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COP
Circular Ocean-bound Plastic

Pathways for cleaning collected Ocean-bound Plastic

Report

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Report on Pathways for Clean-Up of the collected Ocean-bound Plastic

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Abstract

This report presents ongoing activities within Work Package 4 of the Circular Ocean-bound Plastic (COP) project, focusing on the development of effective cleaning methods for ocean-bound plastics (OBP) to prepare them for further processing, such as mechanical or chemical recycling. Through an extensive literature review, we identified two primary categories of cleaning technologies: conventional methods and ultrasonic washing systems, along with commonly used cleaning agents in both industrial and laboratory settings. The effectiveness of these methods largely depends on the type of contamination, particularly organic material, which is prevalent in marine-collected plastics.

Various cleaning agents were evaluated, including hydrogen peroxide (H_2O_2), Fenton's reagent, acid digestion, alkaline treatments, and surfactants. While H_2O_2 and acid-based methods showed some potential, they also posed challenges, such as incomplete organic removal or the degradation of certain plastics. On the other hand, biodegradable and eco-friendly surfactants, such as ECOSurf, emerged as promising alternatives due to their efficiency in removing oils, grease, and biofilms. The plastic samples collected from pilot areas were shredded to increase surface area for more effective cleaning. These samples were then cleaned using various chemical agents, such as acids, alkalis, oxidants, and surfactants, as well as physical methods, such as stirring or ultrasonication. Additionally, various cleaning parameters, such as temperature and time, were evaluated.

Our results indicated that alkaline-based cleaning methods and ultrasonication-assisted surfactant cleaning were the most effective in removing marine-based contaminants. While visual observations and quantitative analyses confirm the superior performance of alkaline and ultrasonication-based methods, spectroscopic techniques such as FTIR (Fourier Transform Infrared Spectroscopy) and Raman were less successful in evaluating cleaning effectiveness. The spectral data showed similar shapes and intensities across different treatments, suggesting that spectroscopic methods may not fully capture subtle variations in cleaning efficiency, especially when contaminants are not drastically altered or removed at the molecular level.

The study underscores the need for a multi-technique approach, combining spectroscopic analysis with visual inspection, and quantitative methods, to achieve a more comprehensive and accurate evaluation of cleaning performance.

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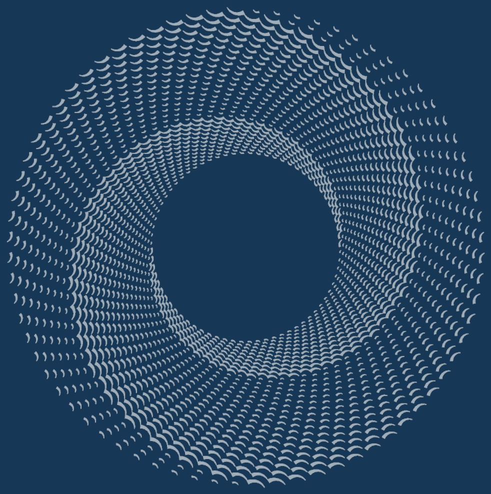
1.

Introduction



1. Introduction

Each year, 14 million tons of plastics enter the ocean, making up approximately 80% of the marine debris found in various aquatic environments, from surface waters to deep-sea sediments. The primary sources of plastic debris in the ocean are terrestrial, including urban and stormwater runoff, sewer overflows, littering, inadequate waste disposal and management practices, industrial activities, tire abrasion, construction activities, and illegal dumping. Plastic pollution in marine environments has severe consequences for marine organisms and ecosystems, leading to suffocation, entanglement, laceration, infections, and internal damage. Due to its inability to decompose, plastic persists for long periods, significantly disrupting marine ecosystems. This issue has escalated into a critical global crisis, with billions of plastic items accumulating into massive aggregations that constitute approximately 40% of the earth's oceanic expanse [1]. Moreover, microplastics are formed due to the breakdown of larger plastic debris into smaller particles. This fragmentation can occur through physical, chemical, and biological processes. Photodegradation, caused by UV radiation from sunlight, weakens plastics, while wave action, tides, and abrasion from sand and rocks further fragment them physically. Biodegradation occurs when certain marine organisms, such as bacteria or fungi, partially degrade plastics. Additionally, chemical degradation, influenced by salinity, pH changes, and oxidation, accelerates the breakdown process [2].

