University of Applied Sciences and Arts Northwestern Switzerland
School of Engineering

Project report

Selection of Suitable Detection Methods for Microplastics

Figure 1: Illustration of the project (Furrer, 2025)

Document name	Project report MSE-P7-Haag
Client	FHNW IBRE
Project leader	Lukas Haag
Project coach	Prof. Dr. Petar Mandaliev, FHNW
Responsible for the module	Daniel Weiss, FHNW
Study program	MSE in Energy and Environment
Version	Submission V2
Start date	15.09.2025
End date	15.02.2026

Management Summary

Initial Situation and Goal

The increasing occurrence of microplastics in environmental compartments such as water, soil, air, and food represents a growing challenge for environmental science and policy. Microplastics originate both from the degradation of larger plastic fragments and from the direct release of primary particles. They enter the environment through pathways such as wastewater, tire abrasion, and atmospheric transport, where they accumulate over long periods of time. Despite their ecological relevance, reliable detection and quantification of microplastics are hampered by methodological variability, the lack of standards, and heterogeneous sample matrices. The wide range of available analytical methods results in datasets that are not directly comparable, thereby limiting the interpretability of current assessments. The aim of this project is therefore to systematically document and evaluate existing measurement methods in order to support the development of standardized and practice oriented analytical approaches.

Methodology

This thesis is based on a comprehensive literature review and specifically investigates how different environmental media, including air, water, soil, and food, can be analysed for microplastics.

Results

The analysis shows that a variety of sampling methods exist for the collection of microplastic samples, each of which is highly specialized and tailored to the respective environmental medium. In addition, different approaches to sample preparation are applied, likewise specific to the individual matrices, enabling the subsequent use of various analytical techniques depending on the respective research question. At the same time, it became evident that the issue of cross contamination is frequently neglected in many studies, particularly during the sampling stage. Due to insufficient documentation and inconsistent definitions of microplastics, studies are therefore in some cases difficult or even impossible to compare.

Conclusion

The literature demonstrates that the lack of standardization remains a central challenge in microplastic analysis and significantly limits comparability between studies. Differences in sampling and detection methods indicate that no universal analytical strategy exists and that method selection must always be adapted to the research question, the sample matrix, and the particle size range of interest. The guidelines of the BMBF status paper (Braun, 2020) emphasize the importance of a uniform presentation of results and the separate reporting of particle number and mass, while conversions between these parameters should be avoided due to high associated uncertainties. Consistent quality control, particularly regarding preventing cross contamination during sampling (Cruz-Salas et al., 2023), is essential to obtain reliable results. The developed flowchart supports structured methodological decision making and contributes to transparency and comparability in microplastic related studies, but it does not replace detailed method planning.

Acknowledgements

I would like to express my gratitude to everyone who supported me during this project.

Special thanks go to my advisor, Prof. Dr. Petar Mandaliev, who conceived this project and supported and guided me throughout the entire process with his professional expertise, valuable advice, and insightful questions.

I would also like to extend my special thanks to Fulvio Di Lorenzo, who introduced me to the practical work and taught me the methods used at FHNW to analyse soil samples for microplastics.
Further thanks go to Dr. Ralf Kägi, whose targeted questions and expert knowledge supported this work during both the interim and final presentations.

Table of Content

List of Figures

List of Tables

Glossary

Table 1: Glossary

Word	Explanation
Anodisc filter	Inorganic membrane filter made of aluminium oxide, commonly used for fine particle filtration.
Blank filters	Control filters used to detect contamination during sample processing.
Blank sample	Control sample processed without environmental material to assess background contamination.
Doppler current profiling	Measurement of water current velocities using the Doppler effect.
Environmental contaminant	A substance present in the environment that can cause adverse effects.
Fenton reaction	Advanced oxidation process using hydrogen peroxide and iron ions to degrade organic matter.
Fluorescence	Emission of light by a substance after excitation by radiation.
Large microplastic (LMP)	Microplastic particles larger than 1 mm.
Microplastic	Plastic particles with a size range from 1 µm to 5 mm.
Nanoplastic (NP)	Plastic particles smaller than 1 µm.
PM10 & PM2.5	Particulate matter with aerodynamic diameters ≤ 10 µm and ≤ 2.5 µm.
Pyrogram	A plot showing the thermal degradation behavior of a sample, representing the intensity of pyrolysis products as a function of temperature or time.
Small microplastic (SMP)	Microplastic particles smaller than 1 mm.

Abbreviation List

Table 2: Abbreviation List

Abbreviation	Explanation
CL	Confidence Limit
DI-water	Deionized water
FTIR	Fourier Transform Infrared Spectroscopy
ISO	International Organization for Standardization
LMP	Large microplastics
MP	Microplastics
NOAA	National Oceanic and Atmospheric Administration
NP	Nanoplastics
PM 10	Particulate Matter with aerodynamic diameter ≤ 10 µm
QA/QC	Quality Assurance / Quality Control
Raman	Raman Spectroscopy
SEM	Scanning Electron Microscopy
SMNP	Small micro- and nanoplastics
SMP	Small microplastics
wt%	weight percent

1 Introduction

This chapter explains the topic and objectives of the study. It also provides a clear overview of the structure of the thesis.

1.1 Initial Situation

The increasing presence of microplastics (MP) in various environmental compartments, such as bodies of water, agricultural soils and crops, poses an increasing challenge to science and environmental policy. MP particles are formed either by the breakdown of larger plastic fragments or by being released directly into the environment as primary particles. They enter the entire environment through a variety of pathways, such as wastewater, tyre abrasion, the breakdown of larger plastics into smaller and smaller particles, and atmospheric transport. They can then accumulate in soil and water over long periods of time.

Given their ecological relevance, the development and evaluation of reliable methods for detecting, quantifying and characterizing MP is becoming increasingly important. However, the scientifically sound detection of these particles is hindered by methodological differences, inconsistent standards and varying sample properties. The multitude of available analytical approaches, including spectroscopic, thermoanalytical, imaging, and fluorescence-based methods, leads to heterogeneous data, making it difficult to directly compare results and standardize the assessment of pollution.

To obtain reproducible, practical and meaningful data, it is essential to systematically compare existing measurement methods. Only through the development and application of standardized protocols can a reliable basis be created that enables the consistent assessment of MP pollution in environmental resources, thus supporting regulatory decisions.

Against this background, the present project aims to systematically document current measurement methods for determining MP in water, soil, air and food, and evaluate their suitability for practical environmental analysis. The project's specific objectives are explained in more detail in the following chapter.

1.2 Aims of the Project

The P7 project aims to systematically record and evaluate the suitability of current measurement methods for determining MP in water, soil, air and food for practical environmental analysis. The focus is on analysing well-established methods from the fields of spectroscopy, thermal analysis, imaging and fluorescence. By comparing these methods specifically with the requirements of MP-specific environmental analysis, the project will create a sound basis for decision-making in future investigations.
The project's specific objectives can be summarized as follows:

- **Conducting a comprehensive literature** review on spectroscopic, thermoanalytical, imaging, and fluorescence-based analytical methods.
- **Systematically recording** the currently available measurement methods for determining MP in water, soil, air, and plants.
- **Critical evaluation of the methods** in terms of applicability, significance, detection limits, and practical relevance.
- **Comparison of the identified methods** with the requirements and typical questions of MP-specific environmental analysis.
- **Derivation of a scientifically sound basis for decision-making** for the selection of suitable analysis methods in environmental research.

1.3 Report Structure

This report is structured as follows: First, there is an introduction to the topic and a description of the methodology employed in this study. Next, the definitions of MP found in the literature are presented, alongside the definition that will be used in this and future studies. Having clarified the definition of MP, Chapter 4 then examines various media, including air, liquid, soil and food. It demonstrates how these media are analysed for MP in the literature. Having described the available analysis methods, the next key aspect addressed is the reduction of cross-contamination, to ensure that the results accurately reflect actual MP quantities. Chapter 6 describes how the measuring instruments used in the literature to analyse MP sample’s function and what their relevant parameters are. Building on this, Chapter 7 explains how to create a flowchart to inform the selection of a method. Finally, Chapter 8 discusses the results and Chapter 9 draws a conclusion.

2 Methodology

This project's methodological approach is based on a systematic and comparative analysis of the measurement methods for determining MP in various environmental compartments, as described in the specialist literature. The aim was to gain a comprehensive and structured understanding of the current state of research and derive conclusions for practical environmental analysis.

2.1 Literature Review

The first step was to conduct a literature review to establish the current state of research in MP analysis. This involved evaluating scientific articles, technical reports, and standards. The literature was selected based on the following criteria:

- Relevance to the quantitative or qualitative determination of MP in environmental samples.
- Description of established or newly developed measurement methods.
- Information on performance parameters, such as detection limits, reproducibility and scope of application.
- Relevance to practical environmental analysis.

2.2 Categorization of Measurement Methods

The identified methods were categorized according to their underlying analytical technique. Four main groups were formed:

- Spectroscopic methods (e.g. FTIR, Raman and NIR spectroscopy)
- Thermoanalytical methods (e.g. pyrolysis GC/MS, DSC and TGA)
- Imaging methods (e.g. light and electron microscopy)
- Fluorescence-based methods (e.g. Nile red staining and fluorescence microscopy).

This classification enables a structured comparison of the respective strengths, weaknesses and fields of application.

2.3 Evaluation and Comparison

The methods were evaluated using qualitative and quantitative criteria based on the requirements of MP-specific environmental analysis. The following aspects were particularly important:

- Sample preparation and processing
- Detection and quantification options
- Material and particle size determination
- Time required

3 Classification of Plastic Sizes

This chapter classifies the various size categories of plastic to ensure consistent terminology in this thesis and future master's degree projects. This is necessary because, at the time of writing this thesis between autumn 2025 and January 2026, there are still no defined standards for the size categories of macro-, meso-, micro- and nanoplastics. In the field of MP, different definitions are used in the literature, depending on the source. However, this variation occurs primarily in the definition of MP.

According to Loganathan and Kizhakedathil's definition, plastic fractions larger than 1 m are classified as mega. Particles larger than 25 mm are classified as macro, while those between 5 mm and 25 mm are classified as meso. Particles smaller than 5 mm are classified as micro, while particles smaller than 1 µm are classified as nano(Loganathan & Kizhakedathil, 2022). According to ISO 24187:2023, the International Organization for Standardization standard, the category of MP is further subdivided. Large MP are defined as particles in the size range of 1–5 mm, while small MP are defined as particles in the size range of 1 µm to 1 mm (International Organization for Standardization, 2023). The definition of MP as particles smaller than 5 mm stems from the fact that marine organisms can ingest particles of this size and smaller. This definition was first introduced by the U.S. National Oceanic and Atmospheric Administration (NOAA) in the 1990s and has since been adopted by many others (Thompson et al., 2024).

In addition to sources that propose classifying MP as particles smaller than 5 mm, there are also approaches that set the limit at 1 mm. One example of this is the definition used by LabPlas. This definition focuses more closely on ISO filter size standards, ensuring that the results are compatible with various plastic classifications. At the same time, it excludes industrial plastic pellets, which have a different chemical composition to plastic that has decomposed due to environmental influences. Furthermore, the LabPlas consortium subdivides MP into smaller groups. It is one of the groups of scientists that introduced the term small micro- and nano-plastics (SMNP), which is now widely used to distinguish between the different routes by which plastic particles can be exposed to. Particles larger than 10 µm cannot usually penetrate biological membranes. Modern filtering and analysis methods have lowered the detection limit from around 100 µm (e.g. plankton nets) to around 10 µm. This size range corresponds to the maximum particle size that most zooplankton species can ingest and that mussels can efficiently retain. The 10 µm threshold is also a well-known

reference point in fine dust monitoring (PM_{10}, $PM_{2.5}$), for example. Below this value, electrostatic surface charges become relevant, causing particles to aggregate with organic material, another potential exposure route for aquatic organisms. Taking these factors into account, the LabPlas consortium defines SMP as plastic particles measuring less than 10 µm (LabPlas project, 2024).

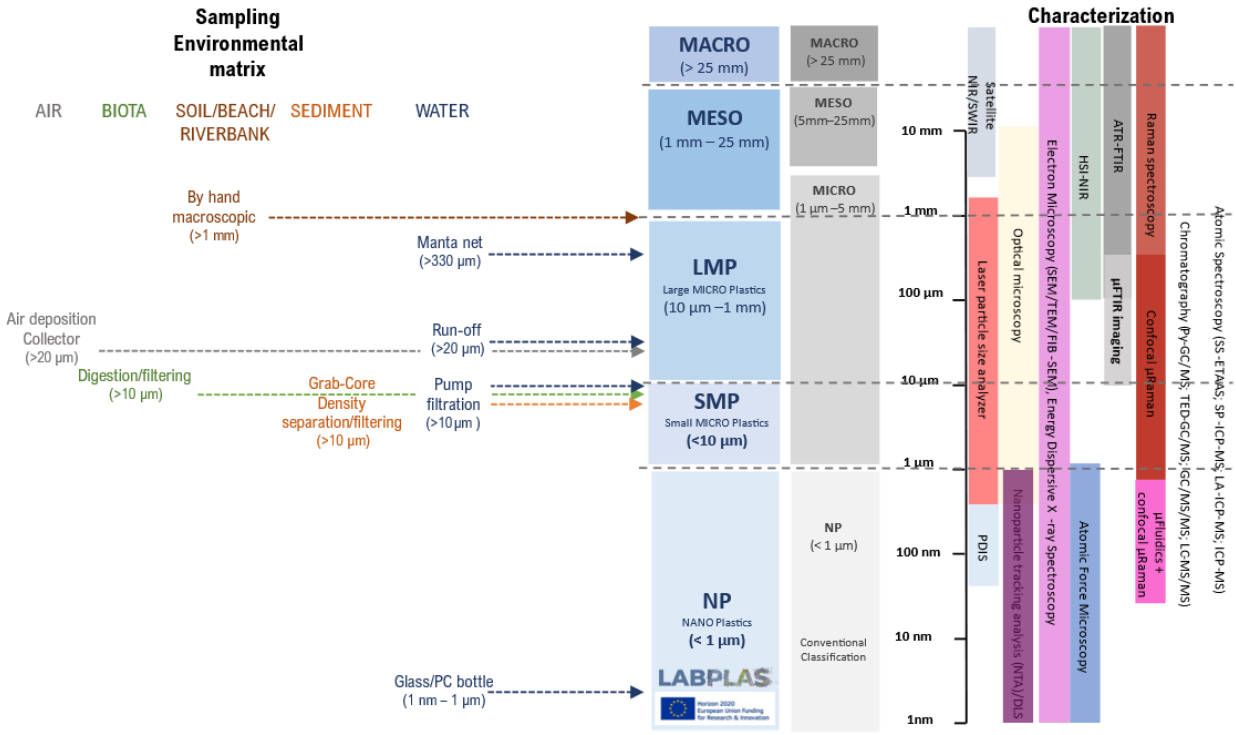


Figure 2: Methods for Classifying Plastic Particle Sizes and Detection Techniques (LabPlas project, 2024)

The above Figure 2 illustrates the two most common plastic classification systems, as explained in the text. It also shows the methods used to characterize different plastic fractions and the sampling techniques employed to detect them in environmental media. Larger plastic fractions, such as macro- and mesoplastics, can be collected relatively easily using nets or manual collection. Smaller particles, such as micro- and especially nanoplastics, require more complex detection methods, including Raman or FTIR spectroscopy, as well as electron or atomic force microscopy. Thus, the graph highlights the close link between size classification, the detection limits of sampling methods, and the analytical techniques required for reliable identification.

However, to ensure consistent use of the term MP in this work, a clear definition must be established. The most common definition in the literature considers particles smaller than 5 mm till 1 µm, which will also be applied here. This ensures consistent terminology and comparability with other studies.

4 Sampling and Detection of Plastic in Various Media

This chapter discusses how the various plastic fractions can be collected and detected in different environments. MP have become a widespread environmental contaminant that enters all environmental matrices via various pathways. It is present in the air, soil, liquids and, ultimately, living organisms and food. In addition to direct environmental input, the entire processing chain and food contact materials play an important role as sources of MP contamination in relation to food.

Modern MP sampling is based on three fundamental strategic approaches, which are applied differently depending on the matrix under investigation and analytical objectives. Selective sampling focuses on the direct collection of visually identifiable particles and is primarily suitable for MP fragments measuring 1–5 mm. This method is best suited to surface sediments and is particularly effective for larger plastic particles (ITRC (Interstate Technology Regulatory Council), 2023; Löder & Gerdts, 2015; Sharma et al., 2024).

In volume-reduced sampling, the total volume of the sample is reduced during the sampling process through in-situ filtration, with only a representative portion retained for further analysis (Crawford & Quinn, 2017; Weber & Kerpen, 2022; Zobkov & Esiukova, 2018).

Bulk sampling captures the entire sample volume without reducing it during the process. Although this comprehensive method ensures that all particle size classes are fully preserved and minimises selective losses, it requires more complex downstream processing steps (Campanale et al., 2020; ITRC (Interstate Technology Regulatory Council), 2023).

4.1 Microplastics in Liquids

This subchapter focuses on MP in liquids and the methods used to detect them.

4.1.1 Sampling for Various Water Bodies

Sampling MP in liquid media is one of the most complex challenges in modern environmental analysis. Highly standardised protocols are required to ensure comparable, reproducible and scientifically reliable results (Almuhtaram et al., 2022; ASTM International, 2020). The considerable heterogeneity of particle size, ranging from macroscopic plastic fragments to MP and nanoparticles, as well as the diversity of aquatic environments, requires specific sampling strategies tailored to each location.

Freshwater systems

Figure 3: Multi-Depth-Net-method for sampling MP (Lenz et al., 2022).

Multi-Depth-Net-method:

Multi-depth net methods (Figure 3) allow for simultaneous sampling at different depths, as well as the collection of data using nets with different mesh diameters at the same depth. The average measurement time per sampling point is 20–45 minutes, depending on flow velocity and turbidity (i.e. the risk of clogging). Sample volume is determined using mechanical flowmeters, with additional acoustic Doppler current profiling (ADCP) providing increased accuracy. While the net sampling method is highly practical for taking representative samples across the cross-sectional area of a body of water, it requires complex logistical preparation and time-consuming net cleaning (Lenz et al., 2022).

Pump-method:

Most studies of MP in aquatic environments use various types of net (e.g. manta nets) for sampling purposes. However, in recent years, pump-driven, fractionated filtration systems (Figure 4) have become increasingly popular.

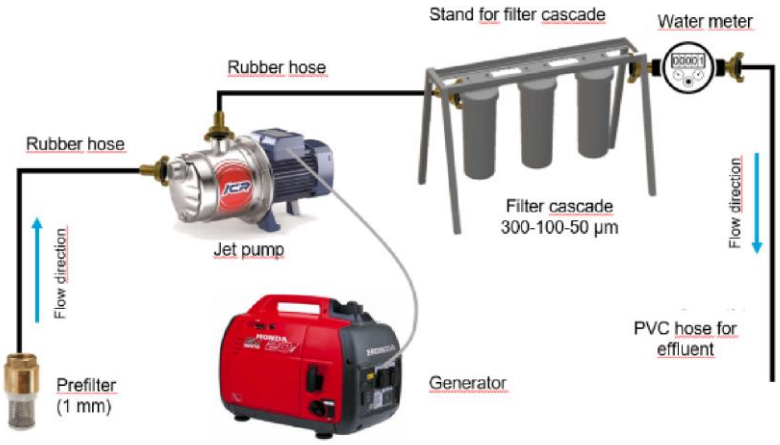


Figure 4: Pump-method for sampling MP (Lenz et al., 2022)

One such system was developed by WESSLING Hungary Ltd. Its compact design makes it suitable for sampling from smaller boats, as well as from the shore. A generator-powered jet pump sucks in surface water through a foot valve with a 1 mm pre-filter and feeds it through rubber hoses to stainless steel filters. Filtration is carried out using 10-inch cartridges with mesh sizes of 300 µm, 100 µm, and 50 µm. This concept was developed in close collaboration with the project

partners. During in situ fractionated filtration, at least 1,000 litres of water were filtered to capture particles in the size range between 50 µm and 1 mm. The sample volume was determined using a flow meter (Lenz et al., 2022).

Sedimentation box:

This passive sampling device, illustrated in Figure 5, is used to collect particulate matter, including MP, suspended in water. It works by reducing the flow velocity inside its chambers so that fine particles, such as MP, can settle out of the water column and be collected. The box is placed in the main current at a depth of around 60 centimetres for approximately two weeks. There are six inlet openings at the front through which river water flows, passing through a total of six chambers before exiting the box through four outlet openings.

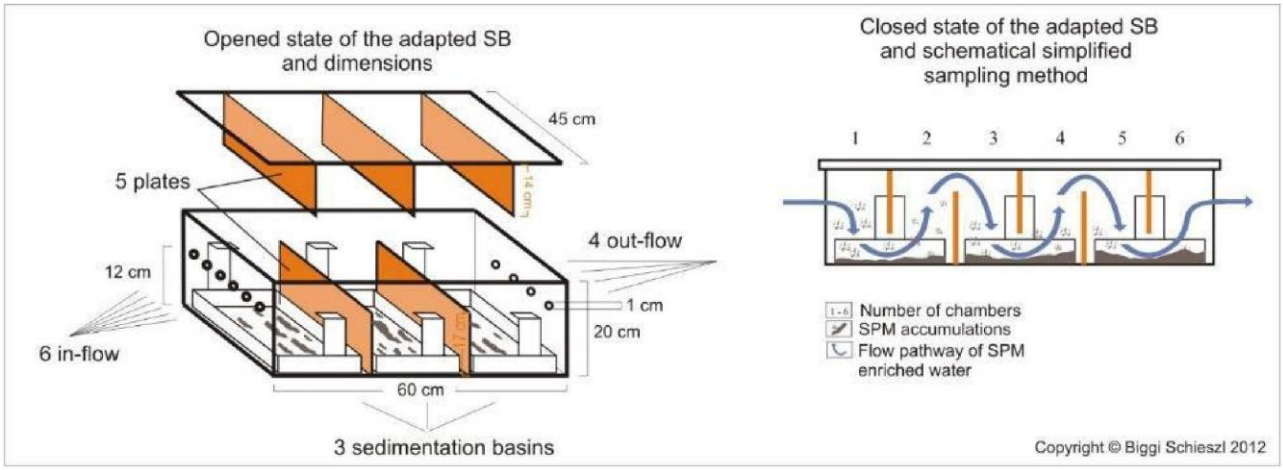


Figure 5: Sedimentation box for sampling MP (Lenz et al., 2022)

Once the exposure period has ended, all openings are closed and the collected sediments and particles are transferred to the laboratory by decanting. The box can be attached to various fixed points, such as pontoons or buoys. To ensure a representative measurement, a moderate flow velocity of between 0.5 and 1.0 meters per second is recommended. At higher flow velocities, some openings can be closed with silicone plugs to minimize turbulence and sample loss (Lenz et al., 2022).

