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Stuck in the Sludge: A Study on Microplastics in Sewage Sludge across Swedish Wastewater Treatment Plants

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“The truth is: the natural world is changing. And we are totally dependent on that world. It provides our food, water and air. It is the most precious thing we have and we need to defend it.” - David Attenborough

Abstract

Wastewater treatment plants (WWTPs) are a notable source of microplastic (MP) release into the environment, with MPs present in domestic sewage, industrial effluents, and stormwater. Although WWTPs retain a significant portion of MPs, some are still discharged in treated effluents and sludge, which is often reused in agriculture. Thus, WWTPs represent a critical pathway for MPs into marine, freshwater, and terrestrial ecosystems. This study aimed to understand the fate and distribution of MPs in sewage sludge and assess the potential release of MPs into soils through sludge application. Sludge samples were collected in triplicate from seven WWTPs in the Mälardalen region, Sweden, and analysed by FTIR imaging with siMPle software. Sixteen MP types were detected, dominated by Polyester, Polypropylene (PP), and Polyethylene (PE). The total average count was 1'311 ± 102 MPs/g total solids. Variations in MP abundance and mass were analysed related to industrial inputs, external sludge sources and polyacrylamide use in sludge digestion. Larger WWTPs showed better MP removal, and finer primary screening meshes correlated with smaller MPs in sludge. Of the 15'365 tonnes of REVAQ-certified sludge applied annually to agricultural soils by these WWTPs, 0.1% consists of MPs, which is a small but environmentally significant fraction highlighting ongoing MP accumulation risks in soils. This study offers a robust method for MP quantification and calls for improved removal technologies, standardized methods, and stricter sludge reuse regulations to reduce environmental contamination.

Keywords:
Microplastic, wastewater influent, sewage sludge, polyacrylamide, agricultural fertiliser

Sammanfattning

Avloppsreningsverk (ARV) är en betydande källa till utsläpp av mikroplaster (MP) i miljön, där MP förekommer i hushållsspillvatten, industriella utsläpp och dagvatten. Även om ARV behåller en stor andel av mikroplasterna, släpps en del fortfarande ut med det renade avloppsvattnet och slammet, vilket ofta återanvänds inom jordbruket. Därmed utgör ARV en viktig spridningsväg för mikroplaster till marina, sötvattens- och terrestra ekosystem. Denna studie syftade till att förstå mikroplasternas öde och fördelning i avloppsslam samt bedöma den potentiella spridningen av MP till jordar genom slamanvändning. Slamprover samlades in i tre upprepningar från sju ARV i Mälardalsregionen, Sverige, och analyserades med FTIR-avbildning med programvaran siMPle. Sexton typer av mikroplaster identifierades, dominerade av polyester, polypropen (PP) och polyeten (PE). Det genomsnittliga antalet var 1’311 ± 102 MP/g totaltslam. Variationer i förekomst och massa av MP analyserades i relation till industriella inflöden, externa slamkällor samt användning av polyakrylamid i slambehandling. Större ARV uppvisade bättre avskiljning av MP, och finare galler i den primära silningen korrelerade med förekomst av mindre MP i slammet. Av de 15’365 ton REVAQ-certifierat slam som dessa ARV årligen sprider till jordbruksmark, utgör 2,2 % mikroplaster – en liten men miljömässigt betydelsefull andel som understryker risken för fortsatt MP-ackumulering i jordar. Studien presenterar en robust metod för kvantifiering av MP och efterlyser förbättrad reningsteknik, standardiserade metoder samt striktare reglering av slamåteranvändning för att minska miljöföroreningar.

Nyckelord:
Mikroplast, avloppsvatten, avloppsslam, polyakrylamid, gödselmedel för jordbruket

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List of abbreviations

ABS	Acrylonitrile-butadiene-styrene
ATR-FTIR	Attenuated Total Reflection-FTIR
BOD	Biological Oxygen Demand
CAS	Conventional Activated Sludge
COD	Chemical Oxygen Demand
CV	Coefficient of Variability
DS	Dry Sludge
ENK	Enköpings Kommun
EPA	Environmental Protection Agency
ESK	Eskilstuna Energie & Miljö
FTIR	Fourier-transform Infrared Spectroscopy
GAC	Granular Activated Carbon
IFAS	Integrated Fixed-film Activated Sludge
KAP	Käppala Förbundet
MBBR	Moving Bed Bioreactor
MBR	Membrane Bioreactor
MP	Microplastic

NOD	Nodra AB
PA	Polyamide
PAC	Powdered Activated Carbon
PAN	Polyacrylonitrile
PC	Polycarbonate
PE	Polyethylene
PE	*Population Equivalent*
PET	Polyester (or Polyethylene Terephthalate)
POM	Polyoxymethylene
PP	Polypropylene
PS	Polystyrene
PU	Polyurethane
PVC	Polyvinyl Chloride
siMPle	Systematic Identification of Microplastics in the Environment
SS	Suspended Solid
SYV	Syvab AB
TEK	Tekniska Verken AB
TS	Total Solid
VAX	Växjö Kommun
WWTP	Wastewater Treatment Plant

CONTENTS

1 Introduction

Microplastic (MP) pollution has emerged as a critical environmental and public health issue, with research on microplastics growing exponentially over the past decade. Growing concern has prompted research into sources, pathways, mitigation, and impacts. This work contributes to existing knowledge on MP contamination in wastewater treatment plants (WWTPs) and its subsequent release into the environment.

Recent studies report conflicting findings on MP exposure through sources including drinking water, salt, products derived from plants, products derived from animals (especially seafood), alcoholic beverages and packaged foods. This bioaccumulation of MPs in human tissues, such as faeces, blood, semen, breast milk, thrombi, colon, atheroma, and liver, underscores the need for further research in this area (Bocker & Silva, 2025). The long-term exposure to human health can be alarming as the use of plastics remains unavoidable (Dokl et al., 2024). At present, only 21% of the world's plastic is recycled or incinerated (Brown, 2019). This indicates that the issue of the use, production and disposal of plastic deserves attention and careful consideration.

MPs are solid plastic particles in the form of fibres, flakes and grains with a size between 1nm and 5mm. They are categorised into primary and secondary MP, where primary MPs are intentionally produced in small sizes and secondary MPs are formed through the fragmentation of plastic objects into microscopic particles (Naturvårdsverket, 2021). MP fragments are highly hydrophobic and small, facilitating the uptake by living organisms as well as binding with other harmful compounds. Besides MPs, nanoplastics (NPs) have also gained attention, raising health concerns because NPs are more reactive due to their small size. (Bocker & Silva, 2025). The density of MPs exerts a significant influence on their environmental behaviour, with heavier particles settling in sediments and lighter ones remaining suspended in the water column. Furthermore, the chemical composition of MPs has been demonstrated to influence their interactions with pollutants and organisms. This is due to the capacity of MPs to bind to metals and other contaminants, thereby modifying their toxicity and transport dynamics (Mahapatra et al., 2024).

Chanda (2024) emphasises that ecosystems are the primary accumulators of MPs, with freshwater, marine water and terrestrial ecosystems serving as reservoirs. Freshwater systems include rivers, lakes, creeks (natural) and WWTP (engineered). WWTPs, both in developed and developing countries, are a significant source of MPs in freshwater systems (Chanda et al., 2024). Although WWTP can remove a significant percentage of MP, a portion still gets released into the environment, despite advanced treatment (Conley et al., 2019). The main sources of MPs pollution in terrestrial ecosystems include WWTP discharges, agricultural practices, atmospheric deposition, uncontrolled sites, landfills, and anthropogenic activities (Chanda et al., 2024).

In contrast to ordinary pollutants, MPs don’t undergo a continuous fragmentation during biodegradation (Zhang & Chen, 2020). MPs that are produced by households and industries land up in WWTPs, which are also an important component of the urban water system. Thus, WWTPs have developed into a potential source for MPs (Carr et al., 2016). Since WWTPs were not originally designed to remove MPs, their presence reduces treatment efficiency. Wastewater treatment is divided into primary, secondary and tertiary processes, with the latter considered as an advanced treatment method. According to Zhang (2020), primary treatment involving fine screening (3-10mm) can reduce MPs, whereas coarse screening (16-25mm) allows MPs to pass into later treatment stages. Effective screening is therefore important in minimising the MP load entering secondary treatment. To replicate the same treatment outcome, an increase in the dosage of reagents is necessary. The impact of MPs in secondary treatment has been demonstrated to affect denitrification, which can result in the accumulation of ammonium in water (Cluzard et al., 2015). Additionally, a weak negative correlation has been observed between MPs and phosphorus removal, possibly due to issues related to sensitivity (Ling et al., 2017). In the context of sludge digestion, fibres and white MPs are frequently observed. Anaerobic digestion is a common method employed for the stabilization of these materials (Ak et al., 2013). Notably, methane production, in the digestion process, is significantly hindered by MP. In advanced treatment aiming to remove MPs, membrane bioreactor (MBR) technology has been shown to be more effective than conventional activated sludge (CAS) (Lares et al., 2018) and filtration play an important role in MPs removal.

Sludge, defined as a black, muddy residue resulting from wastewater treatment, is categorised into primary sludge and secondary sludge. The formation of primary sludge occurs during the initial processes of sedimentation and chemical precipitation. Meanwhile, secondary sludge is constituted by the waste biomass that is produced during biological treatment (Nathanson & Ambulkar, 2025). The aim of sludge treatment is typically to reduce the volume of the sludge and stabilize the organic materials. Treated sludge is considered to be a good fertilizer for the soil. However, sludge can also be incinerated or disposed of in landfills. Some WWTPs receive sludge from the food industry, which is then combined with the WWTP sludge for sludge treatment. Sludge treatment comprises three processes, namely thickening, digestion and dewatering. After some of the plastic and microplastics have been removed by the wastewater treatment, the remaining MPs are trapped in the sludge and the sludge treatment takes over the part of the treatment that removes the remaining MPs (Lechner & Ramler, 2015).

The most common detected polymers or MPs in a WWTP are PE, PET, PS, PA, PES, PVC, PP and PU (Sadia et al., 2022). The widespread contamination of soils with these diverse groups of MPs has raised concerns about their long-term effects on soil health. MPs readily interact with emerging pollutants due to their small size, porosity, hydrophobicity and surface functional groups (Premarathna et al., 2023). They serve as vectors for transporting toxic substances to plants and animals. In an effort to counteract these effects, several remediation techniques, including biodegradation and phytoremediation, have been the focus in this field of research (Hechmi et al., 2024). MPs is released into the environment primarily via effluent in the ocean or through the application of sewage sludge in agricultural soil (Okoffo et al., 2020). Sewage sludge is utilised in agricultural soils with the intention of enhancing fertility and facilitating the circular economy within the agriculture and wastewater treatment sectors (Bawa et al., 2024). Bawa (2024) determined through his research that WWTPs concentrate approximately 78-99% of MPs in the sludge. This poses a significant challenge in the management of sludge, where MPs accumulate. The removal of MPs from sludge as well as sewage sludge that has been proposed include thermal destruction by high -temperature incineration (Vahvaselkä & Winquist, 2021). However, methods involving thermal destruction may lead to the formation of persistent MPs, which pose a new source of contamination in bottom ash (Yang et al., 2021).

The fate of MPs once they have accumulated in sludge is largely dependent on the method of sludge disposal. When sewage sludge is applied to farmland as fertiliser, MPs enter the soil environment, where they have the potential to persist and interact with soil ecosystems. To understand the behaviour of MPs in the environment, studies by Rilling and Wang (2023) that put a focus on MPs pollution in soil argue that this threat is greater than the MPs pollution in aquatic environment. In contrast to the behaviour of MPs in the ocean, where they undergo high mobility and can be transported both vertically and horizontally by currents, MPs in soil exhibit reduced mobility. This results in a longer contact period, which enables the leaching of toxic chemicals. The consequence of this longer contact time is a decrease in microbial activity, an adjustment of the soil pH, and the formation of "plastic-rock complexes" as MPs bond to inorganic soil particles (Rillig et al., 2023; Wang et al., 2023).

In recent years, the EU has recognised the urgency of tackling MP pollution and set a target to reduce MP emissions by 30% by 2030 (European Commission, 2023). Action plans emphasise scientific research, while legislation addresses both intentional and unintentional releases of MPs. A broad restriction on MPs in products has been introduced, and member states must manage marine litter and plastic waste under the Water and Waste Directives. Sweden, as member of the EU since 1995, follows this framework (Åkerblom et al., 2022). The Urban Wastewater Treatment Directive requires at least secondary treatment of collected wastewater to meet discharge standards based on BOD (biochemical oxygen demand) and COD (chemical oxygen demand). Since the establishment of the Swedish EPA (Environmental Protection Agency) in 1967, national investments, particularly in industrial treatment, have significantly improved water quality. By 2020, the utilisation of WWTP sludge as a fertiliser had reached 43%. In order to enhance the quality of the sludge, a quality control system has been implemented within the wastewater industry. The aim of REVAQ certification is to systematically reduce the number of undesirable substances before they enter the WWTP.

1.1 Objective of Work and Research Questions

The current thesis work investigates the presence and characteristics of MPs in seven WWTPs in the Mälardalen region, such as Enköpings Kommun, Eskilstuna Energie & Miljö, Käppala Förbundet, Nodra AB, Syvab AB, Tekniska Verkan and Växjö Kommun. The primary objectives are twofold: firstly, to understand the fate of MPs in sewage sludge, and secondly, to assess the amount of intentional disposal of MPs associated with its reuse in agriculture.

The study encompasses the identification and quantification of MPs in digested and dewatered sewage sludge samples, the impact of treatment technologies as well as sludge handling employed in various WWTPs, and the evaluation of removal efficiency and contamination risks. To this end, the study will examine the polymer type, count, and mass of MPs present in the sewage sludge. In addition to the distribution of area and shape, statistical tests will be employed to reinforce the analysis. Another analysis will encompass sludge quantities produced, the disposal of sludge, and flows into agriculture. Correlations between different discovered parameters will also be discussed.

The following three research questions have been put forward:

- *What is the type, abundance, mass, area distribution and shape of MPs found in the sludge samples from different WWTPs?*
- *What are the differences and influences on the frequency of MPs in the different WWTPs, specifically regarding inlet mix and chemical sludge handling?*
- *What disposal methods do WWTPs use, and how much MP contamination results from fertilising agricultural soil with sludge?*

Chapter 3 will provide a more detailed description of the research methodology and the scientific manner to achieve the objective.

1.2 Limitations

This study is based on information exchanged with designated personnel from various wastewater treatment plants (WWTPs). Due to time or capacity constraints, not all seven plants were able to participate in online meetings. Information was primarily gathered via email, and five WWTPs agreed to online calls. Two of the plants also permitted on-site visits, including guided tours. Notes were taken during these interactions and email correspondence was used to confirm details and clarify any remaining questions. However, detailed process information was not available for all plants. Consequently, assumptions could only be made based on the collected figures, and no in-depth data collection was conducted during the study period. Additionally, as another individual carried out the measurements, only the measurement and extraction protocols were accessible. The method used is relatively novel and cannot be directly compared with those in other studies. Contamination cannot be entirely ruled out. Although three blank samples were analysed for method validation, the evaluation is based on a single sampling occasion.

2 Background and State of the Art

The following part of this paper moves on, to describe in greater detail the essential background needed to comprehend the current research study. It begins with the categorisation of wastewater treatments, followed by a focus on sludge production. With regard to MPs, the last part will be a brief list of MPs with their characteristics and applications.

The Swedish EPA defines the term wastewater, otherwise referred to as sewage, as wastewater collected in sewerage systems. Domestic wastewater is constituted of water utilized for various domestic activities, including toilet flushing, bathing, dishwashing, and laundry. Industrial wastewater is defined as wastewater discharged from areas used for commercial or industrial activities that is not domestic wastewater or rainwater (Åkerblom et al., 2022).

2.1 Categories of Wastewater Treatment Stages

When wastewater enters the treatment plant through the sewage, it needs to be purified from contaminants, so that it can be returned as an effluent to the freshwater. The treatments are in general similar everywhere. It was established by legislation and follows a scheme of conventionally four to five successive steps. The typical contaminants found in municipal wastewater are chemical oxygen demand (COD), biological oxygen demand (BOD), phosphorus (P), nitrogen (N), suspended solids (SS) and total solids (TS) (Valanko et al., 2020). In Figure 1 there is the primary treatment, consisting of mechanical treatment methods where large solids are separated from the waste stream using screens and sand traps (Gerba & Pepper, 2019; Valanko et al., 2020). It is also called as preliminary treatment, since it prepares the water for further treatment steps and avoids the reduction of the efficiency or damaging of the equipment (Crini & Lichtfouse, 2018). The gaps of the screens are usually between 3 and 20mm and the sand traps are usually aerated to also remove grease and fat, other than just heavy particles (Valanko et al., 2020). SS then settle in the sedimentation tank, also known as clarifier, leaving sludge behind, called primary sludge. (Gerba & Pepper, 2019). During this primary stage, a significant proportion of plastic, primarily in the form of fragments and fibrous residues, is removed. Around 70–90% of MPs larger than 300μm are eliminated. However, the process is less effective at removing smaller and lower-density MPs (Hechmi et al., 2024). Depending on the screen mesh size, MPs may cause blockages in fine screens. To maintain the same treatment efficiency, higher doses of reagents might be required (Zhang & Chen, 2020).

The secondary treatment (see Figure 1) consists of biological treatment where the remaining SS are decomposed from microorganisms and pathogens are reduced (Gerba & Pepper, 2019). The type of biological treatment processes is vast and depend on different parameters of the wastewater that is treated and operating parameters. As stated in Valanko et al. (2020) handbook on water treatment, biological treatment can be categorised into three distinct degradation processes: anaerobic, aerobic and anoxic. In addition, a variety of processes are employed, including the activated sludge process, which utilises a sequence batch reactor, and biofilm processes such as the biological trickling filter, bio-rotor, moving bed bioreactor (MBBR), biological filters, fluidized bed and granulated flocs. MPs can serve as surfaces for microbial colonisation, effectively acting as carriers for biofilm formation. Over time, this can lead to an increase in overall microbial biomass and a rise in waste sludge production of up to 9% under long-term exposure conditions (Zhang & Chen, 2020). Conventionally nitrogen is removed by two processes called nitrification and denitrification. However, a recent discovery involving anammox (anaerobic ammonium oxidation) bacteria has emerged as a novel method for nitrogen removal. With a combination of biological treatment and membrane technology, a MBR has been shown to enhance the concentration of SS in comparison to activated sludge (Valanko et al., 2020). The contaminants present in a biological treatment are then converted into biological sludge and carbon dioxide (Valanko et al., 2020). The percent of TS increases every treatment step, making the sludge go from black liquid to black muddy mass. The MP removal rate in conventional secondary treatment using activated sludge is relatively low, averaging around 16%. However, WWTPs that incorporate coagulation and flocculation can achieve significantly higher removal efficiencies depending on

MP size and density. For instance, aluminium-based coagulants have proven effective in removing smaller, high-density MPs, with removal rates reaching 70.7%. However, outcomes vary based on coagulant type, dosage, and MP characteristics (Hechmi et al., 2024).

The final treatment step before the effluent is discharged, is the tertiary treatment (see Figure 1), which is considered as an additional step. Physicochemical treatment processes such as coagulation, filtration, activated carbon adsorption, ion-exchange, advanced oxidation, reverse osmosis and additional disinfection take place (Crini & Lichtfouse, 2018; Gerba & Pepper, 2019). Activated carbon such as powdered activated carbon (PAC) or granular activated carbon (GAC) are used to remove persistent organic compound and trace elements (Vajargah et al., 2023). In terms of MP removal, chlorination remains largely unstudied. Advanced oxidation processes (UV, ozonation and photocatalysis) have demonstrated removal efficiencies of 60–90% while combining reverse osmosis with ultrafiltration that could also achieve almost complete MP removal. Under optimised conditions, the photo-Fenton process can achieve up to 96% MP removal. Additionally, membrane filtration systems are among the most effective technologies for MP elimination. MBRs reach 99.9% efficiency, followed by dissolved air flotation at 95%, disc filters ranging from 40% to 98.5%, and rapid sand filters at 97% (Hechmi et al., 2024).

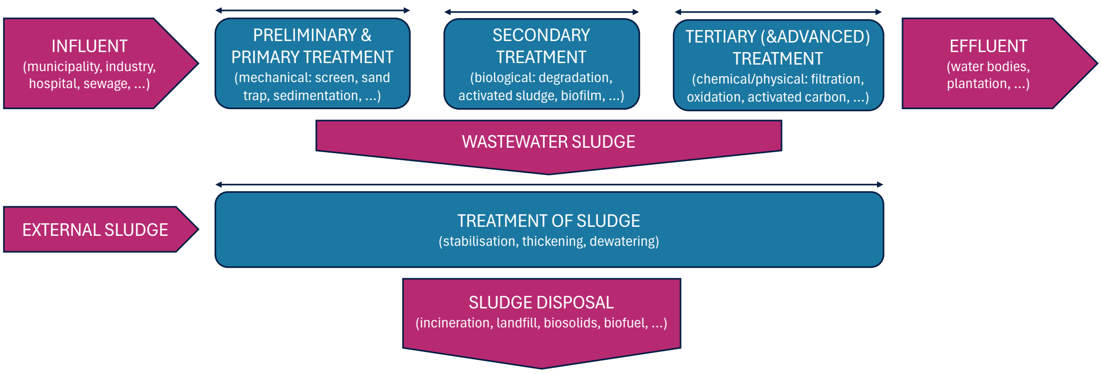

Figure 1: *Overview of main wastewater treatments (adapted from (Crini & Lichtfouse, 2018)).*

Despite the fact that a significant proportion of MPs are removed during the wastewater treatment process, smaller, high-density particles frequently remain attached to suspended solids (SS), which then accumulate in the resulting sludge (Hechmi et al., 2024).

