the probability that an aquatic organism interacts with a microplastic particle is very high, taking into account the huge volumes of plastics discharged into the hydrosphere. The main question, however, is whether the respective individual will ingest it or not.

The chances are higher if the abundance of microplastics in the biotope is high. This logic also applies to physico-chemical processes. The more plastic fragments are present in a river or a sea, the higher the probability that physical or chemical stress will degrade some of the particles present. Therefore, generally speaking, a higher abundance of microplastic shall lead to a higher rate of biodegradation, physical disintegration and chemical decomposition.

In order to have a better comprehension of the processes that take place in coastal environments, a study simulated the natural conditions found in such an ecosystem.

All the marine invertebrates (Li et al., 2015) that were part of this study ingested microbeads. The project found a positive correlation between the abundance of microplastics and the presence of microplastics in the organisms of marine invertebrates.

4.1.1.4.Density

The density of a microplastic can be used in order to determine its vertical coordinates in the water column. It is expected that heavy polymers are found in the lower levels of a water body, while lighter plastics will remain close to the surface[18] (Backhurst and Cole, 2000; Katsanevakis et al., 2007; Stefatos and Charalampakis, 1999). From source to sink, density influences the transport of plastics. If the density of a microplastic particle is approximately 1 g/cm^3, this fragment will flow in the upper layers of a river. As it enters into the ocean, it will gradually flow upwards and will remain in the epipelagic zone[19]. Aquatic organisms feeding on planktonic food,

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[18] Lattin et al. (2004) quantified microplastic concentrations >333 l m at varying depths, 0.8 and 4.5 km off the southern Californian coast.

[19] The epipelagic zone is region situated 200 meters below the ocean’s surface, where sunlight occurs.

Table 3. Densities of plastic materials that are frequently found in the aquatic environment

Source: Duis and Coors 2016.

Plastic class	Abbreviation	Density (g/cm^3)
Expanded polystyrene	EPS	0.01-0.04
Low-density polyethylene	LDPE	0.89-0.93
High-density polyethylene	HDPE	0.94-0.98
Polypropylene	PP	0.83-0.92
Polyethylene terephthalate	PET	0.96-1.45
Polyamide(nylon)	PA	1.02-1.16
Polystyrene	PS	1.04-1.1
Polymethyl methacrylate(acrylic)	PMMA	1.09-1.20
Polyvinylchloride	PVC	1.16-1.58
Polycarbonate	PC	1.20-1.22
Polyurethane	PU	1.2
Alkyd	-	1.24-2.10
Polyester	PES	1.24-2.3
Polytetrafluoroethylene	PTFE	2.1-2.3

filter feeders and other species that live in the upper water column will most probably interact with buoyant plastics, such as polyethylene.

There are two main processes that can modify the density of microplastics.

Firstly, the development of a microbial community on the surface of the plastic contributes to an increase in its density (Andrady, 2011). As soon as biofouling occurs, the plastic starts sinking (Andrady and Song, 1991; Costerton and Cheng, 1987; Railking, 2003). ***Secondly,*** the metabolism of some aquatic species can partially degrade a microplastic and implicitly change its density.

Biofouling is, however, a reversible process: de-fouling may take place due to the presence of microorganisms, foraging organisms, chemical or physical factors.

Therefore, the density of a microplastic depends on the polymer type, but also on the biolayer that is depositing on its surface and the thickness of the microbial community.

In conclusion, the cycle of the plastic can continue until it decays completely or it sediments. Presently, it remains difficult to estimate the quantities of plastics situated on the seafloor or on stream beds (Barnes et al., 2009). Isolated sampling might also lead to erroneous results, due to different geologic structures[20], irregular water currents or biochemical factors.

4.1.1.5.The role of additives

4.1.1.5.1.Biodegradable plastics

Biodegradable plastics is a new branch of the plastic industry. These products have been seen as a potential alternative for the inert plastics and have currently many applications in the packaging industry, but also in personal care and cosmetic products. Nonetheless, these goods can also generate smaller fragments that later become microplastics (Thompson et al., 2004). Generally, biodegradable plastics consist of synthetic polymers, combined with vegetable oils, starch or other substances[21] that can trigger and speed up the degradation rate (Derraik, 2002; Ryan et al., 2009; Thompson et al., 2004). Most of these goods can easily decompose in composting plants (Moore, 2008; Thompson, 2006). The major disadvantage of this degradation process is that most of the synthetic polymers will remain almost intact, while the additives will be easily decomposed (Andrady, 2011; Roy et al., 2011; Thompson et al., 2004).

It was found that microorganisms degrade the starch component of a biodegradable polyethylene, without degrading the polyethylene components (Reddy et al. 2003).

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[20] Which implies that the sediments have different densities.

[21] (e.g. TDPA™)

The outcome is a weakened plastic, which can easily disintegrate into smaller fragments (Palmisano and Pettigrew 1992). Thus, the degradation of biodegradable plastics is de facto a biodisintegration process (Klemchuk 1990), which can, in turn, generate secondary microplastics.

4.1.1.5.2.Anti-degradation additives

Generally, plastic polymers are biochemically inert (Roy et al., 2011; Teuten et al., 2009). Nevertheless, various chemicals are added during the production phase in order to modify the properties of the final product. Such additives can change the color, increase the resistance to heat or accelerate biodegradation. Most commonly, additives are used to extend the lifetime of the plastics. These ingredients represent an environmental concern for two main reasons. **Firstly**, a plastic fragment containing additives that extend its lifetime can remain intact for centuries if it is discharged into the environment. **Secondly**, these chemicals can leach out and contaminate the surroundings. Most of these substances are hazardous chemicals that have a detrimental impact on the flora and fauna. The rates of leaching depend on the polymer structure, its pore size and the additive itself. Also, imperfections during the polymerisation of the plastics influence this process.

Phthalates are added to PVC as emollients and represent up to 50% of the weight of the final product. The high concentrations of phthalates found in aquatic environments were associated to landfill leachates (vom Saal and Myers, 2008).

Moreover, the presence of additives has an impact on the density of the product.

A polymer that normally is lighter than water can sink if heavier additives are applied. This holds true for heavy polymers, which can float upwards if certain plasticizers are added. Disintegrated fragments such as secondary microplastics, but also primary microplastics are more likely to leach out the additives they contain. The main reason is their large surface-area-to-volume ratio. Moreover, the ingestion by biota can trigger chemical reactions between the leachate and the substances found in the gastrointestinal tract (Cole et.al, 2011).

Subsequently, the additives may cause endocrine disruption, tumors or even death.

The impact of the above-mentioned chemicals is noticeable during the early developmental stages of animals. In the long run, hormonal imbalance may be detrimental for the gender structure of a population and can lead to its extermination.

4.2.Biodegradation

Biodegradation is the concept which is characterized by a series of physical, chemical and enzymatic processes taking place consequently or concurrently (Hueck, 2001). The physical and chemical properties of a plastic fragment gradually change once biodegradation starts. The outcome of these processes depends on the polymer, as well as on the environmental conditions (Lugauskas et.al, 2003). The microorganisms that induce biodegradation are diverse and can belong to fungi, protozoa, bacteria or lichenaceae groups (Wallström et.al, 2005). In general, such microorganisms do not act independently, but they form a structure that partially or completely covers the particle that is to be degraded.

The goal of these microorganisms is to feed on the particle present and they use it as carbon and nitrogen sources (Crispim and Gaylarde, 2005). There are three main pathways that facilitate the biodegradation of plastic polymers: physical, chemical and enzymatic biodegradation.

4.2.1.Physical biodegradation

The inertness of plastics does not allow organisms to colonize their surface. Microorganisms generally adhere to hydrophobic surfaces by secreting polysaccharides, proteins and other polymers that together act like a glue (Capitelli et.al, 2006). The secretion protects the organisms against physical stress[22]. Particular organelles penetrate the polymer thanks to the corrosive character of the substances released, causing cracks and weakening the plastic(Bonhomme et.al, 2003).

4.2.2.Chemical biodegradation

The Brownian movements, surface electrostatic charges or the Van der Waals attraction were found to influence the bacterial adhesion (Van Loosdrecht et al., 1987). However, bacteria and fungi generally attach to surfaces that are hydrophilic.

Such chemicals are attracted to water molecules and in most cases are soluble in water. On the other hand, hydrophobes have a nonpolar structure and are not soluble in water. Plastics have become widespread also because of their hydrophobicity. However, hydrophilic synthetic polymers exist, too. One example is

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[22] E.g. UV radiation

polyvinyl alcohol, having various applications as a thickening agent in industry, medicine or 3D printing.

Hydrophobic polymers, such as PP and PE are not necessarily immune to biodegradation (Ehrenstein et al., 2013). The slime that forms the biofilm can lower the surface tension and make a hydrophobic surface less hostile for microorganisms. In addition, atmospheric pollutants (Warscheid and Braams 2000) are attracted by the biofilm and could contribute to the expansion of the biolayer (Zanardini et al., 2000). Chemolithotrophic bacteria release inorganic acids that speed up the degradation of plastics (Crispim and Gaylarde, 2005; Warscheid and Braams, 2000)[23]. Chemoorganotrophic microorganisms use organic acids instead (Jenings and Lysek, 1996). The presence of the biofilm can trigger the hydrolysis of several plastics. This chemical process subsequently generates oligomers, monomers and organic acids. Once some segments of the polymer break apart into tiny fractions, the acids decrease the pH inside the pores (Göpferich 1996), increasing the surface erosion. Moreover, fungi and filamentous bacteria can feed on organic acids to develop their mycelia network (Hakkarainen et al., 2000). Thus, the organic acids not only corrode the outer layer of a plastic polymer but also facilitate the multiplication of organelles that provoke physical biodegradation (Warscheid and Braams, 2000).