Comparison of freshwater methods

	Net-sampling	Pump-method	Sedimentation box
Practicability/ handling			
Duration of preparation, measurement and cleaning			
Sampling requirements and costs			
Necessary skills			
Official approvals (e.g. bridge sampling necessary)			
Representative sampling over water column			
Representative sampling over the river cross section			
Captured particle size range	(250) 500-5000 µm	50 µm -1000 µm	< 1cm
Sampled water volume per sample (m^3)			 unknown

Figure 6: Comparison of Different Sampling Methods in Running Waters (Lenz et al., 2022)

The three methods of sampling MP differ significantly in terms of the effort involved, how practical they are, and how informative they are. This is illustrated in a simple way in Figure 6. Although net sampling is complex, preparation and cleaning are efficient. The high expertise and permit requirements reduce its practicality but enable representative sampling across the entire water column and river cross-section. This method tends to capture larger particles, ranging from 500 to 5,000 micrometres in size.

The pump method is easier to use and incurs moderate costs. It requires less expertise, is versatile and can capture even smaller particles, between 50 and 1,000 micrometres. It is possible to take representative samples across the water column, and the sample volume can be determined more precisely than with the sedimentation box.
The sedimentation box is characterised by its straightforward handling and low cost, requiring hardly any special skills or permits. However, it is only suitable for qualitative trend analyses as it is difficult to collect samples across the water column and river cross-section, and the sampling volume is unknown. It mainly collects very small particles under 1 cm (Lenz et al., 2022).

Standard ASTM D8332-20:

In addition to the sampling methods mentioned above, there is a standardised sampling method (ASTM D8332-20) for collecting and quantifying MP particles (less than 5 mm) and fibres (less than 15 mm with an aspect ratio of 30:1) in various water matrices. Approved on 15 July 2020 and published in August 2020, the standard was developed by ASTM International, a US organisation based in West Conshohocken, Pennsylvania. ASTM collaborates closely with the US Environmental Protection Agency and other national and international organisations.
ASTM D8332-20 was developed in accordance with the internationally recognised principles of standardisation set out in the World Trade Organization Technical Barriers to Trade Committee's Decision on Principles for the Development of International Standards. The method has been validated for drinking water, surface water, wastewater (inflow and outflow) and seawater, and can be applied to other aqueous matrices, provided its applicability is demonstrated (Advanced Standards Transforming Markets, 2025).
Sampling is carried out in accordance with ASTM D8332-20 by filtering water samples through stainless steel sieves of different mesh sizes. The procedure varies depending on the content of suspended solids in the water matrix and is divided into three categories. The method also depends on whether the system under investigation is under pressure. The structure of the measurement method is shown in the following Figure 7.

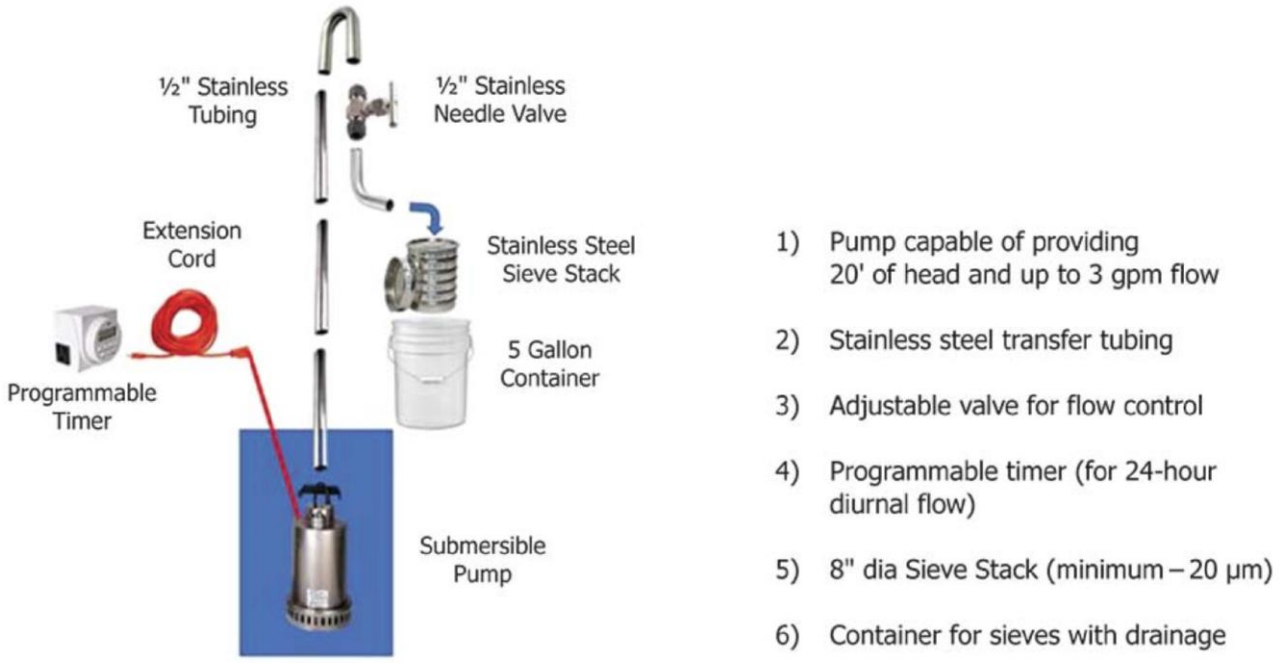


Figure 7: Setup of the Sampling Method According to ASTM D8332-20 (Advanced Standards Transforming Markets, 2020).

For water with a high suspended solids content, such as wastewater inflows, continuous sampling is carried out over a 24-hour period. Eight stainless steel screens with mesh sizes of 20 µm, 50 µm, 150 µm, 300 µm, 500 µm, 1000 µm and 5000 µm are prepared and cleaned first, according to laboratory standards. The screens are then stacked in descending order of pore size, with the screen with the smallest mesh size at the bottom. The stack is then placed in a 5-gallon metal container equipped with either a drain valve and spacers or 20 3/8-inch-diameter holes in the bottom to allow water to flow through. A stainless steel submersible pump conveys the wastewater through stainless steel pipes to the screen stack at a flow rate of approximately one gallon per minute. A flow control valve regulates the flow rate and a flow meter records the processed volume, with a target of 1,440 gallons (approximately 5,450 litres) over 24 hours, allowing for a tolerance of ±5 percent. A digital timer restricts the pump's operation to three-hour segments within the 24-hour period. After each three-hour segment, the screens are visually inspected for clogging. If clogging is imminent, the screen is rinsed with a minimal amount of reagent water and the contents are transferred to a 0.25 litre glass collection vessel (petri dish), which is then stored at 4 ± 2 °C. After 24 hours, the water flow is stopped and the total flow volume is documented. The petri dishes are labelled with the sampling location, screen size and processed water volume. The contents of each sieve fraction are rinsed with a minimal amount of reagent water, sorted by sieve size and transferred to separate petri dishes.

These are then stored at 4 ±2 °C. If desired, all sieve fractions can be combined by rinsing and transferring them to the same petri dish.

For water with medium suspended solid content, such as surface water and secondary-treated wastewater, four stainless steel screens with mesh sizes of 5,000 µm, 500 µm, 150 µm and 20 µm are used. The cleaned screens are stacked in descending order of pore size and placed in a 5-gallon metal container. Water is pumped through the sieve stack, and the processed volume is controlled to 1,500 L within ±5 percent. After filtration, the retained material from each screen is rinsed with reagent water and transferred to separate 0.25 L glass collection dishes, labelled accordingly and stored at 4 ± 2 °C. If required, all sieve fractions may be combined into a single collection dish.

For water with low to very low suspended solid content, such as drinking water and tertiary-treated wastewater, two stainless steel screens with mesh sizes of 300 µm and 20 µm are used. The cleaned screens are stacked with the larger mesh on top and placed in a 5-gallon metal container equipped with a drain. Water is pumped through the sieve stack, and the processed volume is controlled to 1,500 L within ±5 percent. After filtration, the retained material from both screens is rinsed with reagent water, combined in a 0.25 L glass collection dish, labelled accordingly, and stored at 4 ± 2 °C.

In all three sampling methods, it is crucial to measure the water flowing through the screens in order to record the total volume and enable the calculation of the number of particles and fibres per unit volume or mass per unit volume. For water with a high suspended solids content, the flow rate through the sieves must be monitored and regulated appropriately to prevent clogging of the perforations in the sieves. If clogging occurs, the flow volume must be reduced and recorded (Advanced Standards Transforming Markets, 2020).

Drinking water-sampling

Sampling to determine the presence of MP in drinking water is carried out in accordance with the standard procedure set out in Commission Delegated Decision (EU) 2024/1441. At the sampling point, water is pumped directly through a specified filter cascade. This consists of four filters connected in series, which have different pore sizes and functions. The first two filters collect MP, while the other two act as procedural blanks (control filters) to detect possible background contamination (Commission Delegated Decision (EU) 2024/1441 of 11 March 2024 Supplementing Directive (EU) 2020/2184 of the European Parliament and of the Council by Laying down a Methodology to Measure Microplastics in Water Intended for Human Consumption, 2024).

Two main filters are used for collection: the first has a pore size of 100 µm and the second has a pore size of 20 µm. This enables MP and fibres ranging from 20 µm to 5 mm in size (particles) and up to 15 mm in length (fibres) to be collected. This is followed by two further 20 µm filters, which are used exclusively for contamination control.

The filters are made of materials that are as chemically stable and inert as possible, primarily polycarbonate (PC) or polyether sulfone (PES). This choice of material prevents the release of particles and minimises chemical interactions with the MP to be examined in the water. In certain cases, glass fibre or stainless steel can be used as filter material, provided they do not introduce any analytically interfering substances. The holders and connecting elements are preferably made of glass, stainless steel or other proven low-contamination materials. Plastic components are only used when unavoidable, and only if it can be proven that no MP are released.

The filters are inserted into specific pressure filter holders that are mounted directly onto pipes or taps. Water flows through the filters under pipe pressure, one after the other, with each filter being precisely numbered and the installation steps documented in detail. Before sampling, the filter holders and all equipment are thoroughly cleaned. After filtration, the filters are airtightly sealed in glass or metal containers and transported to the laboratory to minimise contamination. The sampling environment, clothing, gloves and materials used are also selected in such a way that additional sources of foreign plastic are excluded as far as possible.

A minimum volume of 1,000 litres of water is filtered directly for each sample in order to capture as many types of MP as possible. If direct filtration is not possible, the water can be stored temporarily under controlled conditions. All liquids used for cleaning or as reagents are purified in advance using a 0.45 µm filter. The work steps are consistently documented to make the sampling process transparent and traceable (Commission Delegated Decision (EU) 2024/1441 of 11 March 2024 Supplementing Directive (EU) 2020/2184 of the European Parliament and of the Council by Laying down a Methodology to Measure Microplastics in Water Intended for Human Consumption, 2024).

4.1.2 Sample preparation in Liquids

Freshwaters-systems:

The preparation and analysis of MP samples vary considerably depending on the sampling method used, requiring specific preliminary steps prior to instrumental analysis.

Multi-Depth-Net-method:

The preparation process begins with the pre-cleaning of the collected samples, which is specific to the method used. Net samples contain heterogeneous mixtures of particles with a high level of organic contamination, necessitating multi-stage preparation. First, any visible MP particles measuring over 20 mm are removed mechanically. This is followed by enzymatic or chemical digestion using Fenton's reagent (H_2O_2/Fe^{2+}), which oxidizes organic contaminants. Subsequent density separation in a $ZnCl_2$ solution (1.7 kg/L) then separates the MP particles from the mineral components due to their differing densities (Lenz et al., 2022).

Pump-method:

Pump samples are characterized by a homogeneous size distribution and reduced bycatch, which simplifies processing. The particles can be applied directly to Anodisc filters (0.2 µm pore size) via vacuum filtration and fed into spectroscopic analysis without the need for time-consuming pre-cleaning. This efficient preparation method reduces both sample losses and contamination risks (Lenz et al., 2022).

Sedimentation box:

Sedimentation box samples mainly contain inorganic impurities and are first homogenized. Fractionation is carried out using stainless steel sieves (1000 µm, 500 µm and 100 µm) for size separation. The fractions are then separated by density separation in a $CaCl_2$ solution, after which they are purified by H_2O_2 oxidation. Finally, they are prepared on aluminium oxide filters (Lenz et al., 2022).

Standard ASTM D8332-20:

Unfortunately, the standard does not specify any concrete steps for preparing samples for laboratory analysis, nor the method for subsequent analysis. When asked about sample preparation, ASTM International, did not respond.

Drinking water-systems:

Since drinking water is already clean, no further steps are necessary after sampling to prepare the sample for analysis. However, if the technical properties of the filters or the presence of interfering substances make direct analysis difficult, the MP particles are removed

from the filters using density separation or chemical-enzymatic cleaning, before being transferred to an alternative carrier (Commission Delegated Decision (EU) 2024/1441 of 11 March 2024 Supplementing Directive (EU) 2020/2184 of the European Parliament and of the Council by Laying down a Methodology to Measure Microplastics in Water Intended for Human Consumption, 2024).

4.1.3 Detection of Microplastics in Liquids

Freshwater-systems:

FTIR microscopy as an analytical method

FTIR microscopy has established itself as the standard analytical method for all three sampling methods. The method combines optical microscopy with infrared spectroscopy for the simultaneous morphological and chemical characterization of MP particles. Modern focal plane array (FPA) detectors capture up to 16,384 spectra simultaneously and enable the automated analysis of large filter areas (up to 13×13 mm) with spatial resolutions of 25 µm. The method-specific analysis strategy takes into account the different particle size spectra: net samples (500–5000 µm) require full-area analysis due to heterogeneous distribution, pump samples (50–1000 µm) allow representative partial area measurements, while sedimentation box samples (<1 cm) are measured in their entirety (Lenz et al., 2022).

Automated evaluation and quality control

Spectral analysis is performed using reference libraries containing over 200 polymer types and machine learning algorithms for the detection of environmentally degraded particles. Systematic quality control through blank samples, recovery tests, and interlaboratory comparisons ensures reproducible results. Detection limits vary depending on the method used, with FTIR analysis capable of detecting particles down to 10 µm, although smaller fractions become increasingly difficult to identify. Two laboratory approaches are available for mesh samples: Lab Method A analyses the entire filter surface fully automatically using FTIR and systematically detects all larger particles. Lab Method B uses manual selection of individual conspicuous particles under a light microscope and examines them specifically using ATR-FTIR. Method A allows comprehensive quantification, while Method B ensures targeted polymer identification but may overlook smaller or less conspicuous particles. This information is illustrated in the Figure 8 below (Lenz et al., 2022).

	Net-sampling + Lab-method A	Net-sampling + Lab-method B	Pump-method + FTIR-microscope	Sedimentation box + FTIR-microscope
Captured particle size range	(250) 500-5000 µm	250) 500-5000 µm	50 µm -1000 µm	< 1cm
Sample composition	Heterogenic sample composition (size, material), mainly organic impurities	Heterogenic sample composition (size, material), mainly organic impurities	Homogenic size distribution, little bycatch	Homogenic size distribution, mainly inorganic impurities
Time for sample preparation	😐 ☹	☹	🙂	🙂
Time for measurement of microplastic particles	😐	☹	😐	😐
Estimated costs of sample preparation and analysis per sample	☹ 😐	☹ 😐	☹ 😐	☹ 😐

Figure 8: Comparison of Sample Preparation Methods for Analysis (Lenz et al., 2022)

Standard ASTM D8332-20:

Unlike the other two sections and their sources, ASTM D8332-20 does not specify how samples should be prepared for analysis to minimise foreign contamination; it refers to subsequent analysis methods instead. After sampling, the samples are stored in petri dishes at 4 ± 2 °C and then prepared for analysis as a separate step.

Three main analysis methods are mentioned. Pyrolysis gas chromatography/mass spectrometry (Py-GC/MS) can be used to determine the mass of MP in a sample. Spectroscopic methods such as infrared (IR) spectroscopy and Raman spectroscopy can be used to count the number of particles and fibres in a sample and identify the polymer type. If desired, suitable instruments such as a scanning electron microscope (SEM) can be used to determine the size, shape, and surface characteristics of MP particles and fibres.

The standard emphasises that all particles smaller than 5 mm in their largest dimension and fibres shorter than 15 mm in length should be retained for preparation and analysis. Spectroscopic methods allow the quantity (mass or number) and composition (polymer type) of MP particles and fibres to be determined. The choice of analysis method depends on the specific project objectives: Py-GC/MS is suitable for mass-based quantification, while spectroscopic methods are suitable for number-based quantification (Advanced Standards Transforming Markets, 2020).

Drinking water-systems:

The filters obtained during sampling are processed further in the laboratory under controlled conditions. Where possible, MP particles are analysed directly on the filter using micro spectroscopy, such as FTIR or Raman. These methods allow the shape, size and chemical composition of the collected particles and fibres to be determined.

Using blanks is central to this process: at least ten control samples are processed for each filter type to determine background levels and possible laboratory contamination. Recovery rates are regularly checked by means of recovery experiments, in which MP particles are deliberately mixed into water samples to test their recovery. Recovery rates must be within predefined limits to ensure the reliability of the analysis.

The collected MP particles are evaluated and classified for analysis according to clearly defined criteria. Their size is determined using optical imaging or chemical mapping methods. Shape is determined by the length-to-width ratio. The type of plastic is identified by comparing the measured spectrum with stored reference libraries containing at least the ten most important synthetic polymers, natural materials, cellulose and mineral materials. If the particle density is high, a representative section can be analysed and the number of findings extrapolated to the entire filter area.

Throughout the entire process, comprehensive documentation of all work, equipment use and hygiene steps is essential to ensure the comparability and quality of the analysis data across Europe. The final report contains information on the concentration of detected MP particles and fibres per cubic meter of water, categorized by size, shape and material. Adherence to the EU regulation's detailed specifications for sampling, filter selection, preparation, and analysis provides a high-quality data basis for assessing drinking water quality in terms of MP contamination (Commission Delegated Decision (EU) 2024/1441 of 11 March

2024 Supplementing Directive (EU) 2020/2184 of the European Parliament and of the Council by Laying down a Methodology to Measure Microplastics in Water Intended for Human Consumption, 2024).

4.2 Plastic in Soil according to the FHNW approach

This subchapter outlines the procedure for determining MP in soil media, based on the approach adopted by FHNW in collaboration with the University of Plovdiv, Bulgaria, for past and future projects. However, this procedure may still change based on the results of this work and future findings.

4.2.1 Sampling of Microplastics in Soil

Slaveya Petrova is employed at the University of Agricultural Sciences in Plovdiv, Bulgaria. Her responsibilities include taking soil samples for analysis. This subchapter is based on our personal communication and the documents and information she provided regarding the procedure for taking soil samples for MP analysis. The university will continue to provide soil samples for subsequent research, which is why documenting the current sampling procedure in detail is crucial to ensuring methodological comparability and traceability of the results.

Soil sampling for MP analysis is carried out in strict accordance with international guidelines and standards, particularly those of the European Soil Data Centre (ESDAC), the Food and Agriculture Organization of the United Nations (FAO), and the Soil Health Institute. These documents provide a structured framework for the representative collection, preparation and storage of soil samples, aiming to minimise systematic errors and foreign contamination.

In accordance with ESDAC recommendations, great importance is attached to precisely documenting the site selection, defining the sampling grid and selecting and cleaning the tools used. Where possible, a uniform grid should be laid out for agricultural land (e.g. a 5 x 5 m grid). If this is not practicable (e.g. due to advanced plant growth), alternative strategies such as transect methods (e.g. a randomised zigzag pattern) can be used. This ensures a high degree of representativeness of the area sampled and comparability with other studies (European Soil Data Centre, 2025).

The FAO guidelines ensure that soil samples are taken at a uniform depth (typically 0–30 cm) and in defined quantities (e.g. 1 kg). They expressly recommend using metal or aluminium-containing equipment for sampling, storage and processing, to prevent MP contamina-

tion throughout the entire sampling process. After collection in suitable containers, the samples must be carefully air-dried in the laboratory. Subsequent sieving through a 2 mm sieve removes larger soil components and ensures homogenisation of the sample material, which is also standard according to the FAO and the ESDAC (ICBA, 2020).

The Soil Health Institute protocol emphasises the need for strict quality assurance. Between sampling and analysis, samples must be transferred directly to clearly labelled aluminium tubes to avoid cross-contamination. Consistent storage and processing procedures, regular equipment cleaning, and digital traceability of all steps are considered standard practice (Soil Health Institute, 2024).

In practice, the exact procedure was adapted to the specific situation in each field. For example, in spring 2025, samples were taken from a field in Katunitsa according to a 5 × 5 m grid pattern (30 randomly selected samples of 1 kg each at a depth of 0–30 cm). After air drying and sieving, mixed samples were formed. During the summer 2025 field campaign, however, plant growth necessitated the use of a random zigzag transect through the field, 1 kg was taken from five freely selected points. Once again, only metal tools and aluminium tubes were used, and the material was air-dried and sieved in accordance with international standards (S. Petrova, personal communication, November 2025).

In summary, the sampling strategy was characterized by the fact that all steps, from sample collection through laboratory analytical preparation to storage, were based on the recommendations of the major international protocols and were implemented consistently with specific adaptations to the local conditions (European Soil Data Centre, 2025; ICBA, 2020; Soil Health Institute, 2024).

4.2.2 Extraction of Microplastics from Soil

Misato Toda developed a protocol for the extraction of MP from soil for ZHAW at the Institute of Natural Resource Sciences (IUNR), in collaboration with FHNW. This protocol has already been applied at FHNW and has been proven to be functional (F. Di Lorenzo, personal communication, 2025). The method is based on a Fenton reaction and a density separation. The protocol of the procedure is listed in the tables below. Through this procedure, the organic components of the soil are broken down, and the MP can be separated from the soil based on density and subsequently analysed.