2.2 Sludge Treatment

Sludge treatment and management is a critical part of wastewater treatment and is a complex and costly step that, if not done properly, would jeopardise the safety and health of the environment (Andreoli et al., 2007). Andreoli (2007) draws attention to Agenda 21 (UN), which is a key document in the field of environmental and sustainable development. According to the principles set out in Agenda 21, the practice of sludge management should be aimed at reducing sludge production, whilst at the same time maximising reuse and recycling, and ensuring that environmentally sound treatment and disposal of sludge is promoted.

Sludge is referred to by different names depending on the treatment process it originates from (see Table 1). Sludge comprises of solid and dissolved materials with a pH of 7-8, slightly negatively charged, that is organic and inorganic with main components containing nutrients, phosphorus and nitrogen (Valanko et al., 2020). Detailed composition can be obtained from Table 2 below.

***Table 1**: Types of sludge in sludge management adapted from (Valanko et al., 2020).*

Treatment Step	Primary Treatment	Secondary Treatment	Tertiary Treatment
Sludge Type	Primary/Mechanical Sludge	Secondary/Biological/Excess Sludge	Tertiary/Chemical Sludge

***Table 2**:List of sludge composition (Valanko et al., 2020).*

Organic	Inorganic	Nutrients	Micropollutant	Toxic and Harmful
▪ Fibres: cellulose, hair, proteins, plastics ▪ Polysaccharides ▪ Fatty acids ▪ Humic substances	▪ Sand ▪ Metal Salts: phosphate, sulphides, hydroxides, carbonates ▪ Ions: potassium, sulphates, chlorides	▪ Phosphorus ▪ Nitrogen ▪ Ammonium	▪ Organic: pharmaceuticals, hormones, flame retardants, biocides, dioxins ▪ Microplastics	▪ Pathogens: bacteria, eggs of parasites, viruses ▪ Toxic Metals

In the section below, the different types of sludge treatments are explained. Starting with sludge stabilisation, thickening, conditioning, dewatering and finally the disposal methods. See **Figure 2** for a diagram of the common sludge treatment scheme used in WWTPs.

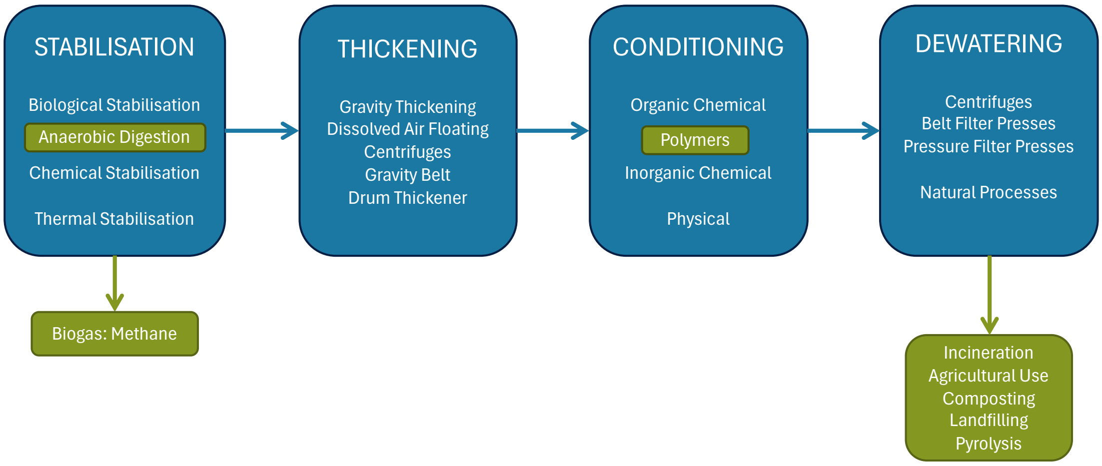

Figure 2: *Scheme of sludge production track.*

Sludge stabilisation was developed to reduce the pathogens and the smell that comes from the degradation of sludge (Andreoli et al., 2007). There is biological, chemical (alkaline) and thermal stabilisation, of which biological is the most widely applied process. Anaerobic digestion is the oldest and most commonly used stabilisation process compared to aerobic digestion (Turovskiy & Mathai, 2006). The process has been shown to reduce organic matter, thereby providing a valuable energy source in the form of biogas (methane). Furthermore, it results in a well-dewaterable sludge phase. Anaerobic digestion is a popular method, due to its insensitivity to changes in the sludge substrate and its relatively simple technical setup (Valanko et al., 2020). Municipal WWTPs typically treat a mix of sludges from various sources. They may also receive external sludges—such as from septic tanks, industrial waste, or other WWTPs—which are processed alongside existing sludges, either before or after stabilisation (Valanko et al., 2020). A longer retention time in anaerobic digestion does not necessarily result in greater microplastic degradation (Lessa Belone et al., 2024). Although extended retention time can improve the biodegradation of certain polymers, it is incompatible with the operational constraints of conventional large-scale WWTPs that use anaerobic digesters. Research of Lessa Belone (2024) indicates that, whether at mesophilic or thermophilic temperatures, anaerobic digestion is generally ineffective at breaking down MPs. Although higher temperatures could potentially promote MP degradation, achieving this on a commercial scale would be impractical due to the excessive energy requirements and difficulties in maintaining process stability.

Under typical anaerobic digesters conditions, MPs are unlikely to be eliminated from sewage sludge because they degrade slowly. However, the process may induce some physical or chemical alterations to MP surfaces. Ultimately, the complete breakdown of MPs is unlikely to be achieved through conventional, large-scale anaerobic digesters processes.

Thickening of sludge is a process that uses centrifuges, gravity belt thickeners, and drum thickeners, which have become more prevalent in modern practice (Valanko et al., 2020). The purpose of sludge thickening is to increase the solid concentration and reduce the volume of it thereby increasing the efficiency and reducing the cost of the subsequent sludge processes (Turovskiy & Mathai, 2006).

Sludge conditioning is a process that is carried out prior to dewatering and has been shown to have a direct impact on the efficiency of the subsequent process (Andreoli et al., 2007). Conditioning can be chemical or less physical techniques, where chemical one involves adding of polymers to the sludge and helps increase the solid concentration of it (Vajargah et al., 2023). Adding polymers is the organic chemical method, whereas inorganic chemicals such as iron, aluminium, magnesium salts and lime can also be added (Valanko et al., 2020). The most common used polymers in municipal WWTPs are cationic polyacrylamides (Valanko et al., 2020). The physical conditioning methods include heat treatment and freeze-thaw treatment (Vajargah et al., 2023).

Sludge dewatering is considered as the final sludge treatment step, where it impacts the transportation cost, increase the heating capacity for incineration, reduce the volume for disposal purposes (Andreoli et al., 2007). The dewatering processes that are most frequently applied include mechanical processes, such as centrifuges, belt filter presses, and pressure filter presses; and natural processes, such as drying beds and drying lagoons (Turovskiy & Mathai, 2006). The reject water produced during the thickening and dewatering processes is typically recycled back into the wastewater treatment system (Valanko et al., 2020).

For the disposal of sludge, the type, size and location of the WWTP is an important issue to consider (Andreoli et al., 2007). A range of options exist when it comes to recycling and disposal of sludge, including incineration, agricultural use, composting, landfilling and biogas production through anaerobic digestion or pyrolysis (Andreoli et al., 2007; Valanko et al., 2020).

2.3 Types of Polymeric Microplastic

Plastics are typically high molecular weight synthetic or semi-synthetic organic compounds composed of long chain polymer molecules. They are defined by their inert nature, since they are resistant to decomposition. However, they are also characterised by their durability with low weight, cost, and moldability (Bahl et al., 2021). A number of MP types were identified during the conducted measurements for this study, which are the subject of further analysis in Table 3. The table displays all the types detected in the sewage sludge samples and provides a comprehensive description of their properties and applications. An understanding of their application can become useful when analysing the occurrence in the sludge samples. The purpose of the table is simply to provide some examples, but the scope of the application is more extensive than that.

Table 3: *Properties and applications of the MPs found in the sludge samples [1]*

Polymer	Abbreviation	Property	Application
Acrylonitrile-butadiene-styrene	ABS	good resistance to medium temperatures combined with good impact resistance (certain types only) and antistatic adjustment, good chemical resistance, UV light can have a negative effect	tubs, portion packages for jams, takeaway cutlery, glossy reusable tubs, TV housing, telephone casing, metal lookalike, reflectors for torches
Acrylic	PMMA	good mechanical properties, more brittle than ABS, visually attractive, light transmission up to 92 % for some types	signage, lenses, number plates, bathtubs, mirrors, salad bowls, kitchen utensils
Alkyd	-	ability to form strong, flexible bonds, gloss retention, compatibility with a wide range of solvents, enhance resistance of other plastics	paint, coatings, adhesive, plastic and composite
Cellulose Acetate	CA	bio-based plastic, translucent and transparent, surface gloss, resin, machinability	x-ray films, cigarette filters, clothes, diapers and sanitary napkins
Epoxy	EP	temperature resistant, tasteless, odourless, resins	adhesives, floor binders, coating for metal drums and cans, encapsulation for electronic components, car drive shafts, helicopter blades, primers and paints
Polyamide (Nylon)	PA	thermoplastic with high temperature resistance, extremely strong and tough, good sliding properties and high wear resistance, contact with moisture may alter properties	oven bags, barrier film in meat and diary packaging, fishing gut, cable ties, zips, plastic screws, tool handles, castors for chairs and ladders
Polyacrylonitrile	PAN	low density, thermal stability, high strength and modulus of elasticity, wool-like character	medical field, textile application, carbon fibres, cement reinforcement, high technology application
Polyethylene	PE	high and low density, relatively low breaking strength and surface hardness, high viscosity, soft to rigid, sensitive to tension cracks, water repellent	milk bottles, fruit juice bottles, shopping bags, stretch wrap, peelable lids, cosmetic tubes, bubble wraps, foam sheeting, irrigation pipes, ventilation ducting, rotationally moulded products
Polycarbonate	PC	thermoplastic with high temperature stability with excellent resistance to all types of temperatures, good resistance to chemicals and UV light	reusable water bottles, lenses, lighting, CDs and DVDs, safety glasses, wine and beer tumblers
Polyester	PET	resins, tough even at low temperatures, low water absorption, resistant to water/oil/alcohol/acids at room temperature	clear water bottles and food packaging, trays, video and audio tapes
Polyoxymethylene (Acetal)	POM	metal-like properties, stiff, high-temperature performance, low creep, wear-resistant, good recovery from deformation	aerosol container valves, stationary components, automotive components, curtain accessories, cigarette lighter, washing peg springs
Polypropylene	PP	high breaking strength, insensitive to tension cracks, high rigidity	yoghurt and margarine tubs, ice cream container, bottles, caps, canister for storage, buckets, jars, straws, takeaway cutlery, nonwoven cloth, shrink labels, coat hangers, battery, brush bristles, hair extensions, appliance housing for kettles and toasters, fishing nets, toilet seats, filter bags
Polystyrene	PS	low elongation at break and heat resistance, excellent electrical insulation properties, not suitable for high centrifugal forces	yoghurt portion packs, display boxes, clear trays, takeaway cutlery and food container, stirring sticks, cake containers, vending cups, tread tags, coat hangers, toys, CD covers, computer housing, pens and rulers, fridge and freezer liners, mannequins, cooler boxes, balls and decoration
Polyurethane	PU/PUR	thermal and acoustic insulation, excellent adhesion to wood, metal, glass and fabrics, high strength-to-weight ratio, fast recovery from deformation, excellent grip,	protective packaging (foam) for transport of sensitive articles, mattresses, cushions, roof insulation, moulds for paving, insulation for fridge and freezers, automotive components, dashboards, steering wheels, wood-lookalike furniture, shoe soles, solid tyres
Polyvinyl Chloride	PVC	durable, lightweight, strong and fire resistant, with excellent insulating properties and low permeability, by using various additives in the manufacturing process, properties such as strength, stiffness, colour and transparency can be adjusted to meet specific requirements	window frames, floor and wall covering, piping, rainwear, insulation for power supplies, blood bags, transfusion tubes, surgical gloves, inflatable pools, tents

3 Materials and methods

The present study employs both quantitative and qualitative methodologies. The primary material consists of sludge samples collected from seven WWTPs, which were analysed using Fourier-transform infrared spectroscopy (FTIR). While FTIR measurements were conducted for this thesis, the preparation of the samples and the setup of the instruments were not part of this work and are therefore not the major focus of this thesis. However, the resulting data were used in the study and interpreted using various statistical calculations and tests. Microsoft Excel was used to perform calculations and visualise the data.

The collection of additional information was achieved through site visits to the WWTPs, online meetings with plant personnel, and the administration of questionnaires. The qualitative component of the research involves the analysis of questionnaire responses and meeting and inspection notes.

A comprehensive literature review was conducted to inform the development of the first chapters and subsequently employed in later chapters to contextualize the findings.

3.1 Fourier Transform Infrared Spectroscopy for Microplastic Characterisation

FTIR has been discovered to be a useful tool for identifying and characterising MPs as well as differentiating between polymers. Subsequent to this, FTIR has become one of the most commonly used techniques for detecting MPs in environmental samples (Andoh et al., 2024). A significant advantage of an FTIR is that it acquires the interferogram in less than a second. ATR-FTIR (Attenuated Total Reflection-FTIR), a common variant of FTIR, enhances its capabilities by enabling the identification of microplastics larger than and smaller than 500µm. Raman spectroscopy is similarly popular but operates on different physical principles (Zhang & Chen, 2020).

FTIR can identify various types of MPs, including fibres and fragments, and is considered more reliable than many other analytical techniques for polymer identification. However, it does have limitations—such as complex sample preparation, potential interference from background materials, and reduced sensitivity at low concentrations (Andoh et al., 2024). Despite these challenges, FTIR remains a widely used and valuable method for the identification of the different varieties of MPs in the environmental matrices. Andoh (2024) mentions its ability to accurately characterise chemical composition, which supports both the identification and quantification of MPs, as well as the tracking of their sources. This makes FTIR a key tool for understanding environmental distribution, interactions, and the long-term fate of MPs, ultimately informing strategies to mitigate their impact on ecosystems.

This study used FTIR to identify MPs in sludge samples through spectral fingerprinting. However, due to the lack of standardised procedures and the limited number of researchers currently using this method on sludge samples, formal method validation could not be performed. There were no certified reference materials available for the particle size range and polymer types analysed, and comparative testing against blank samples was not completely feasible although some were conducted. While the absolute accuracy of individual particle identification cannot therefore be fully verified, the method was applied systematically across all samples to ensure internal consistency. The results are therefore considered reliable for comparative purposes between WWTPs, though interpretation should account for the methodological limitations.

The validation of the sample analysis method was done with blank samples. From the treatment plants, three sludge samples each were analysed. Blank samples were used, to identify background contamination, asses the accuracy of the analysing method and estimate it's uncertainty. If MPs are found in these blanks, it means that the sludge samples are contaminated externally. There were mainly three types of blank samples (with no sludge), that will be presented below.

- **Air blank:** This blank checks for contamination from the air or environment where the MP were extracted from the sludge samples. For this reason, the air blanks were stored for 17 hours and the lens was placed on the sample holder and then transferred to a Petri dish and covered while waiting for analysis.

  - PE and PP were identified, with a total of 1440 particles in EtOH solution. 94% of the particles were PP. The spectral match between the measured sample spectrum with the reference spectrum is 70%.

- **Process blank:** A blank sample goes through the entire sample processing workflow, such as fenton oxidation, filtration and density separation. This helps to find out if MPs were introduced from reagents, or equipments.
  - PE, Polyester and PP were discovered, with a total of 920 particles. 78% of the found MPs is Polyester, followed by PP (17%). The spectral match between the measured sample spectrum with the reference spectrum is 70%.
- **Recovery blank:** This blank mix contains a known amount and type of MPs and helps to find out how many of those MPs were successfully identified. Identifying uncertainty of the sludge samples can be done from the results of recovery blanks.
  - PE, PVC and PP were used as reference particles. The spectral match between the measured sample spectrum with the reference spectrum is 70%.

3.2 Sludge Sample Preparation, Microplastic Extraction, and Quality Assurance

In 2024, sludge samples were collected from seven WWTPs. These samples were taken from digested and dewatered sludge, meaning they were ready for final disposal. After the samples had been subjected to FTIR imaging, a comparative analysis was carried out using the visible image and the infrared map. This was followed by an analysis using siMPle[1] (Systematic Identification of MicroPLastics in the Environment), which compares the infrared spectrum from the FTIR with the reference spectrum database. Additionally blank samples and recovery samples were prepared, also measured with FTIR and analysed using siMPle. All of these steps were made in the Microplastics Research Laboratory at Uppsala University. The section below explains briefly

[1] https://simple-plastics.eu/

the MPs extraction from sludge, that is done independently from this thesis work.

The extraction of MPs from sludge samples is a methodical process that involves oxidation and density separation. The oxidation step involves the use of a combination of Fenton reagent and hydrogen peroxide to break down organic material. Concurrently, density separation is employed to ensure the removal of heavier inorganic material, thereby facilitating the isolation of microplastics. In an effort to mitigate contamination, samples are hermetically sealed with glass caps or covered with aluminium foil, and all chemicals are meticulously filtered prior to use. Furthermore, the employment of blank samples is integral to account for potential contamination arising from the process and air deposition during analysis.

The chemical preparation involves the use of hydrogen peroxide at a concentration of 30%, in conjunction with a Fenton solution composed of 7.5g ferrous sulphate and 6mL of 95% sulfuric acid. The density separation process relies on a zinc chloride solution with a density of 1.4g/cm^3. It is imperative to note that all chemicals and MQ water are subjected to filtration to mitigate the risk of contamination.

During the oxidation process, 4g of sludge, corresponding to about 1g of dry matter, is introduced into a 2L beaker to prevent overflow. The sample is then treated with 25mL of Fenton reagent and 25mL of hydrogen peroxide, initially in an ice bath for 15 minutes, followed by incubation at 58°C with shaking at 120rpm for 30 minutes. This process is repeated three more times, using a total of 100mL of hydrogen peroxide. The temperature is then reduced to 40°C, and the sample undergoes further incubation for 24 hours. After oxidation, the samples are filtered through 10µm filters, transferred to smaller beakers containing 25mL hydrogen peroxide, sonicated for 15 minutes, and then incubated for a further 24 hours.

Subsequent to oxidation, density separation is performed in order to isolate microplastics. The sample is then filtered once more through a 10µm filter and washed with MQ water to remove any residual hydrogen peroxide. The filter is then returned to a beaker containing the previous filter and is rinsed with a zinc chloride solution. Following a 15-minute sonication period, the solution is transferred to a 250mL separation funnel containing 75mL of zinc chloride. The sample is then subjected to agitation, followed by a period of settling, which allows the separation of the sediment. The lower sediment layer (approx. 30mL) is then discarded, and the remaining solution is filtered once more through a

10µm filter. The sample is then transferred to a 20mL test tube, covered with ethanol, and sonicated for a further 15 minutes. Following this step, the ethanol is evaporated at 50°C, and 2mL of ethanol is added to determine the microplastic concentration. Prior to analysis, the sample is vortexed, and 50µL is pipetted onto a zinc selenide lens, where it evaporates on a heating plate at 50°C.

FTIR analysis is then carried out using an Agilent Cary 620 FTIR Microscope. A background scan is performed on a blank lens to exclude peaks from carbon dioxide and water vapour, which could interfere with spectrum identification. The analysis is conducted using a 15x lens at a resolution of 8 cm^{-1}, with 30 scans per pixel in the 3400-850 cm^{-1} range.

The final stage of the process involves data processing using siMPle software, which compares spectra against a reference library to identify and quantify microplastics. The results obtained are presented in the form of either a digital map, which visualizes the detected microplastics, or a tabular data set, which provides detailed information regarding the polymer type, area, estimated weight, and match percentage to reference spectra. The software employs an algorithm that iteratively matches spectra, determining particle size and shape based on boundary limits. In instances where the sample contains a high concentration of microplastics, adjustments to detection limits may be necessary to ensure the accuracy of the results.

It is acknowledged that there are several sources of error and uncertainty that are noted throughout the process. FTIR analysis may be affected by air deposition of microplastics, out-of-focus particles, or spectral interference from white deposits. In siMPle, miscalculations of area and mass can occur, particularly with fibres, which are challenging to analyse due to their cylindrical shape. Additional sources of uncertainty arise from the processes of sample purification, where material may adhere to container edges or be lost during filtration. Contamination risks include exposure to plastic lab materials and unfiltered chemicals. Furthermore, prolonged storage of samples, particularly when stored in refrigeration for over a year, has been observed to result in the growth of mould, thereby raising concerns about the potential impact on the integrity of microplastics and the reliability of the analytical results.

This comprehensive methodology ensures the effective extraction, identification, and quantification of microplastics from sludge, with careful attention to minimizing contamination and addressing potential sources of error.