4.2.3.Enzymatic biodegradation

In general, the physical and chemical biodegradation of plastics are slow processes. In the past, it was believed that if a polymer is inert to stress factors belonging to these two categories, it does not undergo any type of degradation. Nonetheless, the enzymatic biodegradation uses a combination of degradative pathways that together can have destructive consequences for plastics (Howard, 2002; Szostak-Kotowa, 2004) Microorganisms can produce certain enzymes that have the potential to biodegrade even the most resistant plastics. These enzymes breakdown particular chemical bonds (Pelmont, 2005) and can initiate two main mechanisms, known as bulk and surface erosion(Von Burkersroda et al., 2002). Bulk erosion is a type of chemical biodegradation which is induced by certain chemicals. The result is a change in the molecular mass of the polymer due to the fragmentation of the plastic.

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[23] *Such as nitrous acid (e.g. Nitrosomonas spp.), nitric acid (e.g. Nitrobacter spp.) or sulphuric acid (e.g. Thiobacillus spp.)*

On the other hand, matter is lost but the molecular mass of the plastic does not change during surface erosion. These two mechanisms depend on the type of polymer, as well as on how quick the bond cleavage happens.

4.3.Abiotic degradation

Physical stress does not necessarily induce fundamental changes of the properties of a microplastic fragment. Many plastic polymers are designed to withstand outdoor conditions, where they encounter extreme weather conditions and sudden meteorological transformations.

However, once discharged by anthropogenic activities, microplastics can be subject to frequent abiotic stress. Weathering, pressure changes or friction simply reduce the dimensions of a particle by dividing it into smaller parts without changing the molecular structure and bonds.

4.3.1.Mechanical disintegration

The impact of mechanical forces does not result in a degradation process. Instead, a plastic fragment is disintegrated into smaller particles under the action of shear forces. In the hydrosphere, for instance, a particle can be reshaped by precipitation and fluid dynamics, fauna or other naturally occurring phenomena. Damages caused by mechanical factors may not be visible immediately (Duval, 2004), yet little transformations increase the surface area, activate chemical or biotic degradation and subsequently accelerate these processes (Briassoulis, 2005).

4.3.2.Natural photodegradation

Photodegradation is believed to be a factor that significantly contributes to the degradation of plastics in natural environments. In contact with visible (400-700 nm) and high-energy ultraviolet radiation (290-400 nm), the electrons from plastic polymers become more reactive which make it more susceptible to slow degradation processes (Al-Salem, 2009). Through photooxidation and bond cleavage, plastic fragments become brittle and subsequently disintegrate. The disintegration of biodegradable plastics primarily depends on these such processes. Photosensitive chemicals are included in the polymer as an additive or as part of the polymer chain in order to include photodegradation (Kounty et al., 2006).

Each type of bond requires a specific ultraviolet wavelength for cleavage. For instance, the bonds of polyethylene are split at 300 nm, while polypropylene polymers cleave at 370 nm (Singh and Sharma 2008). Such wavelengths cause a loss of the tensile strength and a reduction of the molecular mass, as well as changes in the color of the plastic polymer (Singh and Sharma, 2008). Photo-oxidation and ketone photolysis are the two most important mechanisms that contribute to the photodegradation of plastic polymers**.**

4.3.3.Thermal degradation

Thermal stress occurs when a material is subject to a change in temperature that has an impact on its volume. On the other hand, thermal degradation is the consequence of an increase in temperature that modifies the molecular structure of a polymer and implicitly changes its properties (Arkatkar et al., 2009).

The outcome of this process depends on the melting point of the chemical compound. Generally, the main chain of the polymer is cleaved. In contrast with regular polypropylene, samples that were thermally treated proved to have a higher biodegradation rate (Arkatkar et al., 2009).

At temperatures between 300 and 600 °C, PP, LDPE formed alkanes and other liquid hydrocarbons. Polyethylene decomposes thermally at higher temperature, releasing gases and chemicals that are toxic to humans and animals. Thus, the incineration of plastics remains a disputed process. The exhaust may contain dioxins, furans and other polycyclic aromatic hydrocarbons (Bockhorn et al., 1999; Westerhout et al., 1997). Certain additives added in the plastic may also produce noxious chemicals.

The temperatures needed for thermal degradation are not common in nature.

However, if a plastic fragment experiences recurring thermal stress, the polymers can have higher biodegradation rate. Such a procedure could be applied in the future in order to degrade plastics in a controlled environment.

4.3.4.Chemical degradation

Reactive chemicals, catalysts or microorganisms can trigger numerous chemical degradation processes. In addition to substances that are widespread in nature, the deposition of atmospheric pollutants or the excessive application of agrochemicals can change the macromolecular properties of plastic polymers (Briassoulis, 2005).

Such reactions do not take place immediately and directly. These pollutants can be the precursors of corrosive acids that subsequently attack the outer layer of microplastics. Moreover, oxidative degradation and hydrolysis can also have visible consequences on the appearance and the properties of plastics.

The oxidation of plastic polymers takes place following either thermal oxidation or photooxidation. In the presence of oxygen, carbonyl (CO) and hydroxyl (OH) are formed (Singh and Sharma, 2008). These polar functional groups increase the hydrophilicity of the substance, which implicitly makes it more water loving. A polymer that becomes more hydrophilic is more susceptible to biodegradation. Despite the fact that the global concentration of ozone is very low, the presence of O_3 molecules also has an impact on the quality of plastics. Ozone attacks covalent bonds, causing cross-linking reactions, chain scissions as well as the formation of free radicals (Singh and Sharma, 2008). Elastomers are particularly vulnerable to ozone, which can form cracks. Even in reduced concentrations, ozone molecules cause the cleavage of double bonds in natural rubber, polybutadiene, styrene-butadiene and other polymers present in rubber chains. To prevent such undesirable events, antiozonants are added before vulcanization.

Hydrolytic degradation is another process which can have a negative impact on plastic (Muller et al., 1998). Nonetheless, this degradation pathway depends on the bonds susceptible to hydrolysis. The polymer has to contain hydrolysable covalent bonds, like ether, amide or ester amide (urethane) groups (Lucas et al., 2008). Such chemicals can absorb moisture, which concurrently facilitates the hydrolytic cleavage of the chain (Lucas et al., 2008). Hydrogen ions in acidic solutions or hydrogen anions in alkaline solutions cut the polymer chain (Iskander and Hassan, 2001). Subsequently, the distribution of the molecular mass within the chemical compound changes, which affects the strength of the material and can cause surface erosion. The temperature, water activity and the pH are factors that influence the hydrolytic processes.

4.4.Sampling techniques

The abundance of microplastics is estimated using different techniques. Due to their small size and their distinct properties, an analysis done visually is incomplete and inaccurate. It is necessary to use professional equipment.

Firstly, a liquid or a solid sample is collected. Depending on the goal of the study, the separation of the microplastics is done by filtration, sieving or density flotation.

The challenge of these techniques is that some fragments will always be omitted. The reason for this inconsistency is that the density of most plastic polymers is in the range 0.8 - 1.4 g/cm^3. If a dry sample is analyzed, distilled water is added, the heavier particles are removed while the microplastics will remain in the solution. The aim of this method is to remove the sand and the other sediments, having a density of circa 2.65 g/cm^3 (Hidalgo-Ruz et al., 2012)

Liquid samples are usually treated with a salt (Hidalgo-Ruz et al., 2012). The most common salt used is sodium chloride. It is an inexpensive and environmentally friendly option, however, the disadvantage is that a saturated NaCl solution has a density of 1.2 g/cm^3. Therefore, plastics that have a higher density, such as PVC fragments, will sediment. In order to eliminate this disadvantage, denser solutions are used. Sodium polytungstate has a density of 1.4 g/cm^3. Another option is to use a sodium iodide solution, with a density of 1.6 g/cm^3 (Claessens et al., 2013).

However, the Technical Subgroup on Marine Litter recommends that the separation of microplastics in aqueous solution shall be done using NaCl (European Commission, 2013). The main benefit is that this substance is not hazardous and it is easily accessible. It must be taken into account that the purity of this substance has to be very high since NaCl extracted from sea salt can be contaminated with microplastics.

4.5.The identification of the polymer type

In order to elaborate a hypothesis on the origin of a microplastic, it is essential to know the chemical structure of the particle. The Fourier transform-infrared spectroscopy (FT-IR) remains a widely used method. The spectrometer measures the infrared absorption of the sample, which later allow the used to determine the chemicals present (Cole et al., 2011). Knowing the chemical formula of the polymer does not mean that the origin of the fragment can be identified. Yet, it offers a fundamental piece of information that can be used in determining the pathways of the microplastic. In addition, the characteristics[24] of the fragment and its chemical formula allow the researcher to narrow the possibilities.

Most commonly, microplastics consist of polypropylene, polyethylene, polystyrene, polyester, and polyvinyl chloride (Andrady, 2011; Claessens et al., 2011; Cole et al., 2011). Given the wide range of applications, a single polymer can be found in various goods. Polyethylene, polypropylene and polystyrene are used in PCCPs, but

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[24] Fiber, fragment, pellet etc.

also in plastic bags, containers and others. On the other hand, nylon or polyvinyl alcohol are found in nets, fishing lines, but also in textiles (Browne et al., 2011; Claessens et al., 2011).