Table 3: First Fenton Reaction according to Misato Toda

First Fenton Reaction	1.	Measure 5g of soil and place it in an Erlenmeyer flask (500ml). ! With weigh paper, be careful soil doesn't stick to flask well
	2.	Add magnetic fish and thermometer. Stir by means of magnetic stirrer at 300 rpm.
	3.	Add 10ml $FESO_4$*$7H_2O$ (20g/l) with HNO_3. ! Lift thermometer & stop steering ! When adding liquid spill to the inside wall
	4.	Add 20 ml 30% H_2O_2.
	5.	Add 5ml 30% H2O2 every 2 minutes until 10 minutes are reached.
	6.	Temperature control for 60 minutes and when exceeding 40°C cool the reaction in an ice bath. ! When place back Erlenmeyer on stirrer, stop -> place ->start ! Better watch closely ≈ 45 min
	7.	Stopping the reaction by adding deionized water. ! 55ml -> 1:1 ratio
	8.	Dry the sample in the Erlenmeyer flask for 24–48 hours in a drying oven at 40°C. ! Cover with aluminium folie to prevent contamination

Table 4: Density Separation according to Misato Toda

Density Separation	9.	Place ≈ 20ml NaBr solution (95g NaBr / 100g DI-water) into the separation funnel (250ml, special design with 8mm opening) to avoid clogging.
	10.	Dries sample from step 8 is transferred into the separation funnel via a glass funnel. The walls of the funnel are rinsed with NaBr using a glass pipette.
	11.	Add 150ml NaBr-solution. If soli are too dry → dissolve → ultrasonic, otherwise stick after ultrasonic
	12.	Shake closed separation funnel for 1 minute ! Close lid thigh ! Shake side not up & down
	13.	Treat separation funnel for 2 minutes in ultrasonic bath ! Open tips before start ! Make sure no solution snuggled into draining part bevor star ultrasonic bath → vibration → opening lose (shift) → leak
	14.	Settling for ≈ 10–15 minutes
	15.	The heavy fraction is drained (but stores for recycling) ! The quicker the better ! The heavy stuff could stick to the side of draining channel so, don't trust too much how it looks from horizontal direction ! The last moment of draining shouldn't rely on visual. Because it gets narrow and looks darker & some deration accurse and the line becomes unclear. So, rely on the speed/how it drains & just stop!
	16.	Add ≈ 50ml fresh NaBr-solution
	17.	Shake closed Separation funnel for 1 minute ! Shake side to side ! Could be better to do it after cleaning the opening part to close better
	18.	Settling for ≈ 30–45 minutes
	19.	The heavy fraction is drained (but stored for recycling). ! Drain shortly before filtering ! Start filtering without soil part on bottom
	20.	If necessary, repeat steps 9 to 12 if many soil particles are still visible.
	21.	Filter off clay particles through a metal mesh filer (20µm) using a vacuum pump. ! First H_2O to cover entire filter → vacuum on → filter solution ! Make sure H_20 sucks quickly → proper vacuum ! If it is too formy better eliminate it by adding H_2O onto filter before wash the wall to prevent overflow due to form ! Carefully pore/drop only to the middle!
	22.	(weight metal mesh filter (incl. Retentate)) ! Make sure it's dry! ! Sticks to the funnel!
	23.	Backwash retentate on metal mesh filter wit DI-water in Erlenmeyer flask (250ml) ! Place wash a bit deeper into Erlenmeyer so that particle doesn't stick to the wall after washing
	24.	Dry Erlenmeyer flask for 24–48h in a drying oven at 40°C ! Only depth 30 requires

Table 5: Second Fenton Reaction according to Misato Toda

Second Fenton Reaction	25.	Add magnetic fish and thermometer. Stir by means of magnetic stirrer at 300 rpm.
	26.	Adjust 1ml $FESO_4*7H_2O$ (20g/l) with HNO_3 at pH=3.
	27.	Add 20 ml 30% H_2O_2.
	28.	Add 0.5ml 30% H2O2 every 2 minutes until 10 minutes are reached (4.5ml total). ! Use glass pipette together with 5ml mess cylinder
	29.	Temperature control for 60 minutes and when exceeding 40°C cool the reaction in an ice bath
	30.	Stopping the reaction by adding deionized water. ! At least 5.5ml ! 5ml in mess cylinder + liner magnetic stirrer
	31.	Filter off clay particles through a metal mesh filter (20µm) using a vacuum pump.
	32.	Backwash retentate on metal mesh filter wit DI-water in beaker.
	33.	Filter the sample onto an Anodisc™ filter using a vacuum pump and a glass filtration unit (18mm diameter)

Table 6: Production of NaBr according to Misato Toda

Production	1.	Prepare NaBr-solution in a big schott bottle (2l). 95g NaBr/100g DI-Water. Dissolve and stir until everything has dissolved from the walls
	2.	Control the density with a balance. Give 1ml of the NaBr-solution on the balance, if it is below 1.55g/ml add NaBr.

Table 7: Recycling of NaBr according to Misato Toda

Recycling	1.	After each experiment collect NaBr, mix it with activated carbon and stir at 150 rpm.
	2.	Filter NaBr-solution through a 11µm filter ! Pour a lot of amounts into filtration unit when vacuum is high enough, otherwise leak!
	3.	Check density with a balance

Table 8: Creation of $FeSO_4*7H_2O$ according to Misato Toda

$FeSO_4*7H_2O$	1.	Measure 50ml Di-water, weight up 1g $FeSO_4*7H_2O$
	2.	Pipet 25µl HNO_3 (2M) to 50ml DI-water, stir at 300 rpm.
	3.	Add 1g $FeSO_4*7H_2O$, stir at 300 rpm.
	4.	Check pH

In doing so, efforts were made to avoid the use of plastic utensils as much as possible and to preferentially use glass equipment whenever possible. In addition, thorough rinsing with deionized water followed by covering with aluminium foil was used to reduce contamination from MP inputs originating from the laboratory environment.

4.2.3 Detection of Microplastics in Soil

MP detection at FHNW is based on the available laboratory infrastructure and the established analytical capabilities of the participating institutes used for the identification, quantification, and characterization of MP particles. A key analytical technique is pyrolysis gas chromatography coupled with mass spectrometry (Py-GC-MS), which enables the identification of polymer types independently of particle shape and size. The method allows the assignment of polymers based on characteristic pyrolysis fragments and the quantitative determination of polymer mass, enabling precise sample composition. FHNW supports this analysis through an internal reference database containing polymer-specific spectrum for reliable identification based on gas chromatographic signatures.

Complementary to this mass-based approach, a PerkinElmer Spotlight 400 FTIR microscope (MIR and NIR) is used to determine the chemical composition of individual particles at high spatial resolution. FTIR spectroscopy enables polymer identification via characteristic infrared absorption bands while simultaneously providing morphological information, which is particularly relevant for heterogeneous environmental samples.

Furthermore, an AI-based microscopy system has been developed at FHNW for the automated detection, counting, and analysis of fluorescent MP particles. Machine-learning-based image analysis enables automated particle detection, classification, and quantification, allowing the assessment of MP losses or changes during different process steps. In addition, a second UV light microscope lens is available for larger samples, enabling the analysis of environmental samples with diameters of up to 4 cm.

To ensure reliable interpretation of results, laboratory blanks are routinely processed to assess background MP concentrations. These controls allow the identification and correction of potential laboratory contamination and represent an integral component of quality assurance within MP analytics at FHNW (F. Di Lorenzo, personal communication, 2025).

4.3 Microplastics in the Soil according to alternative Sources

MP in soil are increasingly being described in the literature as a relevant burden on the terrestrial ecosystem. Plastics of various sizes and polymer types have been detected in agricultural and forestry soils, as well as in near-natural soils. Wang et al. characterize MP as persistent contaminants that influence the soil's physical, chemical and biological processes, and which can therefore impair its functions and ecological services in the long term.

From an ecotoxicological perspective, it is significant that MP particles provide surfaces for the accumulation of organic pollutants and metals, while simultaneously releasing additives. This means they act as vectors for further contaminants, as well as being an independent source of emissions. Furthermore, experimental studies suggest that these particles can accumulate in pore spaces and in the rhizosphere. This influences water and nutrient availability, root growth and soil organisms. The direction and strength of these effects depend heavily on the type of polymer, particle size and soil type.

From an analytical and methodological perspective, the presence of MP in soil is particularly challenging because soil is a highly complex and heterogeneous matrix that varies widely in terms of its organic matter, mineral composition and aggregate structure. This results in MP being distributed unevenly on a small scale, making sampling and subsequent concentration data interpretation significantly more difficult.

Wang et al. emphasize that a holistic approach is necessary to detect MP in soil, one that considers the entire process, from field sampling and sample preparation to instrumental analysis, and makes matrix-specific adjustments as required. Only by sufficiently standardizing and transparently documenting this process chain can data from different studies be meaningfully compared and integrated into risk assessments or monitoring programs (Wang & Liu, 2019).

4.3.1 Sampling of Microplastics in Soil

Withana et al. emphasise that, as the first phase of soil MP analysis, sampling is crucial in determining whether subsequent concentration data can be interpreted, since MP are distributed very unevenly in soil and classic soil science schemes must therefore be adapted accordingly. Prior to fieldwork, a sampling plan must be developed that considers land use, anticipated contamination, soil horizons, and logistical factors, explicitly detailing which areas, depth intervals, and sample types (single versus mixed) will be sampled.

About spatial arrangement, Withana et al. recommend basing the design on established methods such as random, systematic or stratified sampling, in order to reflect the small-scale variability of MP in the area. Practical examples include grid-based sampling at fixed intervals, transect-based designs along expected gradients and stratified approaches, where different use or exposure zones are sampled as separate strata (Withana et al., 2024).

The harmonized approach explicitly addresses vertical distribution by sampling topsoil and subsoil separately, since MP often accumulate in the top 0–10 or 0–20 cm, but can also be

transferred to deeper layers through cultivation, bioturbation and infiltration. The topsoil should be sampled at shorter depth intervals (e.g. 0–5 cm and 5–20 cm), and depths greater than 20 cm should be sampled using core samplers or drill cores to investigate long-term accumulation or vertical transport (Gündoğdu et al., 2025).

To keep the analytical effort manageable, Withana et al. recommend working with composite samples, where several individual subsamples from a defined area or horizon are combined into one sample. Such composite samples provide a more accurate statistical representation of spatial heterogeneity, while significantly reducing the number of samples to be processed in the laboratory. The required number of subsamples per composite sample should be determined through preliminary studies or power analyses.

Withana et al. refer to standard soil science tools such as stainless-steel shovels, drilling equipment and core samplers when selecting equipment. The use of plastic equipment should be avoided as far as possible to reduce the risk of contamination. Additionally, samples should be stored in glass or metal containers, or specially tested, particle-washed plastic containers that are airtight, and transported in a cool, dry place, protected from light, to limit subsequent changes to the sample matrix (Withana et al., 2024).

A key element of the harmonised scheme is systematic contamination management, which begins in the field and incorporates field blanks, process blanks and, where applicable, air blanks. For example, field blanks are open containers filled with filtered water that are kept in the immediate working environment. They undergo the same handling steps as the actual samples, thus making background contamination from clothing, equipment or air particles quantifiable (Munno et al., 2023).

In addition, this approach requires detailed documentation of all parameters relevant to sampling, including GPS coordinates, sample depth, soil conditions (e.g. moisture and aggregate structure), weather conditions, land use and visible plastic debris on the surface. This information is essential not only for interpreting individual datasets, but also for combining data from different studies in meta-analyses and subsequently evaluating methodological differences in design (Withana et al., 2024).

4.3.2 Sample Preparation for Microplastics in Soil

Möller et al. are developing a protocol explicitly designed for relatively large soil samples of around 250 g dry weight. This enables more statistically robust detection of MP particles ranging from 5mm to 10 µm. After air-drying, the soil sample is carefully crushed and first fractionated wet using a sieve cascade (typically 5 mm, 1 mm and 500 µm) to remove large

stones and root residues without deforming or further crushing the MP. Particles measuring over 500 µm can be collected separately and sorted manually or examined directly using spectroscopy.

The first key step is to separate the mineral matrix by density using a pre-filtered zinc chloride solution adjusted to a density of approximately 1.8 g/cm³, ensuring that even higher-density polymers are transferred to the lighter, floating fraction. The homogenized soil-$ZnCl_2$ suspension is transferred to a separating funnel, stirred intensively and left to settle for several hours or overnight. The lighter fraction is then collected on a metal filter or stainless-steel sieve with a pore size of approximately 10 µm. Recovery experiments demonstrate that zinc chloride solutions of this density achieve high recovery rates for a variety of common polymers, such as polyethylene, polypropylene, polystyrene and PVC. Consequently, they significantly outperform lighter media, such as sodium chloride, in terms of extraction efficiency, particularly for heavier plastics.

The protocol also explains how the zinc chloride solution can be reused after filtration and concentration adjustment, if necessary, to reduce costs and resource consumption despite the chemical's fundamental hazardous nature. After the mineral content has been separated, the second major stage of sample preparation involves breaking down the organic matter, since plant debris and humus can hinder density separation and interfere with the spectral identification of MP. To this end, Möller et al. use a plastic-friendly, step-by-step chemo-enzymatic cleaning protocol that combines proteases, lipases and cellulases in a defined sequence, with intermediate oxidative steps (e.g. Fenton's reagent), to specifically degrade proteins, fats and cellulose. All reagents and ultrapure water are pretreated with 0.2 µm membrane filters to minimize background particles. The parameters of the individual stages, such as temperature, pH value and reaction time, are selected so that common plastics remain structurally intact, even when particles are in the lower double-digit micrometre range. However, it should be noted that bioplastics, particularly those made from polylactic acid, can degrade visibly under certain enzyme and oxidation conditions.

Between each digestion and purification step, the solution is filtered repeatedly using metal or glass fibre filters with a pore size of approximately 10 µm, in order to collect particles fractionally and efficiently remove reagents. The resulting filter cake is detached from the filter using zinc chloride or a buffer solution. It is then transferred to reaction vessels and subjected to the next purification or density separation cycle. Möller et al. emphasize that,

after each transfer, the filters should be checked under a microscope for residues to estimate losses and adjust process parameters if necessary.
In the final step, the particle fraction, which has been largely depleted of minerals and organic matter, is transferred to IR-permeable or Raman-compatible carrier materials. Aluminium oxide filters (Whatman Anodisc), with a pore size of 0.2 µm and a diameter of approximately 25 mm, are used for this purpose. Care is taken to ensure that the coating is as thin and homogeneous as possible to avoid overlaps and shadows during micro spectroscopic mapping. Close quality assurance is provided by the protocol using laboratory blanks, process control samples and spike tests with known particle standards, in order to quantify extraction efficiency and losses, and derive correction factors for later evaluation. This is a prerequisite for comparability between laboratories, and for reliable monitoring data (Möller et al., 2022).

4.3.3 Detection of Microplastics in Soil

Huang et al. classify the detection of MP in soils as a multi-stage analytical workflow. This workflow begins with optical pre-sorting and typically concludes with polymer-specific spectroscopic or thermoanalytical methods. Following enrichment and purification, samples are typically examined initially using stereo or light microscopy to identify potential plastic particles based on morphological characteristics such as shape, surface structure and colour. This allows them to be distinguished from mineral or organic residual particles. However, these criteria alone are not considered a definitive basis for identification.
For the chemically unambiguous classification of polymers, the review considers Fourier transform infrared (FTIR) spectroscopy and Raman spectroscopy to be central pillars of particle analysis, particularly in their microscopic forms. µ-FTIR imaging can detect particles on filters in a grid pattern and automatically assign them to polymer classes based on their infrared spectra. The practical detection limit is generally about 20 µm, while µ-Raman can penetrate the single-digit micrometre range due to its higher spatial resolution. However, it is more sensitive to organic matrix residues and fluorescence interference.
Huang et al. explain that both spectroscopic approaches require extensive reference databases containing the characteristic band patterns of different polymers, in order to enable reliable spectral assignment. Modern evaluation methods use spectral matching algorithms and increasingly machine learning methods that recognise patterns in high-dimensional datasets, enabling the automated classification of large numbers of particles. This is particularly advantageous for monitoring tasks involving many samples.

As a complementary strategy, the review discusses thermoanalytical methods, such as pyrolysis-GC-MS and thermal extraction-desorption-GC-MS. In these methods, plastics are thermally decomposed in a defined atmosphere, and the resulting fragments are separated by chromatography and detected by mass spectrometry. While these techniques provide mass-based information on the total content of individual polymer classes or sum fractions, they cannot directly detect particle number or morphology. This makes them particularly suitable for cases where the overall exposure is the main focus, or where the matrix is too complex for microscopic mapping.

Huang et al. emphasise that the choice of detection method must be closely coordinated with the preceding sample preparation and the target parameter (e.g. number concentration, mass, size distribution or polymer mix), since different combinations of extraction and analysis steps can result in significantly different recovery rates depending on the polymer and soil types. Therefore, it is recommended that method chains are planned in a modular way. Möller et al. suggest combining density separation and enzymatic-oxidative purification with µ-FTIR mapping for particles in the double-digit micrometre range, and supplementary Raman or pyrolysis GC-MS analysis for smaller or spectrally challenging fractions.

Moreover, the review draws attention to contemporary developments in the field, including the integration of automated image analysis with artificial intelligence (AI) for the evaluation of spectra, the proposal of standardization for report formats and detection limits, and the execution of interlaboratory comparison studies. These endeavours are geared towards the advancement of the existing array of methods towards a harmonized protocol. Ultimately, this should facilitate the capacity to directly compare soil MP data from disparate studies and regions. This, in turn, should enable the derivation of reliable trends and thresholds for risk assessments. It should be noted that such a process is hardly possible without the coordination of analysis (Huang et al., 2023).

4.4 Plastics in Seafood

This section explains how MP can be extracted from organic substances, particularly seafood, and analysed. It is based on the study Microplastics in Fresh and Processed Seafood: A Survey of Products Sold in Germany by Julia Süssmann et al., as it reflects the current state of research and has been cited several times. Suitable methods for sampling, sample preparation, and detection are particularly crucial for the reliable determination of MP.

The detailed protocols and individual work steps are described in the publication. This chapter presents the procedure in a simplified form to enable subsequent comparison and to ensure that the approach remains comprehensible to the reader (Süssmann et al., 2025).

4.4.1 Sampling Seafood

Sampling is carried out under contamination control with DIN-TS 10068:2022-09. All laboratory glassware, including beakers, petri dishes, and filter holders, is subjected to a thermal treatment known as annealing, which involves heating to a temperature of 500°C for a duration of five hours. Alternatively, the glassware undergoes a rinsing process involving the addition of 10 millilitres of deionized water, also referred to as DI water, which has a conductivity of less than 1 µS/cm. This rinsing is performed thrice, ensuring the removal of any potential contaminants or residue. Following these procedures, the glassware is covered with aluminium foil to prevent further exposure to heat or moisture. Liquid media, including washing water, brine, and digestion solution, are filtered through glass fibre filters with a pore size of 0.7 µm (Macherey-Nagel GF-5) immediately before contact with the sample. The filters and solutions utilized are also subjected to multiple rinses with purified deionized water (10 millilitres per rinse) following each stage of the process to mitigate contamination. For procedural blanks, at least three preparations per sample series are made with 100 millilitres of filtered DI water or 10 millilitres for subsequent quantitative polymer determination. It is imperative that the samples always remain covered during all phases of the experiment (aluminium foil or cleaned petri dishes).

Frozen products undergo a five-step washing process with 10 mL of DI water each. The resulting washing solutions are collected in separate containers that have been previously cleaned and treated in the same way as the actual sample. The extraction of liquid and solid components from the canned products is conducted using stainless-steel sieves with a mesh size of 1000 µm. Subsequent analysis of the liquid and solid fractions is performed separately.

All solutions and devices utilized, including syringes, must undergo a cleaning process with a 0.7 µm glass fibre filter unit or be rinsed with deionized water prior to use. The process of sample preparation should be carried out under laminar flow or, alternatively, in covered areas.

The meticulous documentation of cleaning and blanks, in conjunction with the precise composition and application of the solutions, is paramount for ensuring the transferability of the MP sampling method to disparate matrices and laboratories (Süssmann et al., 2025).

4.4.2 Sample Preparation of Seafood

Following the recording and homogenization of the food samples, all inedible components are removed. The homogenization process is typically executed through the utilization of stainless steel or glass instruments, such as a stainless-steel hand mixer. At least half of the homogenate is retained as a reference sample. The precise mass of the initial sample is meticulously documented, and subsequent aliquoting is executed in accordance with the characteristics of the respective matrix.

Liquid components, such as brine or condensation water, are meticulously separated and collected. Frozen products undergo a five-step wash process with 10 mL of DI-water at each stage. The wash water is analysed separately (Süssmann et al., 2025).

Enzymatic alkaline digestion

The objective of the multi-stage enzymatic and alkaline digestion process is to achieve matrix reduction. Initially, a pepsin solution composed of 0.1% liquid pepsin in 0.063 mol/L hydrochloric acid is employed. This solution is prepared immediately prior to use. The pepsin solution is added in a volume of approximately 400 millilitres per 50–100 grams of homogenized food. The mixture is then incubated for two hours at 40°C with continuous stirring.

Subsequently, the process of alkaline digestion is initiated through the incorporation of a 50 wt% potassium hydroxide solution (1:1 g/g from KOH pellets and deionized water). For standard samples, approximately 50 millilitres of the solution should be added, and the digestion should be conducted overnight (12–16 hours) at a temperature of 40 °C. For smaller sample quantities (5–10 g), 90 mL of pepsin solution and 10 mL of KOH solution are sufficient (Süssmann et al., 2025).

For liquid matrices, a 10 wt% KOH solution is employed at a 1:1 (v/v) ratio to the sample, which is then subjected to an incubation period of four hours at 40°C under constant agitation. Oligomers or oily liquids are pretreated with isopropanol (1:2 v/v) and subsequently left to stand for approximately 30 minutes to allow precipitates to separate.

Optionally, oxidative treatment with 15% hydrogen peroxide can then be carried out to remove any remaining organic residues (Süssmann et al., 2025).

Filtration and purification

The samples that have been opened are then filtered using pressure or vacuum through a glass fibre filter (pore size 1.2 µm). If the filter becomes clogged, it can be replaced with a 2.7 µm filter. To ensure quantitative transfer, all containers and filters are rinsed several times with deionized water.

To reduce any residual matrix components, the filters are immersed in a 15% H_2O_2 solution, with a volume ranging from 1 to 2 millilitres. Following this step, the filters are allowed to dry overnight at ambient temperature. Subsequent to complete desiccation, the specimens are immersed in 10 millilitres of deionized water and isopropanol (Süssmann et al., 2025).

4.4.3 Detection of Microplastics in Seafood

The screening process for MPs employs specific fluorescent dyes, most commonly Nile Red, enabling the differentiation of polymer particles from natural matrix components. The staining protocol is adapted to polymer polarity: filters are first treated with Nile Red in n-hexane to stain apolar polymers, followed by Nile Red in an ethanol–acetone mixture for polar polymers. Excess dye is removed by rinsing with deionized water and isopropanol, after which the filters are re-stained with Evans Blue to suppress background fluorescence.

Evaluation is conducted using a fluorescence microscope equipped with a 5x objective and a minimum digital resolution of 3–5 µm. Image analysis is based on strictly defined thresholds for brightness, size, and colour, derived from comparative measurements of reference polymers and matrices. Particles exceeding these thresholds are classified as MPs. Method accuracy is verified through recovery experiments using spiked reference particles.

For further characterisation, a subset of positive samples undergoes polymer identification and mass determination via pyrolysis gas chromatography/mass spectrometry (Py-GCMS). After matrix extraction and filter drying, quantitative and qualitative analysis is performed using internal standards and external calibration polymers. Limits of detection and quantification are determined from procedural blanks and recovery tests. Statistical evaluation is applied to distinguish between sample classes, procedural steps, or packaging types.

Rigorous documentation, systematic use of blanks, and recovery assessments ensure data quality. The method is adaptable to various matrices and sample sizes, provided contamination is minimised and matrix reduction and detection procedures are appropriately tailored (Süssmann et al., 2025).