3.3 Identification and Quantification of Microplastics

Each plant was represented by three samples. The results obtained from the software were processed using the MS Excel. Each sample spectrum was once matched unmodified with the reference database and once with a modified spectrum. Modified meaning, a spectral match threshold of 70% was applied for polymer identification, with only matches equal to or above this level (specifically for PP, PVC, and Polyester) being considered reliable. Spectra falling below this threshold were excluded on the basis of insufficient differentiation. The following parameters are given: the type of MP, the number of pixels, the area on the map [μm^2], the dimensions (major and minor) [μm], the Feret length, the volume and the mass. These parameters were then applied to calculate values such as length/width ratio, elongation and compactness according to the Bettersize guide (Bettersize, 2022). Furthermore, the number of occurrences of MPs and the mass per gram of total solids in sewage sludge were taken into consideration. Since a subsample of 50μL and 100μL in some cases was taken from the samples with 20mL ethanol added, the number of particles and mass per gram of dry sludge (here, DS = TS) was calculated. The wet weight and weight of TS of the sludge samples where known, from which gram of TS was calculated. For each plant, a profile of the detected MPs was created, including their size distribution, occurrence count and mass, and shape. In this analysis, all three samples were considered together for one plant. Finally, a collective analysis was made, in which all seven plants were considered together and compared to obtain the overall result. The collective analysis revealed the presence of sixteen MPs in all seven WWTPS. In order to facilitate the understanding of the results, graphs were created for each of the three analysis parts. In the final step, the study estimated the MP load entering agricultural soils via sludge used as fertilizer, based on the proportion of sludge applied and earlier measurements of MP count and mass.

Additionally, a statistical test, a one-way ANOVA test was performed to interpret the measurement results (also see Appendix G, K, L). First, the test was performed to compare MP counts (MP/gTS) as well as the MP mass (ng/gTS) across all WWTPs (n=7). Second, the test was run to make investigation on the variation in MP count and mass across all detected MP types (n=16).

3.4 Data Collection from WWTPs

For each WWTP (see **Figure 3**), a designated individual was assigned to be contacted. In the majority of cases, this individual was a process engineer. The primary objective of the initiative was to obtain basic information about the treatment process and some key data about the plant. The first step was to contact each plant by email. The feasibility of a plant visit or online meeting was also requested. A total of seven WWTPs were visited in person, namely Syvab AB and Tekniska Verken AB, while three online meetings were held with representatives of WWTPs in Käppala Förbundet, Eskilstuna Energie & Miljö and Nodra AB.

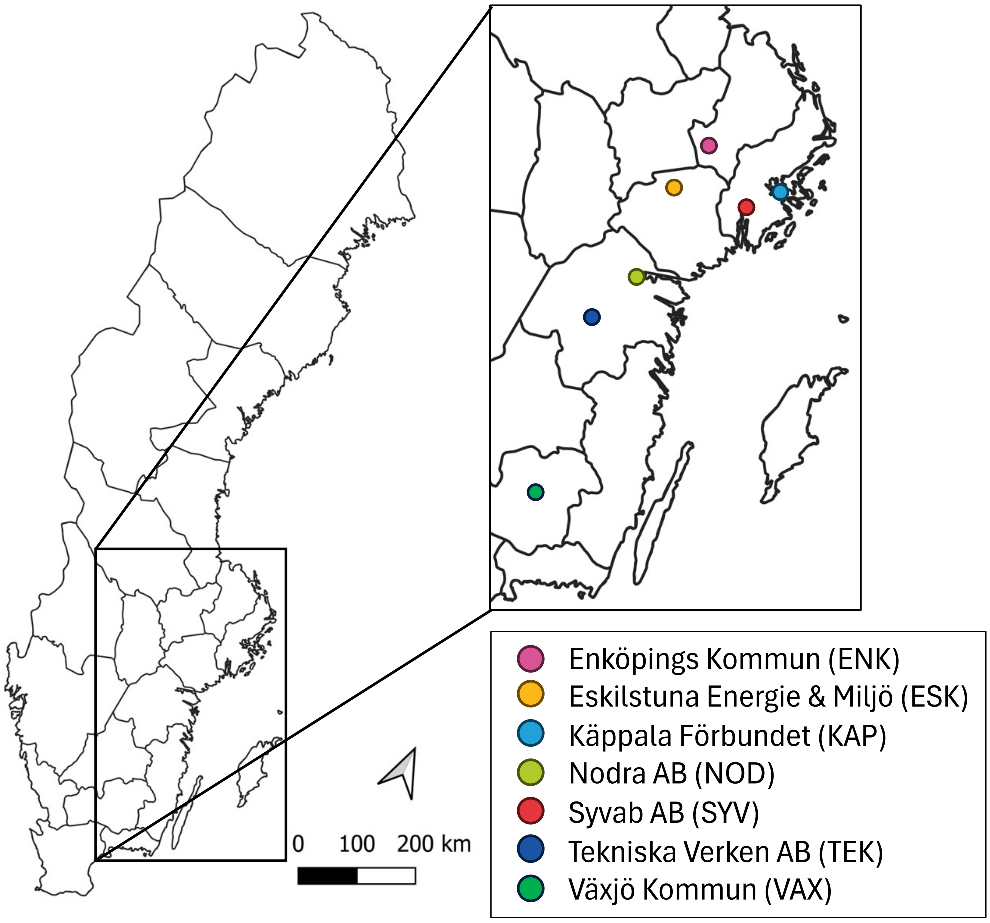

Figure 3: *The seven WWTPs analysed in this study are all located in Sweden.*

In a second step, a questionnaire was distributed with instructions to answer each direct question concerning details on sludge treatment, influent and effluent (see Appendix A).

From the questionnaire sent to the WWTP, key figures about the size of the plant in form of *population equivalent*, information about origin of influent and the disposal of the effluent, treatment types, sludge treatment and relating parameters were revealed. The source inflow of wastewater was part of the survey, considering municipalities, industries and hospitals. For the effluent only the Baltic Sea or other water bodies were considered as recipient. The influence of industrial wastewater is a contributing factor next to the domestic wastewater that is being treated at a WWTP, regarding the type of MPs found in sludge. Therefore, the industrial influence has been categorised into three groups to help the analysis:

- **Minimal (1-5%) :** The system is predominantly influenced by domestic wastewater and the industrial contribution to the influent is negligible.
- **Moderate (5-20%):** The industrial load is present, but its impact is considered secondary to the domestic component. It contributes to the influent characteristics without exerting a significant effect on treatment processes (Mikosz, 2015).
- **Elevated (20-35%):** A significant industrial contribution, which may begin to influence treatment processes and influent characteristics, although domestic wastewater remains the main contributor.
- **High (35-50%):** A high share of industrial wastewater starts to influence the treatment processes and special or advanced treatments have to be introduced. The industrial waste can only be treated with a pre-treatment. Industrial contribution > 50% have designated WWTPs to treat industrial wastewater systems where the treatment processes depend on the contaminats from the industry, which vary from industry to industry.

4 Results and Analysis

4.1 Source of Sewage Sludge and Sludge Treatment

The results refer to the measurement and calculation outcomes from the seven WWTPs located in Mälardalen region namely Enköpings Kommun (ENK), Eskilstuna Energie & Miljö (ESK), Käppala Förbundet (KAP), Nodra AB (NOD), Syvab AB (SYV), Tekniska Verken (TEK) and Växjö Kommun (VAX) (also see **Figure 3**).

As illustrated in Table 4, three out of seven WWTPs treat more than one municipality. KAP treats the most municipalities, with eleven in total, followed by SYV with six municipalities. It is evident that all WWTPs are subject to the influence of industry. It is apparent that three plants (ESK, SYV, VAX) have a minimal industrial influence, while two plants (ENK, NOD) belong to the moderate influence category. TEK and KAP have a rather elevated industrial influence with a percentage share exceeding 20%. VAX has stated that there are small businesses and industries with almost no contribution to the PE value, for which an influence of less than 5% is estimated. Every plant has at least one hospital connected, except SYV. Every plant expects stormwater run-off that flow into the plant through leakages. The recipient of two WWTPs are nearby laying lakes, that flow later into the Baltic Sea, that is the recipient of the effluent water from all the other WWTPs.

As illustrated in **Table 4**, the study also demonstrates the nature of the external sludge that is received by the plants, in addition to the common applied spacing for the primary fine screening, which is 2mm (NOD, VAX), 3mm (ENK, KAP, TEK) and 6mm (ESK, SYV). Furthermore, the number of MPs found is also mentioned in the same table to facilitate comparison of the different factors.

*Table 4:**Wastewater inlet and external sludge sources of the 7 WWTPs listed with other factors that may influence MPs abundance in sludge.*

	ENK	ESK	KAP	NOD	SYV	TEK	VAX
PE [-]	30 380	108 137	554 224	182 300	200 228	170 600	95 000
No. of Municipalities	1	1	11	2	6	1	1
Inlet Industries	10%	5%	31%	12%	5%	23%	< 5%
No. of Hospitals	1	1	2	1	0	1	1
External Sludge	none	food waste, ice cream factory waste, smaller WWTP	none	private houses, fats from restaurants	food waste and fats from restaurants	countryside	food waste, sludge from private sewage systems
Opening of Fine Screens (Primary Treatment)	3 mm	6 mm	3 mm	2 mm	6 mm	3 mm	2 mm
Industrial Influence	moderate	minimal	elevated	moderate	minimal	elevated	minimal
Polymer Types Found	**9**	**10**	**8**	**13**	**6**	**9**	**9**

It is also noteworthy that, of all the WWTPs analysed in this study, TEK and ESK are the two single WWTPs that employ an additional treatment step. TEK utilises ozonation and a MBBR process alongside IFAS for the removal of pharmaceuticals. SYV treats the water in the final stage using disc filters with a pore size of 10µm. Whereas ESK applies a constructed wetland to exert the treated water after final sedimentation with a retention time of 6 days. KAP and NOD utilise MBBR, while SYV is testing MBR in their pilot projects, however the main wastewater stream remained unaffected during sampling by this initiative.

The biogas produced in the digesters during the sludge treatment is used as biofuel for busses and other vehicles. A part of it is also used for heat and electricity at the facility, indicating sustainable approaches at WWTPs.

Taking a closer look at sludge in **Table 5**, it shows the yearly sludge production. What stands out in the table is that KAP treats the largest volume of polluted wastewater, followed by SYV, NOD and TEK. PE corresponds to biodegradable organic matter with a biochemical oxygen demand of 70g dissolved oxygen per day over seven days period (BOD7) (Åkerblom et al., 2022). The plant, which is designed to treat a more limited volume of wastewater and is therefore the smallest of the seven treatment plants, is the ENK plant and has also the lowest sludge production weight. From the resulting values, the order of the plants based on PE values can be expressed as KAP > SYV > NOD > TEK > ESK > VAX > ENK. The proportion of TS in all the WWTPs range between 24-31%, with an average value of 27% of TS in sludge production. Furthermore, the volatile solids

(VS) range was found to be between 9-14%, with an average of 12% across the seven WWTPs. What stands out in the table below, is that the sludge production of KAP is relatively low in relation to the high PE. The correlation between PE and sludge production is strongly linear ($R^2 = 0.932$, $p = 0.0042$), where 93% of the variation in sludge production can be explained by PE values. This also means 7% of the variation are caused by other factors.

Table 5: *Plant dimension (PE) and annual sludge production with terms of total solids (TS)*

	ENK	ESK	KAP	NOD	SYV	TEK	VAX
PE [-]	30 380	108 137	554 224	182 300	200 228	170 600	95 000
Sludge Production [t/y]	1 827	7 988	35 000	9 600	5 378	10 000	6 723
TS [%]	31	28	25	28	24	27	28
VS [%]	14	12	13	13	9	12	10

As shown in **Table 6**, all WWTPs go through the conventional sludge treatment steps. The digestion temperature is linear and range between 35-38°C (mesophilic). The lowest retention time (fastest processing) has VAX and the highest (slowest processing) has TEK. All WWTPs add polymers in their processes:

- **Water treatment:** ENK and KAP do not use any polymers in water treatment. Four plants (ESK, NOD, TEK and VAX) use biofilm carriers in MBBR, IFAS, activated sludge basin or reject water treatment. Polymers are also used in sedimentation stages.
- **Sludge treatment:** All of the seven WWTPs use polymer to thicken activated sludge or condition the sludge for dewatering process. All of them have a common chemical property such as being a cationic polyacrylamide and physically found in off-white granular powder form. Each of the polymers have a different molecular weight and thus a different specific gravity, which varies depending on the company from where they are ordered from and sludge condition.

Table 6: *Sludge treatment parameters (time, temperature, additives) of each WWTP.*

Sludge Treatment	ENK	ESK	KAP	NOD	SYV	TEK	VAX
Digestion Thickening Dewatering	✓	✓	✓	✓	✓	✓	✓
Digestion Temperature [°C]	35	37	37	36	37	37-38	36-38
Retention Time [d]	30-36	18	23-25	20	18-20	30-40	17
Polymers used for Water Treatment	-	Biofilm Carriers	-	Biofilm Carriers	**DPWS**01035 **ZETAG** 4139	An-Ionic Polymer Biofilm Carriers	Biofilm Carriers
Polymers used for Sludge Treatment	**SUPERFLOC** A-110 HMW **SUPERFLOC** C-492	**ZETAG** 7563	**FLOPAM** FO 4650 SSH **SUPERFLOC** SD-7065	**FLOPAM** 2650 SSH **FLOPAM** FO 4440 SH	**ZETAG** 8165	**FLOPAM** FO 4650 SHH	**CSC** 690 UH

4.2 Type, Quantity, Mass and Area of Microplastics from the Sludge Samples

In the following section, the results of the measurements of the sludge samples are examined in more detail. For each WWTP, the type of MP, its abundance and mass were identified. A spectral match threshold of 70% was used for polymer identification, in particular PP, PVC and Polyester.

4.2.1 Microplastics in Sewage Sludge of Enköpings Kommun

In total, nine MP polymers (Acrylic, Acrylic paints, Cellulose acetate, PA, PE, Polyester, PP, PS and PU) were detected in all three samples together (see Figure 4). The polymers were found at an average total count of 1'305±416 MP/gTS and average total mass of 95'728±53'564 ng/gTS (n=3). PE has been the most occurring MPs with 34%, followed by PP (30%) and Polyester (15%). The highest variance for number of particles between the three samples, was calculated for PE. The greatest variance of masses between the samples is seen in Acrylic. The mass of PE comprises of 40% of the total mass of detected MPs in all three samples, indicating heavier or denser particles. This shows that some MPs occur in fewer particles but are heavier, which is important feature to interpret environmental impacts.

The coefficient of variation (CV) for the MP count across the three samples was calculated to be approximately 32%, indicating a moderate level of variability (see Appendix H - J). The absolute differences in particle count between the samples were as follows: 396 between Sample 1 (S1) and Sample 2 (S2), 437 between S1 and Sample 3 (S3), and 833 between S2 and S3. In terms of mass, the CV was higher, at approximately 56%, suggesting greater variability in MP mass among the samples. The absolute mass differences were 57'802 between S1 and S2, 49'213 between S1 and S3, and 107'014 between S2 and S3.

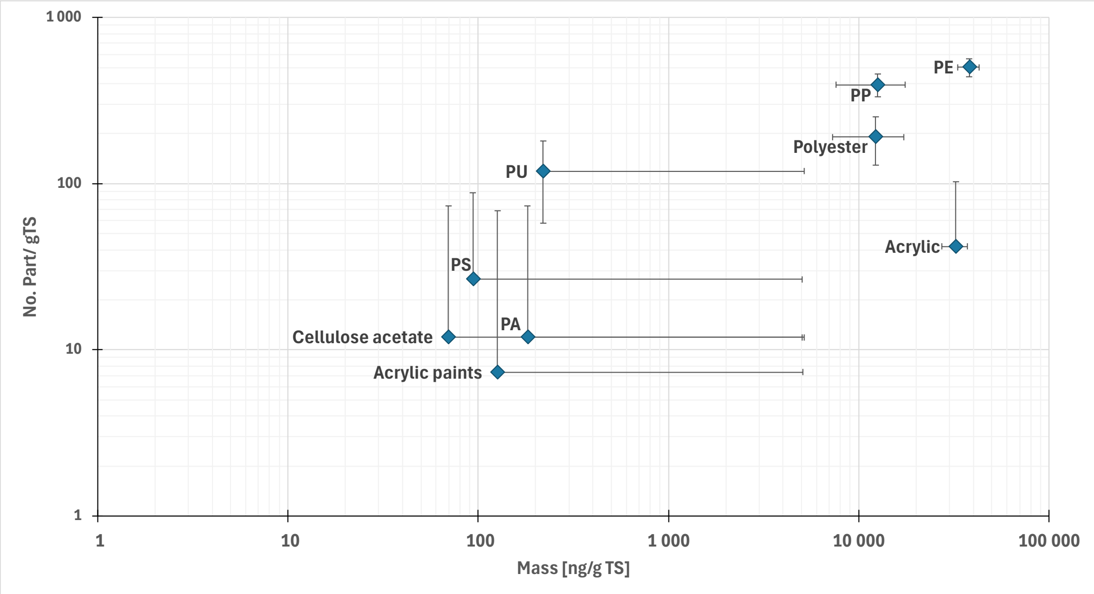

Figure 4: *Mass of nine MP polymers (x-axis: ng/gTS) versus the count of the polymers (y-axis: count/gTS), as measured in ENK. The values shown are average values of three samples.*

With regard to the distribution of MPs in terms of area, the detected MPs were found to be of medium size, with an area ranging from 1'000–5'000μm² (see Table 7). Notably, the samples from ENK did not contain a high frequency of MPs with larger area. The largest dimension detected was 264μm whereas the smallest dimension was 13μm.

Table 7: *Area categorisation based on the visual images of the scanned MP particles found in the sludge samples from ENK*

Area	[μm²]	Frequency
Very Small	0 - 500	39
Small	500 - 1 000	35
Medium	1 000 - 5 000	48
Large	5 000 - 10 000	3
Very Large	> 10 000	9

4.2.2 Microplastics in Sewage Sludge of Eskilstuna Energie & Miljö

As demonstrated in **Figure 5**, the total number of MP types identified is ten (Acrylic, Cellulose acetate, PA, PAN Acrylic fibre, PE, Polyester, PP, PS, PU, and PVC). The polymers were found at an average total count of 1'433±339 MP/gTS and average total mass of 238'562±124'815 ng/gTS (n=3). The most occurring MPs is PP (40%), followed by Polyester (22%) and PE (16%). The highest variance in particles between the samples, has been calculated for PP. Polyester

(34%) and PE (30%) have the highest mass considering all three samples together. The greatest variance for number of particles between the three samples, was calculated for PP. The highest variance in mass between the samples is owned by Polyester.

The CV for the MP count across the three samples was calculated to be approximately 24%, indicating a moderate level of variability. The absolute differences in particle count between the samples were as follows: 310 MP/gTS between S1 and S2, 368 MP/gTS between S1 and S3, and 677 MP/gTS between S2 and S3. In terms of mass, the CV was higher, at approximately 52%, suggesting greater variability in MP mass among the samples. The absolute mass differences were 197'733 ng/gTS between S1 and S2, 230'825 ng/gTS between S1 and S3, and 33'092 ng/gTS between S2 and S3.

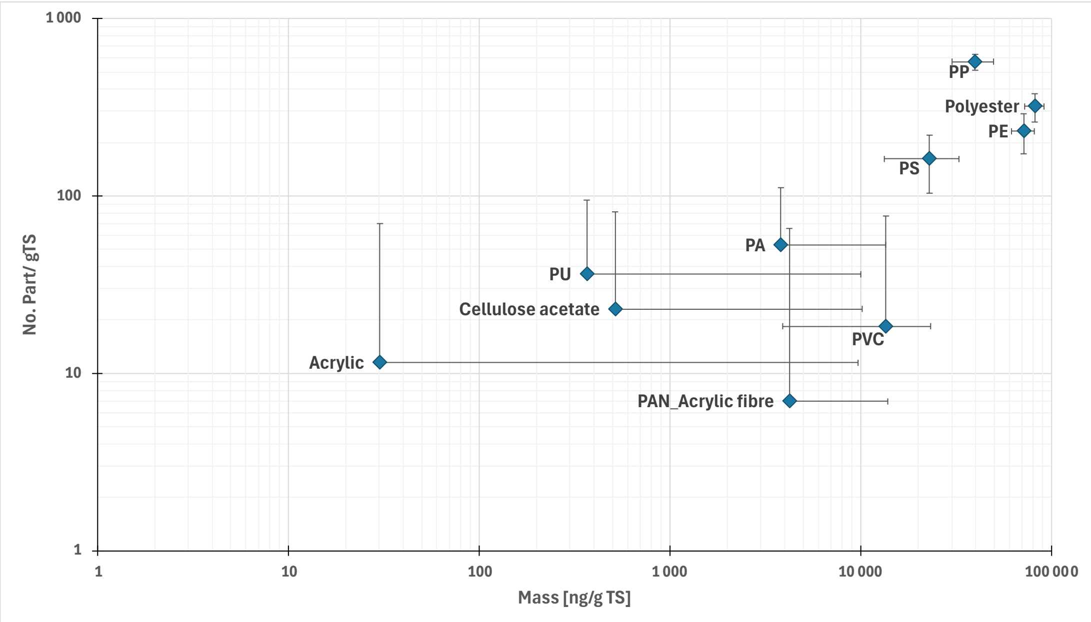

Figure 5: *Mass of ten MP polymers (x-axis: ng/gTS) versus the count of the polymers (y-axis: count/gTS), as measured in ESK. The values shown are average values of three samples.*

With regard to the distribution of MPs in terms of area, the detected MPs were found to be in a spectrum between very small and medium size, with an area ranging from 0–5'000µm² (see Table 8). Notably, the samples from ESK did also not contain a high frequency of MPs with larger areas. The largest dimension detected was 837µm whereas the smallest dimension was 18µm.

Table 8: *Area categorisation based on the visual images of the scanned MP particles found in the sludge samples from ESK*

Area	[μm^2]	Frequency
Very Small	0 - 500	32
Small	500 - 1 000	27
Medium	1 000 - 5 000	56
Large	5 000 - 10 000	17
Very Large	> 10 000	15

4.2.3 Microplastics in Sewage Sludge of Käppala Förbundet

In total, eight types of MPs (Acrylic, PA, PE, Polyester, PP, PS, PU and PVC) were detected in KAP (see **Figure 6**), of which more than half of it consist of PP (57%). The polymers were found at an average total count of 1'145±943 MP/gTS and average total mass of 93'357±33'291 ng/gTS (n=3). Looking at the mass, Polyester takes up almost half (48%) of the weight. The strongest variance in particles and mass between the three samples has PP and Polyester respectively.