The Circular Ocean-bound Plastic (COP) project is dedicated to addressing the urgent issue of plastic pollution in the South Baltic Sea. In collaboration with partners from Denmark, Sweden, Germany, and Poland, the project aims to identify opportunities for collecting, recycling, and reusing ocean-bound plastic waste in the region. Three pilot areas have been selected for implementing project activities: Aarhus, Rostock, and Gdansk. Each pilot city acts as a testing ground for innovative initiatives and technologies aimed at removing OBP from the water column and developing solutions to mitigate local OBP generation. This report is a result of ongoing activities within Work Package 4 of the COP project, reflecting the continuous efforts to address plastic waste management and recycling strategies of the litters collected from pilot areas.

The main goal of this report is to explore clean-up pathways for collected ocean-bound plastic (OBP), focusing on methods for effective washing and preparation of collected samples for further processing, which is a crucial step in transforming raw plastic waste into materials suitable for recycling or repurposing. Proper cleaning and preparation ensure the plastic can be efficiently recycled or converted into new products without contamination or degradation. The collected OBP is first sorted by resin identification codes (RIC 1–7), as each type of plastic requires a specific recycling process tailored to its material properties.

The RICs are represented by the familiar recycling triangle symbol, which contains a number from 1 to 7. These codes are used to identify the type of plastic material in a product, helping with sorting and recycling. The numbers 1–6 refer to specific, widely used plastics, while 7 covers other materials, including newer, more specialised or mixed plastics. Table 1 shows a breakdown of the most common plastic types associated with these numbers.

Table 1 The most common plastic types associated with the Resin Identification Codes (RIC)

Name of polymer	Common products	% Global production (PlastsEurope, 2023)	RIC symbol
Polyethylene Terephthalate (PET)	Water bottles, cups, jars, trays	6.2%	01 PET
High-Density Polyethylene (HDPE)	Detergent bottles, grocery bag	12.2%	02 PE-HD
Polyvinyl Chloride (PVC)	Cleaning supply jugs, sheeting, automotive product bottles	12.7%	03 PVC
Low-Density Polyethylene (LDPE)	Bread bags, paper towels, tissue overwrap, trash bags	14.1%	04 PE-LD
Polypropylene (PP)	Juice bottles, straws, hangers, shipping bags	18.9%	05 PP
Polystyrene (PS)	Food packing containers, CD cases, cartons, toys, costume jewellery	5.2%	06 PS
Miscellaneous plastics (includes polycarbonate, polylactide, acrylic, acrylonitrilebutadiene, polyurethanes, fibreglass, and nylon)	SME Polycarbonate, nylon, ABS, acrylic, safety glasses, CDs, headlight lenses	30.7%	07 O

The process for washing of OBP samples will have to be designed to meet the following criteria: performance, economic, and environmental.

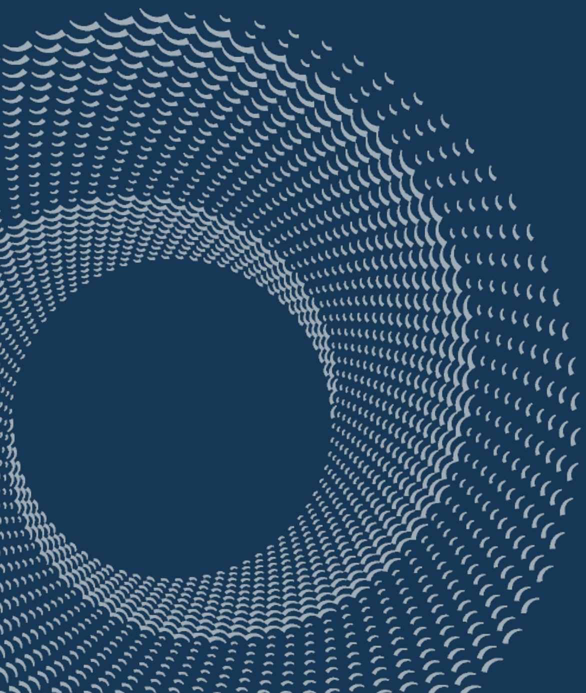
1. **Performance** - a viable washing process is essential for efficiently cleaning plastic within a short timeframe. The commercially preferred solution would likely be a continuous process, incorporating an automated feed for shredded plastic residue and enabling the continuous removal of oils, dirt, and other compounds. To optimise both time and efficiency, we aim to develop a one-step process that completes the cleaning within one hour.