While dealing with microscopic fragments, the identification of the chemical is an essential step for quantitative analyses. As the literature review has shown, foreign particles can have a similar appearance and may be mistakenly counted as microplastics.

5.Results

5.1.Findings of the literature review

5.1.1.*Suspended Microplastics and Black Carbon Particles in the Jade System, Southern North Sea (Dubaish and Liebezeit, 2015)*

A research team from the University of Oldenburg, Germany, has analysed surface water samples from the Southern North Sea in order to identify possible microplastics. The samples were collected from June to November 2011 and the results concluded that the land-based sources of microplastics are dominant.

The origin of the microplastics is most probably in urban areas, where industries[25] and the treated sewage of the communities unintentionally discharge small quantities of pollutants together with the treated effluent. In addition, larger microplastics originate from pre-production pellets that are accidentally lost during shipping (McDermid and McMullen, 2004).

The liquid waste of the paper recycling plant contained between 2.8 and 32.7 mg total microplastics/L[26]. Due to the high quantity of small plastic fragments, the number and the polymer type was not inspected.

The wastewater treatment plant from Wilhelmshaven discharged approximately $9x10^8$ particles per year[27]. A nearby floodgate[28] was also found to release 1.9×10^{11} particles/year. While the input of the wastewater treatment plant primarily depends on the anthropogenic activities that discharge the used water into the sewer, the floodgate collects excess water from hinterland and also receives the treated

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[25] a vinyl chloride plant, a paper recycling plant

[26] Over 4 h.

[27] average discharge of 11,288 m^3 (2007–2011).

[28] Floodgates may discharge excess fresh water for hinterland but also sewage treatment plant (STP) effluents.

sewage from other treatment plants. The fibers were the most dominant type of microplastics: the highest value was 1.100 particles/L. The study therefore acknowledged that polyester and
acryl textiles discharge high quantities of fibers during washing (Browne et al.,2011). In addition, the plastic pellets were believed to originate also from PCCPs (Fendall and Sewell 2009).

Five PCCPs were analysed and the results showed that the microplastics represent between 1.2 to 4.7 wt%. The plastics were granular fragments, larger than 40μm.

The potential contamination with airborne particles was examined. A 1.2-μm cellulose nitrate filter used for sixty minutes detected no fibers and no granular material, showing that the abundance of microplastics in the laboratory where the experiments were done was negligible. The authors acknowledge that this study may show an underestimation. During the filtration phase, polystyrene and polycarbonate microplastics could have reacted with the hydrofluoric acid[29] used to remove inorganic particles.

Key findings

- Urban land-based sources of microplastics are dominant;
- Paper recycling plants have a relatively high output of microplastics;
- Floodgates may release more microplastics than a single wastewater treatment plant;
- Underestimations could result from the filtration and separation methods.

5.1.2.Widespread distribution of microplastics in subsurface seawater in the NE Pacific Ocean (Desforges, 2014)

Seawater samples were collected in August and September 2012. The sites were selected 1200 km away from the Pacific Ocean's coast, as well as in the regular sampling stations close to the Vancouver Island. The depth of the samples was 4.5 meters below the water surface. Large debris was separated using a 5 mm filter. The remaining solution was filtered through a series of copper sieves with the smallest size of 62.5 μm.

The concentration of microplastics identified varied from 8 to 9180 particles/m^3. The mean size of the particles was 606 ± 221 μm. The study also found that larger

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[29] The concentration of the solution was 40%

particles were present in the offshore samples. A linear correlation between the dimensions of the microplastics and the distance from the shore was established.

The most abundant size class was 100- 500 µm, observed in the Queen Charlotte Strait. Microplastics were 4-27 more abundant at sites near shore than offshore. In general, over 70% of the microplastics were fibers. The abundance of fibers diminished relative to the distance from the shore.

The mean abundance of microplastics is higher than the values reported in the North Pacific Gyre and other regions of the Pacific Ocean.

The higher magnitude of microplastics found in the coastal area confirms that findings of other studies. Land-based anthropogenic activities remain the dominant source of microplastics found in oceans (Barnes et al., 2009; Browne et al., 2011; Collignon et al., 2012; Dubaish and Liebezeit, 2013; Ribic et al., 2010).

The higher proportion of fibers nearshore was associated with recreational and fishing activities, as well as the discharge of wastewater effluents. Vancouver, Victoria and Seattle are three urban agglomerations that release their wastewater into the coastal region of Washington State (USA) and British Columbia(Canada). Microplastics could also originate from harbours and shipping (Dubaish and Liebezeit, 2013). Additional hypotheses regarding the origin of the microplastics can not be made since the polymer types were not identified.

The authors concluded that the concentration of microplastics found in the Queen Charlotte Strait was unexpected, given the low population density and the lack of major industries. However, three main reasons were identified. The dynamic currents from and outside the Strait could lead to an accumulation of microplastics.

Secondly, aquaculture and recreational activities were also associated with high plastic pollution (Hinojosa and Thiel, 2009).

Lastly, the Tohoku earthquake and the subsequent tsunami from March 2011 generated more than a million tonnes of debris that was discharged into the Pacific Ocean. It is possible that the eastward current transported some of this waste toward North America.

Key findings

- The mean abundance of microplastics in littoral areas with a low population density was higher than in the North Pacific Gyre. This unforeseen result was associated with marine currents and natural hazards;

- The abundance near shore can be up to 27 times higher, while the dimensions of the microplastics decrease proportionally with increasing distance from the shore;
- Land-based anthropogenic activities remain the dominant source of microplastics found in oceans. The abundance of fibers close to the shore also shows its predominant land-based origin.

5.1.3.Microplastic pollution in the surface waters of the Laurentian Great Lakes (Eriksen et al., 2013)

Neuston samples from the Laurentian Great Lakes were collected in July 2012.

Sampling was done at 21 stations using a manta trawl. The content was filtered using a 333 µm mesh. Only one sample did not contain microplastics, while eight samples had an average of 20% fly ash. The mean abundance of microplastics was approximately 43.000 particles/km^2. A record of 466 000 particles/km^2 was found downstream from Cleveland and Erie. A great spatial variability was noticed. Lake Erie contained 90% of all the plastic, while the samples 20 and 21 had 85% of all the microplastics identified.

The highest concentration was found in the most populated region, Lake Erie.

The mean concentration of microplastics from Lake Superior was slightly higher than those from Lake Huron. The authors believed that the reason is the smaller distance between the sampling sites and the shoreline(from Lake Superior).

The size class of the particles was evaluated using scanning electron microscopy (SEM). Almost a fifth of the particles smaller than 1 mm were not plastics as believed initially, but aluminum silicate from coal ash. The high concentration of coal and fly ash was associated with the 144 coal power plants bordering the Great Lakes. Most of these particles entered the hydrosphere through wet or dry deposition. Without conducting the SEM, such particles could have been counted together with the very similar microplastics.

It is therefore of utmost importance to use FT-IR or SEM/EDS to avoid miscalculations. A high number of the microplastics were spheres, allegedly used in PCCPs. Two PCCPs were also inspected[30]. The microbeads found in these products were similar to the spherical multi-colored microplastics found in the samples[31].

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[30] Facial cleansers containing polyethylene microbeads

[31] Similar shape, size, colour and elemental composition

All the sites are close to a heavily urbanized region. The treated water from wastewater treatment plants is discharged into the Great Lakes. Subsequently, St.Lawrence river transports this debris into the Atlantic, where it can be a potentially enter the North Atlantic Gyre.

Key findings

- The highest concentration was found in the most populated region, Lake Erie;
- Eight samples had an average of 20% fly ash. The high concentration of coal and fly ash was associated with the 144 coal power plants bordering the Great Lakes.

5.2.The analysis of the processes and flows

The **Figure 3.** presents the main result of this paper. Microplastics enter the system in the raw form, right after they are produced from fossil fuels. In production facilities [Production], the unprocessed plastics are transformed according to their end use. The main sources are the following: personal care and cosmetic products, adhesives, paints, expanded polystyrene, 3D printing ink. Accidental losses from shipping also are included. Following application or use, these sources can end up as waste that is sent to incineration or landfilled. Another important pathway is the flow to the wastewater treatment plant. Additional secondary sources are also transported to this facility. These sources are textile fibers, city dust and tyre dust. Depending on the end use of the sewage sludge, microplastics can end up in the biofuel digestate or in soils. They can also enter the hydrosphere, where biota can accidentally ingest them. Lastly, in time, the microplastics will degrade into other secondary microplastics or into nanoplastics.