The CV for the MP count across the three samples was calculated to be approximately 82%, indicating a high level of variability. The absolute differences in particle count between the samples were as follows: 551 MP/gTS between S1 and S2, 1'837 MP/gTS between S1 and S3, and 1'286 MP/gTS between S2 and S3. In terms of mass, the CV was higher, at approximately 36%, suggesting greater variability in MP mass among the samples. The absolute mass differences were 34'565 ng/gTS between S1 and S2, 66'565 ng/gTS between S1 and S3, and 31'999 ng/gTS between S2 and S3.

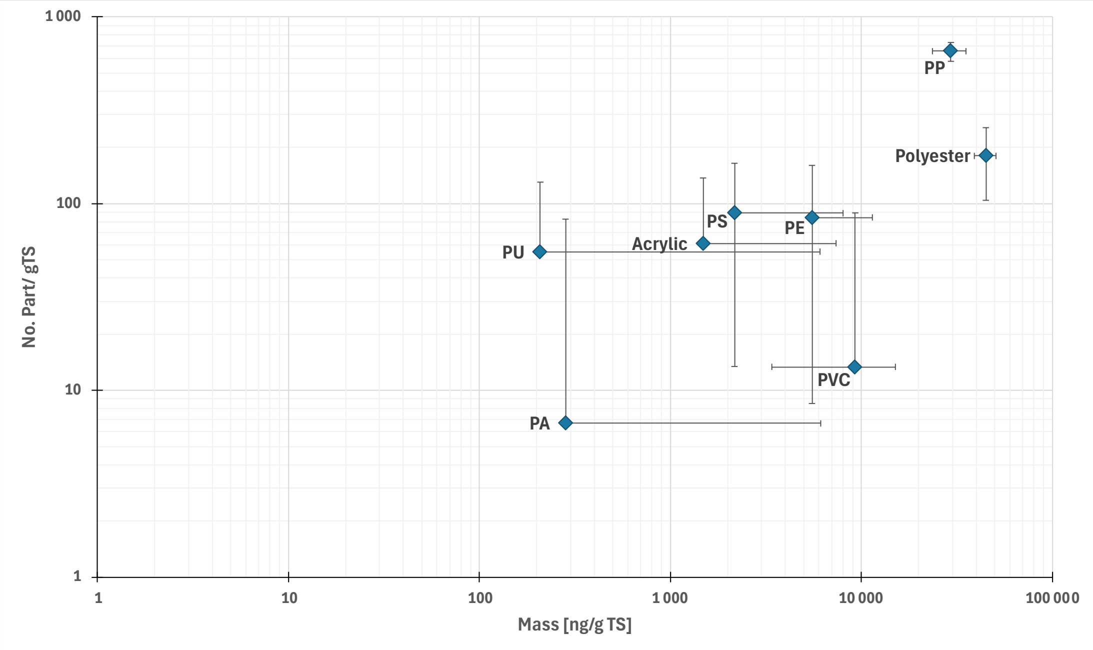

Figure 6: *Mass of eight MP polymers (x-axis: ng/gTS) versus the count of the polymers (y-axis: count/gTS), as measured in KAP. The values shown are average values of three samples.*

With regard to the distribution of MPs in terms of area, the detected MPs were found to be in a spectrum between very small and medium size, with an area ranging from 0–5'000µm² (see **Table 9**). There were only 13 particles with larger areas detected. The largest dimension detected was 479µm whereas the smallest dimension was 13µm.

Table 9: *Area categorisation based on the visual images of the scanned MP particles found in the sludge samples from KAP*

Area	[µm²]	Frequency
Very Small	0 - 500	31
Small	500 - 1 000	28
Medium	1 000 - 5 000	41
Large	5 000 - 10 000	5
Very Large	> 10 000	8

4.2.4 Microplastics in Sewage Sludge of Nodra AB

What is striking about the figures in this graph (see **Figure 7**) is that the number of MPs identified are almost 13 times higher than those of other plants. This amount is carried by the count of Polyester, comprising 81% of the total MPs count and owning highest variability. A total number of thirteen MP types (ABS, Acrylic, Alkyd, Cellulose acetate, Epoxy, PE, Polycarbonate, Polyester, POM, PP, PS, PU and PVC) were detected in NOD samples. The polymers were found at an average total count of 17'128±6'081 MP/gTS and average total mass of

408’471’376±660’647’725 ng/gTS (n=3). It is important to mention that due to the fact that many of the MPs particles in this sample seemed to be overlapping each other, leading to a mismatch in weight and count. On the other hand, if all the samples are combined, the majority of the mass (99%) is contributed towards Polyester.

The CV for the MP count across the three samples was calculated to be approximately 36%, indicating a moderate level of variability. The absolute differences in particle count between the samples were as follows: 959 MP/gTS between S1 and S2, 10’020 MP/gTS between S1 and S3, and 10’979 MP/gTS between S2 and S3. In terms of mass, the CV was higher, at approximately 162%, suggesting greater variability in MP mass among the samples. The absolute mass differences were 1,161,607,660 ng/gTS between S1 and S2, 1,126,117,485 ng/gTS between S1 and S3, and 35,490,175 ng/gTS between S2 and S3.

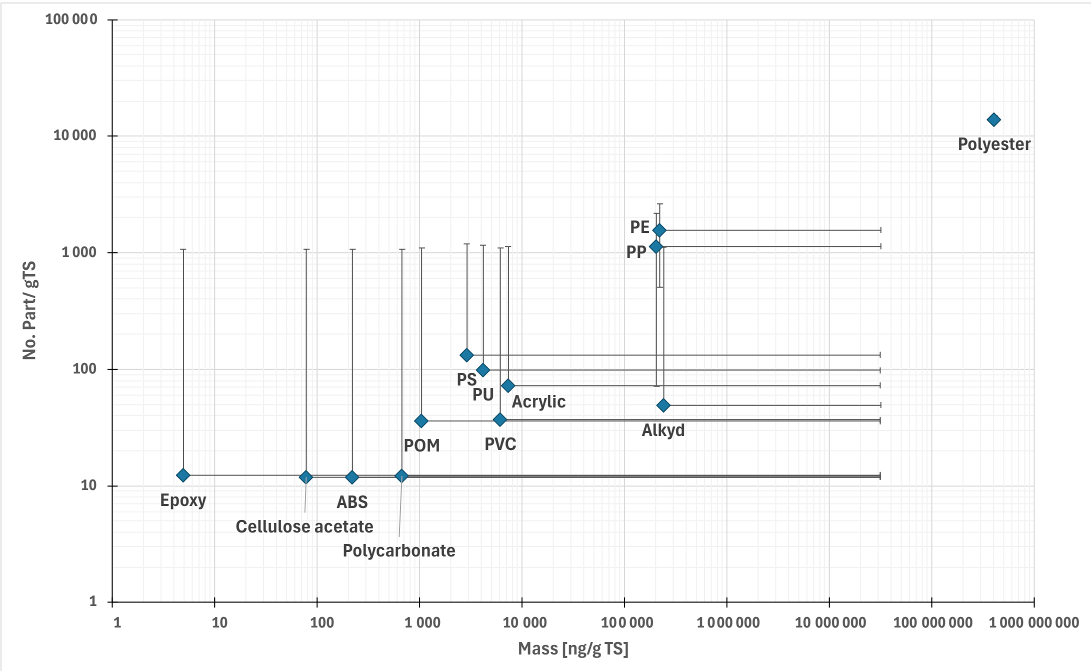

***Figure 7:** Mass of thirteen MP polymers (x-axis: ng/gTS) versus the count of the polymers (y-axis: count/gTS), as measured in NOD. The values shown are average values of three samples.*

The results, also shows that the area of the particles is distributed in all five categories, with 216 particles displaying very large area.

With regard to the distribution of MPs in terms of area, the detected MPs were found in all five categories, with 216 particles displaying even very large area (see **Table 10**). The largest dimension detected was 5’843µm whereas the smallest dimension was 7µm.

Table 10: *Area categorisation based on the visual images of the scanned MP particles found in the sludge samples from NOD*

Area	[µm^2]	Frequency
Very Small	0 - 500	293
Small	500 - 1 000	352
Medium	1 000 - 5 000	466
Large	5 000 - 10 000	84
Very Large	> 10 000	216

4.2.5 Microplastics in Sewage Sludge of Syvab AB

A total number of six MP types (Epoxy, PE, Polyester, POM, PP and PS) were discovered in SYV sludge samples. The polymers were found at an average total count of 1'274±1'244 MP/gTS and average total mass of 7'755'960±11'999'617 ng/gTS (n=3). PP is the most occurring MPs with 70%. Even though 70% particles of PP were found, it does not mean that is also the heaviest type of MPs. As seen in **Figure 8**, PE takes up 93% of all the mass of the MPs, whereas for PP it is just 5% of the mass.

The CV for the MP count across the three samples was calculated to be approximately 98%, indicating a very high level of variability. The absolute differences in particle count between the samples were as follows: 2,132 MP/gTS between S1 and S2, 44 MP/gTS between S1 and S3, and 2,176 MP/gTS between S2 and S3. In terms of mass, the CV was higher, at approximately 155%, suggesting greater variability in MP mass among the samples. The absolute mass differences were 21,040,884 ng/gTS between S1 and S2, 20,517,107 ng/gTS between S1 and S3, and 523,777 ng/gTS between S2 and S3.

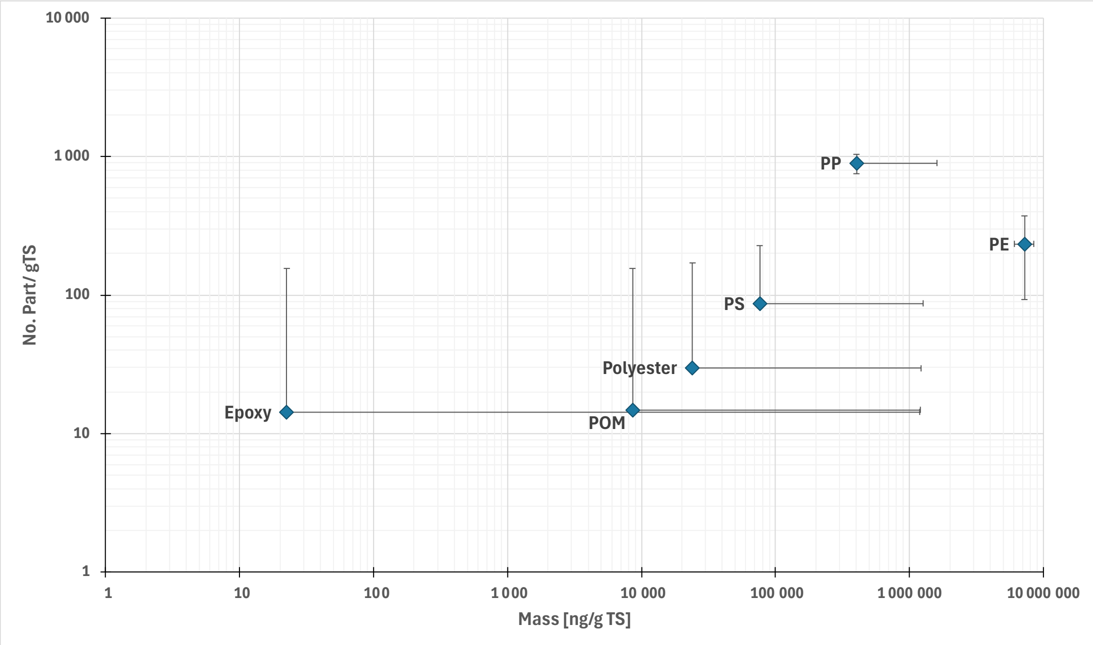

Figure 8: *Mass of six MP polymers (x-axis: ng/gTS) versus the count of the polymers (y-axis: count/gTS), as measured in SYV. The values shown are average values of three samples.*

Regarding the distribution of MPs in terms of area, the detected MPs were found mostly in medium size, with an area ranging from 1'000–5'000µm² (see **Table 11**). There were 20 particles with larger areas detected. The largest dimension detected was 767µm whereas the smallest dimension was 18µm.

Table 11: *Area categorisation based on the visual images of the scanned MP particles found in the sludge samples from SYV*

Area	[µm²]	Frequency
Very Small	0 - 500	17
Small	500 - 1 000	24
Medium	1 000 - 5 000	43
Large	5 000 - 10 000	9
Very Large	> 10 000	11

4.2.6 Microplastics in Sewage Sludge of Tekniska Verken AB

Nine different types of MP (Acrylic, Acrylic paints, PA, PE, Polyester, PP, PS, PU and PVC) were detected in TEK. The polymers were found at an average total count of 1'309±1'083 MP/gTS and average total mass of 137'238±148'280 ng/gTS (n=3). The analysis in **Figure 9** reveals that almost half (48%) of the MPs identified were of the PE type, followed by PP (38%). Conversely, the mass is highest for PE (48%) followed by PP (43%).

The CV for the MP count across the three samples was calculated to be approximately 83%, indicating a high level of variability. The absolute differences in particle count between the samples were as follows: 200 MP/gTS between S1 and S2, 1'301 MP/gTS between S1 and S3, and 1'101 MP/gTS between S2 and S3. In terms of mass, the CV was higher, at approximately 108%, suggesting greater variability in MP mass among the samples. The absolute mass differences were 45'935 ng/gTS between S1 and S2, 53'652 ng/gTS between S1 and S3, and 99'586 ng/gTS between S2 and S3.

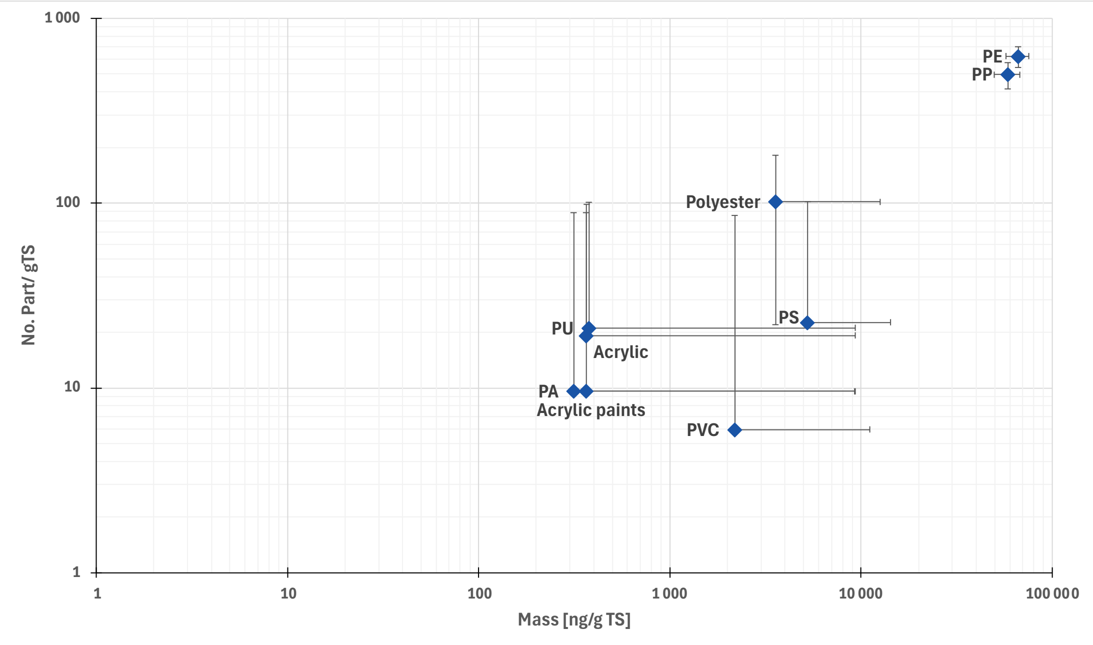

Figure 9: *Mass of nine MP polymers (x-axis: ng/gTS) versus the count of the polymers (y-axis: count/gTS), as measured in TEK. The values shown are average values of three samples.*

The area of the MPs in TEK are scattered over all the five categories, also containing very large particles (see Table 12). Regarding the distribution of MPs in terms of area, the detected MPs were mainly found to be of medium size, with an area ranging from 1'000–5'000µm². Notably, the samples from TEK did not contain a high frequency between the area categories. The largest dimension detected was 491µm whereas the smallest dimension was 7µm.

Table 12: *Area categorisation based on the visual images of the scanned MP particles found in the sludge samples from TEK*

Area	[µm²]	Frequency
Very Small	0 - 500	35
Small	500 - 1 000	43
Medium	1 000 - 5 000	76
Large	5 000 - 10 000	19
Very Large	> 10 000	17

4.2.7 Microplastics in Sewage Sludge of Växjö Kommun

Acrylic, Cellulose acetate, Epoxy, PE, Polyester, POM, PP, PS, PU and PVC are the nine detected polymers in the sludge samples from VAX (see **Figure 10**). The polymers were found at an average total count of 1'401±521 MP/gTS and average total mass of 92'142±103'055 ng/gTS (n=3). PP (38%), PE (30%) and Polyester (24%) are the most common appearing MPs in all the samples. Although most of the mass is distributed by Polyester (77%).

The CV for the MP count across the three samples was calculated to be approximately 37%, indicating a moderate level of variability. The absolute differences in particle count between the samples were as follows: 159 MP/gTS between S1 and S2, 971 MP/gTS between S1 and S3, and 812 MP/gTS between S2 and S3. In terms of mass, the CV was higher, at approximately 112%, suggesting greater variability in MP mass among the samples. The absolute mass differences were 708 ng/gTS between S1 and S2, 178,849 ng/gTS between S1 and S3, and 178,141 ng/gTS between S2 and S3.

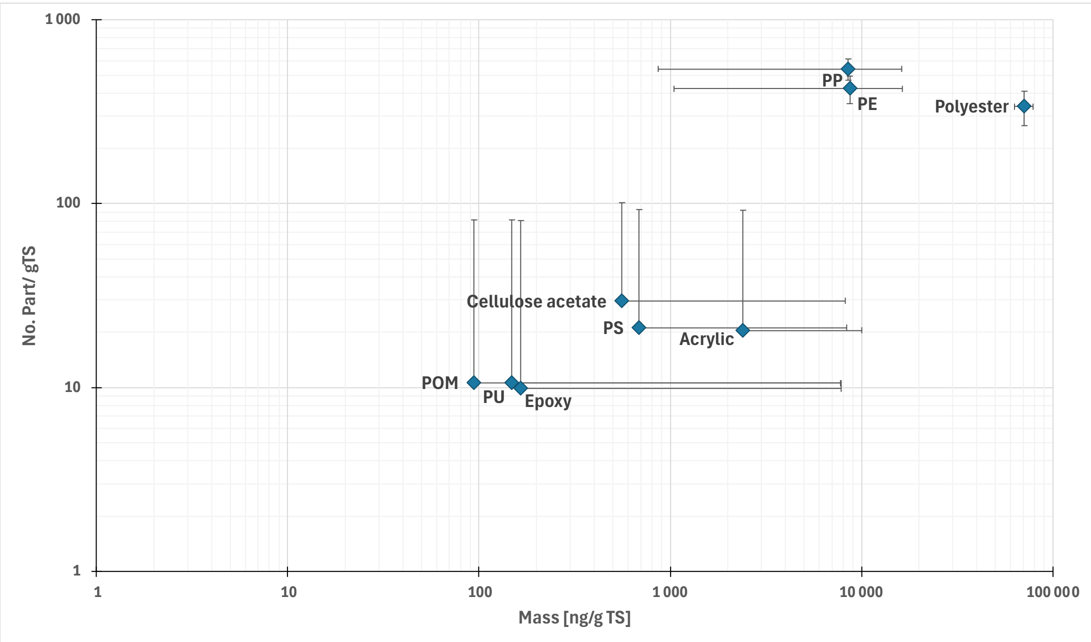

Figure 10: *Mass of nine MP polymers (x-axis: ng/gTS) versus the count of the polymers (y-axis: count/gTS), as measured in VAX. The values shown are average values of three samples.*

The area is evenly distributed between the categories very small, small and medium as seen in the table below

With regard to the distribution of MPs in terms of area, the detected MPs were found to be in the spectrum between very small to medium size, with an area ranging from 0–5'000μm² (Table 13). It is noticeable that the samples from VAX only contain seven MPs with larger area. The largest dimension detected was 392µm whereas the smallest dimension was 13µm.

Table 13: *Area categorisation based on the visual images of the scanned MP particles found in the sludge samples from VAX*

Area	[µm^2]	Frequency
Very Small	0 - 500	39
Small	500 - 1 000	39
Medium	1 000 - 5 000	54
Large	5 000 - 10 000	6
Very Large	> 10 000	1

4.3 Comparative Analysis between the Wastewater Plants

For the comparative analysis, NOD will be considered an outlier and excluded for the analysis that follow. This is also due to the observations in the samples, where the MPs were overlapping leading to inaccurate measuring results. NOD accounts for almost 70% of all the MPs counts across all the WWTPs, skewing the dataset extremely and therefore affects the interpretability between the rest of the WWTPs. From the sixteen detected MPs, three of them only appear in NOD. Meaning for the comparative analysis excluding NOD, only thirteen MPs are existent. The comparative graphical representation with NOD can be found in the Appendix (see Appendix C - F) and will not be discussed in this section.

In average 1'311±102 MP/gTS (n=6) were detected considering all six WWTPs. With NOD included the average count would be 3'571±5'979 MP/gTS (n=7). The maximum number of MP particles was observed in ESK, followed by VAX; and the least amount was observed in KAP (see **Figure 11**).