The subsequent Figure 9 illustrates the procedure delineated in this chapter, offering a succinct synopsis of the constituent steps. A flow chart delineates the protocol for the preparation of samples and the detection of MP.

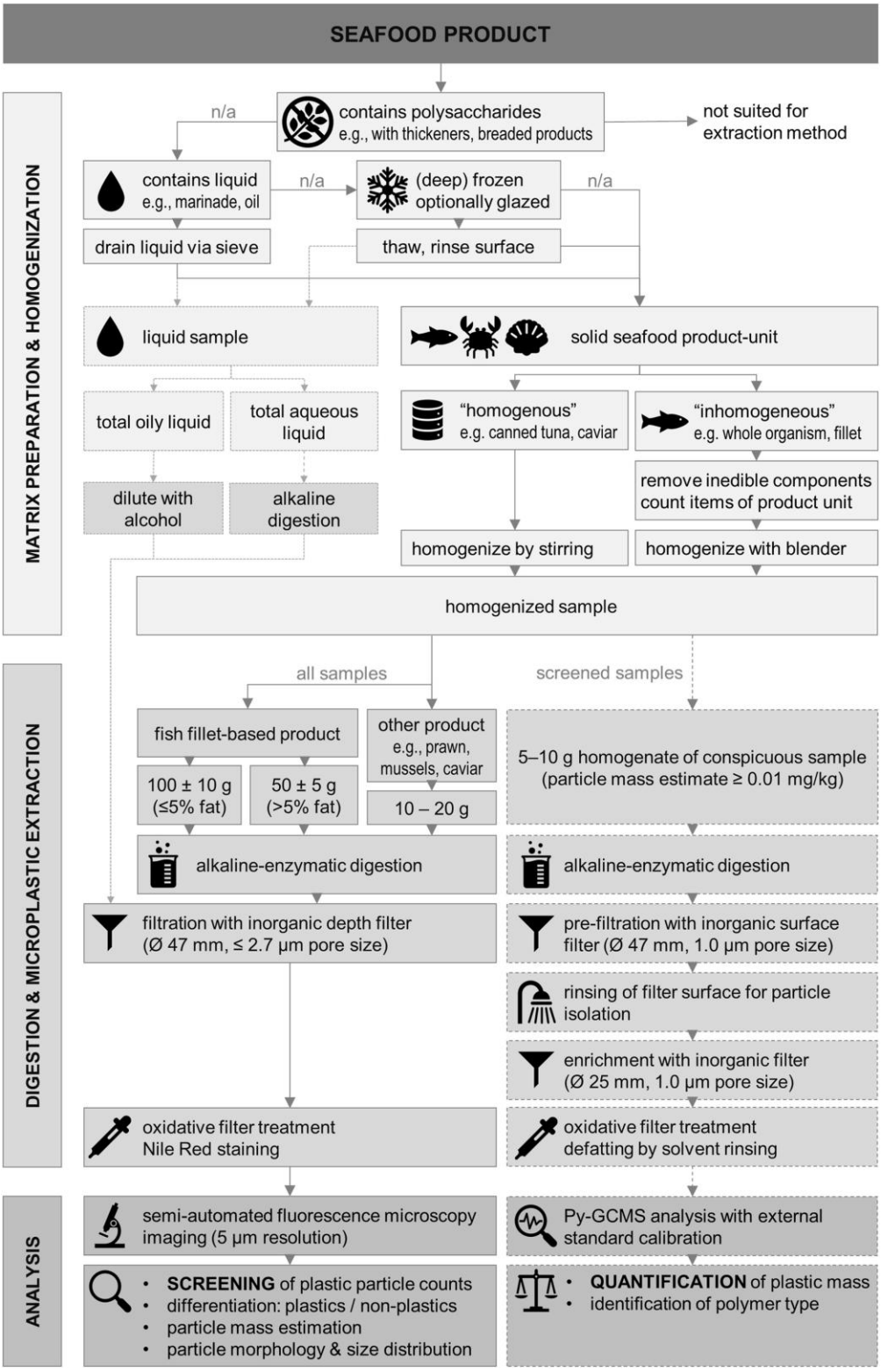


Figure 9: Process Flow Diagram of Seafood (Süssmann et al., 2025)

4.5 Plastics in Plants

In recent years, substantial progress has been made in understanding the origin, distribution, and ecotoxicological effects of MPs in aquatic systems, leading to improved analytical detection methods and initial risk assessment approaches. In contrast, research on MPs in terrestrial ecosystems remains considerably less advanced, particularly regarding soil–plant interactions in agricultural systems.

This knowledge gap is especially relevant given the importance of agricultural land, which accounts for approximately 38% of the global land area and is central to food security and sustainable development. Agricultural soils are increasingly acting as sinks for MPs due to factors such as plastic mulching, sewage sludge application, wastewater irrigation, and atmospheric deposition (Chen et al., 2025).

Therefore the present chapter concentrates on MP in plant-based foods and alludes to the review by Z. Chen et al. published in June 2025, which examined the state of research in the soil-plant system, existing knowledge gaps, and future research approaches (Chen et al., 2025).

4.5.1 Sampling of Microplastics in Plants

Sampling represents the initial stage in the investigation of MPs in plants and has a decisive influence on the validity of subsequent analyses. Chen et al. provide a comprehensive overview of numerous laboratory studies that predominantly employ model exposure scenarios with defined MP types and concentrations. These studies mainly use polystyrene microspheres in well-defined size classes ranging from nano to submicrometric particles, with a focus on crops such as wheat, lettuce, rice, cucumber, mung beans, and oilseed rape.

Samples are generally obtained from controlled laboratories or greenhouse experiments. Chen et al. distinguish between hydroponic systems and soil-based cultures, with hydroponic setups primarily used to elucidate uptake mechanisms, while soil experiments better reflect realistic agronomic conditions. Exposure durations range from short term studies of 48 to 72 hours to longer experiments lasting up to 65 days, covering different developmental stages of the plants. To capture species specific differences in MP distribution, harvested plants are separated into individual organs such as roots, shoots, leaves, and fruits where applicable, as accumulation patterns differ markedly between leafy vegetables, cereals, and legumes (Chen et al., 2025).

4.5.2 Sample Preparation of Food

The objective of sample preparation is to separate MP particles from complex plant matrices and to render them amenable to subsequent detection methods without altering their physical or chemical properties. Chen et al. emphasize that this step is particularly challenging in plants. The organic matrix consists of lignin- and cellulose-rich tissues, and MP are often present in low concentrations and heterogeneous distribution. In the studies evaluated, the plant material is broken down into defined tissue fractions after harvesting, washed, and then subjected to chemical digestion to remove organic matter. This process entails the utilization of oxidative and chemical reactions, encompassing hydrogen peroxide, acids, and alkalis. These reactions are meticulously engineered to disintegrate plant components while maintaining the structural integrity of the polymers employed.

Depending on the experimental setup, sample preparation is supplemented by density separation, especially if plant samples contain soil adhering to them or originate from soil-bound exposure experiments. The utilization of high-density salt solutions is a critical component in the separation of MP and mineral particles. It has been observed by Chen et al. that the recovery efficiency can be significantly influenced by factors such as particle size, polymer density, and the type of soil. The result of sample preparation is filtrates or solid fractions in which the MP particles are enriched compared to the initial sample. These filtrates or solid fractions serve as the starting point for optical, spectroscopic, or thermoanalytical methods (Chen et al., 2025).

4.5.3 Analytical Methods for Detecting Microplastics in Plants

Chen et al. present a comprehensive overview of the various analytical approaches employed for the detection and characterization of MP in plant tissues. A variety of methodologies are employed in the study of particles, including optical microscopy, fluorescence techniques, electron microscopy, and μ-FTIR and micro-Raman spectroscopy. In several of the evaluated studies, the uptake of fluorescence-labelled PS particles in root and shoot tissue is visualized by confocal or fluorescence microscopy. However, as Chen et al. emphasize, the strong autofluorescence of plant tissue presents a significant limitation for the interpretation of these images. Electron microscopy techniques (SEM, TEM) are primarily employed to visualize the spatial localization and morphology of MP at the cellular and tissue levels. However, these techniques are only suitable for extensive screening studies to a limited extent due to the substantial preparation effort required.

For polymer-specific identification, µ-FTIR and µ-Raman spectroscopy are primarily used, which enable assignment to specific polymer classes but are limited by their respective size resolution. In addition, Chen et al. discuss mass-based methods such as thermogravimetric analysis and pyrolysis GC-MS, which are particularly suitable for the quantitative determination of the total polymer mass in environmental matrices, but do not provide any information about particle number, shape, or size. The review concludes that a combination of these methods, i.e., the combination of imaging, spectroscopic, and thermoanalytical techniques, is necessary to reliably investigate the uptake, distribution, and potential effects of MP in plants and to reduce the current methodological uncertainties (Chen et al., 2025).

4.5.4 Methodological Limitations of an Integrated Soil & Plant approach

In Chapter 4.3 of the souce, Chen et al. highlight that soil and plant compartments have largely been studied separately and that no uniform methodological framework for the integrated detection of MPs in soil–plant systems has yet been established. This separation is mainly due to pronounced differences in the physical and chemical properties of the two matrices. Soils are highly heterogeneous, with variable organic matter content and complex mineral phases, whereas plant material consists predominantly of an organic matrix with species-specific tissue structures and heterogeneous MP distribution among organs.

Consequently, most studies apply separate protocols for soil and plant samples, both in sample preparation and analytical procedures. This hinders direct mass balances and the quantitative linkage between soil MP concentrations and plant uptake. Chen et al. note the absence of standardized extraction and digestion protocols and a harmonized analytical strategy covering both compartments, limiting the comparability of results.

Based on these findings, the authors emphasize the need for a systemic, multi-methodological approach that considers soil and plants as an interconnected system. This includes coordinated sample preparation protocols, defined quality control measures, and combined spectroscopic and thermoanalytical methods to enable consistent MP quantification across the soil–plant continuum (Chen et al., 2025).

4.6 Plastic in the Air

This subchapter addresses the detection and analysis of MP from the medium air.

4.6.1 Sampling Microplastic in the Medium Air

Sampling MP in the atmosphere constitutes a methodological imperative in determining the concentration and distribution of MP particles in the air. According to Chen et al. (2020), two primary methods exist for detecting airborne MP particles: passive atmospheric deposition and active sampling using pump systems. The following Figure 10 illustrates these two approaches. These two approaches differ in terms of their operational mechanisms and their specific areas of application and advantages (Chen et al., 2020).

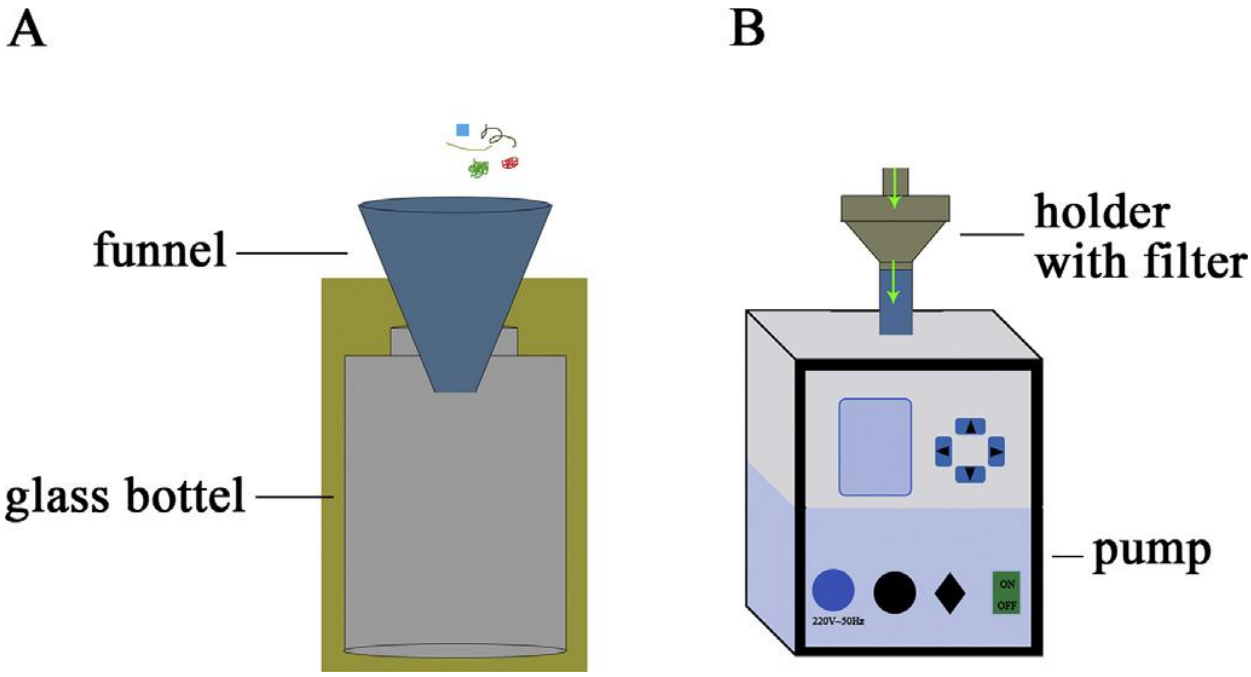


Figure 10: Left side(A): Passive Method | Right side(B): Active Method for Microplastic Sampling

Passive Atmospheric Deposition

Passive sampling is a method of collecting MP particles that settle on surfaces due to gravitational forces and meteorological conditions, such as wind or precipitation. The method under scrutiny has been demonstrated to encompass the comprehensive scope of atmospheric deposition, encompassing both wet and dry deposits. The passive collection system generally comprises a stainless steel or glass funnel positioned in an elevated location, such as on the rooftop of a building. Beneath the funnel, a glass bottle is positioned to collect falling particles and rainwater. The system is supported and protected by a fixed mounting apparatus, such as a box or rack.

This method is particularly well-suited for continuous, long-term data collection over extended periods, such as weeks or months, and is especially advantageous in locations where access to a power supply is limited or in remote areas where traditional methods are difficult to implement. A significant benefit of passive sampling is its simplicity and reliability, as there is no interruption to collection during the sampling phase. After each collection period, the samples are meticulously extracted from the glass bottles and stored in a discrete manner. The funnel and bottle are then meticulously rinsed with distilled water to ensure the removal of any extraneous particles. It is imperative that all samples be covered to prevent contamination and subsequently stored until further processing.

The expression of MP pollution resulting from atmospheric deposition typically occurs in the form of the number of particles per square metre per day. During the monitoring period, meteorological conditions should be systematically recorded to enable subsequent correlation analysis between meteorological events and MP deposition (Chen et al., 2020).

Active sampling using pumps

In contrast to passive approaches, active sampling employs pump systems to collect airborne MPs and was originally developed for monitoring particulate air pollutants such as PM10 and PM2.5 before being adapted for MP research. The system consists of a pump unit and replaceable filter-based collection devices, with adjustable intake flow rates depending on the study design.

Applied flow rates vary widely. Dris et al. (2017) sampled indoor air at 8 L/min for 4–7 hours at breathing height, while Liu et al. (2019) investigated atmospheric MPs at heights of 1.7 m, 33 m, and 80 m in Shanghai using a flow rate of 100 L/min for more than 60 minutes (G. Chen et al., 2020).

A key advantage of active sampling is its efficiency and the ability to process large air volumes within short timeframes. However, reliance on electrical power limits its use in remote locations. The method allows precise quantification of sampled air volumes and enables estimates of daily human inhalation exposure when conducted at breathing height and representative respiration rates. Sampling is performed continuously during the exposure period, with meteorological conditions recorded concurrently. After collection, particles are transferred and stored for subsequent analysis, and MP concentrations are expressed as particles per cubic meter (Chen et al., 2020).

Influences on Sampling

The choice of an appropriate sampling strategy and suitable sampling tools is essential for generating meaningful MP data, as numerous factors strongly influence the results. Atmospheric MP concentrations are closely linked to anthropogenic activities, population density, and industrialization. For example, urban areas of Paris show significantly higher airborne MP levels than suburban regions. Altitude also affects MP concentrations, which generally decrease with increasing height above ground, as demonstrated in Shanghai, where higher MP levels were detected at 1.7 m than at 80 m.

Temporal variability is equally important, as atmospheric MP pollution varies seasonally and between dry and wet periods. Meteorological conditions such as precipitation, and wind influence MP concentrations, transport, and deposition, thereby affecting sample collection.

Consequently, careful consideration of sampling location, altitude, timing, weather conditions, and sampling method is required prior to sampling, regardless of whether passive or active approaches are applied. To obtain a representative annual assessment of atmospheric MP pollution, repeated sampling across different seasons and both dry and wet periods is necessary (Chen et al., 2020).

4.6.2 Sample Preparation for the Medium Air

To prevent contamination and ensure data reliability, rigorous quality control measures are essential. Sampling should be conducted opposite to the wind direction, and at least three replicate samples should be collected. In the laboratory, all processing must take place under a laminar flow hood. Cotton laboratory clothing and nitrile gloves are required, non plastic tools must be used, and all glassware should be rinsed at least three times with distilled water. To assess background contamination, blind samples processed alongside real samples and clean filters exposed within the laminar flow hood are routinely employed.

Following airborne MP sampling, careful sample preparation is critical for accurate analysis. Although standardized protocols are lacking, most studies rely on two key steps: removal of organic matter and separation of MP particles from the matrix. Organic matter removal is necessary to avoid interference with subsequent separation and identification. Commonly used reagents include oxidizing agents, acids, alkalis, and enzymes. In atmospheric MP studies, hydrogen peroxide (H_2O_2) and sodium hypochlorite (NaClO) are most frequently applied. Typically, samples are treated with 30% H_2O_2 at room temperature, while Klein et al. (2019) used 6–14% NaClO for 24 hours to dissolve biological material.

More recently, the Fenton reagent, a mixture of H_2O_2 and Fe^{2+} ions, has been proposed as a more efficient alternative due to its enhanced digestion capacity. In some cases, brief ultrasonic cleaning is applied to remove adsorbed material from MP surfaces. However, oxidants and acids may damage MP particles, making strict control of reagent concentration, temperature, and reaction time essential.

After organic matter removal, MPs are isolated by density separation, the most widely used technique. $ZnCl_2$ solutions with densities of 1.6–1.7 g/cm³ are commonly applied due to their high recovery efficiency across a broad range of polymer types. Alternative media include NaCl, and other high density salt solutions. Gentle agitation during separation prevents particle aggregation. Recycling salt solutions and repeated extraction steps are recommended to enhance efficiency and reduce environmental impact. Recovered particles are dried, stored under controlled conditions, and subsequently analyzed using techniques such as stereomicroscopy, FTIR, Raman spectroscopy, SEM, and Py GCMS (Chen et al., 2020).

4.6.3 Detection of Plastic in the Medium Air

Following the sampling and sample preparation of airborne MP, the particles are subjected to identification and characterization. Identification approaches can generally be divided into morphological analyses, which determine particle abundance, size, shape, and colour, and chemical analyses, which aim to identify the polymer composition. As no standardized protocols for MP identification have yet been established, the combination of multiple analytical methods is recommended in order to minimize statistical uncertainties and to obtain a comprehensive characterization of the particles (Chen et al., 2020).

Visual identification using stereomicroscopy

The simplest and most frequently applied identification method is visual inspection using stereomicroscopy. This approach allows the characterization of MP particles with respect to size, shape, and colour. For image analysis and particle quantification, software tools such as HistoLab or DinoCapture are commonly employed.

To reduce the high risk of misidentification, several criteria should be considered during visual identification: particles should exhibit no visible organic or cellular structures; fibres should display a uniform thickness along their entire length; colour should be consistent and homogeneous; and transparent or white particles should be verified using high-resolution microscopy or complementary analytical techniques. Visual identification is particularly suitable for the rapid counting of large numbers of MP particles.

However, this method has several limitations. Fibers are generally easier to identify than other particle shapes, and coloured particles are more readily detected than white or transparent ones. As stereomicroscopy does not allow reliable discrimination between natural and synthetic particles, it is recommended to combine MP inspection with additional analytical methods for particle identification. Moreover, the results are strongly influenced by observer subjectivity and diligence, microscope quality, and particle shape, colour, and size, which can lead to over- or underestimation of MP abundance. For MP particles smaller than 500 µm, visual identification is not always applicable, as decreasing particle size is associated with increasing particle numbers and reduced identification accuracy (Chen et al., 2020).

Fourier Transform Infrared Spectroscopy

FTIR is the most widely used technique for the identification of the polymer composition of MP. FTIR spectroscopy provides a unique spectral fingerprint for each sample. By comparing the spectra of target particles with reference materials stored in spectral libraries, the polymer type can be directly identified. Compared to visual analysis, FTIR enables the analysis of smaller particles and yields more reliable identification results.

µ-FTIR spectroscopy is considered an ideal technique for the identification of airborne MP particles, as it allows the detection of particles down to approximately 20 µm. Using this method, the chemical composition of MP has been identified in atmospheric deposition and ambient air samples from locations such as Dongguan, Shanghai and Paris, where polymers including PE, PP and PS were detected.

In addition, attenuated total reflectance FTIR spectroscopy (ATR-FTIR) and focal plane array FTIR spectroscopy (FPA-FTIR) have also been applied in MP studies. ATR-FTIR is more suitable for the identification of irregular MP particles larger than 500 µm, whereas FPA-FTIR enables the screening-based identification of all MP particles deposited on filter media. However, these two techniques have not yet been widely applied to the identification of atmospheric MP, as airborne MP typically occur in smaller particle size ranges. All FTIR-based techniques require expensive instrumentation, and MP identification using FTIR is time-consuming and demands well-trained operators, which has limited the characterisation of large sample sets. Despite these limitations, FTIR remains a robust and reliable technique and is currently the most commonly applied method for the environmental characterisation of MP (Chen et al., 2020).

Scanning Electron Microscopy

Scanning electron microscopy (SEM) is another widely used technique for the identification of MP. A high-intensity electron beam is generated and scanned across the surface of the sample. High-resolution images, with a resolution of up to 0.5 nm, are produced through interactions between the electron beam and the sample surface. MP particles can be distinguished from other particulate matter by comparing characteristic surface features.

SEM enables the identification of mechanical degradation features on MP by examining surface textures such as grooves, pits, fractures and exfoliation. For example, grooves and pits observed on the surface of airborne MP may indicate collisions and abrasion caused by atmospheric dynamics, whereas fractures may result from wind-induced mechanical stress. The combination of SEM with energy-dispersive X-ray spectroscopy (SEM–EDS) additionally provides information on the elemental composition of particles. For instance, the elemental composition of MP present in suspended dust has been determined using SEM–EDS. Although SEM has been successfully applied for MP identification, it is a time-consuming technique in terms of sample preparation and image acquisition and is therefore not suitable for the analysis of large quantities of MP particles (Chen et al., 2020).

Pyrolysis–Gas Chromatography–Mass Spectrometry

Pyrolysis–gas chromatography–mass spectrometry (Pyr-GC-MS) has so far rarely been applied in research on atmospheric MP, but it is widely used in studies investigating MP in other environmental compartments. The chemical composition of MP can be determined using this method by analysing the thermal degradation products generated during pyrolysis. Identification is achieved by comparing the resulting pyrograms with reference and library databases.