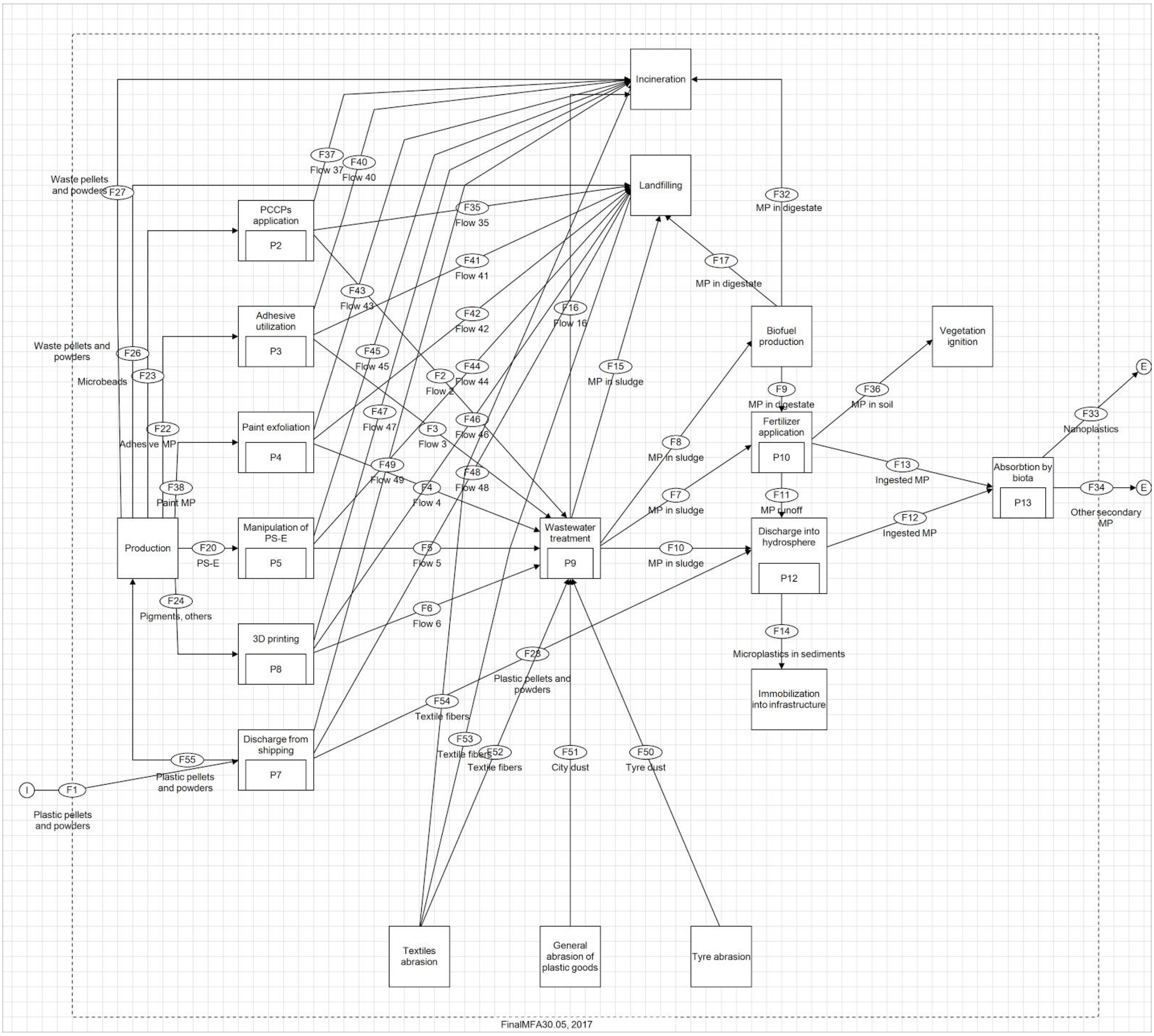

Figure 3. The global qualitative Material Flow Analysis of the microplastics[32] [33]

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[32] This figure was designed using STAN2. Copyright © 2012 by Institute for Water Quality, Resource and Waste Management, Technische Universität Wien, Karlsplatz 13/226, A-1040 Vienna, Austria; all rights reserved.

[33] The flows which do not appear in this MFA are presented in the Annex of this thesis.

6.Discussion

6.1. Waste management strategies and their impact on microplastics

The quantity of plastic waste generated by a community primarily depends on the lifestyle and on the habits of the residents. A society that sorts plastic waste in order to be recycled will not produce significant quantities of macroplastics. Without macroplastics in the environment, there will be fewer secondary microplastics derived from plastics larger than 5mm. However, in the case of primary microplastics, the patterns vary. Even with a very high recycling rate, the efflux of primary microplastics can also be high. This is mainly because of the diverse sources of primary microplastics.

Contrarily, the waste management strategies of a community can have an impact on the microplastic particles that enter the environment. For example, the presence and the type of a wastewater treatment plant can decrease the volume of microplastics that are discharged into the hydrosphere. If an urban area has a waste incinerator facility that also reduces the amount of plastic waste released. Moreover, the inappropriate disposal and management of landfill waste pose a severe threat to the environment. A natural phenomenon may increase the dispersion of tiny fragments that were supposed to be landfilled. Such particles can contain heavy metals, persistent pollutants, but also synthetic polymers including microplastics. Once these small microplastics become airborne, they can travel considerable distances and later enter the pedosphere or the hydrosphere through atmospheric deposition.

In many European states, including Austria, Sweden, Belgium or Germany, landfilling untreated waste is illegal. Only ashes resulting from waste incineration or waste that is treated in mechanical biological treatment plants can be landfilled.

6.2.Wastewater treatment

In addition to the direct discharge of untreated effluents, the output of a wastewater treatment plant can also be a source of microplastics. There are two issues that lead to the discharge of small plastic polymers into the hydrosphere. Malfunctions of the plant can reduce the purification efficiency of the system. Secondly, excessive precipitations lead to sewer overflow, when untreated sewage directly enters the hydrosphere. Apart from these two possibilities, it has been discovered that minuscule fragments percolate through the sludge and leave the wastewater plant through the output (van Wezel et al., 2016). In general, sewage sludge immobilizes significant quantities of microplastics (Brandsma et al., 2014), including primary microplastics from PCCPs (van Wezel et al., 2016). The incineration of the sludge therefore ends the flows of microplastics. Nonetheless, in many countries sludge is either landfilled or used as fertilizer due to its high phosphorus content (Fytili and Zabaniotou, 2008).

In contact with the soil, microplastics can either sediment in the pedosphere or they can be washed away via runoff. Eventually, most of these plastic polymers will enter the hydrosphere, where they can interact with the biota, sediment or degrade (UNEP, 2005).

6.2.1.The utilization of waste products from waste water treatment

6.2.1.1.Sewage sludge

The sludge resulted from wastewater treatment plants can be used for various purposes. In Ireland, circa 80% of the sewage sludge is applied in agriculture (Water.ie)[34]. On European level, more than a third is used as fertilizer (Leslie, 2014). Given the fact that existing filtering methods are unable to remove all the synthetic particles present in the wastewater (Fendall and Sewell 2009; Gregory, 1996), it is assumed that the difference between the microplastics from the input water and those in the output of the plant are intercepted by the mechanical filters or immobilized by the sludge (Dris et al., 2015). Depending on the filtering techniques, up to 99% of the microplastics can be retained in the sewage sludge.

The chemicals found in the wastewater go through a series of degradation processes. The high microbial diversity and the numerous physical stress factors may contribute to changes in the properties of the microplastics, as well as slight modification of the chemical structure. Moreover, according to international and domestic guidelines, the sludge has to go through a treatment process before it is used in agriculture. Such procedures may include composting, anaerobic digestion or lime stabilization.

6.2.1.2.Biofuel production

Biofuels generally rely on waste products whose degradation generate gases and liquids which could subsequently be used for combustion. In addition to the

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[34] Water.ie; National Wastewater Sludge Management Plan https://www.water.ie/projects-plans/wastewater-sludge-management/Final-NWSMP.pdf

production of environmentally friendly fuels, this technique is becoming more and more popular since the volume of organic waste can be significantly reduced. For instance, a biogas plant can use food and post-harvest waste an input. A more common practice is to utilize a constant input throughout the year. This option allows the producer to estimate the output of the plant with a relatively high degree of precision. While some substrates have to be purchased for considerable sums, sewage sludge is cheaper and constantly available. Therefore, it remains a widely used input for biogas plants. The output of the municipal wastewater treatment plants preponderantly contains dead microorganisms and mineralised organic matter (Kumar, 2012). Small and microscopic fragments of solid waste are also part of the sludge. Such chemicals generally undergo little chemical modifications during the treatment of the wastewater or they remain inert.

Depending on the characteristics of the input, various techniques are used (Kumar, 2012). Initially, the input of the biogas plant is homogenized in an aqueous solution. Water dissolves most of the soluble matter, while bacteria break down insoluble organic polymers into soluble derivatives. The organic acids produced by acidogenic bacteria are subsequently transformed into acetic acid, ammonia, hydrogen and carbon dioxide. Ultimately, methanogens feed on these compounds and generate methane and carbon dioxide. The whole process is done anaerobically. The temperature has an impact on the output of the plant as well as on the kinetics of the processes. The biodegradation can be psychrophilous (Vavilin and Angelidaki, 2005), mesophile (Angelidaki et al., 2005), thermophile (Angelidaki et al., 2005), or extra thermophile (Liu, 2003).

The elimination of the small solid particles is not the goal of a biofuel plant. The biofuel is the only product that has an economic value, therefore the digestate is considered a waste product which is either used as fertilizer or landfilled.

6.2.1.3.Composting

Composting remains a less common waste management practice. In general, biodegradable waste is composted in either large-scale composting plants or small scale composting. On an industrial scale, sewage sludge can also be used as an input, together with the municipal organic waste and other vegetable residues.

In aerobic conditions, microorganisms degrade the sewage sludge, killing most of the pathogens and parasites. The presence of oxygen is essential to ensure proper aeration of the compost and reduce odor pollution. A minimum water content is also necessary for the successful biodegradation (Singh and Sharma, 2008). If these conditions are met, aerobic microorganisms will decompose the organic waste and will produce a mixture that is rich in nutrients, as well as gases and heat. The increase in temperature plays an important role because it activates numerous dormant microorganisms. Additional oxygen could also speed up the degradation of the waste. However, regulating the temperature in order to maintain the activity of the thermophilic organisms is more feasible. Naturally, the compost pile can reach up to 65-70°C few days after the initiation phase (Chang et al., 2006). After that, the temperature declines steadily but it is artificially maintained in order to provide an adequate environment for the thermophilic organisms. Once the whole process ends, the compost is screened in order to eliminate all the matter which was not degraded as well as other unwanted solids present.