The statistical analysis (ANOVA) revealed primarily that there is no statistically significant difference in MP counts between the WWTPs ($F=1.28$, $p=0.27$, $\alpha=0.05$). The level of MP presence is relatively consistent across the seven WWTP sludges with the average sum counts ranging from 1'145 MP/gTS (KAP) to 17'128 MP/gTS (NOD). It is evident that the MP count in NOD is more than ten times higher than other plants. Therefore, a second test was run without NOD. As before, there is no significant difference ($F=0.02$, $p=1.00$, $\alpha=0.05$). The extreme values of NOD bring in higher variability, that is likely to influence the overall variability. Secondarily, the ANOVA test conducted to analyse the variation in MP counts across the sixteen MP types showed uniformity across the groups and thus no statistical significance ($F=1.25$, $p=0.25$, $\alpha=0.05$).

The proportional contribution of the three most common MPs changes since NOD has 80% of Polyester in its samples. Even if the ranking of the MPs changes, the three most frequently occurring MPs remain the same, namely PP (45%), PE (27%), Polyester (15%) accounting for 87% of all detected MPs. This trend is also revealed in **Figure 11**, where PP (violet), PE (light green) and Polyester (pink) stand out in all the WWTPs. The MPs abundance with less than 1% recorded are PAN, Acrylic paints, Cellulose acetate, Epoxy, POM and PVC.

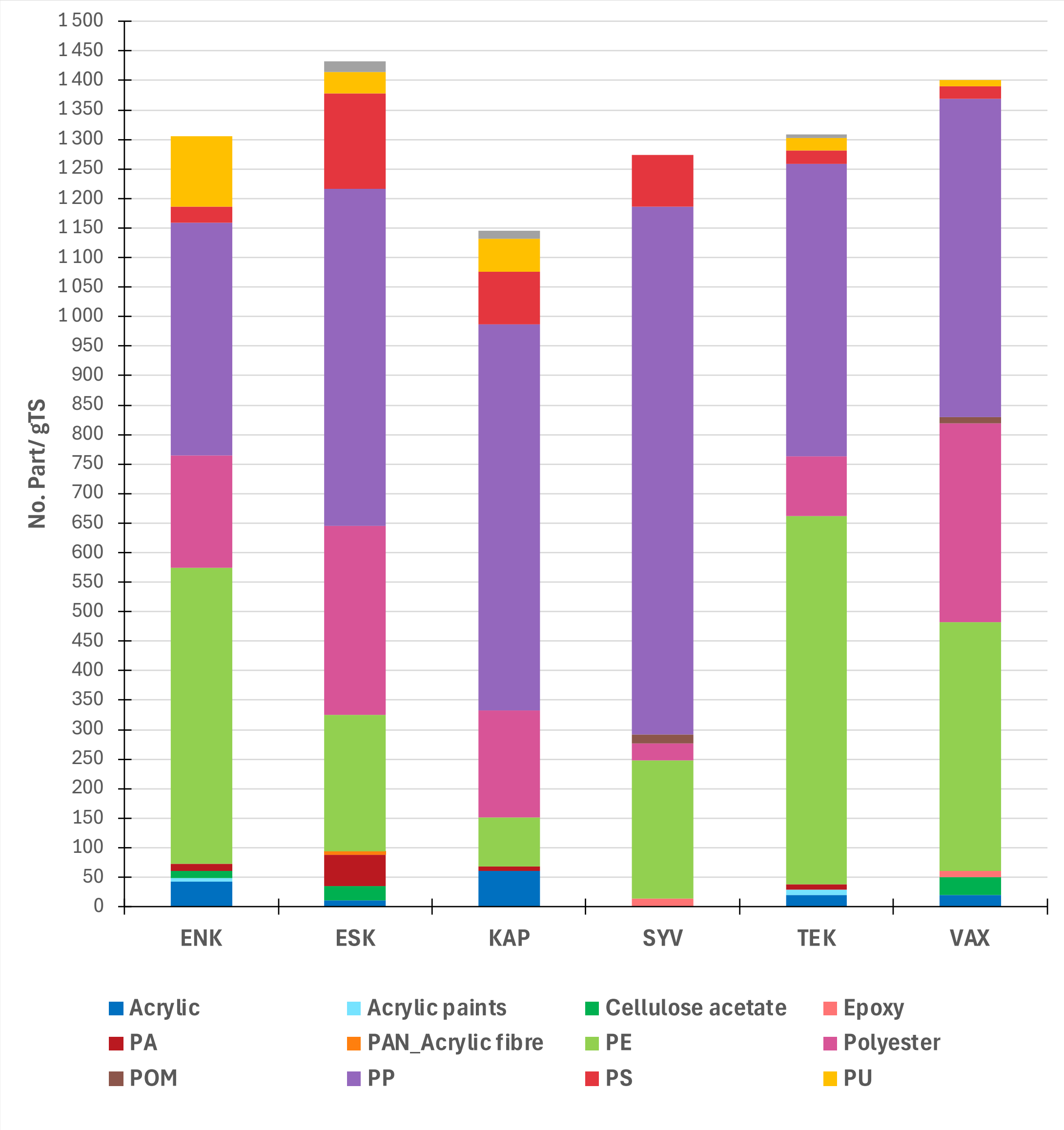

Figure 11: *Average counts and abundance of the different of MPs in the sludge samples from all treatment plants except NOD. NOD is not included due to data skewing.*

An examination of the other comparative size reveals that the mass between the seven WWTPs exhibits greater variability than the previous size with respect to the number of particles. The average CV for the count of MPs is 56%, whereas for the mass it is 97%.

In average 1'402'165±3'113'218 ng/gTS were detected considering all six WWTPs. With NOD included the average mass would be 59'554'909±153'883'945 ng/gTS. The maximum mass for MP was observed in SYV, followed by ESK; and the least amount was observed in VAX (see **Figure 12**). From the graph, it is apparent that ENK, KAP and VAX have similar mass with different polymer profiles and an average of 93'742±1'824 ng/gTS.

The ANOVA test was run for the mass as well, where the results primarily show no statistical significance between the sludge of all WWTPs either ($F=1.00$, $p=0.43$, $\alpha=0.05$). The average mass concentration varies from 92'142 ng/gTS (VAX) to 408'471'376 ng/gTS (NOD), making NOD stand out as an outlier again. The test without NOD shows no significant difference either ($F=1.12$, $p=0.36$, $\alpha=0.05$). Secondarily, does the analysis based on mass across the sixteen MP ($F=1.00$, $p=0.46$, $\alpha=0.05$) shows uniformity across the groups and thus no statistical significance. The test results suggest that the MP presence in the sludge from WWTPs is more likely driven by general exposure driven by external factors. It is important to note that despite the strong trends in the data, the statistical power is limited by the high variability and the limited number of replications.

As evident in **Figure 12**, PE (light green) stands out as is it the polymer with highest mass, accounting for 88% of all the masses across the plants together. The mass ranking is followed by PP (7%) and Polyester (3%).

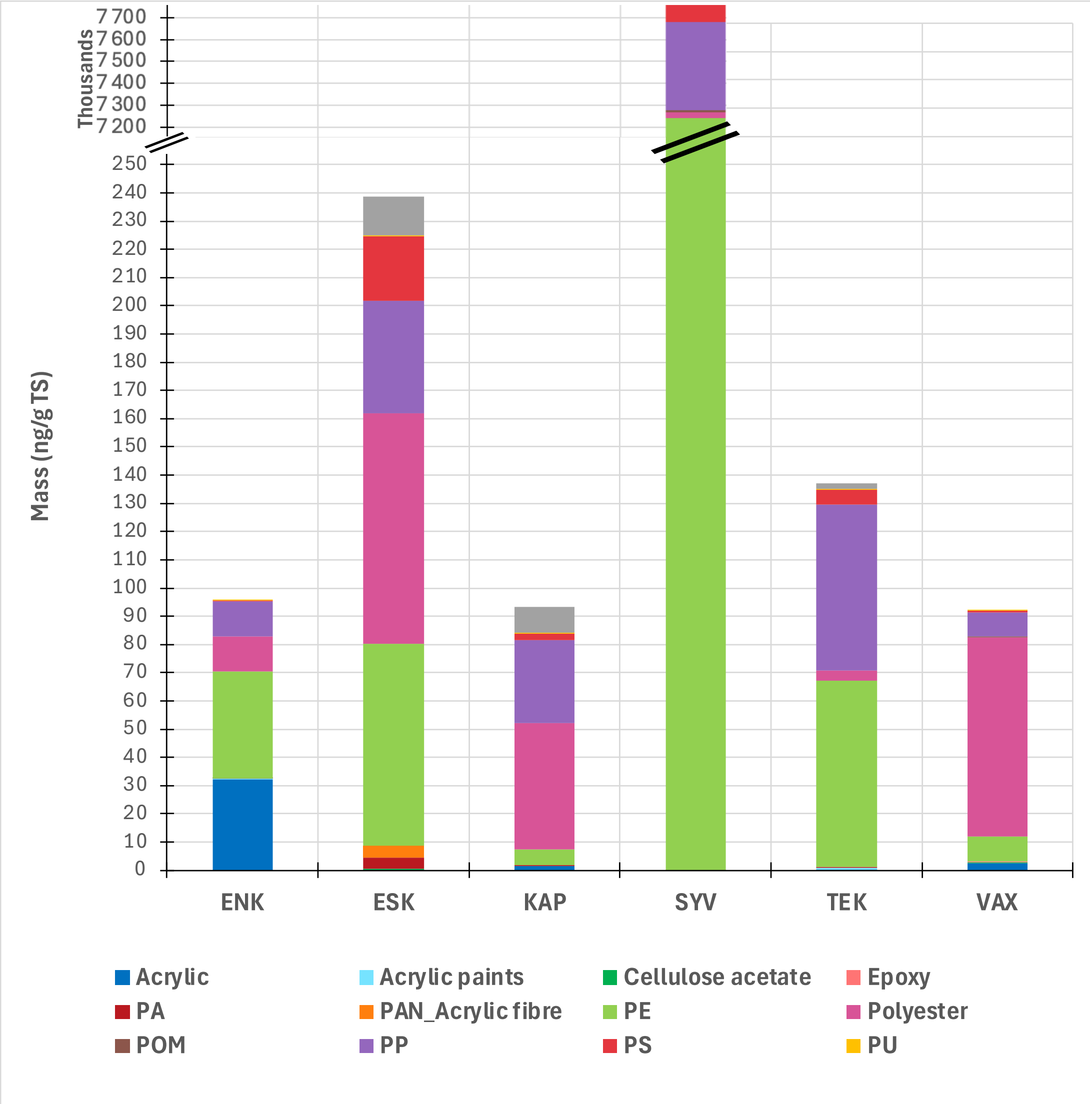

Figure 12: *Average mass of the different of MPs in the sludge samples from all treatment plants except NOD. NOD is not included due to data skewing.*

Besides the two ANOVA tests made before for count and mass, a correlation analysis was also performed to find out the relationship between the MP abundance and mass for each WWTP. For this the Pearson correlation coefficient and the significance of correlation was calculated, with n=16 and d_f=14. Significant positive correlations were found for ENK (r=0.71, t=3.78), ESK (r=0.76, t=4.34), KAP (r=0.69, t=3.53) and TEK (r=0.99, t=25.58). VAX (r=0.52, t=2.29) shows a moderate but statistically significant correlation. SYV (r=0.24, t=0.91) displays a weak and statistically insignificant correlation. Finally, NOD (r=0.99, t=28.36) exhibits a very high correlation, which is due to the disproportionately high MP levels.

4.4 Morphology of Detected Microplastics

If the ratio between the major and minor dimension is high, it indicates that the particle is rather stretched out or fibre-like. Using the data from all sludge samples analysed in this study, the ratio between the major and minor dimension of PE, Polyester, POM and PP shows higher ratios indicating fibrous shapes (see **Figure 13**). Most polymers exhibit a distribution that is closest to the value of 0.5, indicating that they are neither perfectly circular (0) nor excessively elongated (1). It is evident that polymers can exhibit a wide range of shapes, which makes it impossible to categorise them according to the type of MP. The compactness of a polymer is closer to 1, the more similar the projected contour is to a circle. Most polymer types have fairly low compactness values (around 0.3–0.5), suggesting irregular shapes rather than smooth, spherical ones. There is less variation in compactness in contrast to the L/W ratio. It is important to note that the shapes of the polymers could not be identified by FTIR, which is why these calculations were made.

A distribution of the three most common occurring MPs is visualised in **Figure 14**. All seven WWTPs were considered here, since the distribution pattern remain the same, just with a higher frequency because of the high number of MPs count in NOD. The distribution of area of particles of PE is characterised by a predominance of medium-sized particles which represents sizes between 1'000-5'000μm², just as with Polyester and PP. Nevertheless, the distribution graph clearly demonstrates that the majority of the distribution is comprised of very small and small particles together (100-1'000μm²). The number of outliers (>10'000μm²) is highest for Polyester with over 200 particles.

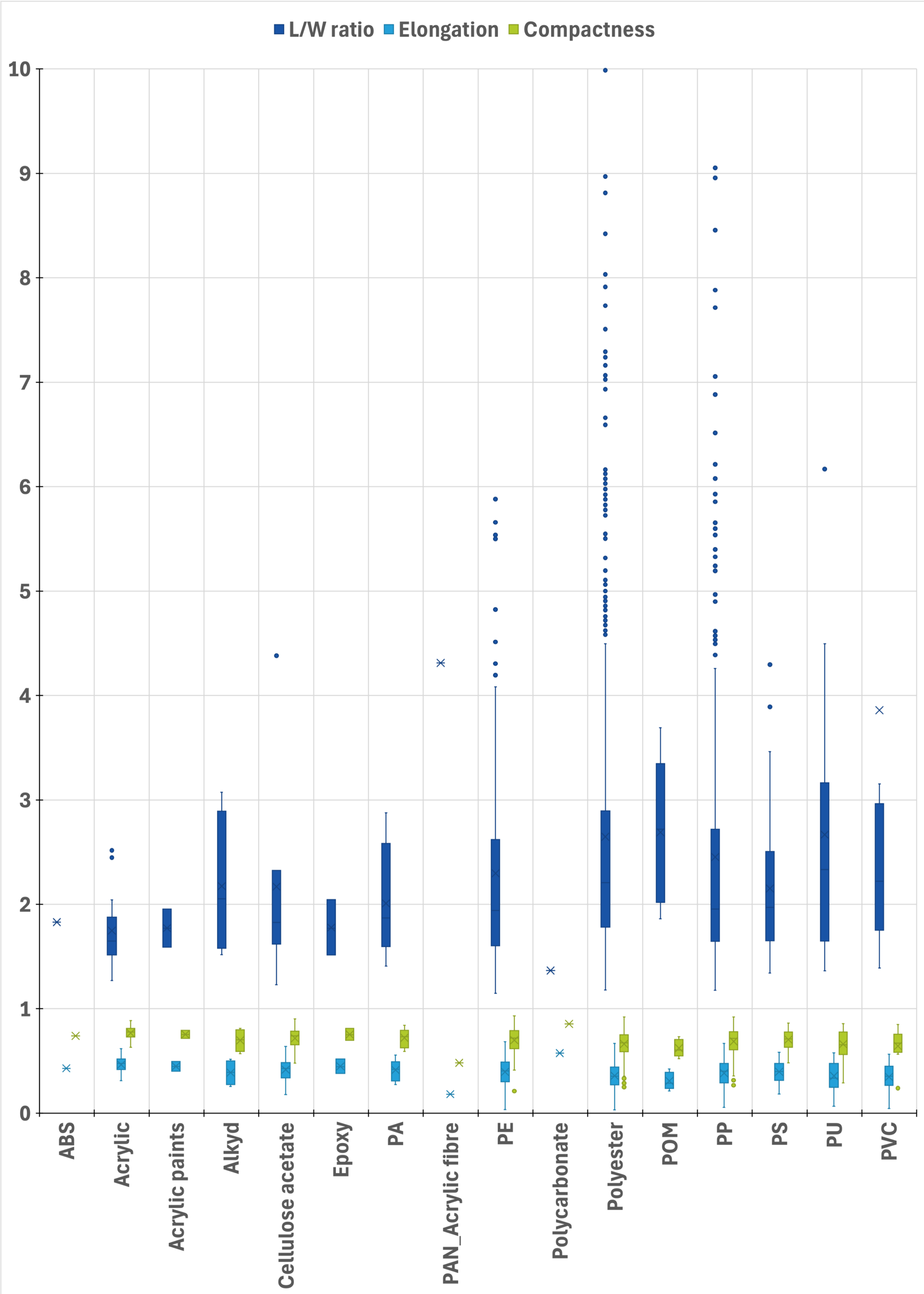

Figure 13: *Morphological characteristics of the MPs in the sludge samples from all treatment plants: dark blue bars show the length/width ration (L/W), light blue bars show the elongation factor, the green bars show the compactness.*

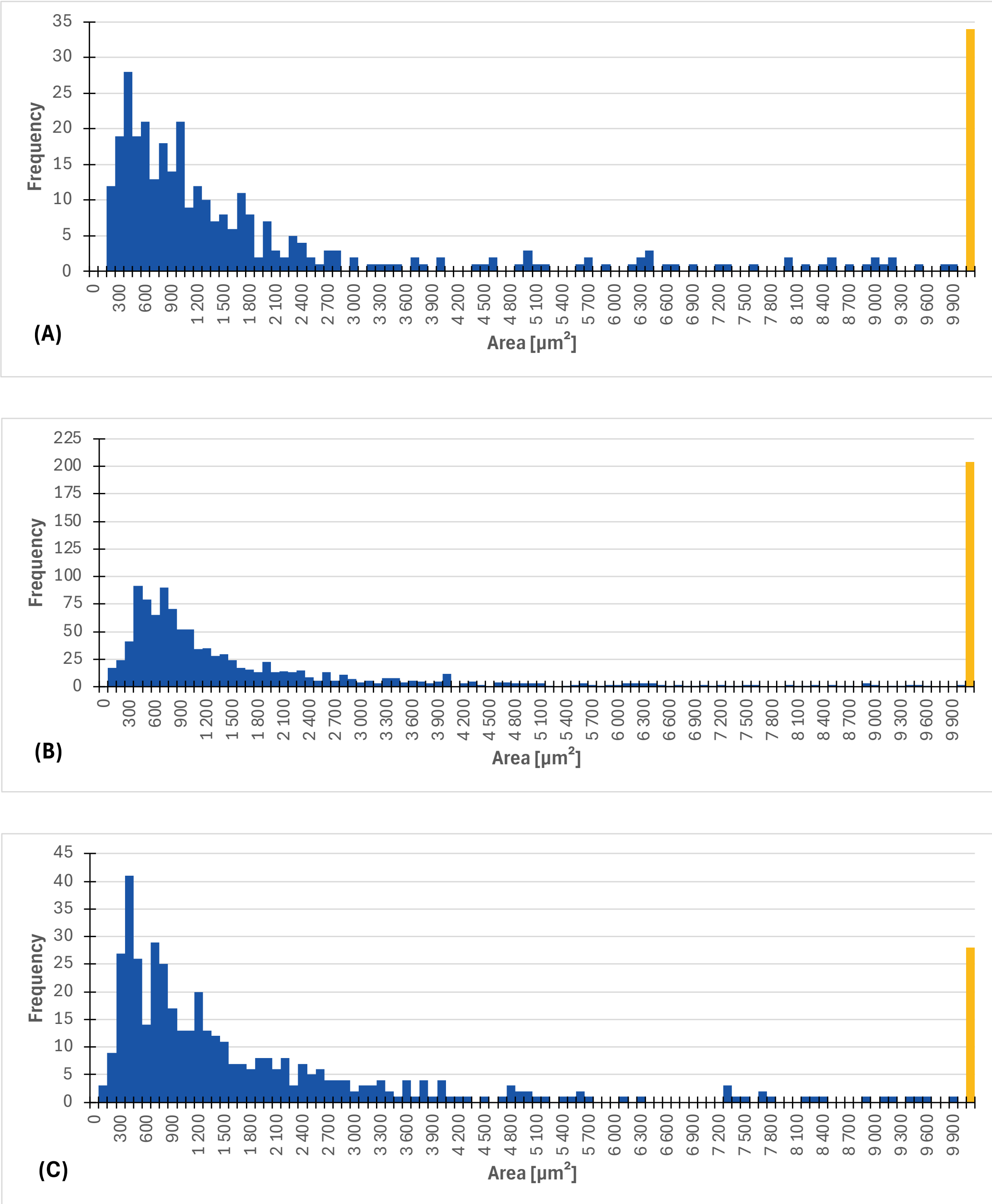

Figure 14: *Distribution of particle area of PE (A), Polyester (B) and PP (C). The yellow bar shows the outlies >10'000 µm².*

4.5 Microplastic Abundance per Wastewater Plant in Relation to Population Equivalent

To find correlations and justification for the abundance of the MP types, certain parameters of the WWTPs were analysed. One of these is the *population equivalent* (*PE*), which represents the organic biodegradable load of a plant.

KAP has the highest *PE* and is one of the larger WWTPs analysed in this research. Whereas ENK has the lowest *PE*. As previously mentioned, NOD demonstrates an outlier result when comparing its *PE* (see **Figure 15**). Three out of the seven WWTPs have a PE close to 200'000.