2. **Economy** - To develop a sustainable method for recovering plastics, the process must ensure that the recovered plastics are cost-competitive. Generally, recycled plastics need to be priced lower than standard virgin-grade commercial plastics in order to be viable in the marketplace. This is why the cleaning methodology must be as cost-effective and straightforward as possible. Minimising complexity and expense in the cleaning process is crucial to ensure that the overall recovery of plastics remains economically viable and competitive with virgin-grade commercial plastics.

3. **Environmental Impact -** The washing system must be designed to comply with all environmental, safety, and health regulations. It should not produce or release any hazardous gases, liquids, or solids into the environment. Additionally, the aqueous washing process should operate at ambient temperature, ensuring that no localised overheating occurs during operation, which could pose safety risks.

2.

Review on existing cleaning methodologies



2. Review on existing cleaning methodologies

To identify the most suitable option, we conducted a thorough literature review of potential cleaning systems. This research helped evaluate various methods and determine the most effective and sustainable solution for our needs. We found, that technologies identified as having the potential for cleaning or washing plastic generally fall into two categories:

1. **Conventional Methods:** These involve the mechanical transport of plastics through a cleaning solution, utilising agitation and scrubbing processes.

2. **Ultrasonic Washing Systems:** These systems clean primarily through ultrasonic waves, either with or without additional mechanical agitation.

The effectiveness of cleaning solutions largely depends on the type of contamination present. Marine-collected samples are typically rich in organic material, which is why our approach focuses on removing organic matter. One widely used method for eliminating organics from environmental samples is oxidation with hydrogen peroxide (H_2O_2) [3][4]. However, the effectiveness of H_2O_2 has been questioned. Cole et al. [5] reported that after treating biogenic material with 35% H_2O_2 at ambient temperature for 7 days, only 25% of the material was removed. Similar results have been observed by Nuelle et al. [6], where hydrogen peroxide frequently bleached organic matter rather than completely removing it. Furthermore, the authors highlighted that H_2O_2 can degrade certain polymers, such as polyethylene (PE) and polypropylene (PP). A potential alternative to H_2O_2 oxidation is the use of Fenton's reagent. Fenton's reagent is a solution of hydrogen peroxide (H_2O_2) mixed with an iron catalyst, typically iron(II) sulfate ($FeSO_4$).

It is used in chemical oxidation processes to generate hydroxyl radicals (•OH), which are highly reactive and capable of degrading organic compounds, including pollutants and contaminants, which are typically recalcitrant in H_2O_2 [7]. Additionally, the reaction proceeds much faster, often requiring less than an hour to treat wastewater samples. Other potential methods for removing organic matter are derived from existing studies on extracting microplastics from biota. Acid digestion techniques, such as using hydrochloric acid (HCl) and nitric acid (HNO_3), have proven highly effective in breaking down organic material [4][8].

However, these acids can also damage plastic particles, leading to their degradation. Therefore, these methods must be carefully tested, with particular emphasis on evaluating the integrity of the plastic structure after the washing process. Alkaline digestion methods have also been explored, including the use of potassium hydroxide (KOH) and sodium hydroxide (NaOH). Mintenig et al. [9] successfully employed NaOH digestion to remove organic material from sewage sludge samples. However, Dehaut et al. [8] demonstrated that using 10 M NaOH can degrade certain plastics, such as PC and PET. While alkaline treatments are effective at breaking down humic acids, Bläsing and Amelung [10] noted that humins and other alkali-insoluble compounds in soils remain unaffected. These humins, which include raw organic matter, bacteria, and fungi, are likely present in sewage sludge and may not be fully removed by the aforementioned treatment processes [11].