Polyethylene samples that were composted for 40 days remained unchanged. Biodegradable polyethylene showed surface erosion (Vieyra et al., 2013). Additives that speed up the degradation of plastics were found to decay at slower rates in comparison with starch based polymers (Mohee and Umar, 2007). Thus, it is likely that microplastics which were initially part of the sewage sludge will be transferred to the output of the compost plant. It is expected that the stress factors of a composting plant could induce a type of degradation, depending on the polymer presents.

6.2.1.4.Fertilizer application

There are numerous pathways that lead to the deposition of microplastics in the pedosphere. Quantitatively speaking, the highest share may originate from the direct utilization of sewage sludge as fertilizer (Leslie, 2014). This practice is done in order to increase the phosphorus content of agricultural soils, but also to improve the fertility of afforested land or degraded soils. Secondly, the atmospheric deposition may also be a factor that increases the concentration of microplastics in soils. Unlike sludge fertilization, it is expected that a higher concentration of microplastics originating from atmospheric deposition is found in urban and peri-urban areas, as well as in the proximity of improperly managed landfills (Dris et al., 2015). Moreover, the frequency of microplastic particles is higher in riparian zones (Allsopp et al., 2016). Seasonal flooding and runoff are believed to be the two main factors responsible. In estuaries or deltas, but also all over the littoral zone, the constant water flow could be a source of microplastics (Browne et al., 2011).

6.3.The sedimentation of microplastics in the pedosphere

In addition to the scarce data from the hydrosphere, there is not sufficient information about the concentration of microplastics in the pedosphere.

It is expected that the soil type, as well as the treatment which is applied has an impact on the concentration of microplastics. While most of the low-density polymers can be easily washed off by precipitation, some fibers can reside for more than 15 years after the sewage sludge was applied (Zubris and Richards, 2005). The fact that microplastics were present below the depth of plowing indicates that the soil biota could also facilitate the transport of plastics (Zubris and Richards, 2005).

In order to have a better understanding of the processes that lead to the degradation of plastics in the pedosphere, one shall take a look at experiments testing the resistance of biodegradable polymers. Generally, soil burial experiments test the resistance of plastic polymers. For instance, it was determined that the soil type could influence the degradation rate of polycaprolactone (PCL) (Cesar et al., 2009). An experiment conducted in a laboratory concluded that this polymer degrades faster in clay soils rather than in sandy conditions. The higher density of microorganisms found in clay soils played an essential role (Cesar et al., 2009). On the other hand, samples of biodegradable polymers exposed to ultraviolet radiation degraded faster than the buried fragments (Kijchavengkul et al.,2010). Polypropylene that was thermally pre-treated had a smaller mass and lower tensile strength than the non-treated sample.

6.3.1.Vegetation ignition

In agriculture, controlled fires are often used in order to eradicate invasive species and to increase the fertility of the soil. This practice is more common in the developing world since it is cheaper than the application of agrochemicals and the utilization of mechanized agriculture. There is concern that the ignition of the top soil increases the concentration of aromatic compounds and other toxic chemicals in the soil. On the other hand, nutrients can burn and leave the soil in gaseous form or as ash. An issue which remains insufficiently addressed is the fate of the microplastics present in the soil, originating from sewage sludge or atmospheric deposition. Given the properties of the plastic polymers, it is likely that some of these plastic fragments will ignite and burn completely. However, the tilling methods that are applied on that land or simply the activity of the fauna mix the outermost layer of the soil and implicitly move the biosolids down into lower levels. Thus, it is expected that not all the microplastics present in the soil will ignite. A detailed study is needed in order to assess the consequences of a controlled fire occurring on land fertilized using sewage sludge. The results could be diverse. It is well known that the combustion of plastic polymers generates a series of persistent pollutants that are extremely harmful to the human health and the environment. For instance, burning PVC produces dioxins, furans and other aromatic compounds that cause lung diseases and are considered carcinogens. A study done in 2005 aimed at identifying the chemicals that result from the combustion of plastics contained in waste (Simoneit et al., 2005). Garbage samples were collected from Chile, where improper waste management remains an issue. Their combustion produced alkanes, alkanals, plasticizers, polycyclic aromatic hydrocarbons and other harmful chemicals. Some of these compounds formed particulate matter, while the rest sedimented as solid ash (Simoneit et al., 2005).

In comparison with municipal waste, the plastic content in the soil remains however low. It is nonetheless worrying that in some countries controlled vegetation ignition remains a common practice. In Japan, “yakihata” is a traditional agricultural technique that relies on the controlled ignition of the vegetation. Taking into account that in Japan sewage sludge has been regularly used as fertilizer (JSC, 2010), it is expected that a high volume of pollutants would be released in spring when yakihata takes place.

6.4.Waste disposal

6.4.1.Landfilling

Landfilling remains one of the most common waste management options (Barnes et al. 2009). In developed countries, once the waste is landfilled, it is protected by several layers of insulating material and subsequently covered with soil (Rayne, 2008). In contrast, in developing countries as well as in some countries with an economy in transition, waste is often disposed without a complex analysis of the site or any protective infrastructure. This approach leads to high concentrations of leachate and substantial risk of accidents. Landfill surface runoff could also increase the dispersion of plastic waste through precipitation or air currents. Microplastics found in landfills could also enter the hydrosphere if natural disasters occur.

It was believed that once landfilled, biodegradable plastics will transform into environmentally friendly chemicals. Nonetheless, after a landfill is sealed, the water content remains relatively constant, while the oxygen concentration gradually decreases. Not only biodegradable articles decay at very low rates but also non-biodegradable products are exposed to the same background conditions. It was found that under semi-aerobic conditions, the reduction of the plastic waste volume was faster than in anaerobic landfills (Klemchuk, 1990).

In conclusion, plastic polymers can remain almost intact for considerable periods of time. It was estimated that polyethylene would need up to 500 years to decompose in a landfill (Lapidos et al., 2007). On the one hand, this could be seen as a positive outcome, since no corrosive and toxic degradation products are generated.

6.4.2.Incineration

The incineration of municipal waste is considered to be one of the most effective waste management strategies. There is concern with regard to the particulate matter resulting from the combustion of the waste, however, in theory, no plastic polymer would withstand the high temperatures found in the combustion chamber of an incinerator. Therefore, we hypothesize that incinerators end the flow of microplastics. In addition to the microscopic fragments that result from the controlled incineration of waste, the combustion of plastic also generates many toxic chemicals [35]. An alternative to the classic incineration of plastic waste is to use plasma pyrolysis. This procedure burns the input at temperatures between 3*25°C - 850°C* using a plasma torch. The advantage is that the atmosphere is deprived of oxygen and the volume of noxious chemicals is significantly lowered. Nonetheless, the higher costs of this technology demonstrate that it might not be implemented on a large scale.

6.5.The degradation of microplastics in the hydrosphere

Once they enter the hydrosphere, microplastics are mainly disintegrated through grinding or as a result of water turbulence. Generally, plastic fragments are subject to the stress factors presented in the section **4.3.Abiotic degradation**

Particles that are lighter than water tend to float and are therefore more exposed to UV radiation than fragments with a higher density. The sedimentation of the

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[35] For additional information, please see 4.3.3.Thermal degradation

microplastics depends primarily on their density, however, the activity of microorganisms and other aquatic species plays a fundamental role, too. Plastic samples were degraded to a greater extent in freshwater, than in seawater (Bernhard et al., 2008). It was also found that a higher oxygen content of a water body contributes to a faster oxidation (Sudhakar et al., 2007).

In deep water bodies, where photooxidation does not take place, the degradation of plastic polymers is very low (Watters et al., 2010). Hardly any microorganisms survive in such conditions. The low biological diversity means that the rate of biodegradation is not significant (Browne et al., 2007). Thus, it is likely that a plastic fragment will not biodegrade, but instead, it will break down into smaller pieces mainly due to physical stress (Barnes et al., 2009). Depending on the density of one plastic polymer, there are two scenarios that can take place in deep waters. Heavier microplastics can result in secondary microplastics, as well as nanoplastics that will continue to persist in the benthic zone. On the other hand, lighter polymers which previously sedimented as part of a cluster of pollutants or excretion of the fauna can subsequently escape and float up into the water-column. Therefore, the benthic zone can act as a source of freshly degraded plastic fragments, but also as a reservoir of primary microplastics which were trapped into aggregations of sediments.

6.5.1.Spatial distribution

Taking into account the negative impacts microplastics may have on human health, it is desirable to limit the intake of food items that originate from regions having a high concentration of plastics. The complete elimination of seafood dishes is not a viable long-term solution and it might have dramatic consequences for the labor force working in this industry. However, identifying the most polluted areas and reducing the fishing activities in the neighboring territory could be the first step.

A study done in the Belgian territorial waters found microplastics[36] in all the samples collected (Claessens et al., 2011). A harbor sediment sample contained the highest concentration, possibly due to slow water currents, river runoff and direct intentional and unintentional discharge from shipping activities (Claessens et al., 2011).

Another project which spanned over two years found that the mean concentration of microplastics in the surface layer of the Danube was 0.938 items/m^3

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[36] Microplastics, <1 mm in diameter

(Lechner et al., 2015). This was significantly higher than the concentration from 2012, when 0.055 items/m^3 were found. Moreover, while in 2012 less than a third[37] of the microplastics were pre-production plastics, the former study concluded that 86% of the particles were pre-production plastics. This difference was attributed to accidental losses from a plastic factory caused by strong precipitations (Lechner et al., 2015).