Because the analysis is based on characteristic thermal decomposition products of polymers, the shape, size, and colour of MP particles do not influence the results obtained by Pyr-GC-MS. In contrast to Raman spectroscopy, the method is not affected by additives present in the plastic material. Instead, Pyr-GC-MS enables the simultaneous identification of polymer types as well as associated additives and degradation products, which is particularly advantageous for the analysis of MP from different environmental matrices. Another key advantage of the method is that only very small amounts of MP material are required for chemical characterisation.

However, Pyr-GC-MS also has notable limitations. MP particles must have a minimum size of approximately 100 µm, as they need to be manually transferred into the pyrolysis tube.

Furthermore, only a single MP particle can be analysed per measurement run. A complete analytical cycle typically takes more than 30 minutes, which severely limits the throughput and hampers the analysis of large sample numbers. In addition, Pyr-GC-MS is a fully destructive technique, meaning that analysed samples cannot be used for subsequent investigations.

Due to these limitations, Pyr-GC-MS is not suitable as a stand-alone method for comprehensive MP characterisation. Instead, it should be applied as a complementary technique alongside other identification and analytical methods. When combined with imaging or spectroscopic approaches, Pyr-GC-MS can provide valuable insights into the chemical composition of MP and thereby enhance the overall robustness and interpretability of the results. (Chen et al., 2020).

Recommendations for comprehensive detection

To minimize statistical errors and achieve an integrated assessment, it is recommended that multiple identification methods be combined in studies monitoring atmospheric MP. Initially, prepared samples should be sorted and counted based on shape, size, and colour using visual identification techniques such as stereomicroscopy. High-resolution microscopy and fluorescence microscopy can be employed for the detection of smaller MP particles, while SEM is suitable for studies that require detailed examination of particle size and surface texture.

Following morphological identification, FTIR spectroscopy and Raman spectroscopy are typically used to characterise MP and identify their polymer types. Pyr-GC-MS further enables the determination of the chemical composition of MP, including any additives present (Chen et al., 2020).

4.7 Conclusions and Observations

As demonstrated in this chapter, the implementation of sampling and detection strategies for MP necessitates meticulous planning tailored to the specific characteristics of each matrix. Furthermore, the implementation of these strategies must be accompanied by rigorous quality control measures and a coordinated effort with clearly defined target parameters, including but not limited to the particle count, mass, polymer mix, and size distribution. Standardised or clearly structured protocols are imperative for the effective management of liquid systems. These include the EU Delegated Decision 2024/1441 for drinking water and the ASTM D8332-20 for various water matrices. These protocols delineate the utilisation of

defined filter cascades, procedural blanks and documented volume determination. In the context of freshwater systems, network-based, pump-operated and sedimentation-based approaches have been demonstrated to be effective in addressing diverse size ranges, logistical requirements and degrees of representativeness.

The present chapter is intended to provide a comprehensive overview of the extant literature and established practices in this field, as opposed to a complete representation of the available methods landscape. A plethora of alternative sources, variants and specialised methods have been developed, including alternative density separation media, nano-specific detection pathways and AI-supported evaluation approaches. The efficacy of these resources is contingent upon the specific question, matrix, and available resources. The selected sources have been frequently cited and applied, indicating a high level of acceptance within the professional community. Alternatively, they represent standards and guidelines (e.g. EU 2024/1441, ASTM D8332-20, soil science guidelines from ESDAC, FAO and the Soil Health Institute) that should serve as the primary reference for future work.

The work on soil was based on the quality-assured procedure that has been established at FHNW. The protocol for sampling, extraction and detection described herein aligns with the methods that are already in use. This ensures that new datasets remain directly comparable with existing results.

The extraction process is based on a combination of the Fenton reaction and density separation, which controls the organic and mineral matrix and reduces polymers gently. The detection process combines mass-based Py-GC/MS with particle-based FTIR microscopy and is validated by blanks and recovery tests.

The procedure for soil sampling is based on the experience and knowledge of Slaveya Petrova at the University of Agricultural Sciences in Plovdiv, who is responsible for sampling agricultural soils and will continue to assume this role in future projects. The field protocols employed by the researcher are closely aligned with international guidelines established by the European Soil Data Centre, the Food and Agriculture Organization of the United Nations, and the Soil Health Institute. However, these protocols have been adapted to specific locations and farming practices, with the aim of generating practical and methodologically comparable data. This approach is intended to ensure methodological consistency across projects without compromising the flexibility required for diverse site conditions.

5 Literature Review on the Reduction of Contamination in Microplastic Samples

In the previous chapter, the sampling of different environmental media for MP analysis, their preparation, and subsequent evaluation were described. One aspect that was only briefly addressed there is the potential for cross-contamination during sampling and sample preparation, which is, however, crucial for the reliability of the results. The following chapter focuses specifically on this issue, with reference to the study *"Measures to Prevent Cross-Contamination in the Analysis of Microplastics: A Short Literature Review."* (Cruz-Salas et al., 2023).

In this review, 1,477 publications were initially identified, of which 115 studies were selected for detailed analysis after applying defined inclusion and exclusion criteria. The studies cover various marine compartments (including beaches, the water column, sediments, mangroves, and marine fauna) and were uniformly analysed regarding the reported measures to prevent cross-contamination. Figure 11 schematically illustrates the selection steps from the initial number of hits to the final corpus of 115 studies.

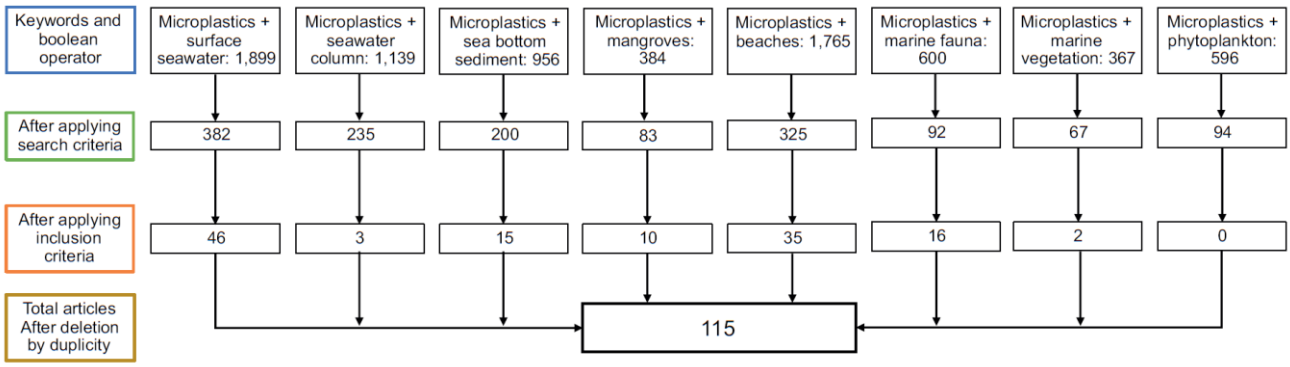


Figure 11: Overview of the Selected Studies (Cruz-Salas et al., 2023)

Of these 115 studies, 61 explicitly report at least one measure to reduce cross-contamination during sampling, while 54 studies do not report any measures. The three most frequently described preventive steps in the field are the use of non-plastic sample containers (25 studies), non-plastic sampling tools (24 studies), and non-plastic samplers (21 studies). Nearly one third of the evaluated studies implement more than one measure during sampling, which is illustrated in Figure 12, differentiated by the number of measures applied.

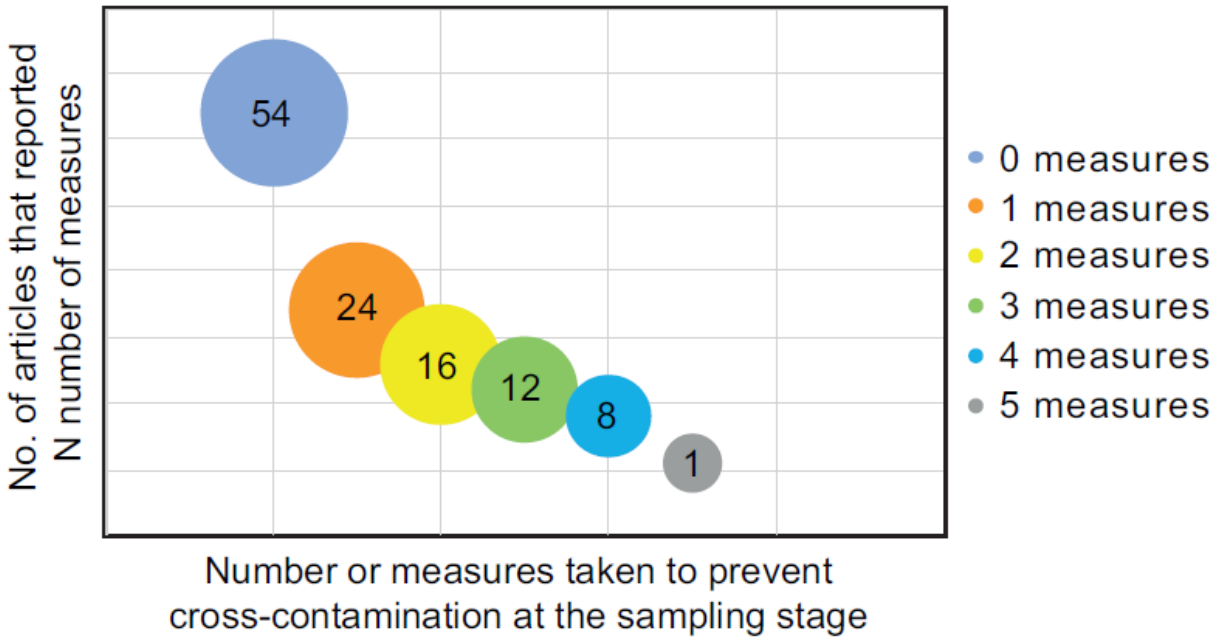


Figure 12: Overview of the Number of Measures Implemented to Reduce Cross-Contamination During Field Sampling (Cruz-Salas et al., 2023)

The following Figure 13 summarizes which specific measures were implemented in the field and by how many studies to prevent or reduce contamination. In addition to the choice of materials, these measures include rinsing equipment with filtered water, using procedural blanks, and covering samples and equipment. Overall, despite the ubiquitous presence of MP, it is evident that nearly half of the studies in the field documented either very few or no measures for contamination control.

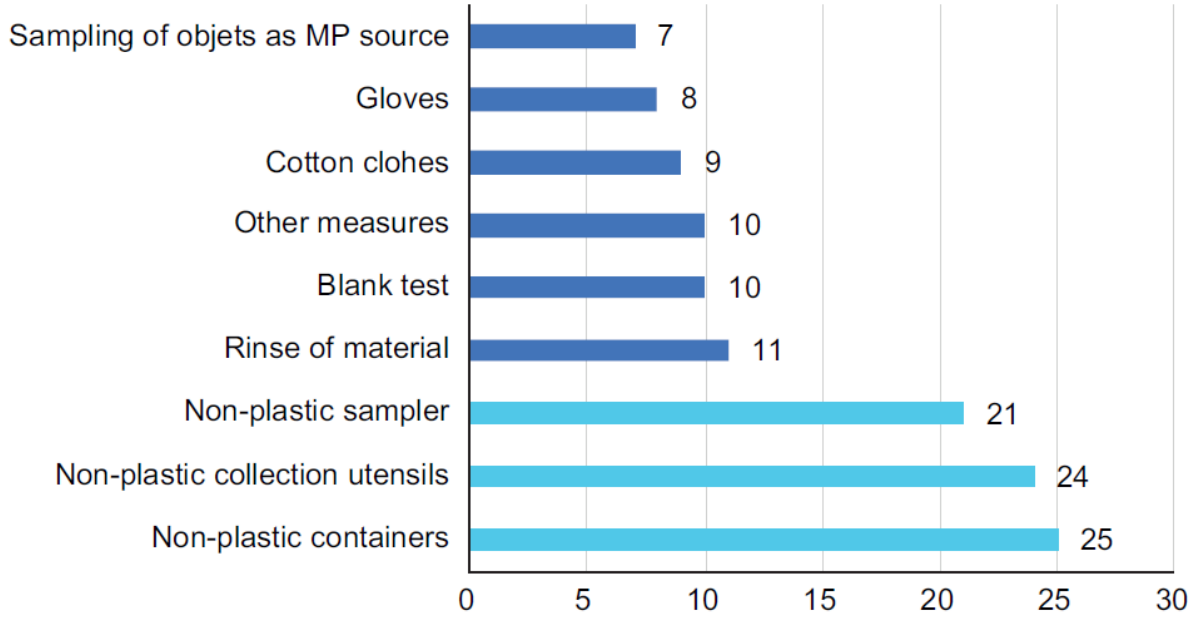


Figure 13: Frequency of Measures applied to Minimize Cross-Contamination during Microplastic Sampling in the Field (Cruz-Salas et al., 2023)

In the laboratory, by contrast, cross-contamination receives significantly more attention. All 115 evaluated studies describe at least one measure to prevent cross-contamination during sample processing, with the majority implementing more than five different measures. Figure 14 shows the distribution of studies based on the number of measures implemented in the laboratory.

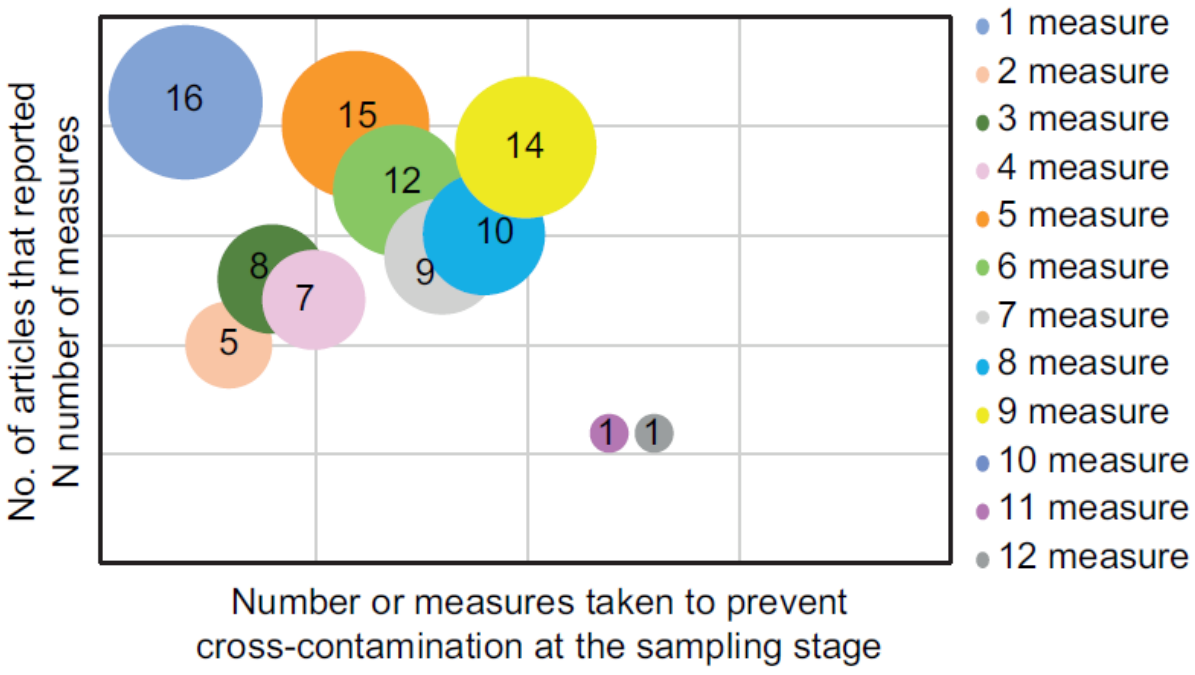


Figure 14: Number of Measures taken in the Laboratory when Sample Processing (Cruz-Salas et al., 2023)

In total, 98 different approaches to reducing contamination were described across the 115 studies. Laboratory blanks were used most frequently (72 studies), followed by rinsing of equipment and glassware (56 studies) and the use of cotton lab coats (56 studies). The most used measures and their prevalence are summarized in Figure 15.

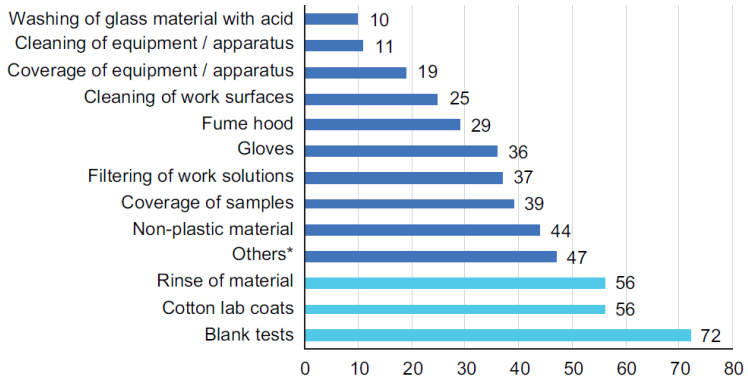


Figure 15: Frequency of Measures applied to Minimize Cross-Contamination during Microplastic Sample Processing (Cruz-Salas et al., 2023)

Although many studies implement extensive contamination prevention measures, only a few explicitly report on the effectiveness of these measures, such as comparisons between blanks and samples or between different laboratory environments. From the studies that provide such information, it can be inferred that the implemented measures can prevent approximately 4.8 to 69% of contamination in the field and 0.1 to 48.8%in the laboratory, depending on the setting. The authors conclude that standardized protocols, including defined minimum requirements for contamination control and acceptable levels of contamination, are essential to ensure the comparability and reliability of MP data.

Based on their systematic evaluation, Cruz-Salas et al. identified five main sources of cross-contamination during MP analysis: deposition from the air (both in the field and in the laboratory), abrasion from plastic sample containers, samplers, and tools, microscopic fibres from synthetic clothing and textiles (e.g., cleaning cloths or curtains), contamination from reagents, solvents, and water, and cross-contamination between individual samples.

For each of these contamination sources, the review recommends specific preventive measures, which are summarized in Figure 16 below.

Air	Wear of plastic materials	Synthetic clothes and textiles	Reagents, solutions, and water	Cross-contamination between samples
Evaluate blank samples during sampling and at each stage of laboratory sample processing. Subtract, from the total number of MP, the particles found in the blank samples. Rinse the samplers, containers, utensils, and general material before using and dry them in an oven. Cover samplers, containers, utensils, apparatus, and work surfaces with aluminum or cotton cloth until use. Process samples in a closed room, with fans turned off. Process the samples in a fume hood.	Thoroughly inspect samplers, containers, and plastic utensils before using in the field and laboratory. Take samples of burrs present in plastic materials. Discard from the final MP quantification particles similar to the burrs of plastic materials. Use glass or stainless-steel samplers, containers, and utensils.	Wear cotton clothes during laboratory sample sampling and processing. Wear a cotton gown during sampling, only when wearing synthetic textile clothing, and at all stages of sample processing in the laboratory. In case of wearing synthetic clothing and using other synthetic textiles, carry out a record of these. Use cotton flannels to clean samplers, containers, utensils, apparatus, and work surfaces.	Filter water (distilled, deionized, marine, Milli-Q, or potable) before using. Filter solutions for sample digestion or density separation before using.	Rinse the samplers, containers, and material in general between each sample taken in the field. Rinse laboratory supplies and utensils before processing each sample in the laboratory.

Figure 16: Measures Recommended by Source of Microplastics Contamination (Cruz-Salas et al., 2023)

Building on the main sources of cross-contamination identified by Cruz-Salas et al., more detailed conclusions can be drawn from recent quantitative studies regarding which measures are particularly effective in practice and which, despite their widespread use, contribute only limitedly to contamination reduction. In particular, the studies by Jones et al., Aminah and Ikejima, Bhat et al., Wesch et al., and Munno et al. quantify both the extent of procedural contamination and the effect of individual measures, thereby allowing a prioritization of the recommendations summarized in Table X above (Aminah & Ikejima, 2023; Bhat et al., 2024; Jones et al., 2024; Munno et al., 2023; Wesch et al., 2017).

The Figure 17 below provide a simplified illustration of the extent to which different methods contribute to the introduction of MP into the sample.

Figure 17: Simplified Illustration of the extent to which different Methods contribute to the Introduction of Microplastics into the Sample (Jones et al., 2024).

	200 nm – 700 µm	5 µm +
Water		
Milli-Q	Low	Low
Reverse osmosis	Moderate	Low
Tap water	High	Moderate
Consumables		
Plastic labware	Low	Low
Glass labware	High	Low
Laboratory dust	High	Moderate
Airflow		
Bench (open air)	Moderate	Low
Biological safety cabinet	Low	High
Fume hood	High	Low
Experiment duration	Low	Low

Figure 18: Summary of the Risk of Introducing Detectable Contamination of Plastic Particles when Performing an Experiment to Quantify Nano or Microplastic Contamination (Jones et al., 2024).

A key finding concerns the contamination source of laboratory water. Jones et al. shows in Figure 18 that all common laboratory water sources contain measurable amounts of MP, with Milli-Q water being the least contaminated at an average of 21.7 particles/ml (95% CI 4.7–64.4), followed by reverse osmosis water with 29.9 particles/ml (95% CI 9.6–77.3) and tap water with 151.7 particles/ml (95% CI 62.2–387.0). These results support the use of high-purity, filtered water, as already recommended in many protocols, but also high-

light that Milli-Q water cannot be considered “particle-free.” Furthermore, the design of procedural blanks must explicitly take into account which type of water is used at each stage of the procedure (Jones et al., 2024).

Similarly pronounced are the differences between various consumables. While the literature review by Cruz-Salas et al. describes the replacement of plastic equipment with glassware as a standard measure to prevent contamination, the experimental study by Jones et al. reaches the opposite conclusion: In experiments where Milli-Q water was pipetted back and forth between two vessels for twenty minutes, the particle count in glass vessels averaged 1,356.9 particles/ml (95% CI 975.3–1,861.1), whereas plastic vessels contained only 6.9 particles/ml (95% CI 0.7–19.2), a difference of nearly two orders of magnitude. The explanation given is that single-use plastic consumables are produced under ISO 13485 and ISO 9001 standards, individually packaged, and delivered sterile, whereas glassware is often stored loosely in boxes and is therefore already significantly contaminated with dust and fibres before use. For practical purposes, this means that the blanket recommendation “glass instead of plastic” should be critically reconsidered and weighed according to the research question (particle counting vs. trace chemistry) (Jones et al., 2024).