Another important class of substances used for cleaning plastics before recycling are surfactants. These are particularly effective in removing organic contaminants such as oils, grease, and biofilms. Surfactants work by reducing the surface tension between the plastic surface and the contaminants, facilitating easier separation and removal of dirt and organic matter. Their ability to dislodge and break down these residues makes them essential in preparing plastics for further processing in recycling operations. Hanninen et al. [12] used sodium dodecyl sulphate (SDS) solution to remove plastic particles from thick natural waxes. Non-ionic surfactants, such as Triton X-100, are also widely used due to their ability to reduce surface tension without reacting with other substances. In fact, Triton X-100 has been widely used in cleaning products for almost 50 years, being an effective and economic emulsifying, wetting agent, dispersant, and solubiliser [13].

However, surface-active agents (or surfactants) can interact with eukaryotic cell membranes and cause biological damage, particularly at high concentrations [14]. Although, surfactants are effective in many applications due to their ability to alter surface tension and interact with cell membranes, they do pose a risk to biological systems at high concentrations by disrupting cellular membranes and inducing toxicity.

Therefore an increasing attention is given to a range of eco-friendly surfactants that are specifically designed to be both effective and sustainable. These surfactants are biodegradable, non-toxic, and made from renewable resources, making them gentler on both the environment and biological systems, including human skin and cell membranes. ECOSurf is a biodegradable, nonionic surfactant that is highly effective in cleaning applications due to its excellent wetting properties and ability to remove oily soils [15].

Finally, several studies have employed enzymatic digestion to remove organic material from plastics. Cole et al. [5] were the first to demonstrate the use of proteinase K for extracting microplastics from seawater. Their method achieved over 97% removal of biogenic material. However, the technique was limited to small sample volumes (0.2 g dry weight) and relied on proteinase K, a costly enzyme, making it impractical for processing large samples with high organic content. Moreover, the diversity of organic compounds in such samples likely necessitates the use of multiple enzymes to achieve complete breakdown. Mintenig et al. [9] implemented an enzymatic-based procedure to extract microplastics from wastewater samples, using protease, lipase, and cellulase—enzymes that are less expensive than proteinase K. Despite this cost advantage, their method required more than six days to complete, presenting a significant limitation in terms of efficiency. Considering these factors, we opted not to apply enzymatic treatments in our study.

Based on the literature study, we categorise cleaning agents into four main types, as outlined in Table 2: acids, alkalis, oxidants, and surfactants. While commercial cleaning products often combine these agents, their specific composition is tailored to the type of contaminant targeted for removal [16].

Table 2 Common cleaning agents and their general function

Type	Examples	General functions
Acids	HCl, HNO_3	• pH regulation • Dissolution of inorganic precipitates • Acidic hydrolysis of macromolecules
Alkalis	NaOH, KOH	• pH regulation • Alteration of surface charges • Alkaline hydrolysis of proteins • Catalysing saponification of fats
Oxidants	H_2O_2, Fenton's reagent	• Oxidation of organics • Disinfection
Surfactants	SDS, Triton X-100, ECOSurf	• Dispersion/suspension of deposits
Enzymes	Proteases, lipases	• Catalysing lysis of various substrates

Moreover, physical cleaning using ultrasonic waves, or mechanical agitation are often combined with chemical agents. The sound waves generate cavitation bubbles, which can dislodge dirt and organic matter from hard-to-reach surfaces. Ultrasonic cleaning employs high-frequency sound waves (typically between 20 kHz and 40 kHz) to create cavitation bubbles in a liquid cleaning solution. When these bubbles form and collapse, they generate intense pressure and temperature changes that can dislodge dirt, grime, and organic matter from surfaces. According to Huang et al. [17] this technique shows significant potential for applications in ship and marine engineering. Unlike traditional chemical, physical, or electrochemical methods, ultrasonic cleaning achieves a superior level of cleanliness without creating secondary pollution. It is capable of thoroughly cleaning and decontaminating every part of a structure, regardless of its size, shape, or complexity. Mechanical agitation involves physically moving the cleaning solution to enhance its contact with the surfaces being cleaned. This can be done through stirring, shaking, or using brushes.