The sediments collected from the river bank of the Rhine in Germany river contained between 228 and 3763 fragments/kg, while its tributary, the Main river had 786-1368 fragments/kg (Klein et al., 2015).

Two beaches of Lake Garda were inspected in order to find out the abundance of microplastics. A higher concentration (1108 fragments/m^2) was found on the northern shore than on the southern side (108 fragments/m^2). The author concluded that the difference was caused by the wind, which has a strong influence on the water circulation patterns from this lake (Laforsch et al., 2013).

A similar investigation found a concentration of 0.29 items/m^3 in the surface layer of the River Rhône (de Alencastro, 2014). This study done in Switzerland determined the microplastic levels on the beaches of six lakes. The concentration ranged from 20 to 7200 fragments/m^2 (de Alencastro, 2014).

In contrast, the abundance of microplastics in the surface layer of Lake Geneva was six times lower (Faure et al., 2012).

The contribution of a municipal WWTP was examined by a research group from Chicago, USA (McCormick et al.,2014). While the upstream concentration in the surface layer was 1.94 items/m^3, downstream of the WWTP 17.93 items/m^3 were found (McCormick et al., 2014).

In Canada, the sediments from St.Lawrence River contained dissimilar microplastic concentrations (Eriksen et al., 2013). One sampling site contained 0 fragments, while the highest concentration was 136.926 items/m^2. This was found in the effluent canal of a nuclear power plant. The cause for this high concentration is subject to further research.The results showed that in average 43 000 microplastic particles per km^2 were found. In addition, the same study estimated that in the vicinity of Detroit and Cleveland the concentration is 466 000 microplastics per km^2 (Eriksen et al., 2013).

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[37] 31%

Table 4. A summary of the abundance of microplastics and their spatial distribution, as presented by Rocha-Santos and Duarte, 2015.

Source: Rocha-Santos and Duarte, 2015.

Location	Maximum concentration observed
USA, Laurentian Great Lakes	466 000 particles km $^{-2}$
Waters around Australia	839 particles km $^{-2}$
Sub-alpine Lake Garda, Italy	1108 particles m $^{-2}$
Portugal, Beach	218 particles m $^{-2}$
North Western Mediterranean Sea	1 particles m $^{-2}$
Venice Lagoon, Italy	2 175 particles kg $^{-1}$
Belgium, Coastal zone	213 particles kg $^{-1}$
Belgium, Coastline	18 particles kg $^{-1}$
Singapore, Coastal mangrove ecosystems	63 particles kg $^{-1}$
Germany, Beach, Norderney Island	4 particles kg $^{-1}$
Germany, Beach, East Frisian Islands	621 particles 10g $^{-1}$
Lanzarote Beach, Canary Islands	109 gL $^{-1}$
La Graciosa Beach, Canary Islands	90 gL $^{-1}$
NE Pacific Ocean	9 180 particles m $^{-3}$
USA, California, Coastal waters	3 particles m $^{-3}$
Tamar Estuary, Southwest England	0.040 particle m^{-3}

In Mongolia, the surface layer of Lake Hovsgol contained an average concentration of 0.0203 items/m^2 (Free et al. 2014). According to the author, the cause for this high value is the lack of a waste management system. The sewage is discharged directly into the lake, while the waste is dumped into improvised landfills. Additionally, the population density is low and there is no industrial activity in the vicinity of the lake (Free et al., 2014).

6.5.2.Spatial distribution in the hydrosphere

Despite the fact that there is data on the abundance of microplastics in the upper levels of water bodies or in sediments, there is no clear information on the vertical distribution of plastic fragments in the water column. Intuitively, researchers predict that lighter polymers will float, while heavier fragments tend to sediment. The processes that can influence the density of microplastics are presented in the section **4.1.1.4.Density.**

In addition, for a more precise evaluation, the background conditions of a water body shall be taken into account.

Table 5. The average water density of the largest seas and oceans. Source: Gluedideas.com[38].

Sea/Ocean	Density g/cm^3
Black Sea	1.012
Baltic Sea	1.0086
North Pacific	1.0254
Indian Ocean	1.0263
South Pacific	1.0265
North Atlantic	1.0266
South Atlantic	1.0267
Red Sea	1.0286
Mediterranean Sea	1.0289
Dead Sea	1.24

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[38] Density Of Sea Water Density Colour And Phosphorescence Of The Sea - Fresh, Difference, Surface, Specific And Gravity. Gluedideas.com. N.p., 2017. Web. 30 May 2017.

Fresh water has a density of approximately 1000 kg/m^3. The concentration of salts, minerals, seasonality and water pressure may lead to higher or lower values. In contrast, seawater has slightly different properties. The density of the seawater in the upper levels is between 1020 to 1029 kg/m^3. A particular case is the Dead Sea, which is, in fact, a saturated sodium chloride solution with an average density of 1240 kg/m^3. Desalination plants produce a concentrated output that is also heavier than regular seawater. The salinity of this waste can be up to 120 g/kg, while its density is around 1088 kg/m^3 (Nayar et al., 2016).

The role of pressure can be noticed deep into the ocean. At approximately 10.000m below the sea surface, the water density can be as high as 1070 kg/m^3[39].

Lastly, changes in water temperature modify the water density to a greater extent than salinity does. Like distilled water, the density of seawater increases as the water temperature decreases.

These factors have a major impact on the circulation of the ocean currents. The densest water forms layers on the bottom of the ocean. There, the circulation is mainly horizontal. On the other hand, the swirling effect from the surface level contributes to not only the mixing of seawater but also to the formation of winds.

In conclusion, the vertical coordinates of a plastic particle depend on a multitude of factors. Polymers that are heavier than 1030 kg/m^3 will rarely reside in the upper levels of water bodies. Also, pure microplastics having a density below 1020 kg/m^3 may not be found below the epipelagic zone.

6.6.Absorption by biota

The food source of an animal generally depends on the ecosystem it lives in. Most vertebrates are more mobile than invertebrates, thus their ability to cover larger areas gives them the possibility to feed on various types of food. The position in the trophic web also influences the preferences of one animal. Moreover, their interaction with pollutants depends on the trophic level. For example, a carnivorous mammal could ingest plastic fragments that were previously eaten by its prey. On the other hand, detritivores are more sensitive to small concentrations of pollutants, such as pesticides or insecticides. Such chemicals are not always fatal for these

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[39] Calctool: Pressure At Depth Calculator. Calctool.org. N.p., 2017. Web. 30 May 2017.

species and they may bioaccumulate in their body. The trophic interactions can subsequently transfer these pollutants to the upper levels of the trophic web, leading to biomagnification.

The dispersion of plastic waste in the environment has negative consequences for the biosphere. Since the hydrosphere is believed the main sink of microplastics, it is expected that significant quantities of plastic fragments were ingested by marine animals, birds and many others. Numerous studies proved that marine invertebrates ingest microplastics (Browne et al., 2008; Thompson et al., 2004). Seabirds (van Franeker et al., 2011), lobsters (Murray and Cowie, 2011) and many types of fish (Boerger et al., 2010) were found to contain diverse kinds of plastic chemicals. Plastic was found in the guts of sea birds starting from the 1960s (Ryan et al., 2009). 94% of the fulmars sampled by a study done in 1982 were found to contain plastic (van Franeker, 2010).

Microplastics were found in 35% of the planktivorous mesopelagic fish sampled in the North Pacific central gyre (Boerger et al., 2010). 83% of the lobsters analyzed by a study done in the Clyde Sea contained plastic (Murray and Cowie, 2011).

Most species ingest the microplastics unintentionally (Tourinho et al., 2010; van Franeker et al., 2011). The main reason is the appearance of the tiny clusters of plastic fragments, which are mostly covered by a biofilm layer (Bhattacharya et al., 2010).

The ingestion of microplastics can have several consequences for the biota. Large fragments might block the gastrointestinal tract (Tourinho et al., 2010). The presence of inert particles can cause pseudo-satiation and implicitly a loss in body weight or death (Derraik, 2002). Contrarily, some marine organisms are able to remove solid pollutants from their body (Andrady, 2011). However, microplastics that are ingested can also be absorbed into the body (Browne et al., 2008). Fluorescent samples were found in the circulatory system of the circulatory fluid of mussels 72 hours after ingestion. It was observed that mussels exposed to microplastics can develop an inflammation (Köhler, 2010).

6.7.Absorption by humans

6.7.1.Potential sources in production facilities

Microplastics are also present in products that do not use raw materials and ingredients extracted from areas[40] that are known to be subject to pollution with

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[40] E.g. the marine environment.

plastics. This shows that the dispersion of these synthetic polymers happens through a multitude of pathways.

It is therefore relevant to not only identify these additional flows, but also to quantify them. Theoretically speaking, the mass of tiny plastic fragments found in beverages or food items shall also be proportional to the quantity of synthetic polymers used in the production facility. Moreover, the import that enters the sterile laboratories can significantly contribute to an increase in the diversity and the mass of the microplastic. One indicator can be the presence of microscopic skin fragments in beer. Naturally, humans lose tiny parts of their epidermis, the outer layer of the skin. An entire cell layer can be degraded in one day and may contaminate the surrounding objects. Such cells can penetrate clothing, but also the special protective lab coats used in sterile environments. These little fragments also become airborne (Liebezeit and Liebezeit, 2014). It was discovered that textiles have a similar behavior. When worn, they can act like a direct source of fibers, depending on their composition (Yoon and Brimblecombe, 2000). Thus, contaminants may be present even in the most hygienic factories. Such sources of microplastics have to be quantified in order to have a better comprehension of the processes that generate plastic fragments outside the production facility, but also inside of it.