A particularly critical point concerns the use of aluminium foil, which is recommended in many protocols. In the study by Jones et al., a dedicated foil control experiment was conducted in which fresh aluminium foil was rinsed with Milli-Q water and the rinse water was immediately analysed. Even after this very short exposure, an estimated 168.9 particles/ml (95% CI 93.3–274.7) were detected, identifying aluminium foil itself as a significant source of contamination. The authors explicitly note that while foil is often recommended as a cover for glassware, its use in direct contact with samples or reagents (e.g., as a dust-collection tray or as an interior contact surface during rinsing) leads to a substantial additional particle input. From the perspective of conservative contamination control, it is therefore advisable to avoid using fresh aluminium foil as a direct contact surface and, where a cover is required, to use glass lids or petri dishes instead, or, if foil is used at all, only as a loose, non-wetted covering (Jones et al., 2024)

Another contamination pathway mentioned in the review is the deposition of particles from the air. While Cruz-Salas et al. primarily refer to qualitative information on air control and sample covering, Bhat et al. and Jones et al. quantify both background contamination and the effect of different working environments. In a laboratory setting without specialized air filtration, an average of 55.4 ± 26.9 MP particles per day were deposited onto open petri

dishes over seven days, with fibres in the size range of 10–1,000 µm being dominant. Jones et al., in turn, show that in a twenty-minute pipetting experiment, there were no significant differences in particle numbers in the water between an open bench, a fume hood, and a biosafety cabinet; however, all three environments were considerably higher than the control sample taken directly from the Milli-Q system. From this, the authors conclude that during short-term procedures, the main contribution to contamination comes not from the air but from pipette tips and centrifuge tubes themselves, whereas air deposition is mainly relevant during prolonged, uncovered work steps and passive dust accumulation (Bhat et al., 2024; Jones et al., 2024).

The role of specialized “clean-air devices,” mentioned in the review as one of several measures, is more precisely quantified by the study of Wesch et al. In an experimental design where moistened filters were exposed in different environments, a clean workspace with laminar flow and particle filtration reduced airborne microfiber contamination by 96.5% compared to a standard laboratory room, whereas a standard fume hood only halved the contamination relative to an open bench. This is illustrated in the Figure 19 below.

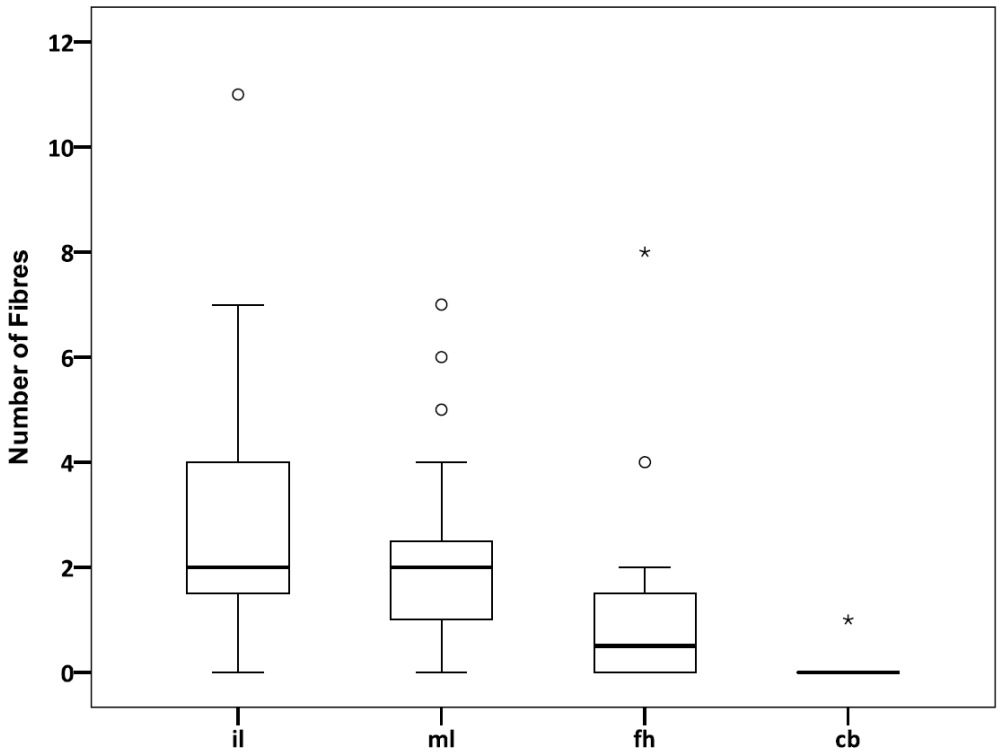


Figure 19: Number of aerial Microfibres monitored in the Samples in four different Setups (il = indoor laboratory, ml = mobile laboratory, fh = laboratory fume hood, cb = clean bench with particle filtration) (Wesch et al., 2017)

These results support the conclusion that laminar-flow workbenches equipped with HEPA filters are among the most effective technical measures for reducing airborne deposition and, where available, should be preferred over standard fume hoods. Wesch et al. confirm this for atmospheric MP samples, showing that laminar flow reduces background contamination in blank samples more effectively than a fume hood or standard laboratory rooms (Wesch et al., 2017).

In addition to air and equipment, the review by Cruz-Salas et al. also highlights reagents and solvents as relevant sources of contamination. The detailed study by Aminah and Ikejima demonstrates that water as well as H_2O_2, $FeSO_4$, and $ZnCl_2$ contain significant numbers of particles prior to filtration, some of which were unambiguously identified as polymers such as polyethylene terephthalate, polyethylene, polystyrene, or polyacrylonitrile using µ-FTIR. Filtration of these solutions through pre-combusted glass fibre filters (400 °C, 2 h) reduced the particle counts by 70–100%, so that no MP particles were detectable in filtered deionized water and filtered $FeSO_4$ and $ZnCl_2$ solutions. This quantitatively supports the recommendation by Cruz-Salas et al. to filter reagents and water, establishing it as one of the most effective and simultaneously cost-efficient measures for contamination reduction (Aminah & Ikejima, 2023).

The importance of procedural blanks highlighted by Cruz-Salas et al. is further elaborated in the interlaboratory study by Munno et al. In that study, standard blanks were analysed in parallel with identically prepared “spiked samples” across 12 laboratories, and the MP particles found in the blanks were recorded in detail with respect to size, colour, and morphology. The number of potential MP particles in the blanks ranged from 7 to 511 particles per sample, with a median of 45 particles, with black fibres in the size range of 20–212 µm being dominant. The detailed breakdown of the data is shown in the Figure 20 below.

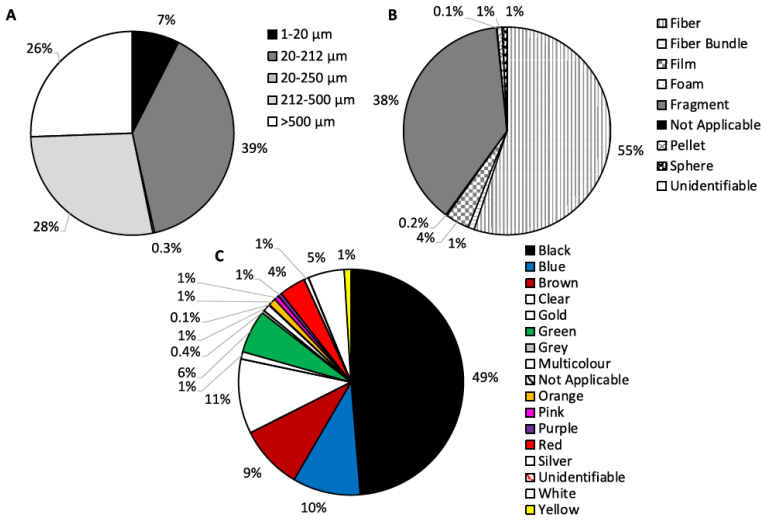


Figure 20: Composition of the Particles detected in the Blanks across the Labs (Munno et al., 2023).

Based on these data, the authors discuss different strategies for blank correction and conclude that subtraction along combined characteristics (size class, colour, and morphology) is most likely to remove only those particles that originate from the laboratory background, while preserving “true” sample particles. This complements the review by adding a methodological perspective on how blank data can not only be collected but also meaningfully integrated into data analysis (Munno et al., 2023).

Finally, the experimental studies allow an assessment of which of the measures identified by Cruz-Salas et al. should be prioritized based on their actual effectiveness. Jones et al. show that switching from glass to plastic consumables and avoiding the use of aluminium foil as a cover reduces introduced particles by an order of magnitude more than changing the working environment from an open bench to a biosafety cabinet alone. Aminah and Ikejima, as well as Bhat et al., demonstrate that the combination of thermal treatment of filters, filtration of all reagents, and working in a simple clean booth with a HEPA unit can reduce background contamination in laboratory blanks to the extent that detection limits below one particle per sample are realistically achievable. Taken together with the systematic literature review, this suggests that technical measures, consistent filtration of water and reagents, and deliberate material should be defined as the core of a “minimum standard” for contamination control, to which additional matrix- or method-specific measures can be added (Aminah & Ikejima, 2023; Bhat et al., 2024; Jones et al., 2024; Munno et al., 2023; Wesch et al., 2017).

6 Measurement Principles and Parameters for Microplastic Detection

This chapter introduces the fundamental operating principles of the analytical instruments discussed in the subsequent sections on spectroscopic, thermoanalytical, imaging, and fluorescence-based methods. It outlines the underlying principles of each technique and highlights key aspects of their application, including detection limits, throughput, and costs.

In general, three main detection approaches can be distinguished. Spectroscopic methods identify polymers by analyzing their chemical structure and comparing the results with reference spectra. Thermoanalytical methods rely on pyrolysis under inert conditions, producing characteristic degradation products that enable polymer identification. In addition, chemical methods selectively digest plastics to detect specific degradation products or elements. Methods that dissolve MPs as largely intact polymers for extraction are not considered chemical methods in this context.

Spectroscopic techniques allow identification of polymer types as well as determination of particle number, size, size distribution, and shape. In contrast, thermoanalytical and chemical methods primarily provide information on polymer types and associated MP contents. These approaches are complementary but, with current technology, their results cannot be directly converted.

For real samples, exclusive reliance on imaging techniques such as light or electron microscopy, or on particle counting methods including light or laser scattering and Coulter counters, carries a high risk of misinterpretation, as MPs cannot be reliably distinguished from natural particles. Such measurements therefore require validation using appropriate reference and blank samples (Dr. Ulrike Braun, 2020).

6.1 Spectroscopic Methods

In this section, the spectroscopic methods FTIR and Raman are examined and presented, as they are among the most important techniques for identifying MP based on their material specific signals. Spectroscopic methods capture chemical structural features and assign them by comparison with reference spectra. They allow the simultaneous determination of polymer type as well as particle number, size, and shape.

6.1.1 Fourier Transform Infrared Spectroscopy (FTIR/µ-FTIR/ATR-FTIR)

Operating principle:

FTIR is a widely used method for non-destructive determination of chemical structures via covalent bonds. Mid-infrared (MIR) radiation excites molecular vibrations, producing characteristic spectra that can be compared with reference spectra. Samples must be water-free, as water's IR spectrum overlaps with the analyte and complicates interpretation.

FTIR variants differ in spatial resolution, sample preparation, and measurement geometry. Conventional FTIR measures larger areas and suits bigger particles. µ-FTIR, combined with a microscope, achieves micrometer resolution, allowing analysis of smaller particles and automated chemical mapping. ATR-FTIR generates the signal at the sample surface, requires minimal preparation, works well for uneven or solid samples, but has lower resolution than µ-FTIR (Dr. Ulrike Braun, 2020).

Measurement principle:

Depending on sample properties and particle size, different reflection and transmission modes are applied:

Transmission measurements:

The IR beam passes completely through the sample. The main advantage is the acquisition of complete spectra representing the entire particle. Disadvantages include susceptibility to total absorption above a certain particle or layer thickness and for materials with high carbon content, which can lead to the loss of spectral details.

Reflection measurements:

The IR beam is directed onto the sample, and the reflected radiation is detected. This mode requires highly reflective samples and is therefore typically applied to strongly reflecting surfaces, such as gold coated filters.

Attenuated total reflection (ATR):

A crystal is pressed against the particles, and the spectrum is recorded at the interface between the crystal and the sample. This method primarily captures the surface structure of the particle but may be problematic due to adhesion effects or mechanical damage to the crystal caused by hard particles (Dr. Ulrike Braun, 2020).

Variants by particle size:

As already indicated, the different FTIR approaches differ in their spatial resolution, which determines the particle sizes that can be analysed.

ATR-FTIR (particles > 500 µm):

Larger particles are analysed directly. Particle selection is performed either manually or by image analysis algorithms. A disadvantage of this approach is the potential for contamination due to particle transfer or damage to the crystal surface.

µ-FTIR (particles < 500 µm):

Measurements in reflection and transmission are carried out using confocal FTIR microscopes. The use of focal plane array (FPA) detectors significantly increases measurement throughput. Depending on detector size and manufacturer, areas of approximately 0.7 mm × 0.7 mm can be analysed in a single measurement (around 1 minute, up to 16,384 spectra). A filter area of 14.8 mm × 14.8 mm can be analysed in approximately 4 hours.

Laser based IR systems (µ-IR):

These newer systems provide substantially higher radiation power compared to conventional IR sources. Each wavenumber is tuned individually, which is more computationally intensive than Fourier transformation but nevertheless enables faster measurement times. A key advantage is that detector cooling with liquid nitrogen is no longer required. In combination with FPA detectors, short measurement times for large areas can be achieved, for example an area of 12 mm × 12 mm in approximately 36 minutes at a pixel resolution of 4.2 µm (Dr. Ulrike Braun, 2020).

Filter materials and measurement range:

IR-transparent filter materials allow for rapid sample preparation. Aluminium oxide is the most used filter substrate, but it has a limited measurement range (3600–1250 cm^{-1}). Alternatives include silicon or metal-coated polycarbonate filters (Dr. Ulrike Braun, 2020).

Data processing:

Imaging-based measurement methods generate large volumes of data, which are processed using specialized software. Commonly used tools include R, Python, or MATLAB, as well as commercial solutions offering various algorithms for spectral assignment. The freely available software siMPle (www.simple-plastics.eu) is capable of analysing both large datasets and individual spectra (Dr. Ulrike Braun, 2020).

Detection limit and quantification thresholds:

The detection limit of µ-IR spectroscopy depends on the instrument, measurement settings, and optics, with particles down to ~10 µm reliably identified, representing the practical threshold for routine environmental monitoring. The method can be affected by residual water, biofilms, mineral deposits, and pigments, requiring careful drying, pretreatment, or enzymatic cleaning. Very small particles (<10 µm) are difficult to detect outside specialized labs (Dr. Ulrike Braun, 2020).

Sample preparation and blanks:

To apply this method effectively to particles <500 µm, chemical or enzymatic sample preparation is often required. For partial analyses, at least 50 particles (>500 µm) or 50 % of the filter area (<500 µm) should be examined.

Reliable FTIR results require systematic blank determinations. Process blanks capture contamination arising from sampling, preparation, and detection; at least one process blank per five samples is recommended. Laboratory blanks assess internally induced contamination; a minimum of three, and ideally up to ten, laboratory blanks are recommended for determining the limit of detection (LOD) (Dr. Ulrike Braun, 2020).

Data integration and evaluation:

Modern analysis software, such as siMPle/MPAPP or the BPF platform, automates particle detection, classification, and statistical evaluation. This enables the efficient use of large datasets for life cycle assessments, long-term studies, and source identification (Dr. Ulrike Braun, 2020).

6.1.2 Near-Infrared Spectroscopy (NIR)

Operating principle:

Near-infrared (NIR) spectroscopy covers the spectral region adjacent to the mid-infrared, where overtones and combination bands occur. In NIR spectroscopy, molecules are excited to vibrate by electromagnetic radiation, and the absorbed energy appears as missing intensity in reflection or transmission spectra. Because these spectral regions are molecule-specific, the position, shape, and intensity of the absorption bands enable substance identification and quantification using chemometric methods and comparison with reference databases (Dr. Ulrike Braun, 2020).

Measurement types:

Point spectrometers:

In contact measurements such as ATR in the MIR range, measurements can be performed on individual particles. However, the optical lens system produces a blurred measurement area, so this method is generally suitable only for MP (>1 mm). Alternatively, increasing the measurement distance allows integration over a larger area, yielding a single spectrum for the measured surface. Using statistical methods, the coverage of the target material or its content in mass percent can be determined.

Imaging spectrometers:

These systems spatially resolve the measurement area into numerous individual measurements, similar to FPA-based FTIR spectrometers. Each pixel in the resulting image contains its own spectrum. Depending on the optical lens, pixel sizes are typically around 50 µm or larger, corresponding approximately to the diameter of the smallest detectable MP particle. Image processing methods enable automated particle detection and size determination (Dr. Ulrike Braun, 2020).

Field applicability and applications:

Since portable, field-ready NIR spectrometers are available, quantification can also be performed in situ. Additionally, NIR spectrometers can be inserted into samples, such as soil, using a measurement probe (Dr. Ulrike Braun, 2020).

Detection limits and advantages:

The practical detection limit of NIR spectroscopy for microplastics in soil is about 1 wt% plastic or 5 % coverage of the measurement area, below which polymer signals are masked by the matrix or individual particles cannot be reliably distinguished. Sensitivity also depends on soil composition, background material, and polymer optical properties. NIR allows very high sample throughput due to its rapid measurement (e.g., 10 minutes for a 47 mm filter) and is relatively robust against contamination, such as biofilms. It has long been used for online quality control in the food industry and automated plastic sorting, with applications for microplastic analysis in soil and water emerging only recently (Dr. Ulrike Braun, 2020).

Sample preparation and limitations:

In all cases, samples must be filtered onto glass fibre filters without organic binders and dried in an oven at a maximum of 50 °C. For NIR measurements, no established protocols currently exist for determining process or laboratory blanks (Dr. Ulrike Braun, 2020).

6.1.3 Raman-Spectroscopy (µ-Raman)

Operating principle:

Raman spectroscopy is a non-destructive method based on the inelastic scattering of light, producing “fingerprint” spectra for polymer identification and characterization of additives, pigments, and inorganic or organic constituents. Coupling with confocal microscopy (µ-Raman) provides high spatial resolution in the submicrometer range, typically around 300 nm (Dr. Ulrike Braun, 2020).

Swiss research institutions, such as Eawag, have conducted extensive studies on Raman spectroscopy for MP analysis and provide methodological guidelines and standard protocols (Eawag, 2024).

Advantages over FTIR:

This technique is particularly relevant for very small, transparent, or pigment-laden particles that are difficult to analyse using FTIR. Raman spectroscopy also enables the characterization of aged or weathered particles, as well as the identification of polymer mixtures and chemical additives in plastics (Dr. Ulrike Braun, 2020).

Automated measurement and throughput:

With automated particle counting, one or more filters can be measured in a batch, typically, 2–5 hours are required per filter. Individual measurements take 10–30 seconds per particle. Modern software enables simultaneous morphology analysis and polymer classification in a single workflow. (Dr. Ulrike Braun, 2020).

Limitations:

A key challenge of Raman spectroscopy is its susceptibility to fluorescence interference from organic matrices, biofilms, or colour pigments. Specialized excitation wavelengths (e.g., 785 nm lasers) or pretreatments such as oxidation or enzymatic cleaning can mitigate these effects. The detection limit is approximately 1 µm, but analyses are restricted to small filter areas, resulting in a significantly lower sample throughput (Dr. Ulrike Braun, 2020).

Software and costs:

Several analysis programs are available, including GEPARD and the TUM Particle Typer for automated analysis. Costs and personnel requirements are comparable to FTIR imaging for comprehensive environmental samples, however, the sample throughput is significantly lower due to the small measurable filter areas (Dr. Ulrike Braun, 2020).

Application spectrum:

Raman spectroscopy is primarily used for drinking water, air samples, and industrial effluents, where small and diverse MP fractions are expected. It is particularly suitable for (Dr. Ulrike Braun, 2020):

- Investigation of nanoplastics
- Analysis of pigment-laden particles
- Identification of aged or weathered polymers (e.g., heavily oxidized PE/PP)
- Characterization of polymer mixtures

6.2 Thermoanalytical Methods

Thermoanalytical methods determine polymer types and MP content, but they are complementary to spectroscopic techniques, as they do not provide information on particle number, size, or shape (Dr. Ulrike Braun, 2020).

6.2.1 Pyrolysis–Gas Chromatography–Mass Spectrometry (Py-GC/MS)

Operating principle:

The method is based on the thermal decomposition of the sample under oxygen-free conditions at temperatures of 500–700 °C. Polymer degradation products are separated by gas chromatography and detected by mass spectrometry (Dr. Ulrike Braun, 2020).

Advantages and robustness:

The technique is robust against matrix interferences such as humus, sediment, or biological components (Dr. Ulrike Braun, 2020). This makes it particularly suitable for complex environmental samples, such as sewage sludge, sediments, or soil, where spectroscopic methods are limited by matrix overlap (Wasser 3.0, 2025).

Sample amount and analysis time:

Typically, only a few milligrams of sample are required to accurately quantify both the total mass and the distribution of individual polymer types. In routine laboratory practice, a complete analysis takes approximately 2 hours, a timeframe that can accommodate multiple samples in a batch (Dr. Ulrike Braun, 2020).

Limitations:

The method does not provide information on particle size, shape, or number; it only measures the total mass fraction per polymer. This is a disadvantage for epidemiological studies or environmental assessments, as toxicological effects are often size-fraction dependent rather than substance-based. Additionally, additives, plasticizers, and certain copolymers can interfere with the pyrogram, making careful calibration essential (Dr. Ulrike Braun, 2020).

Application scope:

Thermoanalytical methods are primarily applied to samples with complex matrices, as well as in cases where mass flows need to be documented, such as in wastewater treatment balances or industrial process control (Dr. Ulrike Braun, 2020).

6.2.2 Thermal Extraction–Desorption Gas Chromatography–Mass Spectrometry (TED-GC-MS)

Operating principle and sample amounts:

The method is similar to Py-GC-MS but employs specialized sample introduction systems for thermal extraction and desorption. With TED-GC-MS, the sample amount can be increased up to 100 mg without contaminating the analytical system, enabling the analysis of samples with very low MP content (Dr. Ulrike Braun, 2020; GERSTEL, 2025).

According to the manufacturer GERSTEL, TED-GC-MS provides automated sample introduction with thermal extraction and desorption, which significantly improves the quantification of very small particle amounts.(GERSTEL, 2025).

Analysis time:

The analysis takes approximately 2 hours per sample, similar to conventional Py-GC-MS (Dr. Ulrike Braun, 2020).

6.2.3 Calorimetric Methods (DSC – Differential Scanning Calorimetry)

Operating principle:

Differential Scanning Calorimetry (DSC) is a thermoanalytical technique that allows precise determination of the thermal properties of polymers under continuously controlled temperature conditions. In a DSC measurement, a sample and a reference are simultaneously heated or cooled, and the amount of heat absorbed or released by the sample during the temperature change is recorded.

Polymers exhibit characteristic phase transitions with increasing temperature, such as the melting of crystalline regions or glass transitions in amorphous fractions. Each polymer type has a specific melting temperature, which appears as a peak in the DSC thermogram. Additionally, the melting enthalpy, the energy absorbed during melting, can be quantified, enabling the determination of the mass and type of the polymer.