The combination of ultrasonic waves or mechanical agitation, as well as chemical agents creates a highly effective cleaning strategy. By leveraging the strengths of each method, businesses can achieve superior cleanliness while maintaining efficiency and safety standards. This approach not only enhances the effectiveness of cleaning processes but also extends the lifespan of equipment and components by ensuring they are properly maintained.

3.

Experimental Design

3. Experimental Design

The objective of this activity was to identify and evaluate the most effective and sustainable cleaning method for removing contaminants from marine-collected plastic samples, focusing on conventional, ultrasonic, and chemical-assisted cleaning techniques.

Based on the literature review, there are three hypotheses for evaluating cleaning methods for plastic debris:

1. Conventional cleaning methods using mechanical agitation and surfactants can effectively remove surface-level contaminants but may be less effective for complex geometries.

2. Ultrasonic cleaning with and without chemical agents will be more effective in removing embedded contaminants without damaging the plastic structure.

3. Oxidative and acid digestion treatments will achieve higher organic removal rates but may affect the integrity of certain polymers.

3.1. Methods

The collected plastics were first sorted manually referring to their Resin Identification Codes (RIC 1-7), which classify plastics based on their polymer type. According to Andrady et al. [18], the largest amount of plastic produced in Europe is used for packaging applications. Consequently, the most common polymers found in the ocean include polypropylene (PP), polyethylene terephthalate (PET), polyethylene (PE), and polystyrene (PS). Therefore, we focused particularly on these types of samples in our analysis.

After sorting, the plastics were cut into smaller pieces, increasing the surface area for more efficient cleaning and easier handling in subsequent processes. The shredded plastics were then dried in an oven at 60°C for 24 hours. Following this, the plastics underwent a washing process using both chemical and physical methods.

The table 3 summarises all the methods (27) applied to clean the marine-collected plastic samples. A few pieces of cut plastic were placed in a flask and covered with 100 ml of the selected cleaning agent. Depending on the method, additional stirring or ultrasonication was used as physical cleaning aids.

For stirring, a magnetic stirrer was placed in the flask, ensuring a consistent stirring rate of 250 rpm. In the case of ultrasonication, the flask containing the plastic and cleaning medium was placed in an ultrasonic bath.

Table 3 Summary of Cleaning Methods

Method	Cleaning Agent	Physical cleaning	Duration
1	Tap water, cold	Stirring (250 rpm)	1 hour
2	Tap water, warm (40°C)	Stirring (250 rpm)	1 hour
3	1% v/v Triton X-100/cold tap water solution	Stirring (250 rpm)	1 hour
4	Warm tap water (40°C) + Triton X-100	Stirring (250 rpm)	1 hour
5	Tap water, cold	Ultrasonication	30 min
6	1% v/v Triton X-100/cold tap water solution	Ultrasonication	30 min
7	Tap water, cold	Ultrasonication	5 min
8	Tap water, cold	Ultrasonication	10 min
9	Tap water, cold	Ultrasonication	15 min
10	Water/2-propanol (9/1 v/v)	Stirring (250 rpm)	1 hour
11	Water/2-propanol (7/3 v/v)	Stirring (250 rpm)	1 hour
12	Water/2-propanol (5/5 v/v)	Stirring (250 rpm)	1 hour
13	30% H_2O_2	Stirring (250 rpm)	1 hour
14	30% H_2O_2	Stirring (250 rpm)	5 hour
15	1M NaOH	Stirring (250 rpm)	1 hour
16	10M NaOH	Stirring (250 rpm)	1 hour
17	1% HCl	Stirring (250 rpm)	1 hour
18	10% HCl	Stirring (250 rpm)	1 hour
19	Fenton reagent	Stirring (250 rpm)	1 hour
20	Fenton reagent	Stirring (250 rpm)	2 hour
21	Fenton reagent	Stirring (250 rpm)	3 hour
22	5% wt SDS	Stirring (250 rpm)	1 hour
23	10% wt SDS	Stirring (250 rpm)	1 hour
24	5% wt SDS	Ultrasonication	30 min
25	10% wt SDS	Ultrasonication	30 min
26	1% v/v ECOSurf/cold tap water solution	Stirring (250 rpm)	1 hour
27	1% v/v ECOSurf/cold tap water solution	Ultrasonication	30 min

After the washing process, the plastic samples were thoroughly rinsed with tap water to remove any remaining cleaning agents or residual dirt. Once rinsed, the plastics were placed in an oven and dried at 60°C for 24 hours to ensure that all moisture was removed.