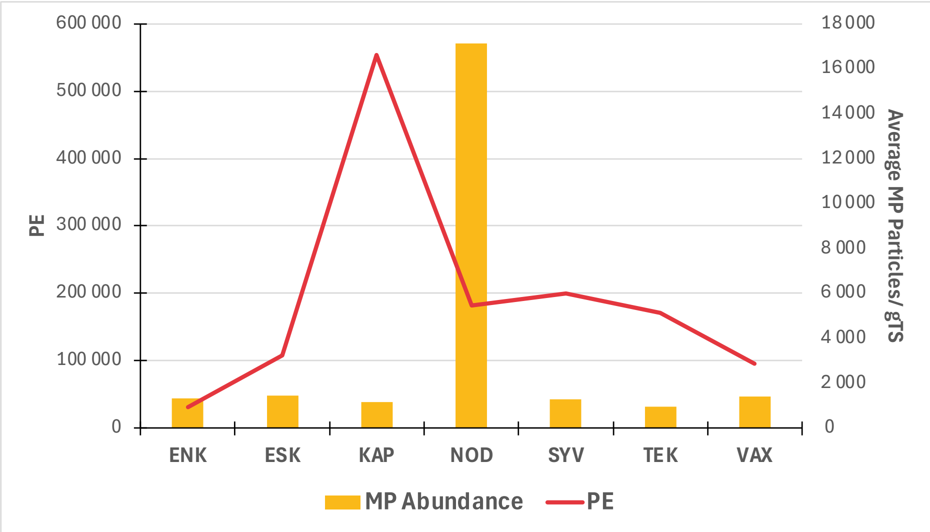

Figure 15: *Variation of the total count of MPs in relation to size of treatment plants expressed as population equivalent (PE)*

4.6 Microplastic Contamination in Agricultural Soil

As seen in **Table 14**, the MP loads estimates indicate that 11 tonnes of MPs are transferred to agricultural soils on an annual basis, which is the amount without considering the outlying WWTP, NOD. Including NOD would result in 340 tonnes of MPs, together with approximately 15'000 tonnes of sludge applied as fertilised into the agricultural soil in Sweden, for sludge application rates in the year 2024. Excluding the outlier, this represents 0.1% (2.2% with NOD) of the total sludge mass applied to the soil composed of MPs. This percentage is derived from the sum of the five plants (KAP, NOD, SYV, TEK, VAX) that apply sludge as agricultural fertiliser. The sludge that is prepared for use as sewage sludges for agricultural fertilisation at the five plants has obtained REVAQ certification. ENK employs sludge in the production of construction materials, whilst ESK disposes of it in landfill, given the demand for soil in that context.

***Table 14:** MPs in sludge landing in agricultural soil based on data from 2023 (only SYV) and 2024. The final row excludes the WWTP which was considered an outlier.*

	ENK	ESK	KAP	NOD	SYV	TEK	VAX	TOTAL
Final Disposal of Sludge	Construction Soil	Landfill (Construction Soil)	Agriculture	Agriculture, Landfill	Agriculture, Incineration	Agriculture	Agriculture	
% of Sludge Produced for Agriculture	0%	0%	100%	30%	95%	100%	100%	
Sludge to Agriculture [t/y]	0	0	8’750	806	1’226	2’700	1’882	**~ 15’000 t/y**
(avg) MP Particles in Sludge [MP/g TS]	1’305	1’433	1’145	17’128	1’274	967	1’401	**~ 25’000 MP/gTS**
(avg) MP Mass in Sludge [ng/g TS]	95’728	238’562	93’357	4.08x10^{8}	7’755’960	77’387	92’142	**~ 417 mio ng/g TS**
MP Particles in Agricultural Soil [MP/y]	0	0	1.00x10^{13}	1.38x10^{13}	1.56x10^{12}	2.61x10^{12}	2.64x10^{12}	**~ 30.6 trillion MP/y**
MP Mass in Agricultural Soil [t/y]	0	0	0.82	329.39	9.51	0.21	0.17	**~ 340 t/y**
	0	0	0.82	-	9.51	0.21	0.17	**~ 11 t/y**

5 Discussion

The discussion begins with a comparison of the results of the study with findings from previous literature findings, followed by a statistical evaluation of the data. It then considers the effect of MP size and shape on removal in treatment processes. Particular attention is given to the improved efficiency of advanced technologies in removing fibre-like MPs. Next, the discussion explores key influencing factors, such as industrial contributions, external sludge inputs, domestic sources and the role of polymers in treatment. The discussion also addresses the lack of correlation between population equivalent and MP abundance, the accumulation of MPs in agricultural soils and brief concerns regarding human health. It concludes with implications for the need for broader regulations to reduce MP pollution.

5.1 Comparison with Previous Studies and Applied Statistical Testing

On average, 1’311±102 MP/gTS and 1’402’165±3’113’218 ng/gTS were detected considering all WWTPs and excluding the outlier NOD. These MP counts can be compared with the results of other studies (see **Table 15**). One possible reason for the higher abundance reported here is the methodological differences, such as variations in measurement tools that capture smaller particles more effectively. Both Horton (2021) and Mintenig (2017) used a filter size of 10µm for extracting MP from sludge samples, similarly to the current study. However, while Horton reported a notably higher concentration range, Mintenig found lower levels. This highlights the variability in concentrations across regions and methodologies, despite the use of a comparable filter size. Additionally, Lusher (2017) used filter paper in Norway (sharing boarders with Sweden), which may have excluded smaller particles, resulting in a much lower reported value.

Another factor could be the filter size used during MP extraction: smaller filter sizes retain more of the tiniest particles. Nevertheless, the types of MPs identified in this study align with those documented in the literature.

Table 15: *Comparison of MP count/gTS found in sludge across ten other studies [2].*

	Author, Year	Country	Measurement	Filter Size [μm]	Predominant Polymer Types	Average or Range of MP in Sludge
1	Lusher, 2017	Norway	FTIR	filter paper	Polyethylene, PET, PP	6 MP/g
2	Talvitie, 2016	Finland	FTIRi	300, 100, 20	PE, PS, PP	76.3±4.3 MP/g
3	Horton, 2021	United Kingdom	microFTIR	stainless steel filter: 10	PE, PP, PET	301-10’380 MP/g
4	Mahon, 2016	Ireland	stereomicroscope, ATR-FTIR	sieves: 250, 212, 63, 45	HDPE, PE, Polyester, Acrylic, PET, PP, PA	4.2-15.4 MP/g
5	Mintenig, 2017	Germany	FTIR, ATR-FTIR, microFTIR	10	PE, PP, PA and PS	1-24 MP/g
6	Miserli, 2025	Greece	ATR-FTIR, multi-modal Raman microscope	silicon membrane filter: 5	PAA, PAM, PVC, PBMA, PE	33.3±8 MP/g
7	Adjama, 2025	India	ATR-FTIR	0.5	PU, Nylon, HDPE, and PP	13.38 MP/g
8	Hajji, 2023	Morocco	ATR-FTIR	46	Polyester, PE, PP	11.27-87.95 MP/g
9	Ren, 2020	China	stereomicroscope, ATR-FTIR	37	PVC, PB, PTFE	220 MP/g
10	Carr, 2016	United States	FTIR	sieve: 45 filter paper: 10	blue PE (Toothpaste)	1 MP/g
	Current study	**Sweden**	**FTIR**	**10**	**Polyester, PE, PP**	**1’311 MP/g (with outlier NOD: 3’571 MP/g)**

A statistically significant discrepancy was observed in four of the seven WWTPs, where the standard deviation of MP mass across the three replicates exceeded the mean. This highlights substantial variability within individual plants, which is likely due to sludge management in batches and temporal changes in influent composition. Such variability makes direct comparisons between plants challenging, as a single average may not accurately represent overall MP levels. This is further supported by the calculated CV, which averaged 56% for particle count and 97% for MP mass. This indicates particularly high relative variability in mass measurements. These results emphasise the need for caution when interpreting MP data and suggest that more standardised or higher replication is necessary to improve comparability of data across treatment plants.

Statistical tests were conducted to examine variability among replicate samples from each plant. The variability in MP counts showed that the three samples from NOD were fairly consistent, which supports its status as an outlier. Conversely, KAP, SYV and TEK, which are larger WWTPs, exhibited higher variability between their three samples. This may be due to the influence of larger volumes on the diversity of the sludge mix (Kılıç et al., 2025).

Initial statistical tests suggest that most WWTPs have similar levels of MP contamination due to common sources or treatment methods. Alternatively, the variability within each plant may be greater than the differences between plants. The unusual results observed at NOD emphasise the need to investigate site-specific factors, such as industrial discharges, stormwater inputs or sampling inconsistencies, that may affect MP concentrations and potentially distort overall assessments. Typically, an increase in MP count corresponds to a higher total MP mass. However, the results for NOD and SYV suggest that factors such as MP type, shape and density may also influence this relationship.

5.2 Comparative Assessment of the Wastewater Treatment Plants

In the comparative analysis, excluding NOD, the most common found MPs were PP, PE and Polyester, comprising more than 85% of all MPs detected in the sludge. These types of plastics were also mentioned in another study, where these three plastic particles were assigned to personal care products, cosmetics, and cleaning agents (Galvão et al., 2020). It also mentions how synthetic textiles degrade during mechanical washing and lead particles such as Polyester, Acrylic and PA into wastewater. This suggests that apart from the industrial influence, external sludge and use of polymer during treatment, the above-mentioned domestic habits are predominant representing the plastic particles found in sludge. Similar results of polymer types can be found in another study, where ATR-FTIR was used as a measuring tool with also 70% as spectral match between measured and matched spectrum (Kılıç et al., 2025). Considering the larger WWTPs such as KAP, SYV and TEK out of the six, they show lower MP abundance in total compared to the smaller plants such as ENK, VAX and ESK. This indicates that larger WWTPs generally show higher efficiency in MP removal, despite elevated industrial influence and external sludge. Taken together, these results suggest that the larger a WWTP is, the better technologies are applied with better efficiency. Larger WWTPs do not necessarily emit higher MPs. When it comes to the mass of MPs, SYV shows the highest mass and TEK the lowest, followed by KAP. SYV must have PE particles in the sludge that are especially heavier compared to the other plants. Notable is that SYV is the only plant using cationic and anionic polymers in three treatments processes, whereas the other plants apply polymers not more than two times. KAP presented the lowest number of MPs and VAX, closely followed by KAP, the lowest mass of MPs in the WWTPs studied. Interestingly, TEK and ENK have almost the same abundance of MP detected, even though TEK has almost five times higher yearly sludge production and double the industrial influence. TEK uses advanced treatment technology, specifically ozonation, which has been identified as one of the most effective methods of removing MPs. The average total MP count across the different WWTPs is as follows: NOD >> VAX > ESK > TEK > ENK > SYV > KAP. Meanwhile, the mass ranking is as follows: NOD >> SYV > ESK > TEK > ENK ≈ KAP > VAX. The mass is representative for the source of external inflows, whereas the abundance is as well representative of the processes during treatments.

5.3 Size and Shape Characteristics of Detected Microplastics

All the seven WWTPs have the majority of the particles with an area ranging between 1'000 and 5'000μm², as captured by the FTIR imaging. It appears that the primary (fine) screening is effective in capturing particles that are large or very large in size, as the frequency of particles detected in that size range (5'000-10'000μm² and larger) the sludge is very low. The size of the holes in the fine screen can trap MPs from being passed on to subsequent processes and ending up in the sludge. The common bar-spacing sizes are 2mm (NOD, VAX), 3mm (ENK, KAP, TEK) and 6mm (ESK, SYV). Alongside this, the number of MPs found is also mentioned in the same **Table 4** to facilitate comparison of the different factors. As this study represents particle size by projected area and most of the MPs identified are fibres, it is assumed that the size range of MPs in sludge falls between 0.2 and 1.8mm.

Besides, the morphology of the detected MPs indicates the majority of the MPs to be fibrous (stretched), mainly PE, PP and Polyester. This morphology is common to find in WWTPs (Galvão et al., 2020). These common polymer types also exhibit a medium sized area distribution as mentioned before. Given that over 80% of MPs that enter WWTPs end up in the sludge (Bawa et al., 2024), and that the majority of these MPs are fibres, mitigation methods to reduce the fibrous MPs ending up in the sludge must be a focus for WWTPs.

5.4 Efficiency of Advanced Treatment Processes in Wastewater Treatment Plants

Previous studies (Chen et al., 2018; Kwon et al., 2022; Nasir et al., 2024) have shown that although advanced treatment significantly reduces the overall load of MPs, certain types, particularly fibre-like MPs, can persist in the final effluent. In some cases (chlorination/UV-oxidation), the abundance of fibres may even increase in the final effluent compared to the secondary effluent. This could be due to the ability of fibres to pass through filters or membranes more easily due to their elongated shape. Consequently, additional final treatment steps may be required to specifically target and remove small and fibrous MPs from the treated effluent. Ozonation has been shown to oxidize both organic and non-organic pollutants, along with a significant number of MPs, eliminating 90% of MPs after a 30-minute processing period (Nasir et al., 2024). However, it is important to note that because the ozonation method only reduces large-size MPs to smaller sizes, the output MP concentration can sometimes be marginally higher than the input MP concentration. Next to ozonation, TEK also uses IFAS (integrated fixed-film activated sludge), which has shown effectiveness in MP removal (Ma et al., 2024). The IFAS process involves the use of biofilm fillers, which can be made of materials like activated carbon, metals, or ceramics, to aid in the removal of MPs.

5.5 Potential Factors Influencing the Presence of Microplastics in Sludge

The abundance of MPs found in WWTPs are dependent on the sampling procedures employed, the concentration ratio of domestic to industrial, as well as methods used for detection and identification of MPs (Kılıç et al., 2025). The characteristics of the wastewater are usually of relevance, as it has been reported that the number of MPs released through industrial wastewater are approximately 3.2 times higher than the amount released by domestic wastewater (Long et al., 2021). Corresponding to that, the WWTP also employ designated treatment processes such as ozonation, MBR, MBBR, IFAS, extended filtration processes and constructed wetland to treat wastewater with moderate and elevated industrial influence. Based on industrial influence, the ranking is KAP > TEK > NOD > ENK > ESK ≈ SYV > VAX. Considering the number of MP types detected, the order is NOD > ESK > TEK ≈ VAX ≈ ENK > KAP > SYV. The diversity of polymers found in sludge may be affected by moderate and elevated industrial influence as well as external sludge. This is although not always the case, since the size of the WWTPs also plays a role. An example to showcase that this is not always the case is KAP, presenting the highest population equivalent, highest industrial influence and no external sludge, but lowest total average in MP mass. KAP has reported that industries such as car washes, waste facilities, chemical industries, laboratories, energy facilities, airport, mechanical workshops, food industry and more are connected. Despite a high industrial influence and largest population equivalent value, the number of plastic types found is limited to eight. Even though being the second largest WWTP, SYV has the least number of polymer types discovered and has a minimal industrial influence. NOD stands out as an outlier due to its notably high Polyester content, which constitutes 99% of the detected polymer mass. As the third largest plant with moderate industrial influence, NOD also receives external sludge, which could introduce MPs from private households. Information from the plant indicates that some affiliated companies process plastic bottles by washing and grinding them into flakes, which is likely to contribute to the high polyester levels, given that this material is commonly found in bottles (also see Table 3). Unique MPs detected at NOD include ABS, Alkyd and Polycarbonate, which are hard plastics and coating materials, even if present in low amounts. However, the reliability of FTIR measurements may be limited, as overlapping MPs in NOD samples made individual identification challenging.

Followed by industrial influence, another factor that could influence the amount of MPs found in sludge is the addition of external sludge to sewage sludge. This external sludge is often food waste, which is sometimes packed in plastic bags that are torn open and separated. It may also include sludge from poorly established WWTPs or private systems that lack regulatory controls or protocol enforcement. As these inputs are neither consistently documented nor traceable, any assumptions about their level of impact on the final sludge are subject to a degree of uncertainty.

Beyond the previously mentioned influential factors, domestic sources are the primarily responsible for the release of MPs, including those from cosmetic products, fibres released from washing machines, tyre debris, fragmented roads and urban runoff. Of these, domestic laundry, and washing machines in particular, are significant contributors to the release of MPs (Hechmi et al., 2024). The most common plastics used plastics in Europe are PP and PE (Plastics Europe, 2024). PP is typically found in items such as food packaging, pipes, vehicle components, and even banknotes, while PE is used in reusable shopping bags, food packaging films, toys, shampoo bottles, and other household products (Anderson, 2022). Polyester or PET is widely used in plastic bottles and textile fabrics (Dalla Fontana et al., 2020). Frequent washing of synthetic clothing releases microfibres into wastewater, making Polyester a major source of these particles. This suggests that the types of MPs found in wastewater mirror the patterns of domestic plastic usage directly. This suggests that the types of MPs found in wastewater mirror the patterns of domestic plastic usage directly.

A further factor that is likely to influence polymer type and mass is internal contamination during treatment processes. It is evident that all seven plants utilise polymers such as biofilm carriers and cationic polyacrylamide, the latter of which is frequently employed for sludge thickening and dewatering. Polyacrylamides are synthetic linear polymers, water-soluble and made of acrylamide or combinations or acrylamide and acrylic acid (Doble & Kumar, 2005). These synthetic polymers have been identified as playing a significant role in the dewatering process of sludge within a WWTP, hence a research study was conducted to find out the fate of polyacrylamides in the context of sludge applied on agricultural land (Hennecke et al., 2018). As part of the experiment for this research, radioactive isotope, carbon-14, was incorporated into the polyacrylamide molecule to facilitate its tracking during environmental degradation studies. Hennecke (2018) states that these elements are strongly bound to organic matter and clay particles and therefore, immobile in soil and very difficult to desorb. This means that they degrade slowly as a component of sludge after land application. The degradation rate was more than 20% within two years and no vertical movement of the polymer or transformation products were found at the end of the study. As MP detection was performed using FTIR, the results were analysed to identify any signals that could represent polyacrylamides. The spectra of polyacrylamide, acrylic acid and poly-acrylic acid present both similarities and distinct differences (Mieles et al., 2023). The spectrum of poly-acrylic acid appears to be more closely aligned with polyacrylamide than with acrylic acid. It can be assumed that the polymers added to the sludge may be partly represented by the particles detected as acrylic, acrylic paints and PAN acrylic fibre, which comprise about 0.5 % of mass (ng/gTS) in all the sludge from six WWTPs together, excluding NOD because of data skewing. Although small, this is still an assumed amount, which could be higher or lower. In the study conducted by Luo (2011), the toxicity of polyacrylamide was analysed. Whilst polyacrylamide is capable of degradation, it does not simply dissolve and become organic material. Instead, it breaks down into other compounds, which can be harmful, and its monomer can be highly toxic (Luo et al., 2011). In addressing the potential for internal contamination via biofilm carriers, it is noteworthy that these carriers are made from various polymers including both organic (PE, Polyester, Polyolefin and PU) or inorganic material (Zhao et al., 2019). The most common materials for biofilm carriers are based on PE because this material has a density close to that of water (Moga et al., 2018). Contamination from biofilm carriers cannot be ruled out, since they are used in biological treatment and support biofilm growth, though they are not expected to degrade. Furthermore, it is not feasible to differentiate the measured MP abundance, given that PE and Polyester are prevalent MPs in wastewater.

Population equivalent (PE) values do not have a correlation with the MP abundance. From Mahon (2017), the lack of correlation between *PE* and MP abundance implies that the differences may occur due to the various input sources such as industrial, stormwater, landfill, and others (Mahon et al., 2017). However, as no data exists on the temporal variation of MPs in sewage sludge, the study implies that the possibility also exists that these variations are a result of fluxes in MPs input which could be a result of peak MP emission times in relation to household and industrial activity. A study from Ma (2024) researching if there is a correlation between MP and population density (Ma et al., 2024), states that although it might be expected that levels of MPs would correlate with population size, studies have not consistently shown this to be the case. This inconsistency may be due to other important factors that are often overlooked, such as industrial activity, land use, the type of commercial activity in the area, and the size of the service area, all of which can significantly influence the presence and distribution of MPs in wastewater. This confirms the intended analysis approaches for the current study, which aimed to assess the correlation between MP abundance and *PE*, as well as to investigate the impact of industrial activity and other factors.

5.6 Implications of Microplastics in Agriculture and their Effects

Finally, this study calculated the mass of MPs that end up in agricultural soil. About 11 tonnes of MPs is spread yearly along with sludge fertiliser on arable land (without outlier NOD). Although it is just 0.1% of the sludge amount prepared for this purpose, it is a concerning amount. The transport process of MPs once it lands on soil, can be by wind and water through surface run off (Hooge et al., 2023). Hooge (2023) also mentions that the MPs can get deeper into the soil through ploughing, bioturbation and ingestion from burrowing soil biota or transportation with infiltrating water. The soil type, climate and landscape properties and application conditions play a role in the fate of MPs. The shape, size, polymer type and surface charge are properties of MP that affect their transport. Hooge (2023) also reports that studies have shown that higher density MPs are preferentially transported downwards in soil profile compared to lower density MPs, and spherical shaped MPs are transported downwards more than fragments. Degradation of MPs in soil is generally low, estimated time would range from several years to several thousand years. A study (Kanold et al., 2024) confirms that increasing concentrations of MP polyester fibres in soil modulate plant growth and have a modest impact on overall plant nutrition, with notable differences observed in two key nutrients. As polyester fibres are hydrophilic, they could benefit plants by enhancing the soil's water-holding capacity and reducing its bulk density, thereby facilitating root growth. Another study (Heinze et al., 2024) has conducted measurements in different depths in soil to understand the distribution of MPs in soil amended with sewage sludge. Across all depths, MP numbers were twice and mass concentration eight times higher when sludge was applied to soil. Most of the MPs had a textile related profile, meaning more fibrous. 48% of the MP mass was detected in plough layer (20cm into the soil), where the average mass was 1470±660 mg/kg. Meanwhile 58% of total MP abundance was found in plough layer with an average of 53.7±6 MP/kg. Here too, most of the plastics (63%) found in soil with sewage sludge were associated with textiles. Although the majority of the MPs were found in ploughed topsoil, there were substantial amounts of MPs in greater depths. These examples indicate that MP in soil is resistant, concerning plants health and affecting soil property. Research on the toxicity of MPs in soil has been conducted on common plastic types, and the results have shown both positive and negative correlations with earthworms, as well as impacts on the bioavailability of heavy metals in soil and ecotoxicity caused by UV radiation in aquatic environments (Contreras-Castillo et al., 2025; Fang et al., 2025; Li et al., 2021).