By analysing the DSC thermogram, different polymer types can be clearly identified, and their proportions in mixed samples can be reliably quantified. The method is particularly advantageous for the analysis of crystalline polymers, such as polyethylene, polypropylene, or PET; amorphous materials, by contrast, exhibit no pronounced melting peaks and are only partially detectable by DSC (Dr. Ulrike Braun, 2020).

Detection limits:

The detection limit of Differential Scanning Calorimetry (DSC) for MP is typically around 50 µg of sample, representing the minimum polymer amount that can be reliably detected. This limit is somewhat higher than for Pyrolysis-GC-MS, which can quantify smaller polymer quantities.

A major advantage of DSC is its low sensitivity to contamination: because the method directly measures the specific melting energy and thermal transitions of target plastics, foreign substances, mineral particles, or organic matrix components generally have minimal impact on the analysis. In contrast, chemical methods can be significantly affected or obscured by such contaminants. Consequently, DSC is particularly suitable for complex samples and mixed materials, enabling reliable quantitative and qualitative determination of crystalline polymer fractions (Dr. Ulrike Braun, 2020).

Limitations:

A major limitation of DSC is its unsuitability for amorphous plastics, such as polyvinyl chloride (PVC) or polystyrene (PS), which do not exhibit clearly defined or characteristic melting

temperatures. Upon heating, amorphous polymers generally do not transition abruptly from solid to liquid but instead display a glass transition, a broad and diffuse temperature range without a pronounced peak in the DSC thermogram. As a result, they cannot be unambiguously identified or reliably quantified.

Furthermore, DSC provides no information on the number of individual MP particles. The technique measures only the total mass and thermal properties of the polymer in the sample, regardless of the number of particles present. Therefore, DSC is suitable for determining the overall content of crystalline plastics, but not for detecting, counting, or characterizing individual MP particles. Differentiation by particle size, shape, or quantity is not possible with this method, unlike spectroscopic or imaging techniques (Dr. Ulrike Braun, 2020).

6.3 Imaging Methods

This subchapter addresses imaging methods, which are based on the optical or electronic visualization of MP particles in a sample. These techniques enable direct visualization, morphological analysis, and particle size determination, and are essential for the preparation and preselection of particles for subsequent chemical identification. The following sections describe the most important technologies and their specific applications.

6.3.1 Light Microscopy

Operating principle and application:

Light microscopy is a fundamental method for the initial inspection and pre-selection of potential microplastic particles in environmental samples. Filters or sample preparations are systematically examined, and particles are visually assessed based on shape (fibres, fragments, beads), surface texture, and colour. Conspicuous or unusual particles are marked as potential microplastics. The method is easy to implement and allows rapid preliminary classification in routine analyses and educational contexts. (Dr. Ulrike Braun, 2020).

Fundamental limitation:

International studies, notably Hidalgo-Ruz et al. (2012), show that visual assessment alone is insufficient for reliable microplastic identification. Natural materials such as cellulose, chitin, or mineral fragments can resemble plastics, leading to frequent misidentifications. Complementary chemical confirmation using FTIR or Raman spectroscopy is therefore essential. Light microscopy primarily serves as a pre-screening tool and preparatory step for subsequent substance-specific analyses (Hidalgo-Ruz et al., 2012a).

Detection limit:

Microscopic analyses are particularly suitable for larger sample volumes and as a preliminary step for automated spectroscopic or fluorescence-based methods. Modern light microscopes can achieve resolutions between 10 and 50 µm; below this range, uncertainty increases significantly (Dr. Ulrike Braun, 2020).

6.3.2 Scanning Electron Microscopy (SEM)

Operating principle:

Scanning Electron Microscopy (SEM) is a high-resolution imaging technique in which a focused electron beam is scanned line by line across the sample surface. The interactions of the electrons with the surface are detected, producing a detailed image at the nanometre scale. When coupled with Energy Dispersive X-ray Spectroscopy (EDX), elemental composition of or within the MP particles can be determined simultaneously, allowing for both morphological and chemical characterization (Dr. Ulrike Braun, 2020).

Surface analysis:

SEM enables the visualization and measurement of specific surface structures of MP particles. This includes mechanical weathering marks, the formation or detachment of biofilms, pigment or metal adsorption, and the detailed examination of structural changes at particle edges. In environmental analytics, SEM is increasingly used to document weathering processes and interactions of MP with other environmental particles (Dr. Ulrike Braun, 2020). Recent trends, such as those reported by analytik.news (2025), indicate that such studies are gaining growing scientific significance (analytik.news, 2025).

Practical relevance:

Despite its significant value for research, SEM involves considerable instrumental and organizational effort. Samples usually require extensive drying and conductive coating, for example with a thin layer of gold or carbon, prior to measurement. Analyses are time- and cost-intensive, making SEM unsuitable for routine monitoring of MP. Its greatest benefit lies in specialized material and environmental studies, as well as in the precise investigation of MP subjected to long-term environmental exposure or complex aging processes(Dr. Ulrike Braun, 2020).

6.4 Fluorescence-Based Methods

Operating principle and labelling:

Fluorescence-based methods use dyes that selectively stain microplastic particles, inducing fluorescence under UV or blue light. Common markers include Nile Red and the Wasser-3.0-detect-mix MP-1, which adhere to plastic surfaces and make particles visible. Stained samples are analyzed with automated image analysis software, enabling digital determination of particle number, size, and distribution. For recovery studies and method validation, samples are often spiked with synthetic fluorescent reference particles to track analysis efficiency and potential losses during preparation (Dr. Ulrike Braun, 2020). Advanced protocols, using Nile Red and Wasser-3.0-detect-mix MP-1, offer significantly improved specificity for distinguishing different polymer types and are now established in standard studies and interlaboratory comparison exercises (Olbrich & Schuhen, 2024).

Improvements through new markers:

The development and application of new fluorescent markers have significantly increased the specificity of these methods for various plastics, such as polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET). Modern markers, such as the Wasser-3.0-mix MP-1, form more specific interactions with target polymers, thereby enhancing discrimination from other environmental particles and reducing detection errors. In particular, the previous challenge of black, heavily pigmented plastic particles appearing less visible due to colour attenuation has been largely overcome through these new markers and improved protocols (Dr. Ulrike Braun, 2020; Wasser 3.0, 2025).

Detection limit:

The practical detection limit of fluorescence microscopy is approximately 1 µm to 10 µm particle size. This means that particles at or above this size can be reliably detected and analysed, whereas smaller particles are generally not unambiguously identifiable using standard methods (Dr. Ulrike Braun, 2020).

Analysis time and throughput:

Acquisition of a single standard filter with modern fluorescence microscopes typically takes 25–30 minutes, while the required sample preparation, including staining and filtration of MP particles, takes an additional 15–30 minutes. As a result, under manual or semi-automated laboratory workflows, it is realistic to process approximately two to four complete samples per hour (Dr. Ulrike Braun, 2020).

Applications and limitations:

Fluorescence-based methods are primarily used for rapid screening and routine monitoring of MP, as they enable the quick and reliable visualization of large particle groups. They are also well suited for method development and control studies, where fluorescent MP reference particles are deliberately added to assess measurement accuracy and loss rates.

A central limitation is that polymer identification is not always unambiguous. For example, Nile Red exhibits reduced affinity for highly polar plastics, such as PVC, which can lead to false-negative results. In general, fluorescence methods are applicable to a wide range of polymers, but for certain functionally modified or heavily treated plastics, marker binding, and thus detection, can be limited. Nile Red remains a well-established standard when compatible with the target polymers, while new markers, such as Wasser-3.0-detect-mix, enhance method versatility and precision (Dr. Ulrike Braun, 2020).

6.5 Comparative Overview

Table 9: Comparative overview of Microplastic Analysis Methods

Method	Particle size limit detection [µm]	Particle size limit sample preparation [µm]	Chemical specificity	Throughput	Duration per sample	Automatable
FTIR Imaging	>10	10-20	Very high	Low; long measurement (4–6 h) but thousands of particles simultaneously	4–6 h	Yes
Laser µ-IR	>5	0.8	Very high	Medium; faster point measurements, smaller particles, more samples in shorter time	2–4 h	Partially
NIR Spectroscopy	>50	50	Medium	Very high; screening method, short measurement time (<1 h), large particles, low specificity	0.5–1 h	Yes
Raman Microscopy	1–5	0.2-1	Very high + additives	Medium; very high specificity, but long measurement time (2–5 h) and complex analysis	2–5 h	No
Pyrolysis-GC-MS	Mass-based	1	High	Medium; runtime ~2 h, but only one sample per run (serial)	2 h	Yes
TED-GC-MS	Mass-based	1	High	Medium; similar to Py-GC-MS, single samples, long runtime	2 h	Yes
DSC	Mass-based	100-300	Medium (crystalline)	Very High; short measurements (0.5–1 h), but not fully automatable	0.5–1 h	Partially
Light Microscopy	10–50 (visual)	10-20	Low (morphology)	High/Medium; rapid visual assessment of many particles simultaneously, but low specificity	0.5–3 h	No
SEM	Nano	0.2-0.45	Medium (with EDX)	Medium; laborious preparation, single particle analysis, long measurement time	1–3 h	No
Fluorescence Microscopy	1–10	0.45	Low (type-limited)	Medium; rapid measurement (<30 min), but type-dependent and limited automatable	25–30 min	Partially

The Table 9 above compares all common methods for MP analysis in terms of detection range, chemical specificity, sample throughput, and analysis duration. It serves as a decision-making tool to select an appropriate analytical strategy based on sample type, study objectives, and laboratory context.

For routine monitoring with high sample throughput, imaging and fluorescence-based methods are particularly suitable. For definitive polymer identification and quantitative analysis of crystalline polymer fractions, spectroscopic and thermoanalytical techniques are preferred. Resource-intensive methods, such as SEM, are primarily applied in research and material aging studies. The information is based on current literature and the key reference values provided in the BMBF status paper (Dr. Ulrike Braun, 2020). In addition to the method-specific technical publication, various sources were consulted to determine the practical detection limit, taking sample preparation into account. In particular, it was taken into account that the effective lower size limit in microplastic analysis is often determined not by instrumental resolution, but by filtration, sieving, density separation, and transfer losses during sample preparation.

For FTIR-based methods, technical application documents from Agilent Technologies and the 2020 status paper on microplastics analysis from the German Federal Ministry of Education and Research were consulted. These sources describe in particular filter-based sample preparation and the resulting practical size limitations (Agilent Technologies, 2021; Dr. Ulrike Braun, 2020).

For laser micro-IR and LDIR systems, the Sample Preparation Guide for the 8700 LDIR System from Agilent Technologies, the work of Whiting et al. (2022), and the status paper from the German Federal Ministry of Education and Research were taken into account. These publications focus in particular on the requirements for suitable substrates and the practical lower limit resulting from filtration and particle transfer (Agilent Technologies, 2022; Dr. Ulrike Braun, 2020; Whiting & et al., 2022).

In the field of NIR spectroscopy, the SWB MP1 method for analyzing drinking water samples and the methodological reviews by Löder and Gerdts were consulted, supplemented by the status paper of the Federal Ministry of Education and Research. These sources show that in practice, the lower size limit is usually limited by pre-screening and filter pore size(California State Water Resources Control Board, 2020; Dr. Ulrike Braun, 2020).

For Raman-based methods, the study by Araujo et al. (2018), recommendations on filter pore sizes in the range of 0.2 to 1 µm, and the status paper of the Federal Ministry of Education and Research were taken into account. It is clear that, despite high instrumental resolution, losses below the filter pore size used can occur (Araujo et al., 2018; Dr. Ulrike Braun, 2020).

For pyrolysis GC-MS and TED-GC-MS, the work of Dümichen et al. (2017) and corresponding discussion and status papers from the Federal Ministry of Education and Research were consulted. Here, the focus is less on a particle size-dependent detection limit and more on sufficient homogenization of the sample (Dr. Ulrike Braun, 2020; Dümichen et al., 2017).

For thermal analysis using DSC, the discussion and status paper of the Federal Ministry of Education and Research and review papers on the analysis of aged microplastic particles were taken into account. In this case, too, the method is not directly limited by particle size, but requires suitable sample preparation (Dr. Ulrike Braun, 2020).

In the field of light microscopy, WTP studies by the Southern California Coastal Water Research Project, the review by Hidalgo-Ruz et al. (2012), and the status paper by the Federal Ministry of Education and Research were taken into account. Here, it is clear that the lower size limit depends heavily on optical separability and the previously used sieve fraction (Dr. Ulrike Braun, 2020; Hidalgo-Ruz et al., 2012b).

For SEM investigations, work by Mintenig et al., corresponding status papers from the Federal Ministry of Education and Research, and technical filter guidelines were taken into account. The practical lower limit here is primarily determined by the membrane filters used (Dr. Ulrike Braun, 2020; Mintenig et al., 2019).

For fluorescence-based methods, the work of Maes et al. (2017) and technical filter recommendations from Sigma-Aldrich were included. Here, too, the filter pore size used significantly determines the effective lower size limit (Maes et al., 2017; Sigma Aldrich, 2020).

However, an important point regarding this table should not be overlooked. The figures given for the treatment methods only apply if all particle sizes are fully recorded during sampling. For instance, when sampling water with a net, depending on the pore size of the net, particles smaller than 41 µm are not sampled at all. The detection limit then shifts to 41 µm for all methods.

7 Creation of a Flow-Chart diagram

Another goal of this work was to create a flowchart based on the literature review, which should serve as an aid for future projects in determining a suitable approach for the process of analysing MP. The following flowchart was developed using Miro. For full resolution: https://drive.google.com/file/d/1ZfKdD-VNB4QznKIoSCiXTfgsVrShVK-o/view?usp=sharing

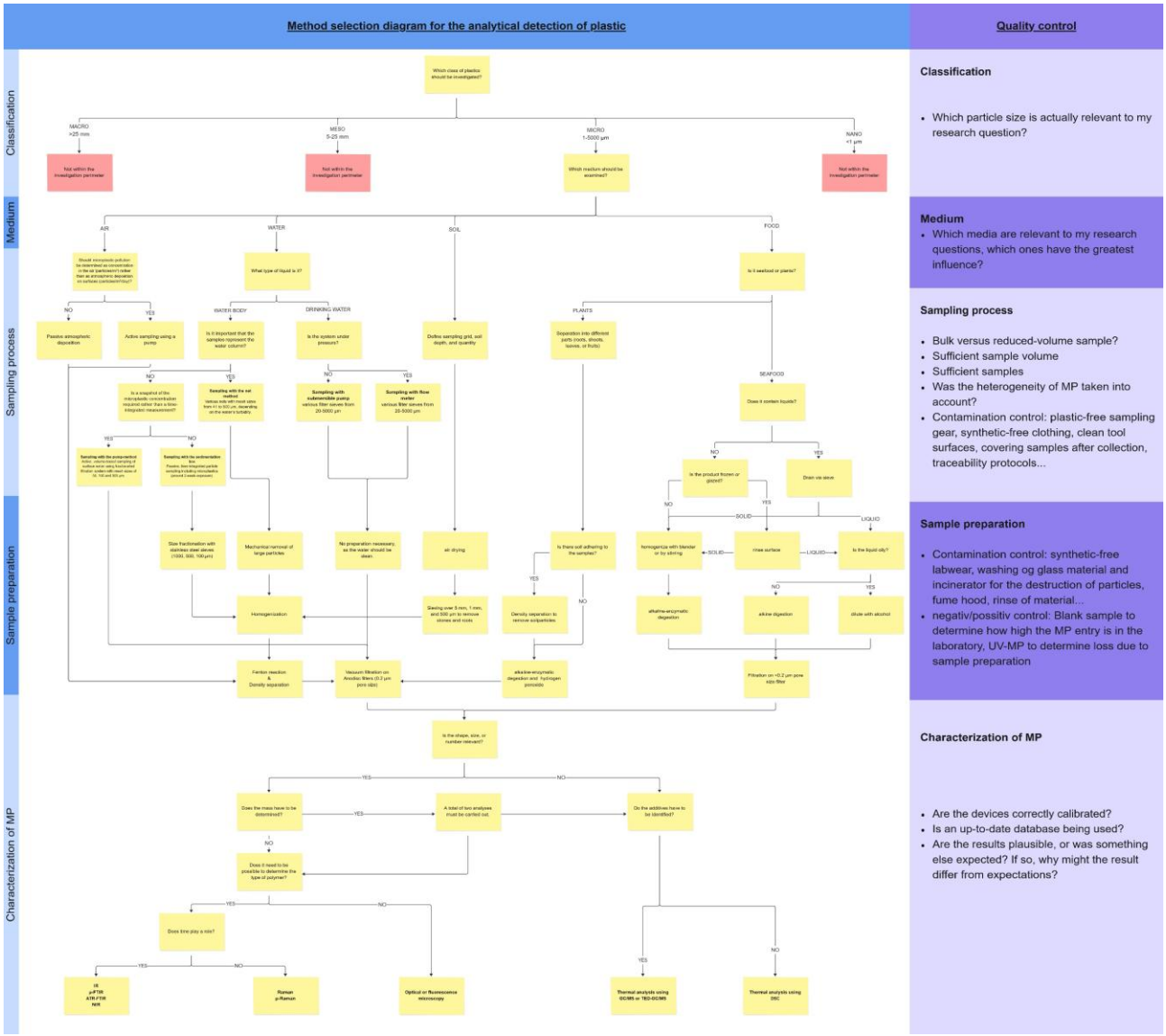


Figure 21: Flow chart Illustrating a simplified Decision-making Process for selecting the appropriate Methods for Microplastic sampling, sample processing, and detection (own creation)

The Figure 21 above shows the flowchart that has been created. It is also stored in the appendix under letter A, where it can be viewed in full resolution. It is basically divided into two parts. On the left-hand side is the actual flow chart, which is structured vertically. This division serves to better orient the reader and clarify which section of the process they are in. Specifically, the reader is first guided through the various size categories and then to the

different media that can be examined. This is followed by the sampling process and sample preparation for the final analysis.
Colours were also used for the size classification. The reason for this is that only the MP class is relevant in this work. At the same time, this colour coding makes it easy to expand the flowchart in the future if additional size classes are to be included in later work.
Targeted questions guide the reader through the flowchart so that an optimal strategy for answering the respective research question can be determined. Subsequently, all paths converge again, as the analysis of the sample can be carried out according to the same basic principle in all media considered. In this section, too, the reader is supported by questions in order to select the appropriate analysis method in each case.
It should be noted that only a limited number of laboratories possess all the devices shown in the diagram. For this reason, all devices mentioned in the flowchart can be used to obtain usable results. An exception arises when the shape and number of particles are of central importance. In this case, thermoanalytical evaluation is not suitable, as this method can only determine the polymer type and mass and does not provide information on particle shape or particle number. Furthermore, not all methods presented in the preceding chapter are listed. This is because, for example, analysis using SEM can provide highly specific information on particle ageing processes, but due to the complex sample preparation it is less suitable for monitoring analyses.
A simplified quality control concept is shown on the right-hand side of the diagram. This is intended to draw the reader's attention to the fact that, in addition to the correct procedure for answering the research question, ensuring reliable results is also of central importance. However, the points shown do not represent a complete quality control strategy but rather serve as a guide to the aspects that should generally be considered.
The specific design of the quality control measures may vary depending on the sampling location, the research question, and the available capabilities of the respective laboratories. Nevertheless, the diagram shows the most important basic aspects that should be considered when planning and conducting such investigations.

8 Discussion

The following chapter reviews the existing literature on classification, sampling and sample preparation methods, as well as subsequent MP analysis. It then addresses cross-contamination and discusses the developed flow chart.

8.1 Discussion on Classification of MP

The classifications of plastic particles identified through the literature review highlight the persistent lack of uniformity in terminology. Internationally binding threshold values for the definition of MP are absent, which limits the comparability of studies and complicates the interpretation of measurement results.

While many studies define MP as particles <5 mm, others apply narrower size ranges, such as methodological recommendations from the LabPlas consortium, which defines MP as particles smaller than 1 mm. These differences directly affect sampling strategies, analytical procedures, as well as reported concentrations and size distributions.

The 5 mm threshold is primarily ecotoxicologically motivated, yet smaller particles are increasingly in focus because they may exhibit different exposure pathways and mechanisms of action, for example through penetration of biological barriers or altered surface properties. Subcategories such as SMP reflect this differentiation.

At the same time, there is a tension between scientific precision and practical comparability: finely resolved classifications allow more detailed analyses but complicate comparisons with broader definitions. The use of the 5 mm threshold in this study represents a deliberate compromise to maintain compatibility with existing literature and ensure comparability of results.

Overall, the classification of plastic particles is central both terminologically and methodologically. A transparent definition is essential for traceability and scientific validity. In the long term, advances in analytical techniques and international standardization may promote harmonization of size classifications, until then, a clear and consistent terminology remains a prerequisite for robust and comparable research outcomes.

8.2 Discussion Sampling of Microplastics

All media investigated in this study exhibit different sampling procedures, yet a common feature is the substantial reduction of sample volume. Exceptions include food items and sedimentation in flowing systems, where either the full volume or a large portion is sampled. Volume reduction, however, necessitates the collection of multiple subsamples to account

for the heterogeneity of MP distribution, with the number and size of subsamples potentially affecting statistical representativeness and comparability between studies.

Water is particularly well documented, as MP were first detected in marine environments, and sampling strategies are already well established, with existing standards available for MP sampling. For air samples, existing standards for PM_{10} and $PM_{2.5}$ particles can be applied. However, these standards do not provide uniform guidance on sampling duration or sampled air volume for MP analysis, as demonstrated by the studies in the subsection on air sampling.

Less-studied media, such as soil or food, currently lack standardised specific MP protocols. While general quality control and particle analysis protocols exist for soil, these are not tailored only for MP. This is also illustrated by the example of the two subsections on soil. According to the approach of the FHNW, a sample is taken from a depth of approximately 30 cm, whereas the other source suggests dividing the soil samples. This recommendation is based on the fact that higher concentrations of MP are present in the upper centimeters of the soil than in the deeper soil layers and that MP is transported into deeper layers primarily through soil cultivation.

This lack of standardization highlights the need for specific, standardized protocols for MP sampling to ensure data reliability, reproducibility, and comparability between studies. The choice of sampling strategy also directly affects analytical outcomes, as variations in sample volume and collection methods may hinder the detection of MP particles.

During the interim presentation with Prof. Dr. Petar Mandaliev, Fulvio di Lorenza, and Dr. Ralf Kägi (EAWAG), the question was raised whether volume-based sampling is appropriate or whether sample volumes should instead be linked to expected MP concentrations, for example, by defining that a minimum of X particles or X mg of MP per sample is required. Such an approach would ensure that sufficient particles are available after sample preparation for reliable analysis.

Overall, these observations demonstrate that standardized sampling procedures for all media, particularly for less-studied ones, are essential for generating robust, comparable, and methodologically consistent MP data. The discussion of volume-based compared to concentration-based sampling also shows that further research/investigation is necessary in order to be able to demonstrate whether a low number of MP can have an influence on the analyzability of the sample.