3.2. Evaluation Parameters

The effectiveness of contaminant removal was assessed through a visual evaluation of the cleaning results. A 5-point scale was used to classify the cleaning effectiveness, where 1 indicated no visible effect, 2 represented minor cleaning with less than 25% removal, 3 denoted moderate cleaning with approximately 50% removal, 4 significant cleaning with most contaminants removed, and 5 indicated complete removal of all visible contaminants. Additionally, spectroscopic analyses (FTIR and Raman) were conducted to confirm surface cleanliness and detect any residual materials. For the most effective cleaning methods, weight reduction was measured post-treatment using gravimetric analysis to compare against initial contamination levels. To evaluate polymer integrity, samples were visually inspected for signs of discoloration, brittleness, or other indicators of degradation. For environmental and safety considerations, we assessed the biodegradability and eco-toxicity of all chemical agents, prioritising environmentally friendly options wherever possible.

4.

Results of plastic litters cleaning

4. Results of plastic litters cleaning

In the following section, we present a detailed analysis of the cleaning effectiveness, focusing on its variation based not only on the type of polymer but also on the source of the plastic, which was collected from various pilot areas. The results highlight how different polymers and their origins influence the performance of the cleaning methods employed, providing insights into the efficiency and limitations of the process for each material. By examining these variations, we aim to identify trends and potential challenges associated with specific polymer types and sources, offering valuable information for optimizing cleaning protocols across diverse applications and environmental contexts.

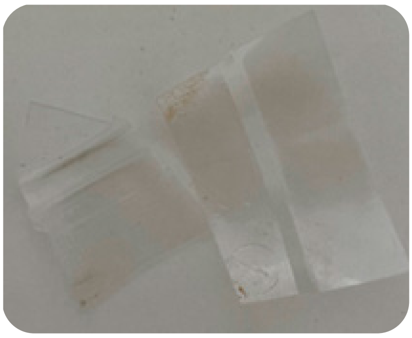
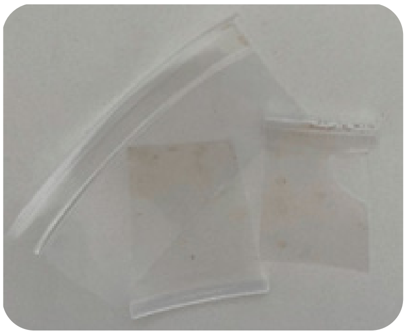
4.1. Polypropylene (PP)

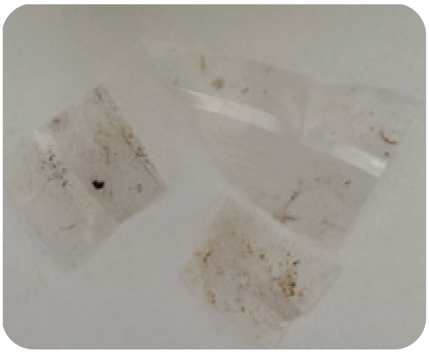
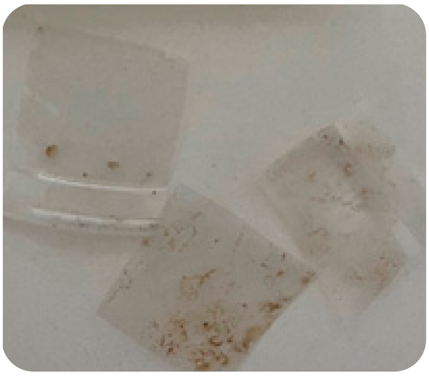
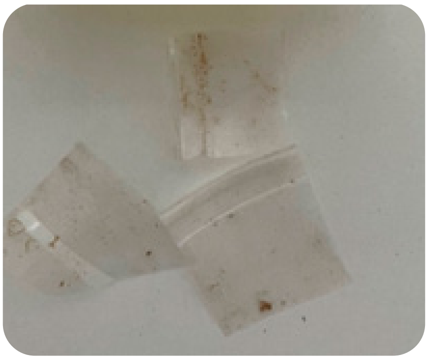
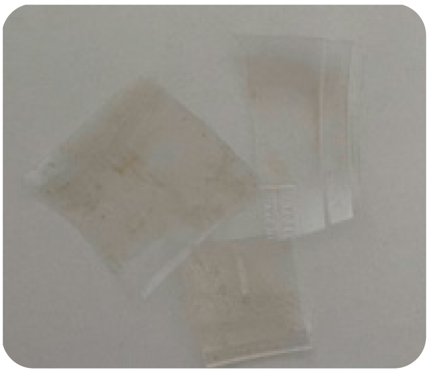
Fig. 1 A photo of plastic (PP) litter retrieved from the Aarhus River, showing the items after being rinsed with water and air-dried.