It is furthermore necessary to identify potential peripheric sources, that could also cause an increase in the background concentration. An unexpected increase in the abundance of microplastics can also originate from washed clothing that is dried in open areas, but also other household activities[41]. It is not yet clear if air filters containing polyurethane foam can also be a source of microplastics.

6.7.2.Seafood and fish

It is believed that humans ingest considerable of the microplastics from marine sources (Rochman et al., 2015).

The amount of microplastics eaten by an individual may depend on the amount of marine food consumed. The gastrointestinal tract of fish, where most of the solid pollutants accumulate is generally removed. Other marine animals, such as mussels or shellfish are eaten without removing the organs.

Most of the seafood eaten by humans is processed and cooked. Despite the fact that there is no clear information on the fate of microplastics during cooking, it is

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[41] Tumble dryer

believed that the high temperature may affect the chemical and physical properties of the plastics present.

Table 6. The microplastic abundance in various seafoods
Source:EFSA CONTAM Panel (2016).

Food type	Microplastic content	Method of analysis
Mesopelagic and epipelagic fish, North Pacific Atlantic Gyre	2.1 particles/fish n= 235 Size = 1-10cm	Stomach content
Pelagic and demersal fish, English Channel	1.9 particles/fish n= 184 (out of 504) Size = 130 to 5000 μm.	Digestive tract content, naked eye detection, FT-IR
Commercial fish species, Portuguese coast	1.4 particles/fish n= 52 Size = 220- 4800 μm.	Digestive tract content, Microscope detection(>500 μm)
Pelagic and demersal fish, North Sea	1-7 particles/fish n = 16 Size = <5000 μm	Gastrointestinal tract contents, sieve filtration(500 μm), FT-IR

Table 7. The microplastic abundance in bivalves.
Source:EFSA CONTAM Panel (2016).

Food type	Microplastic content	Method of analysis
Brown shrimp (Crangon Crangon), Southern North Sea	0.75 particles/g wet weight n= 165 Size = 200-1000 μm	Digestion with $HNO_3/HCLO_4$, Microscope counting
Commercial mussels (Mytilus edulis), from three Belgian supermarkets	0.37 particles/g wet weight n= 9 Size = 200-1500 μm	Digestion with $HNO_3/HCLO_4$, Microscope counting
Commercial bivalves, fish market from China	2.1-10.5 particles/g n=9 Size = 5-250 μm (60%) 5-5000 μm (40%)	Digestion with H_2O_2, floatation with NaCl, Microscope counting and FT-IR

Plastics could also originate from processing material, fishing equipment, textiles or other ingredients[42]. Thus, the removal of the organs does not guarantee that all the

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[42] Sea salt

plastics contained in the fish meat are removed. Additional research on this matter is needed.

The pollutants from marine organisms can be also found in other goods. Food sources that are rich in proteins are frequently added to supplements used in animal farming. Fish meal is used in poultry production or pig farming. Thus, microplastics can be transferred to other non-marine animals (Bouwmeester et al., 2015).

6.7.3.Microplastic pollution in sea salts

In addition to the absorption by biota, microplastics are also part of many goods which are extracted from the hydrosphere. The high concentration of microplastics found in sea salt shows that these fragments are not only widespread in nature, but they are part of our everyday diet. Microplastics were also found in salt that was extracted from mines and wells. Since there has been no contact between a water body and the salt deposit, most probably the plastic is accidentally introduced in the salt during the production phases.

The location and the characteristics of the site where the sea salt is produced have an impact on the proportion of microplastics.[43] In the Yangtze Estuary, the density of microplastic was 4137.3 particles/m^3 (Yang et al.,2015).

5595 microplastics/m^2 [44] were found on the beaches of Hong Kong. Further south, on the coast of Hainan Island, up to 8714 microplastics/kg were recorded. These studies confirm the hypothesis that microplastics tend to sediment in coastal areas, as well as estuaries and deltas. Coincidentally, these regions are also the source of the salt used by many Chinese salt producers. While on China's east coast the density is 559 people/km^2, in the northwest, where most of the saline lakes are found, the population density is 12 people/km^2. The authors of the study concluded that the population density and the economic differences are two essential factors that influence the quantity of microplastics discharged (Yang et al.,2015). Therefore, it was hypothesized that the abundance of microplastics in saline lakes is lower. No clear data on the concentration of microplastics in saline lakes is available so far.

The most frequent plastic polymer in sea salt was PET. Since it is a chemical with a higher density than the salty water (1.38 g/cm^3), presumably it sedimented during

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[43] In China, the sea salts are extracted from the coastal waters in locations where the population density is very high..

[44] Average value

the crystallization phase of the production. Taking into account that it is possible to estimate the content of microplastics in sea salt by investigating the site from where the salt is extracted, estimating the quantity of microplastics ingested by a person is also attainable.

Table 8. The microplastic abundance in honey, beer and salt
Source:EFSA CONTAM Panel (2016).

Food type	Microplastic content	Method of analysis
Honey samples, mostly from Germany	0.166 fibers/g n=19 Size = 40-9000 μm	Sieve filtration, Microscope counting, Fuchsin staining
24 German beer brands	75, 87, 86 microplastics / Liter n= 24 Size = NA	Sieve filtration, Microscope counting, Rose Bengal staining
Chinese salt brands	Sea salt:0.550-0.681 particles/ g n=5 Size = 45-4300 micro m	Digestion with H_2O_2, Microscope counting, FT-IR

Furthermore, other food items rich in microplastic are mussels and other seafood products. However, the difference is that marine products are not found in the everyday diet of a person living in a landlocked country. Contrarily, sea salt remains a common ingredient for most of the dishes.

6.7.4.Microplastics in beer

The origin of foreign items in beer was analyzed since the 1970s. It was believed that the sources of such contaminants are the materials from the production facility. In Germany, 66 components are allowed to be used for brewing beer (Metzger, 2010), out of which nine accessories are used for filtration[45]. Studies concluded that

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[45] Activated charcoal, asbestos, bentonite, cellulose, cotton, isinglass, kieselgur, perlite and wood chippings

particles larger than the pore size of the filters can end up in beer[46]. Asbestos fibers were also found (Glenister, 1975).

Another potential source of microplastic pollution is the recycled or reused glass bottles. Contaminants may remain in the recipient after cleaning. Impurities found in beer were associated with the improper operation of a bottle washing device (Steiner et al., 2010).

The contamination of hop, barley and other vegetal sources used for the production of beer was not yet examined. Synthetic fibers were found in numerous cereals and grains and it is therefore expected that other crops also accumulate such pollutants during the growth phases.

Liebezeit and Liebezeit concluded that the microplastics found in beer were also identified in the regular tap water (Liebezeit and Liebezeit, 2014).

Table 9.Mean microplastic concentration in 24 German beer brands. Source: Liebezeit and Liebezeit, 2014.

Beer type	Fibers (n l^{-1})	Fragments (n l^{-1})	Granules (n l^{-1})	Total (n l^{-1})
Pilsener mean	25	33	17	75
Wheat mean	26	31	30	87
Alcohol-free mean	17	47	22	86

6.7.5.Microplastics in honey

Apart from the microplastics found in salt and beer, it was discovered that other popular food items are contaminated with synthetic polymers. Honey samples were analyzed and the results showed that they contain microplastics. There are two plausible scenarios: the microplastics either deposited on the flowers from where the bees collected the pollen, or they have entered the system when the honey was processed. In both cases, atmospheric deposition is believed to play an essential role.

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[46] PVPP and kieselgur particles were found in beer

6.7.6.A quantitative Material Flow Analysis of the microplastics ingested by humans

Based on a series of assumptions, the amount of microplastics ingested by a regular person on a yearly basis can be estimated. Naturally, humans come in contact with plastic products every day. However, given the regional differences in plastic pollution, the amount of microplastics ingested by humans varies, too.

It has been discovered that three widely used foods, as well as beer, contain significant concentrations of microplastics.

Annually, 183.75 million kiloliters of beer are consumed[47]. In most of the countries, the consumption of beer under a specific age is prohibited. In reality, teenagers start consuming beer from an average age of 14 years old. The World Bank statistics show that 26.11% of the world population is under 14 (World Bank, 2015). Thus, only those above this age are taken into consideration for this calculation. The average consumption of beer on the global level is therefore 33.16 liters per capita/year. Using the values of the study done by Liebezeit and Liebezeit, we conclude that the minimum average content of microplastics ingested by an average human from beer is 2487.3 particles/year, while the maximum average is 2885.2 particles/year.

The amount of sea salt consumed is also very variable. According to the World Health Organisation, an adult shall consume not more than 5 grams per day (WHO, 2016). However, in some European countries, the average salt consumption is around 10 g/day (Desmond, 2006). There is no exact data on the global consumption of sea salt. Given the fact that world population is concentrated in littoral areas, we might expect that sea salt is, in fact, the main type of salt consumed. Thus, for this calculation, an average of 5 grams of sea salt per capita/day is used. On average, such a quantity would lead to the ingestion of around 1123.28 microplastics/year.

The data on the world consumption of honey is also scarce. It is known that around 1.5 million tonnes of honey is produced on global level (European Commission, 2015). We assume that this quantity is evenly distributed so that every human would consume 0.2 kg per year. If every honey type would contain

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[47] Kirin Beer University Report Global Beer Consumption By Country In 2015 | 2016 | News Releases | Kirin Holdings. Kirinholdings.Co.Jp. Last modified 2017. Accessed May 31, 2017. http://www.kirinholdings.co.jp/english/news/2016/1221_01.html.