8.3 Discussion Detection of Microplastics

There are numerous methods for detecting MP, which can be broadly categorized into spectroscopic, thermoanalytical, imaging, and fluorescence-based techniques. Spectroscopic methods enable precise polymer identification but provide limited information on particle number and morphology. Thermoanalytical techniques determine polymer mass and composition but do not allow particle counting or shape analysis, while imaging techniques visualize particle size and morphology but are often time-consuming and less suitable for large sample volumes. Fluorescence-based methods enable rapid detection; however, they face limitations, particularly with plant samples, as Chen et al. report interactions between fluorescent cell structures and MP that complicate or even prevent detection.

The choice of the appropriate method depends on the specific research question, the medium under investigation, particle size, available time, and laboratory equipment. Often, a method is selected based on what is available in the laboratory or can be applied in cooperating facilities. This demonstrates that methodological decisions are driven not only by scientific considerations but also by pragmatic constraints.

The literature further shows that no universal method exists that meets all requirements equally, which complicates the comparability of studies. To enhance methodological consistency and reproducibility, a critical assessment of the advantages and disadvantages of each method is therefore required. One approach could be the combination of multiple techniques to leverage the strengths of individual methods while compensating for their limitations. This approach is also adopted in several studies. It ensures, on the one hand, that the most suitable method is selected for each component of the result, and, on the other hand, that a robust overall result is obtained through the integration of all partial results.

For future research, the development of standardized recommendations is particularly important for novel sample types and difficult-to-detect particle sizes. Such guidelines would improve comparability between studies and increase the validity of MP-specific analyses. At the same time, methodological decisions should always be transparently documented to ensure traceability and scientific reliability.

8.4 Discussion Cross-Contamination

The reviewed studies and literature, particularly Cruz-Salas et al., indicate that cross-contamination is insufficiently addressed, especially during sampling. Their systematic review shows that nearly half of field studies report no explicit measures to reduce cross-contamination. While basic controls are generally applied in the laboratory, contamination occurring during sampling cannot be reliably identified or corrected later. This underscores the need for careful documentation of sampling procedures and the implementation of targeted preventive measures in the field.

In laboratories, the avoidance of plastic tools is often assumed to reduce contamination. However, experimental studies show that this alone is insufficient and can even be counterproductive. Jones et al. demonstrate that glassware and aluminium foil can be significant particle sources, whereas quality-controlled disposable plastics exhibit substantially lower contamination. Material choice must therefore consider production, storage, and analytical objectives. These findings highlight persistent knowledge gaps and the lack of comprehensive studies on cross-contamination.

Laboratory water represents another critical contamination pathway. Even highly purified Milli-Q water can contain measurable MP, making the consistent use of procedural blanks essential. Blanks must reflect actual sample handling, including the water used. Airborne particles are also relevant: consumables dominate during short tasks, while prolonged, open procedures increase airborne deposition. Laminar flow benches with HEPA filtration effectively reduce airborne contamination, outperforming standard fume hoods, though effectiveness is context dependent. Blanks remain crucial to quantify background contamination.

The interlaboratory study by Munno et al. confirms the importance of blanks and shows substantial variability in background contamination across laboratories. Blank correction based on combined characteristics offers a practical approach to separate background from sample-specific particles and integrate blank data systematically. The literature, however, lacks consensus on whether background contamination should be mathematically corrected or only transparently reported. This underlines the absence of standardised protocols and the need for careful reporting to ensure study comparability.

Overall, these findings indicate that standardised protocols defining minimum requirements for contamination control and blank management are still lacking in MP research. Developing such standards is essential to ensure the comparability and reliability of MP measurements.

8.5 Discussion Flowchart diagram

The flowchart provides a structured overview of the literature on MP analysis and serves as a practical tool for methodological decision-making. It guides users systematically through particle size classification, matrix selection, sampling, sample preparation, and analysis. The vertical structure and colour coding of particle sizes enhance clarity and facilitate future extensions to include additional size classes.

The guiding questions in the flowchart support the selection of appropriate methods based on the specific research question and highlight that many principles are applicable across different media. At the same time, limitations become apparent: for example, thermoanalytical methods are unsuitable for research questions where particle count or morphology is relevant. This demonstrates that methodological decision aids must always be critically adapted to the objectives of the study.

A simplified quality control concept emphasizes the importance of blanks, contamination control, and documentation. It serves as a guide rather than a complete protocol and must be adjusted according to the matrix, research question, and laboratory capabilities. The quality control measures presented represent universal minimum requirements that should be applied in all MP analyses to ensure comparability of results.

At the same time, the diagram highlights its limitations: it does not replace detailed planning of sampling or analysis and cannot capture all methodological details. Rather, it provides an initial overview of key aspects and necessary steps that must be considered to address the research question. Once the fundamental steps are defined, materials, procedures, and control measures must be carefully documented to ensure comparability between studies, as discussed in the section on cross-contamination.

Overall, the application of the flowchart demonstrates that structured decision aids can enhance transparency and methodological consistency in MP research. At the same time, the analysis emphasizes that standardized protocols are still lacking, and critical reflection on the applied methods remains essential for producing robust and reliable results.

9 Conclusion

The discussion of the current literature on the classification, sampling, sample preparation, detection, and quality control of MP clearly demonstrates that the lack of standardization remains one of the major challenges in MP research. Inconsistent size definitions, varying sampling strategies, and method-dependent result reporting hinder comparability between studies and significantly limit the interpretability of individual investigations.

The analysis of sampling strategies indicates that volume-based approaches are not equally suitable for all matrices. A systematic evaluation of alternative concepts, such as particle- or mass-based sampling strategies, could not be conducted within the scope of this work due to time constraints. Instead, the concept of aligning sampling strategies more closely with the expected MP load was discussed during the interim presentation. This topic represents a scientifically relevant aspect that should be specifically addressed and further explored in future research or follow-up projects in order to improve the statistical robustness of MP-specific analyses. At the same time, the wide range of available detection methods highlights that no universal analytical strategy exists. The selection of appropriate techniques must always be adapted to the specific research question, the investigated matrix, the relevant particle size range, and practical as well as instrumental constraints.

In this context, the recommendations of the BMBF status paper on MP analytics (Braun, 2020) emphasize the central importance of a standardized and transparent presentation of results. The separate reporting of particle number and particle mass, each normalized to volume or dry mass and explicitly specifying the investigated particle size range, represents a fundamental prerequisite for comparability across studies, environmental compartments, and analytical methods. It must be considered that particle number and particle mass are complementary but not directly convertible metrics. Due to the assumptions required regarding particle shape, density, and size distribution, such conversions are associated with considerable uncertainty and should therefore generally be avoided.

Another key aspect is comprehensive quality control throughout the entire analytical process. Contamination, particularly during sampling, represents a critical and frequently underestimated source of error, as demonstrated, among others, by the study of Cruz-Salas et al. The consistent implementation and documentation of blank samples, the use of suitable reference materials, and the complete traceability of all analytical steps, from the sampled environmental aliquot through the processed laboratory sample to the actual subsample analyzed, are essential for the reliable interpretation of measurement results. In addition,

recovery experiments and stability tests are required to correctly assess method-related losses, degradation, or fragmentation of MP particles, as also suggested by the relevant literature.

Against this background, the flowchart developed within the framework of this work provides structured guidance for methodological decision-making. It supports the systematic selection of appropriate classifications, sampling and analytical strategies, as well as basic quality control measures, but does not replace detailed method development. Rather, it contributes to increased transparency, traceability, and comparability of MP-related investigations.

Overall, this work demonstrates that robust MP analytics depend less on individual highly specialized techniques than on clearly defined terminology, standardized reporting formats, and consistent quality control. Until internationally harmonized standards are established, precise documentation and critical reflection of the applied methods remain essential prerequisites for comparable and scientifically reliable results.

Bibliography

Advanced Standards Transforming Markets. (2020). *ASTM_D8332-20_en-US (1)*. https://doi.org/10.1520/%2520D8332-20

Advanced Standards Transforming Markets. (2025). *About ASTM Overview | ASTM*. About ASTM Overview | ASTM. https://www.astm.org/about

Agilent Technologies. (2021). *A Practical Guide to Sample Preparation and Processing of Microplastics Using the Agilent 8700 LDIR Chemical Imaging System*. Agilent Technologies. https://www.agilent.com/

Agilent Technologies. (2022). *Collecting and Preparing Microplastics for Analysis by the Agilent 8700 LDIR*. Agilent Technologies. https://www.agilent.com/

Almuhtaram, H., McKie, M. J., Yuan, C., & Andrews, R. C. (2022). Sampling microplastics in water matrices: A need for standardized filtration methods. *ACS ES&T Water*, *2*(8), 1286–1296. https://doi.org/10.1021/acsestwater.2c00236

Aminah, I. S., & Ikejima, K. (2023). Potential sources of microplastic contamination in laboratory analysis and a protocol for minimising contamination. *Environmental Monitoring and Assessment*, *195*(7), 808. https://doi.org/10.1007/s10661-023-11410-7

analytik.news. (2025, November 4). *Mikroplastik-Analytik: Der lange Weg zum Detektion*. https://analytik.news

Araujo, C. F., Nolasco, M. M., Ribeiro, A. M. P., & Ribeiro-Claro, P. J. A. (2018). Identification of microplastics using Raman spectroscopy: Latest developments and future prospects. *Water Research*, *137*, 406–417. https://doi.org/10.1016/j.watres.2017.12.056

ASTM International. (2020). Standard practice for collection of water samples with high, medium, or low suspended solids for identification and quantification of microplastic particles and fibers (D8332-20). *ASTM International*. https://www.astm.org/d8332-20.html

Bhat, M. A., Gaga, E. O., & Gedik, K. (2024). How can contamination be prevented during laboratory analysis of atmospheric samples for microplastics? *Environmental Monitoring and Assessment*, *196*(2), 159. https://doi.org/10.1007/s10661-024-12345-3

California State Water Resources Control Board. (2020). *Microplastics in Drinking Water: Method Development for Sampling and Analysis (SWB-MP1)*. SWRCB. https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/documents/microplastics/swb-mp1-rev1.pdf

Campanale, C., Massarelli, C., Savino, I., Locaputo, V., & Uricchio, V. F. (2020). A detailed review study on potential effects of microplastics and additives of concern on human health. *International Journal of Environmental Research and Public Health*, *17*(4), 1212. https://doi.org/10.3390/ijerph17041212

Chen, G., Fu, Z., Yang, H., & Wang, J. (2020). An overview of analytical methods for detecting microplastics in the atmosphere. *TrAC Trends in Analytical Chemistry*, *130*, 115981. https://doi.org/10.1016/j.trac.2020.115981

Chen, Z., Carter, L. J., Banwart, S. A., & Kay, P. (2025). Microplastics in Soil–Plant Systems: Current Knowledge, Research Gaps, and Future Directions for Agricultural Sustainability. *Agronomy*, *15*(7), 1519. https://doi.org/10.3390/agronomy15071519

Commission Delegated Decision (EU) 2024/1441 of 11 March 2024 Supplementing Directive (EU) 2020/2184 of the European Parliament and of the Council by Laying down a Methodology to Measure Microplastics in Water Intended for Human Consumption, Official Journal of the European Union (2024). https://eur-lex.europa.eu/eli/dec_del/2024/1441/oj/eng

Crawford, C. B., & Quinn, B. (2017). Microplastic identification techniques. *Microplastic Pollutants*, 219–267. https://doi.org/10.1016/B978-0-12-809406-8.00010-4

Cruz-Salas, A. A., Álvarez-Zeferino, J. C., Universidad Autónoma Metropolitana, Tapia-Fuentes, J., Universidad Autónoma Metropolitana, Pérez-Aragón, B., Universidad Autónoma Metropolitana, Martínez-Salvador, C., El Colegio de la Frontera Sur, Vázquez-Morillas, A., Universidad Autónoma Metropolitana, Ojeda-Benítez, S., & Instituto de Ingeniería, Universidad Autónoma de Baja California. (2023). Measures to prevent cross-contamination in the analysis of microplastics: A short literature review. *Revista Internacional de Contaminación Ambiental*, *39*, 241–256. https://doi.org/10.20937/RICA.54740

Dr. Ulrike Braun. (2020). *Mikroplastik-Analytik*. https://bmbf-plastik.de/sites/default/files/2020-11/Statuspapier_Mikroplastik%20Analytik_Plastik%20in%20der%20Umwelt_2020.pdf

Dümichen, E., Eisentraut, P., Bannick, C., Barthel, A.-K., Senz, R., & Braun, U. (2017). Fast identification of microplastics in complex environmental samples by a thermal degradation method. *Chemosphere*, *174*, 572–584. https://doi.org/10.1016/j.chemosphere.2017.02.010

Eawag. (2024). *Mikroplastik in der Umwelt—Analytik von Mikroplastik*. https://www.eawag.ch/de/info/portal/themen-im-fokus/mikroplastik-in-der-umwelt/analytik-von-mikroplastik/

European Soil Data Centre. (2025). *Soil Sampling Protocol—ESDAC - European Commission*. https://esdac.jrc.ec.europa.eu/themes/soil-sampling-protocol

Furrer, A. (2025). *Illustration* [Graphic].

GERSTEL. (2025, April 27). *TED-GC/MS zum Nachweis von Mikroplastik*. https://www.gerstel.com/de/chemicals-materials/ted-gcms-microplastics

Gündoğdu, S., Akça, M. O., Gursoy, M., Yılmaz, M., Zhang, X., Rodríguez-Seijo, A., Bibi, A., Di Gioia, M. L., & Velimirovic, M. (2025). Microplastics in soil: A comprehensive review of analytical techniques. *Frontiers in Soil Science*, *5*, 1614075. https://doi.org/10.3389/fsoil.2025.1614075

Hidalgo-Ruz, V., Gutow, L., Thompson, R. C., & Thiel, M. (2012a). Microplastics in the marine environment: A review of the methods used for identification and quantification. *Environmental Science & Technology*, *46*(6), 3060–3075. https://doi.org/10.1021/es2031505

Hidalgo-Ruz, V., Gutow, L., Thompson, R. C., & Thiel, M. (2012b). Microplastics in the marine environment: A review of the methods used for identification and quantification. *Environmental Science & Technology*, *46*(6), 3060–3075. https://doi.org/10.1021/es2031505

Huang, Z., Hu, B., & Wang, H. (2023). Analytical methods for microplastics in the environment: A review. *Environmental Chemistry Letters*, *21*(1), 383–401. https://doi.org/10.1007/s10311-022-01525-7

ICBA. (2020). *Soil_sampling_FG*. https://www.fao.org/fileadmin/user_upload/faowater/docs/WASAG/Soil_sampling_FG.pdf

International Organization for Standardization. (2023). *ISO-24187-2023* (ISO 24187). https://cdn.standards.iteh.ai/samples/78033/ab8efdddef164bc0b1aff6b25bfb9669/ISO-24187-2023.pdf

ITRC (Interstate Technology Regulatory Council). (2023). *Sampling and analysis—Microplastics*. ITRC Microplastics Team. https://mp-1.itrcweb.org/sampling-and-analysis/

Jones, N. R., De Jersey, A. M., Lavers, J. L., Rodemann, T., & Rivers-Auty, J. (2024). Identifying laboratory sources of microplastic and nanoplastic contamination from the air, water, and consumables. *Journal of Hazardous Materials*, *465*, 133276. https://doi.org/10.1016/j.jhazmat.2023.133276

LabPlas project. (2024, March 14). Size definition of microplastics. *LabPlas*. https://labplas.eu/2024/03/14/size-definition-of-microplastics/

Lenz, Mayerhofer, & Obersteiner. (2022, December 31). *Handbook for sampling and sorting*. https://dtp.interreg-danube.eu/uploads/media/approved_project_output/0001/56/fc78aec3f977dfe372db93ed0423f2bc559955cf.pdf

Löder, M. G. J., & Gerdts, G. (2015). Methodology Used for the Detection and Identification of Microplastics—A Critical Appraisal. In M. Bergmann, L. Gutow, & M. Klages (Eds.), *Marine Anthropogenic Litter* (pp. 201–227). Springer International Publishing. https://doi.org/10.1007/978-3-319-16510-3_8

Loganathan, Y., & Kizhakedathil, M. P. J. (2022). A Review on Microplastics – An Indelible Ubiquitous Pollutant. *Biointerface Research in Applied Chemistry*, *13*(2), 126. https://doi.org/10.33263/BRIAC132.126

Maes, T., Jessop, R., Wellner, N., Haupt, K., & Mayes, A. G. (2017). A rapid-screening approach to detect and quantify microplastics based on fluorescent tagging with Nile Red. *Scientific Reports*, *7*(1), 44501. https://doi.org/10.1038/srep44501

Mintenig, S. M., Löder, M. G. J., Primpke, S., & Gerdts, G. (2019). Low numbers of microplastics detected in drinking water from ground water sources. *Water Research*, *159*, 434–445. https://doi.org/10.1016/j.watres.2019.04.080

Möller, J. N., Heisel, I., Satzger, A., Vizsolyi, E. C., & Oster, M. (2022). A protocol to purify soil samples for spectroscopic analysis of microplastics. *Environmental Toxicology and Chemistry*, *41*(4), 844–857. https://doi.org/10.1002/etc.5024

Munno, K., Lusher, A. L., Minor, E. C., Gray, A., Ho, K., Hankett, J., T Lee, C.-F., Primpke, S., McNeish, R. E., Wong, C. S., & Rochman, C. (2023). Patterns of microparticles in blank samples: A study to inform best practices for microplastic analysis. *Chemosphere*, *333*, 138883. https://doi.org/10.1016/j.chemosphere.2023.138883

Olbrich, S., & Schuhen, K. (2024). Mikroplastik-Analytik: Der lange Weg zum Detektions-Standard—Identifikation von Fehlerquellen und die Chance der Fluoreszenz-Mikroskopie. *Analytik News*. https://www.analytik.news

Sharma, P., Saha, R., Kumar, V., Tomar, R. S., & Bhattacharya, P. (2024). Sampling, separation, and characterization methodology for microplastics in various environmental matrices. *Current Opinion in Environmental Science & Health*, *37*, 100172. https://doi.org/10.1016/j.coesh.2023.100172

Sigma Aldrich. (2020, August 13). *Membrane Filters for Microplastics Analysis*. https://www.sigmaaldrich.com/US/en/technical-documents/technical-article/environmental-testing-and-industrial-hygiene/drinking-water-testing/membrane-filters-for-microplastics-analysis

Soil Health Institute. (2024, June 14). *SOP_SoilSampling-v1.2*. https://soilhealthinstitute.org/app/uploads/2023/05/SOP_SoilSampling-v1.2.pdf

Süssmann, J., Krause, T., Fischer, E. K., Walz, E., Greiner, R., Rohn, S., & Fritsche, J. (2025). Microplastics in fresh and processed seafood – A survey of products sold in Germany. *Food Control*, *179*, 111565. https://doi.org/10.1016/j.foodcont.2025.111565

Thompson, R. C., Courtene-Jones, W., Boucher, J., Pahl, S., Raubenheimer, K., & Koelmans, A. A. (2024). Twenty years of microplastic pollution research—What have we learned? *Science*, *386*(6720), eadl2746. https://doi.org/10.1126/science.adl2746

Wang, J., & Liu, X. (2019). Microplastics as contaminants in the soil environment: A mini-review. *Environmental Science and Pollution Research*, *26*(34), 22885–22900. https://doi.org/10.1007/s11356-019-05238-7

Wasser 3.0. (2025, August 24). *Standardisierte Probennahme bei der Mikroplastik-Analytik*. https://wasserdreinull.de/blog/standardisierte-probennahme-bei-der-mikroplastik-analytik/

Weber, F., & Kerpen, J. (2022). Underestimating microplastics? Quantification of the recovery rate of microplastic particles including sampling, sample preparation, subsampling, and detection using µ-Raman spectroscopy. *Environmental Pollution*, *316*(Part 2), 120686.

Wesch, C., Elert, A. M., Wörner, M., Braun, U., Klein, R., & Paulus, M. (2017). Assuring quality in microplastic monitoring: About the value of clean-air devices as essentials for verified data. *Scientific Reports*, *7*(1), 5424. https://doi.org/10.1038/s41598-017-05838-4

Whiting, S. & et al. (2022). A high-throughput, automated technique for microplastics detection, quantification, and characterization in surface waters using laser direct infrared (LDIR) spectroscopy. *Environmental Science and Technology*, *56*(24), 17345–17356. https://doi.org/10.1021/acs.est.2c03119

Withana, M., Senadheera, S., Gunatilake, S., & Rathnayake, U. (2024). Soil microplastic analysis: A harmonized methodology. *Critical Reviews in Analytical Chemistry*, *54*(1), 1–24. https://doi.org/10.1080/10643389.2023.2301052

Zobkov, M. B., & Esiukova, E. E. (2018). Microplastics in a Marine Environment: Review of Methods for Sampling and Analysis. *Oceanology*, *58*(1), 137–143. https://doi.org/10.1134/S0001437018010168

Index of Auxiliary Tools

The following tools were used in this project:

- Comet from Perplexity was used for summarizing reports and webpages, spell checking and formulating sentences more fluently
- ChatGPT was used to formulate thought-like sentences in continuous text
- ChatGPT was used to write definitions for the glossary
- DeepL was used for spell checking and translation
- DeepL Write was used to formulate sentences more fluently

Declaration of Honesty

«I hereby declare that any individual- work submitted for assessment is entirely the product of my own effort

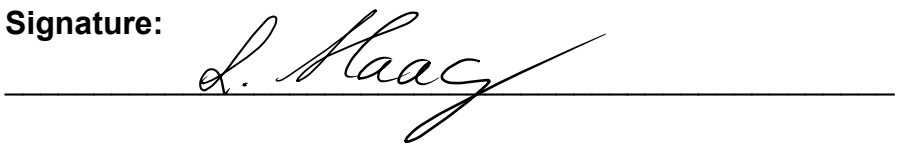
- that I have correctly cited all text passages that do not originate from me, in accordance with standard academic citation rules (e.g. APA or IEEE), and that I have clearly mentioned all sources used.
- that I have declared in footnotes or in an “Index of auxiliary tools” all aids used (AI assistance systems such as chatbots [e.g., ChatGPT], translation [e.g., DeepL] paraphrasing [e.g., Quillbot]) or programming applications [e.g., Github Copilot,
- that I have acquired all intangible rights to any materials I may have used, such as images or graphics, or that these materials were created by me.
- that the topic, the thesis or parts of it have not been used in an assessment of another module, unless this has been expressly agreed with the lecturer in advance and is stated as such.
- that I am aware that my work may be checked for plagiarism and for third-party authorship of human or technical origin (artificial intelligence).
- that I am aware that the FHNW School of Engineering will pursue a violation of this declaration of authenticity and that disciplinary consequences (reprimand or expulsion from the study program) may result from this. »

Windisch, 15.02.2025

Name:

Lukas Haag

Signature:



Appendix

A Flow Chart diagram

Downloadable flow chart of the microplastic analysis workflow.

https://drive.google.com/file/d/1ZfKdD-VNB4QznKIoSCiXTfgsVrShVK-o/view?usp=sharing