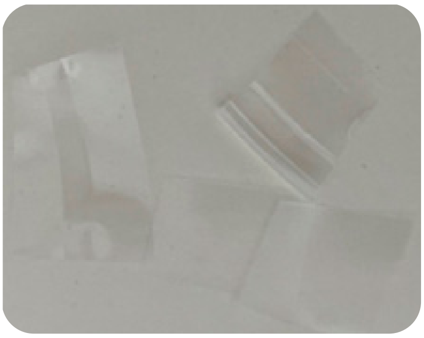
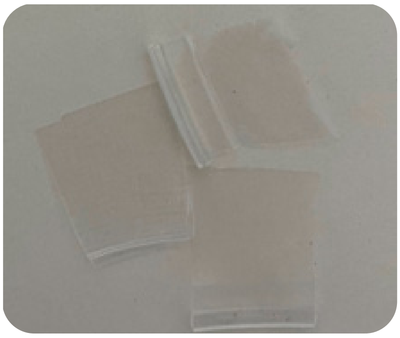
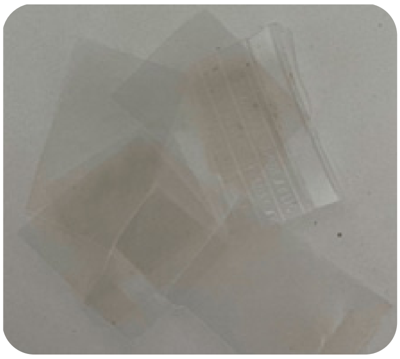
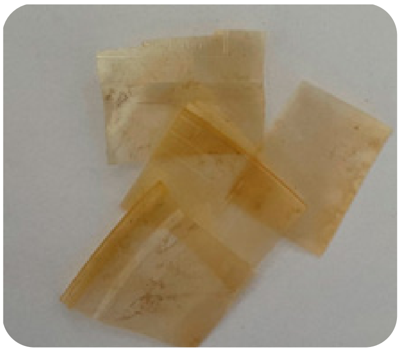
The plastic litter provided by Plast Center Danmark (PCD) partners consists of polypropylene (PP) cups collected from the Aarhus River (fig. 1). According to the partners, sediment adhered to the cups could not be removed with cold tap water alone. To address this, we tested all selected cleaning methods to identify the most effective and sustainable approach and determine which methods yield the best cleaning results. The effectiveness of each method was evaluated using visual evaluation, Raman spectroscopy, and FTIR spectroscopy. Table 4 provides a summary of all the approaches, both chemical and physical, applied for cleaning the PP samples. It includes the effect of washing, illustrated with photos taken after cleaning, and the corresponding points for cleaning effectiveness based on the 5-point scale.