Studies have shown how MPs affect human health. In a big picture, MPs land from water and soil in beverages and edible foods identified as primary sources of intake. These particles enter the body mainly through inhalation, ingestion, and dermal contact. Once inside, they pose several serious health risks. Studies have linked MPs and NPs to metabolic disorders, as well as neurotoxic, genotoxic, and cytotoxic effects (Kumar et al., 2022). One of the key concerns in this study is the ability of MP to cause DNA damage and oxidative stress, which are critical pathways leading to carcinogenesis (cancer development). Additionally, exposure to these particles can trigger chronic inflammation and immune responses, further contributing to cancer risk. MP exposure to the environment affects population fitness, mortality, oxidative stress, DNA damage and population decline due to the amount of MPs landing in soil and water, collaboration between industries and research institutes need to be promoted to strengthen policies on waste disposal and use of plastic (Nasir et al., 2024). Since 2018, the Swedish EPA has been distributing investment funds for the installation of advanced treatment technologies. The need to use advanced treatment techniques varies between treatment plants, depending on the type of micropollutants to be treated and the sensitivity of the recipient. Installing advanced treatment alone does not solve the problem, while efforts must be made to address the issue at source. In particular, the release of micropollutants, including MPs, must be reduced by identifying and replacing substances. (Åkerblom et al., 2022).

6 Conclusions and Outlook

The study aimed to characterise the MPs found in sludge samples, identify the factors influencing their occurrence, and determine the extent to which they spread to agricultural soil through wastewater sludge. This study has helped to establish the types, abundances, masses and areas of MPs found in WWTPs across the region of Malärdalen, Sweden. Samples were taken from each plant with three replicates each. Out of the sixteen different types of MPs detected, Polyester, PP and PE were the most prevalent in terms of both count and mass. The average MP abundance across the WWTPs was found to be 1'311±102 MP/gTS. The area of MPs discovered in the FTIR images had the highest distribution in the medium category (1'000–5'000μm²).

The presence of industrial influences in wastewater inlets, external sludge, and sludge processing with polyacrylamide could be possibly affecting the type and abundance of MPs found in the sludge. FTIR measurement results have made it difficult to understand the high variability between replicates and the relationship between count and mass. Internal MP pollution in WWTPs through polymers added during the digestion process could not be distinguished in imaging and assigned to one type of polymer. Interestingly, WWTPs designed for a larger wastewater treatment capacity have proven to have better MP removal efficiency than smaller WWTPs. Notably, the size of the plant did not influence the abundance of MPs. A smaller mesh size for primary screening has been shown to influence the amount of MPs found in sludge. Not all WWTPs use their final sludge; some send it to incineration, landfill, or construction land. Five out of seven WWTPs use sludge for agricultural fertilisation, three of which use all of their sludge for this purpose. Annually, 0.1% of 14'559 tonnes of sludge consist of MPs that are used as fertiliser on agricultural land, and they come from analysed WWTPs that are REVAQ certified. This demonstrates that a significant quantity of MPs infiltrates agricultural soil on an annual basis, giving rise to concerns about the impact on crops, as well as land and water pollution and ecotoxicology for flora and fauna. Although WWTPs were not originally designed to remove MPs from wastewater, most visible MPs are removed through physical processes such as screening, sedimentation and filtration. Nevertheless, the present study sheds light on the extent to which MPs end up in agricultural soil. Although REVAQ certification permits the use of sludge for agricultural purposes, the environmental and human health implications of MPs must be re-evaluated. However, WWTPs are taking a sustainable approach by using biogas from sludge treatment for vehicle biofuel (buses), with any remaining biogas being used for WWTP facility heating.

The absence of a standardised research methodology for MPs in sludge makes it difficult to compare exposure to MPs in the environment. In addition to external factors such as the wastewater inlet and external sludge, internal factors such as the addition of polymers to the digestion process significantly impact the occurrence of MPs in treated sludge. The reliability of the research may be compromised by the limited number of replicates from each plant and the omission of consideration of seasonal differences. Future research should address the following: firstly, the effect of polyacrylamide in the final stage of sludge treatment should be studied; secondly, effective methods of filtering polymer fibres, especially very small, small and medium sized particles in wastewater treatment processes should be investigated; and thirdly, fluctuations in MP abundance should be examined more closely to establish a better correlation with influent entering the plant from domestic and industrial sources. To ensure the sustainable management of MPs in wastewater treatment, regulatory limits, such as maximum allowable concentrations of MP/L of wastewater and MP/g of sludge, should be established and imposed in WWTPs. The findings of this study emphasise the necessity for policy frameworks that address MP emissions at their source and throughout the treatment process. Furthermore, investment in advanced treatment technologies, including combinations of thermal and chemical processes, should be encouraged to transform MPs into forms that can be more effectively removed in the final treatment stages. Such measures are imperative not only for the protection of environmental and human health, but also for the promotion of a circular and sustainable approach to sludge reuse, particularly in the context of agriculture.

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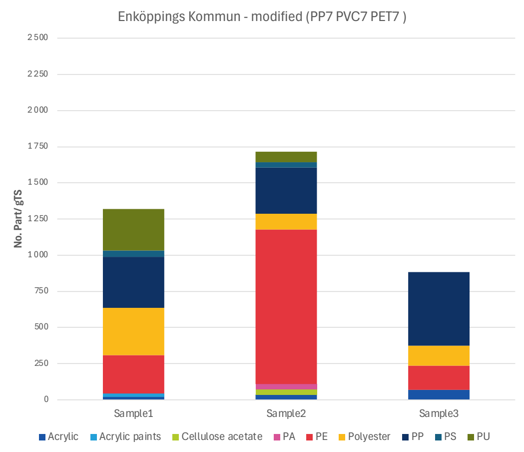
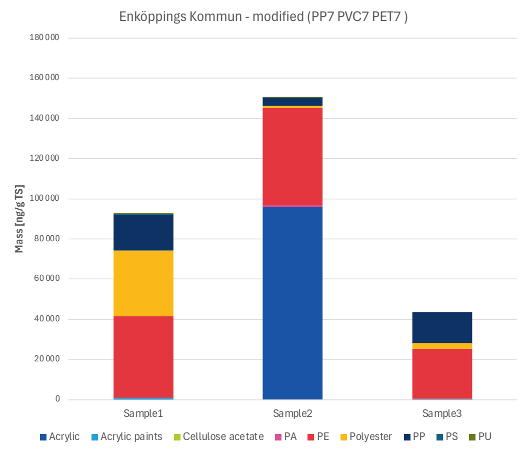
Appendix

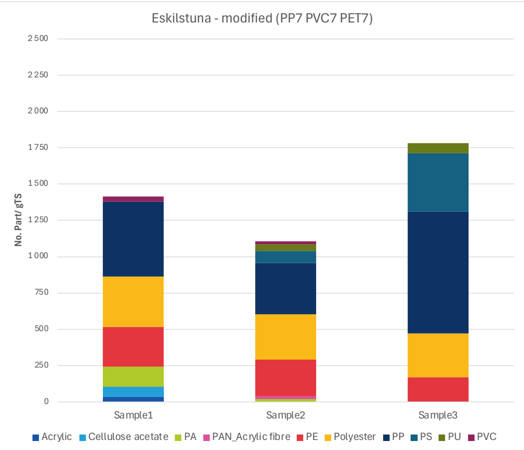
Appendix A: Questionnaire distributed to all seven wastewater treatment plants (ENK, ESK, KAP, NOD, SYV, TEK, VAX) to gather background information on treatment processes, sludge handling, and potential microplastic sources.

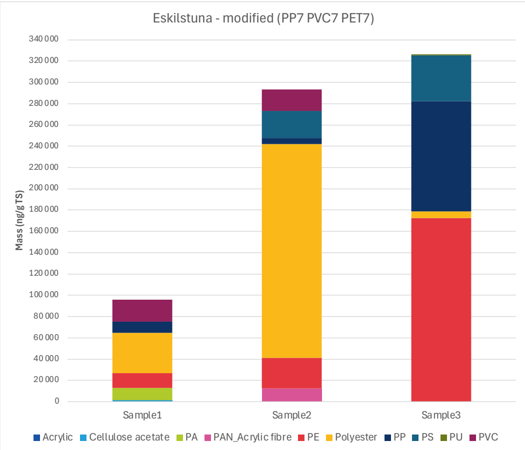
					Instructions:
Name of WWTP	-select-				Select your WWTP from the drop-down list
PE					PE = population equivalent
Influent from:	Muncipalities	Industries	Hospitals	Stormwater Runoff	Please comment how many municipalities are connected to the system as well as the number of industries (mention if type known) and hospitals. If you receive stormwater runoff, please answer with YES, otherwise NO.
Effluent goes to:	Baltic Sea	Other			Please comment YES or NO for baltic sea and specify if others.
Flow rate [m^3/d]					If wet and dry weather is known, mention both, otherwise average is enough.
Sludge production	in tonnes	in % of TS	ref. year		Please enter values if you have data from last year (2024), othervise specify reference year.
Treatment categories	Primary	Secondary	Tertiary	Advanced	Please enter they types of treatments used, if none - leave empty or type 0
Sludge treatments					Please mention all the sludge treatment done at yout WWTP until disposal
Sludge retention time					Enter also unit if **min, h or d**
Digestion Temperature					Indicate whether sludge digestion is aerobic or anaerobic and the temperature in degrees Celsius.
Disposal of sludge from screening					Mention what you do with the sludge remain from the screenings.
Final sludge disposal					Please explain where the sludge is disposed - agriculture (biosolids), incineration, biofuel, landfill, etc. If you know the amount or ratio, please include that too.
Use of polymers for treatment processes					Do you use polymers for any processes? - eg: biofilm carriers or membranes made out of polymers, adding polymers for dewatering sludge, etc. Please be specific and mention the type of polymers, if it applies.
Certifications					Do you follow any certifications? - biosolids, environmental certifications, etc.
Do you monitor the removal efficiency between the influent and effluent?					If you know the removal efficiency of micropollutants, please mention the % value. If you know of others, please specify.
Do you expect microplastics to be present in the digested and dewatered sludge?					What do you think? :)

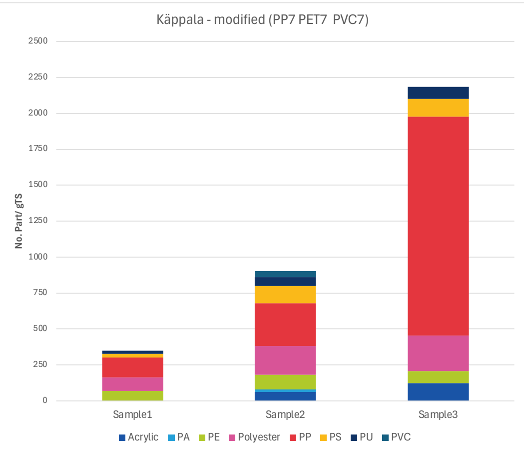
Appendix B: Count (left column) and mass (right column) per gram of total solids of MPs detected in all three replicates for each of the seven WWTPs (ENK, ESK, KAP, NOD, SYV, TEK, VAX)

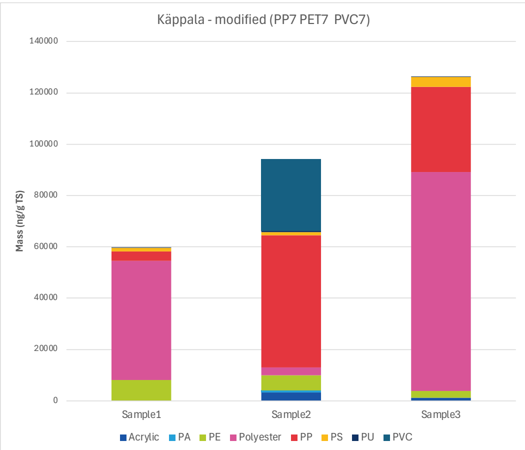


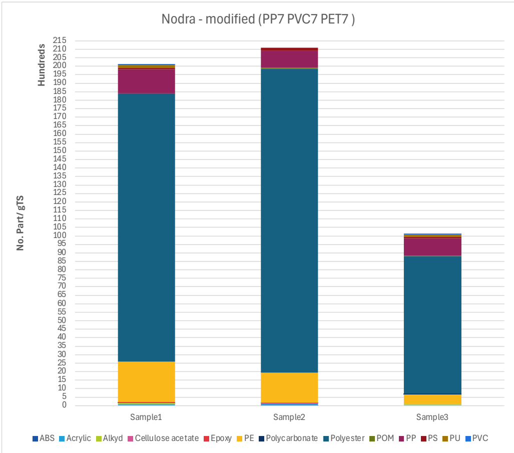


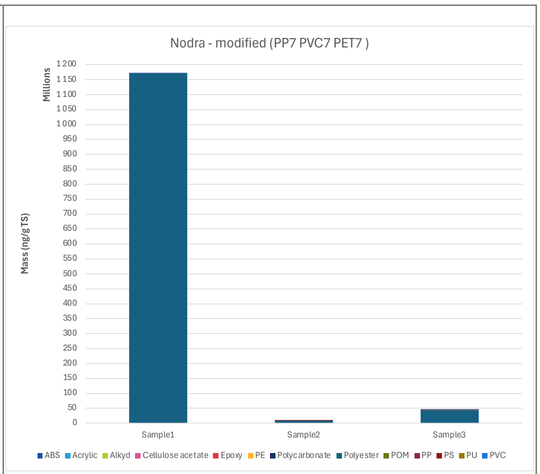


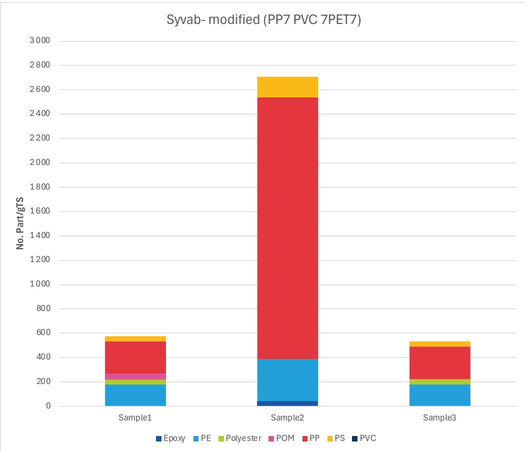


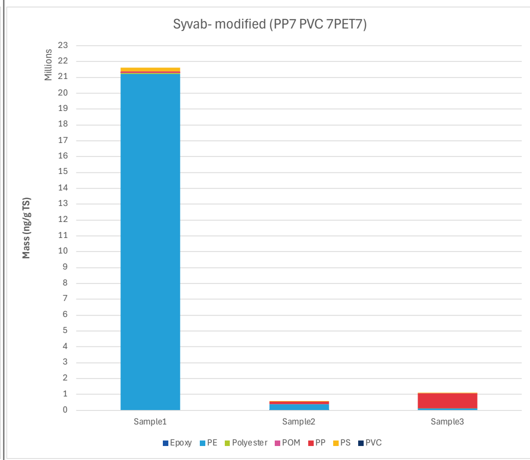


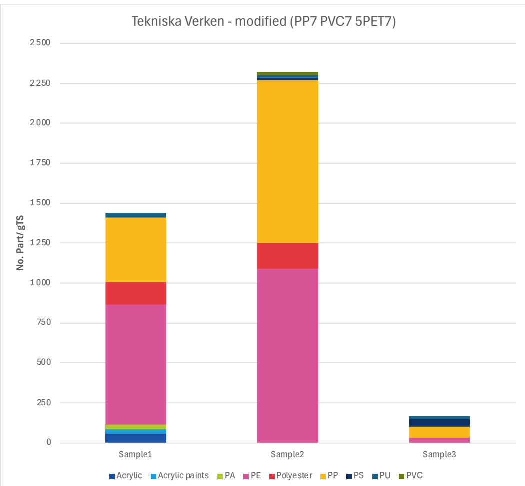


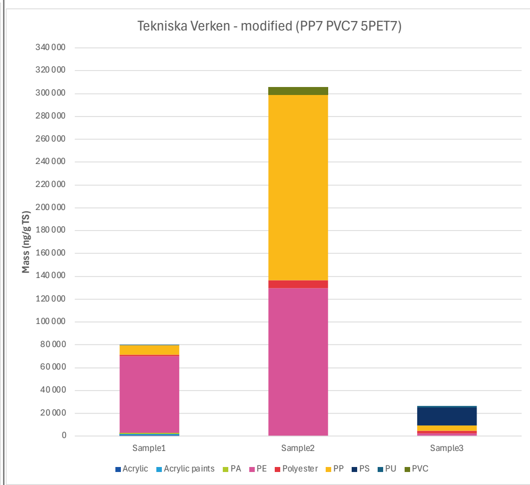

Nodra - modified (PP7 PVC7 PET7)
Hundreds
No. Part/ gTS
Sample1
Sample2
Sample3
ABS Acrylic Alkyd Cellulose acetate Epoxy PE Polycarbonate Polyester POM PP PS PU PVC

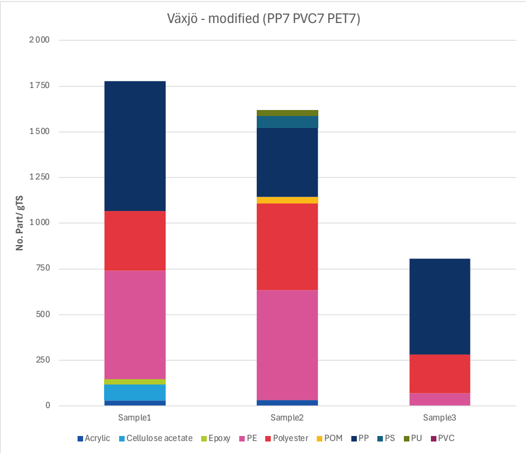

Nodra - modified (PP7 PVC7 PET7)
Millions
Mass (ng/g TS)
Sample1
Sample2
Sample3
ABS Acrylic Alkyd Cellulose acetate Epoxy PE Polycarbonate Polyester POM PP PS PU PVC

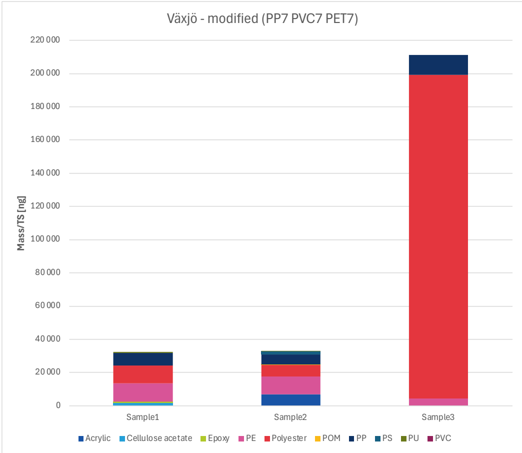

Syvab- modified (PP7 PVC 7PET7)
No. Part/gTS
Sample1
Sample2
Sample3
Epoxy PE Polyester POM PP PS PVC


Syvab- modified (PP7 PVC 7PET7)
Millions
Mass (ng/g TS)
Sample1
Sample2
Sample3
Epoxy PE Polyester POM PP PS PVC

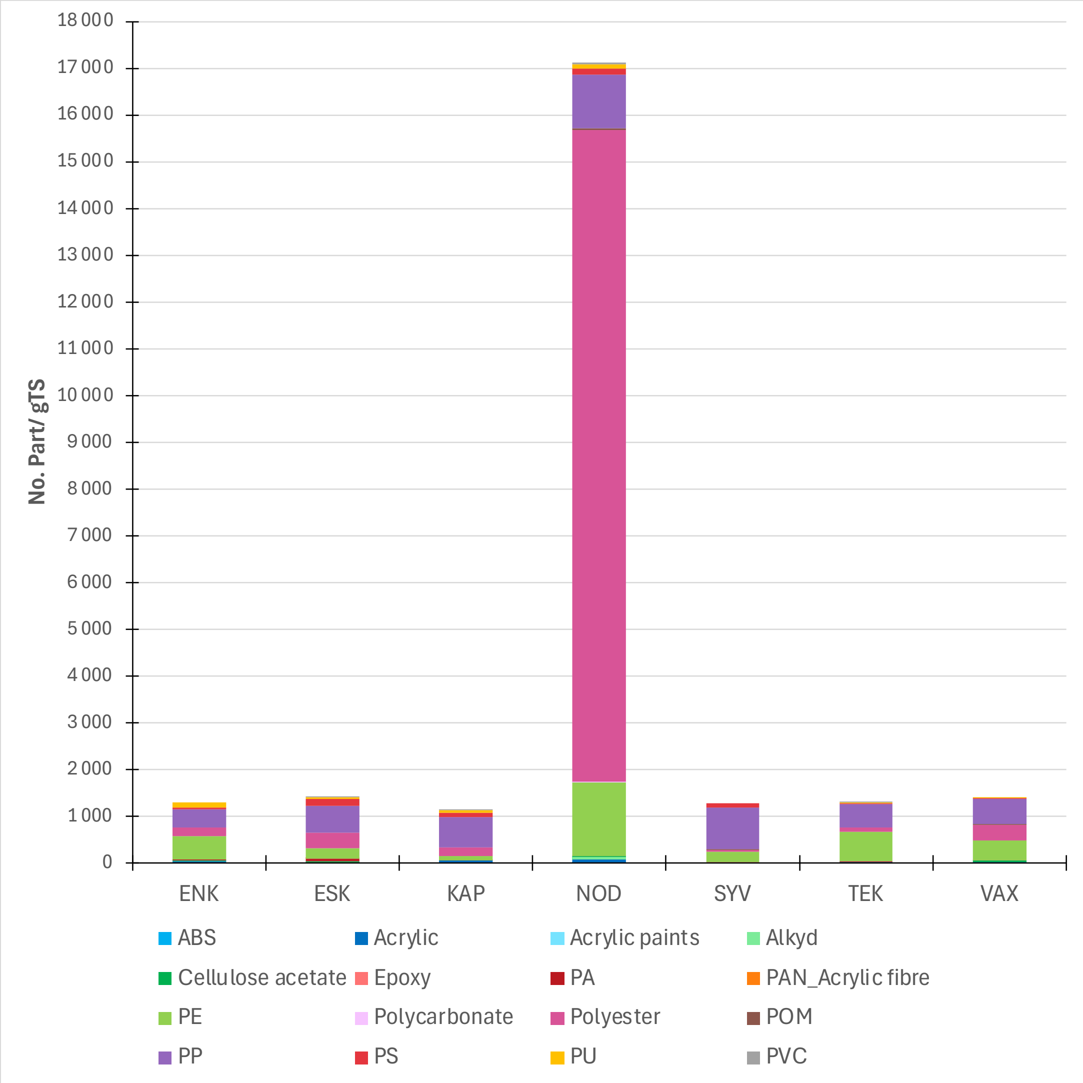

Tekniska Verken - modified (PP7 PVC7 5PET7)
No. Part/ gTS
Sample1
Sample2
Sample3
Acrylic Acrylic paints PA PE Polyester PP PS PU PVC