0.166 particles/gram, an additional 33 fibers would be ingested by every person on Earth.

Perhaps the consumption of seafood shows the most variable patterns. There are different regional particularities that relate to the type of fish, the cooking method and most importantly, the quantity of fish eaten annually. According to the FAO, the fish consumption is more than 20 kilograms per capita (FAO, 2016). The amount of other seafood products is unclear. Thus, for this quantitative analysis, we estimate the average global seafood consumption around 1 kg per capita. Also, combining the data from the **Table 7**, we conclude that the microplastic content in seafood other than fish is

2 particles/g. Therefore, 2000 microplastics could be ingested by a person annually. With regards to the content of microplastics in fish species, given the fact that the gastrointestinal tract and the inner organs are generally removed, we estimate that a fish weighing 500 grams contains one microplastic. In conclusion, 2040 microplastics could be ingested from seafood only.

It is believed that humans excrete up to 99%[48] of the microplastics ingested from food. There are no clear studies on the abundance of microplastics in the human body, it is likely that particles larger than 150 µm are excreted

(EFSA CONTAM Panel, 2016). Only smaller fractions can penetrate into organs.

If 5881.73/year microplastics enter the human body from all the four sources mentioned above, then around 5822 are discharged into toilets and subsequently enter the wastewater treatment plants. This is not a negligible number since a city the size of Vienna could generate almost 32 million microplastics per day.

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[48] Health Fears Over Microplastics In Our Seafood. Sky News. Last modified 2017. Accessed May 31, 2017. http://news.sky.com/story/microplastics-in-seafood-could-be-a-health-risk-experts-fear-10739835.

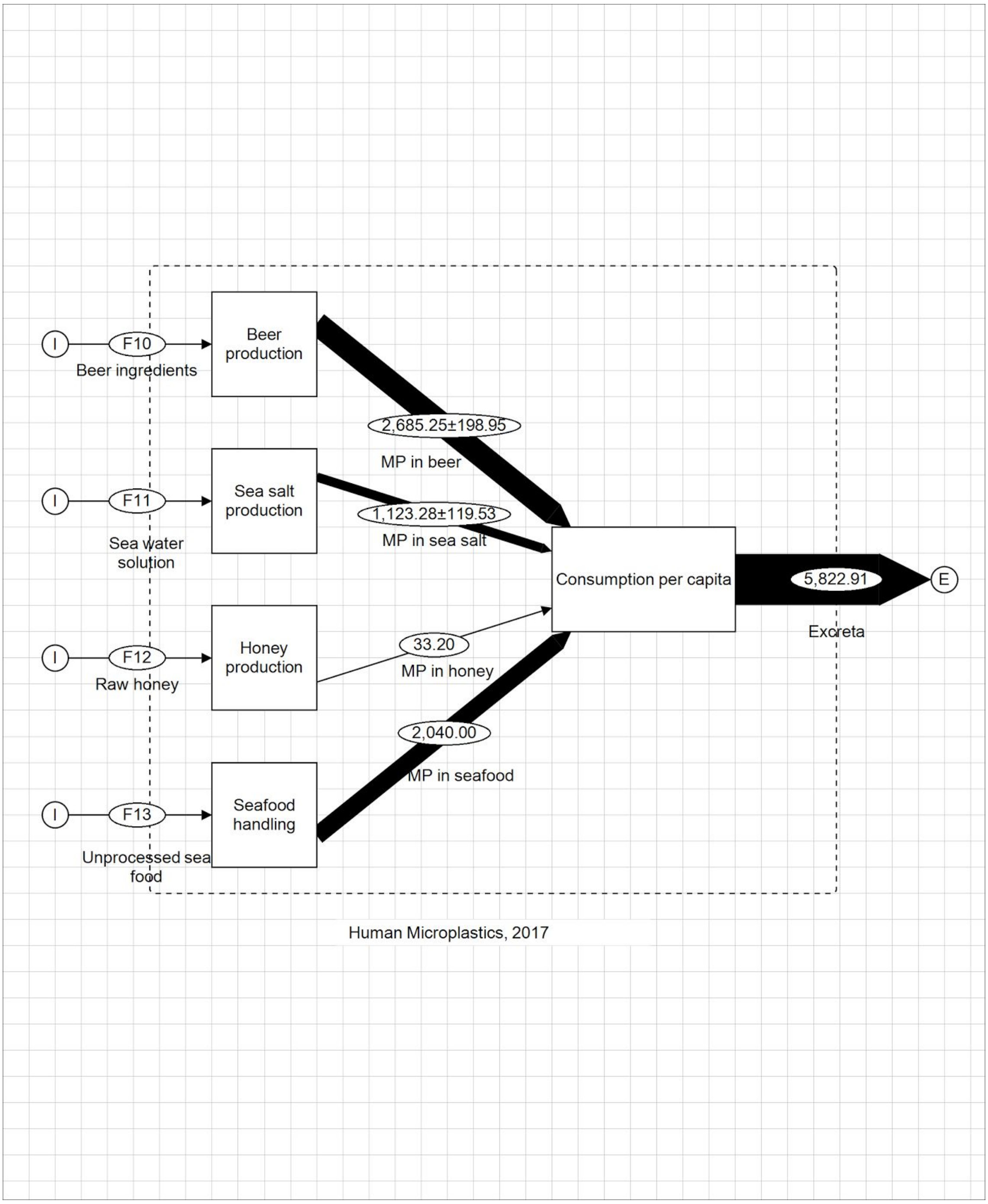

Figure 4. The qualitative Material Flow Analysis of the microplastics ingested by a human per year[49]

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[49] This figure was designed using STAN2. Copyright © 2012 by Institute for Water Quality, Resource and Waste Management, Technische Universität Wien, Karlsplatz 13/226, A-1040 Vienna, Austria; all rights reserved.

7.Concluding remarks

The Material Flow Analysis (**Figure 3.**) demonstrates that there are numerous processes that may facilitate the transport, the sedimentation, but also the degradation of microplastics. Both biotic and abiotic factors have the potential to transform these particles, producing additional secondary microplastics or nanoplastics. These particles might be harmless for humans, yet, the formation of microplastic clusters may be a vector for toxic pollutants.

The literature review confirmed that the inefficiency of the wastewater treatment plants allows the passage of high quantities of microplastics (Dubaish and Liebezeit, 2015). Other industries, such as paper recycling plants or water desalination plants may also release significant quantities. So far, the microplastic content of the leftover brine was not clearly evaluated. Since microplastics were found in sea salt extracted from coastal areas, the output of desalination plants might also generate microplastics that were initially in the input water. Peripheral sources, such as floodgates accumulate microplastics from hinterland activities (Dubaish and Liebezeit, 2015).

A study done in the Pacific has shown that microplastics can also concentrate in regions with a low population density (Desforges, 2014). In this case, the nearby aquaculture industry and recreational activities were believed to release high quantities of microplastics. Marine currents were also associated with a high abundance of fibers, originating perhaps from urban settlements on the west coast of Canada and the United States. Lastly, natural hazards, such as the tsunami provoked by the Tohoku earthquake could also transport high quantities of plastic pollutants.

The main knowledge gap derives from the lack of standardized definition for microplastics. It is also necessary to elaborate on a universal set of sampling and filtration procedures that would estimate the quantity of microplastics in a sample with a high degree of accuracy. The application of concentrated hydrofluoric acid may degrade polystyrene or polycarbonate, while saturated NaCl solutions are not dense enough and allow the heavy microplastics to sediment. Specialised equipment is also mandatory in order to avoid observational errors: fly ash samples were believed to be microplastics before an evaluation using scanning electron microscopy was done (Eriksen et al., 2013).

The role of city dust, as well as other sources, is not yet completely understood. Not only the wear and tear of tyres may produce nano and microplastics, but also the crumb rubber which is widely used for sport courts, play grounds and running lanes. 3D printing may also become a considerable source of microplastics.

While no serious diseases and illnesses have been associated with microplastics, an average human might excrete up to 5800 microplastics per year. Thus, a city with a population of 2 million inhabitants may generate up to 32 million microplastics per day. Further research shall preferably assess the mass of the particles that enter the human body.

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Annex

This table denominates the flows presented in figure 3.

Number of the flow	Flow name
Flow 37	MP in PCCPs
Flow 40	MP in adhesives
Flow 35	MP in PCCPs
Flow 41	MP in adhesives
Flow 43	MP in paint
Flow 42	MP in paint
Flow 16	MP in sewage sludge
Flow 45	Expanded polystyrene particles
Flow 44	Expanded polystyrene particles
Flow 2	MP in PCCPs
Flow 47	3D printing powder
Flow 46	3D printing powder
Flow 3	MP in adhesives
Flow 49	Plastic powders and pellets
Flow 48	Plastic powders and pellets
Flow 4	MP in paint
Flow 5	Expanded polystyrene particles
Flow 6	3D printing powder

This table presents possible degradation pathways

Process	Biotic degradation			Abiotic degradation			
	Physical	Chemical	Enzymatic	Mechanical	Photo-	Thermal	Chemical
Wastewater treatment	X	X	X	X	X		X
Biofuel production	X	X	X	X		X	X
Fertilizer application	X	X	X		X		X
Discharge into hydrosphere	X	X	X	X	X		X
Immobilization into infrastructure							
Vegetation ignition						X	X
Absorption by biota	X	X	X				
Landfilling							X
Incineration						X	X