Tekniska Verken - modified (PP7 PVC7 5PET7)
Mass (ng/g TS)
Sample1
Sample2
Sample3
Acrylic Acrylic paints PA PE Polyester PP PS PU PVC


Växjö - modified (PP7 PVC7 PET7)
No. Part/ gTS
2 000
1 750
1 500
1 250
1 000
750
500
250
0
Sample1
Sample2
Sample3
Acrylic
Cellulose acetate
Epoxy
PE
Polyester
POM
PP
PS
PU
PVC


Växjö - modified (PP7 PVC7 PET7)
Mass/TS [ng]
220 000
200 000
180 000
160 000
140 000
120 000
100 000
80 000
60 000
40 000
20 000
0
Sample1
Sample2
Sample3
Acrylic
Cellulose acetate
Epoxy
PE
Polyester
POM
PP
PS
PU
PVC

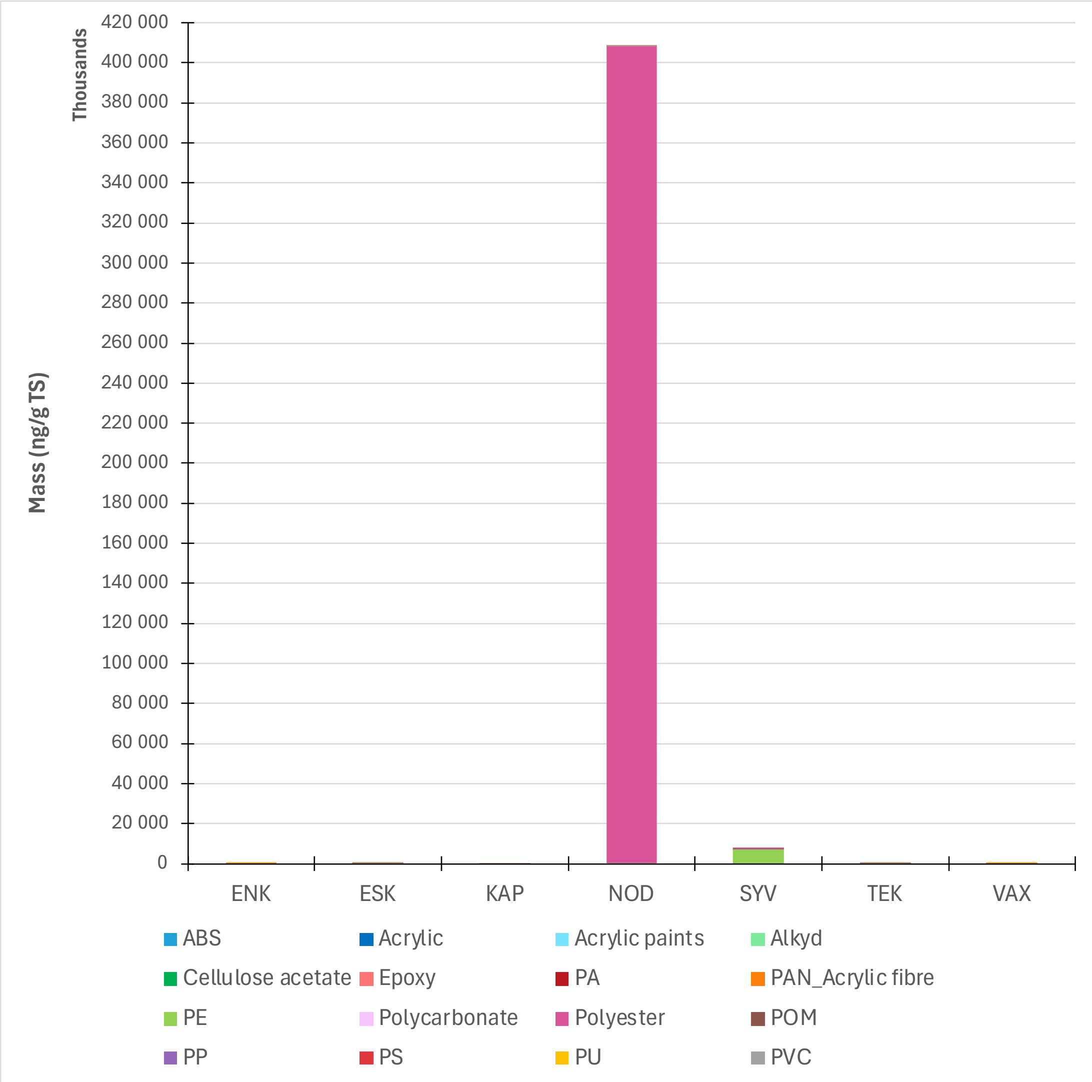
Appendix C: Average counts and abundance of the different of MPs in the sludge samples from all treatment plants including NOD.



Appendix D: Number of MP particles identified in sludge samples from all seven WWTPs, distinguished by polymer type. The data represent cumulative average counts from all three replicates per plant.

	MEAN [MP/gTS]									
	NO OF PART	**ENK**	**ESK**	**KAP**	**NOD**	**SYV**	**TEK**	**VAX**	**SUM**	**%**
1	**ABS**	0.00	0.00	0.00	11.90	0.00	0.00	0.00	12	**0.05%**
2	**Acrylic**	41.83	11.49	61.24	72.64	0.00	19.18	20.46	227	**0.91%**
3	**Acrylic paints**	7.33	0.00	0.00	0.00	0.00	9.59	0.00	17	**0.07%**
4	**Alkyd**	0.00	0.00	0.00	49.27	0.00	0.00	0.00	49	**0.20%**
5	**Cellulose acetate**	11.90	22.99	0.00	11.90	0.00	0.00	29.63	76	**0.31%**
6	**Epoxy**	0.00	0.00	0.00	12.35	14.34	0.00	9.88	37	**0.15%**
7	**PA**	11.90	52.92	6.67	0.00	0.00	9.59	0.00	81	**0.32%**
8	**PAN_Acrylic fibre**	0.00	6.94	0.00	0.00	0.00	0.00	0.00	7	**0.03%**
9	**PE**	501.55	231.31	84.08	1569.18	233.21	623.61	421.98	3665	**14.66%**
10	**Polycarbonate**	0.00	0.00	0.00	12.23	0.00	0.00	0.00	12	**0.05%**
11	**Polyester**	190.80	319.95	180.15	13951.16	29.63	101.53	337.55	15111	**60.46%**
12	**POM**	0.00	0.00	0.00	36.04	14.81	0.00	10.58	61	**0.25%**
13	**PP**	393.85	570.58	655.10	1133.07	894.62	495.80	539.46	4682	**18.73%**
14	**PS**	26.56	162.23	88.99	132.93	86.98	22.62	21.16	541	**2.17%**
15	**PU**	119.05	36.30	55.24	98.31	0.00	21.10	10.58	341	**1.36%**
16	**PVC**	0.00	18.44	13.33	36.92	0.00	5.95	0.00	75	**0.30%**
	SUM	1,305	1,433	1,145	17,128	1,274	1,309	1,401	**24,995**	
	%	**5.2%**	**5.7%**	**4.6%**	**68.5%**	**5.1%**	**5.2%**	**5.6%**		

Appendix E: Average mass of the different of MPs in the sludge samples from all treatment plants including NOD.



Appendix F: Mass of MP particles identified in sludge samples from all seven WWTPs, distinguished by polymer type. The data represent cumulative average mass from all three replicates per plant.

	MEAN [ng/gTS]									
	MASS	ENK	ESK	KAP	NOD	SYV	TEK	VAX	SUM	%
1	ABS	0.00	0.00	0.00	220.60	0.00	0.00	0.00	221	0.00%
2	Acrylic	32266.55	30.19	1489.05	7311.98	0.00	367.13	2394.69	43860	0.01%
3	Acrylic paints	126.38	0.00	0.00	0.00	0.00	365.47	0.00	492	0.00%
4	Alkyd	0.00	0.00	0.00	240778.34	0.00	0.00	0.00	240778	0.06%
5	Cellulose acetate	69.66	517.22	0.00	78.64	0.00	0.00	558.33	1224	0.00%
6	Epoxy	0.00	0.00	0.00	4.91	22.46	0.00	165.11	192	0.00%
7	PA	181.50	3809.01	282.70	0.00	0.00	314.57	0.00	4588	0.00%
8	PAN_Acrylic fibre	0.00	4229.05	0.00	0.00	0.00	0.00	0.00	4229	0.00%
9	PE	37953.80	71582.36	5527.02	221016.27	7243860.08	66280.85	8708.56	7654929	1.84%
10	Polycarbonate	0.00	0.00	0.00	674.98	0.00	0.00	0.00	675	0.00%
11	Polyester	12261.66	81705.15	44971.40	407782465.50	23969.04	3578.33	70855.20	408019806	97.87%
12	POM	0.00	0.00	0.00	1051.26	8592.23	0.00	94.00	9737	0.00%
13	PP	12555.36	39804.28	29441.19	204560.42	402955.31	58514.82	8531.74	756363	0.18%
14	PS	93.63	22946.69	2173.34	2886.39	76560.75	5252.81	685.71	110599	0.03%
15	PU	219.36	367.01	208.45	4170.37	0.00	378.03	148.70	5492	0.00%
16	PVC	0.00	13571.26	9263.86	6156.24	0.00	2186.16	0.00	31178	0.01%
	SUM	95,728	238,562	93,357	408,471,376	7,755,960	137,238	92,142	**416,884,363**	

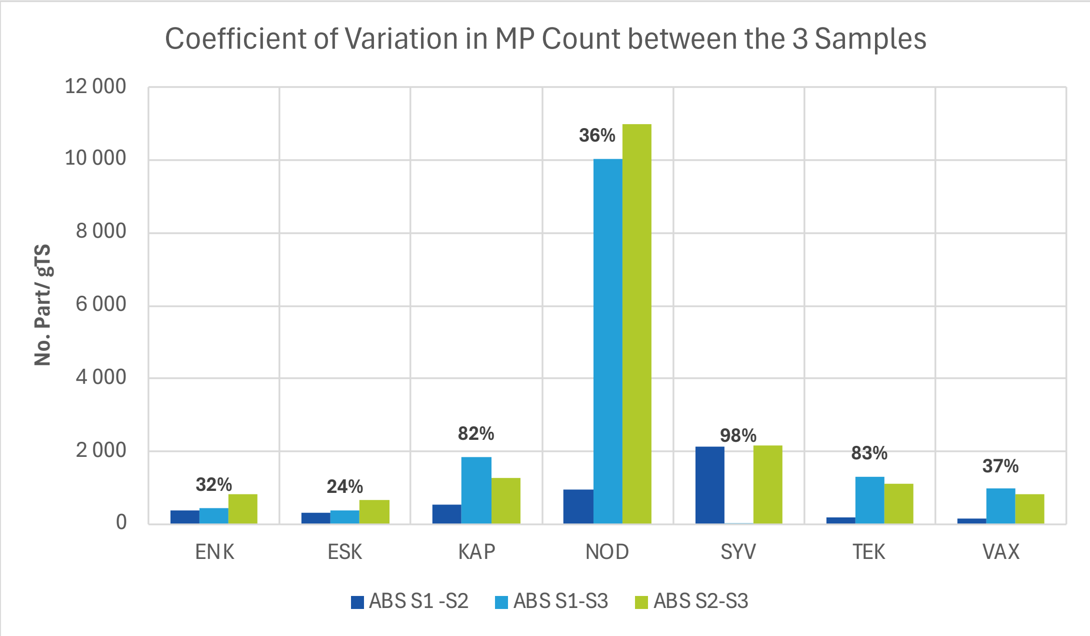
Appendix G: Pearson correlation coefficient (R) calculated to assess the relationship between the number of MP particles and their corresponding mass.

count vs mass	Enköping	Eskilstuna	Käppala	Nodra	Syvab	Tekniska Verket	Växjö
R-TEST	0.711	0.757	0.686	0.991	0.236	0.993	0.522
T-TEST for R	3.779	4.336	3.526	28.357	0.908	31.399	2.292

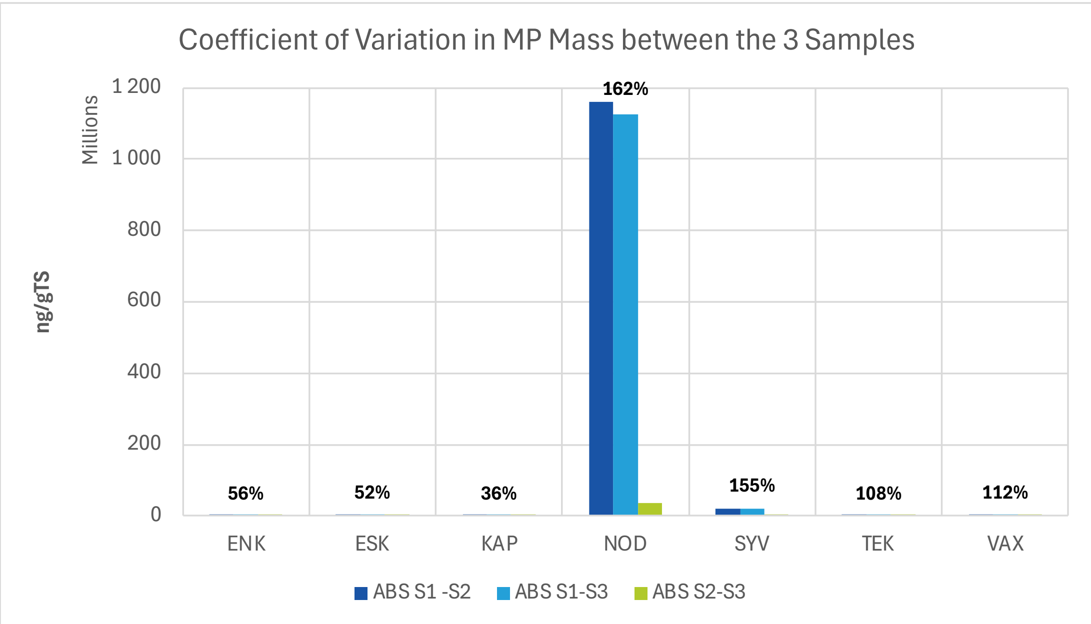
Appendix H: Absolute differences in MP count and mass between the three replicates for each sludge sample across all WWTPs.

NO OF PART	**ABS S1 -S2**	**ABS S1-S3**	**ABS S2-S3**
ENK	395.6	437.3	832.9
ESK	309.6	367.7	677.3
KAP	551.2	1,836.7	1,285.6
NOD	959.0	10,019.7	10,978.7
SYV	2,131.9	44.4	2,176.3
TEK	199.8	1,301.0	1,101.2
VAX	158.7	970.8	812.0
MASS	**ABS S1 -S2**	**ABS S1-S3**	**ABS S2-S3**
ENK	57,801.5	49,212.5	107,013.9
ESK	197,732.9	230,824.5	33,091.5
KAP	34,565.4	66,564.5	31,999.1
NOD	1,161,607,659.5	1,126,117,484.7	35,490,174.7
SYV	21,040,883.7	20,517,106.5	523,777.2
TEK	45,934.5	53,651.8	99,586.3
VAX	707.5	178,848.8	178,141.3

Appendix I: Absolute differences (ABS) between Sample1 (S1), Sample2 (S2) and Sample(S3) for MP count with coefficient of variation (CV) in %.



Appendix J: Absolute differences (ABS) between Sample1 (S1), Sample2 (S2) and Sample(S3) for MP mass with coefficient of variation (CV) in %.



Appendix K:ANOVA testing for MP count across all the WWTPs (n=7) and without NOD (n=6), followed by testing MP mass with and without NOD.

Anova: Single Factor	MP/gTS					
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Enköping	16	1304.77	81.55	23576.03		
Eskilstuna	16	1433.16	89.57	25636.66		
Käppala	16	1144.80	71.55	26781.00		
Nodra	16	17127.91	1070.49	12005597.71		
Syvab	16	1273.60	79.60	50815.35		
Tekniska Verket	16	1308.98	81.81	35964.49		
Växjö	16	1401.28	87.58	30824.31		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	13405305.16	6	2234217.53	1.282	0.272	2.186
Within Groups	182987933.2	105	1742742.22			
Total	196393238.4	111				

Anova: Single Factor	w/ NOD	MP/gTS				
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
ENK	13	1304.77	100.37	27423.83		
ESK	13	1433.16	110.24	29577.14		
KAP	13	1144.80	88.06	31901.05		
SYV	13	1273.60	97.97	61569.61		
TEK	13	1308.98	100.69	42896.20		
VAX	13	1401.28	107.79	36170.31		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	4010.53	5	802.11	0.02	1.000	2.342
Within Groups	2754457.79	72	38256.36			
Total	2758468.32	77				

Anova: Single Factor	ng/gTS					
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Enköping	16	95727.91	5982.99	147798513.87		
Eskilstuna	16	238562.22	14910.14	704711815.60		
Käppala	16	93357.02	5834.81	164528040.26		
Nodra	16	408,471,375.88	25529460.99	10390575593274700.00		
Syvab	16	7755959.88	484747.49	3258847311333.68		
Tekniska Verket	16	137238.16	8577.39	445711756.54		
Växjö	16	92142.03	5758.88	309668612.35		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	8.8801E+15	6	1.48002E+15	0.997	0.432	2.186
Within Groups	1.55908E+17	105	1.48483E+15			
Total	1.64788E+17	111				

Anova: Single Factor	w/ NOD	ng/gTS				
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
ENK	13	95727.91	7363.69	173733920.84		
ESK	13	238562.22	18350.94	812486004.14		
KAP	13	93357.02	7181.31	195184650.89		
SYV	13	7755959.88	596612.30	4001257560201.20		
TEK	13	137238.16	10556.78	534502299.69		
VAX	13	92142.03	7087.85	376881252.84		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3.72774E+12	5	7.45548E+11	1.117	0.359	2.342
Within Groups	4.80402E+13	72	6.67225E+11			
Total	5.17679E+13	77				

Appendix L: ANOVA testing for MP count across all the MP types (n=16) followed by same testing for MP mass.

Anova: Single Factor	**MP/gTS**					
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
ABS	7	11.90	1.70	20.25		
Acrylic	7	226.84	32.41	723.94		
Acrylic paints	7	16.92	2.42	17.47		
Alkyd	7	49.27	7.04	346.78		
Cellulose acetate	7	76.43	10.92	142.56		
Epoxy	7	36.56	5.22	44.10		
PA	7	81.09	11.58	356.60		
PAN_Acrylic fibre	7	6.94	0.99	6.89		
PE	7	3664.92	523.56	246162.83		
Polycarbonate	7	12.23	1.75	21.38		
Polyester	7	15110.77	2158.68	27051976.73		
POM	7	61.44	8.78	181.87		
PP	7	4682.49	668.93	66439.03		
PS	7	541.47	77.35	3209.08		
PU	7	340.58	48.65	2032.20		
PVC	7	74.65	10.66	186.75		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	32162027.60	15	2144135.17	**1.253**	**0.247**	**1.772**
Within Groups	164231210.75	96	1710741.78			
Total	196393238.35	111				

Anova: Single Factor	**ng/gTS**					
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
ABS	7	220.60	31.51	6952.01		
Acrylic	7	43859.60	6265.66	137978937.51		
Acrylic paints	7	491.85	70.26	19163.49		
Alkyd	7	240778.34	34396.91	8282029684.49		
Cellulose acetate	7	1223.85	174.84	62718.87		
Epoxy	7	192.48	27.50	3749.37		
PA	7	4587.77	655.40	1952262.46		
PAN_Acrylic fibre	7	4229.05	604.15	2554982.57		
PE	7	7654928.94	1093561.28	7360381212885.88		
Polycarbonate	7	674.98	96.43	65084.95		
Polyester	7	408019806.28	58288543.75	23750612215850100.00		
POM	7	9737.49	1391.07	10232479.40		
PP	7	756363.12	108051.87	21432845450.60		
PS	7	110599.31	15799.90	780294443.10		
PU	7	5491.92	784.56	2245752.36		
PVC	7	31177.52	4453.93	28969027.70		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.22396E+16	15	1.48264E+15	**0.998**	**0.463**	**1.772**
Within Groups	1.42548E+17	96	1.48488E+15			
Total	1.64788E+17	111				

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