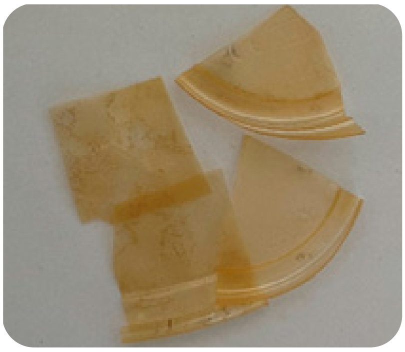
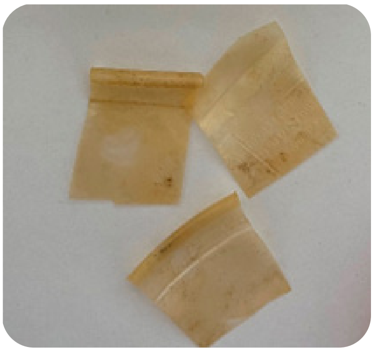
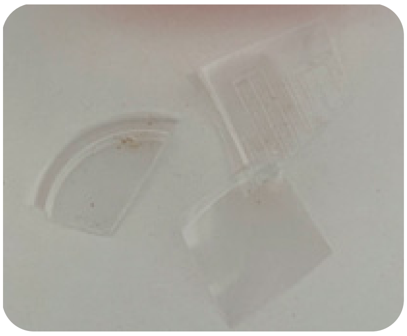
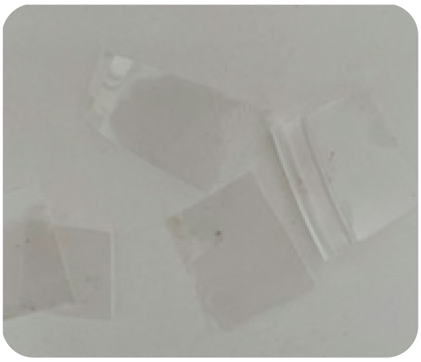
Table 4 Summary of all PP cleaning methods (the number in the sample name refers to the cleaning method), post-cleaning photos, and visual evaluation of cleaning effectiveness (scale 1-5)

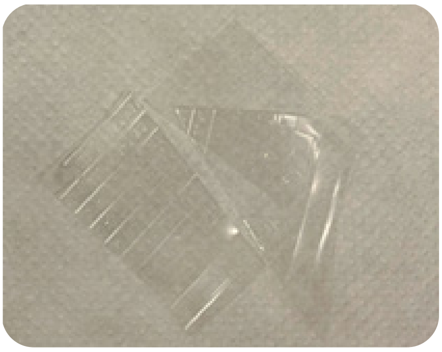
Sample name	Cleaning medium	Physical cleaning	Photo after cleaning	Effectiveness (1-5)
PP_1	Tap water, Cold	Stirring (250 rpm), 1h		1
PP_2	Tap water, Warm (40ºC)	Stirring (250 rpm), 1h		2
PP_3	Tap water, cold + Triton X-100	Stirring (250 rpm), 1h		1
PP_4	Tap water, warm (40ºC) + Triton X-100	Stirring (250 rpm), 1h		2

PP_5	Tap water, cold	Ultrasonic, 30 min		3
PP_6	Tap water, cold + Triton X-100	Ultrasonic, 30 min		4
PP_7	Tap water, cold	Ultrasonic, 5 min		2
PP_8	Tap water, cold	Ultrasonic, 10 min		2
PP_9	Tap water, cold	Ultrasonic, 10 min		2

PP_10	Water/2-propanol (9/1 v/v)	Stirring (250 rpm), 1h		1
PP_11	Water/2-propanol (7/3 v/v)	Stirring (250 rpm), 1h		1
PP_12	Water/2-propanol (5/5 v/v)	Stirring (250 rpm), 1h		2
PP_13	30% H_2O_2	Stirring (250 rpm), 1h		3
PP_14	30% H_2O_2	Stirring (250 rpm), 5h		5

PP_15	1M NaOH	Stirring (250 rpm), 1h		5
PP_16	10M NaOH	Stirring (250 rpm), 1h		5
PP_17	1% HCl	Stirring (250 rpm), 1h		4
PP_18	10% HCl	Stirring (250 rpm), 1h		3
PP_19	Fenton reagent	Stirring (250 rpm), 5h		2 + discoloration

PP_20	Fenton reagent	Stirring (250 rpm), 2h		2 + discoloration
PP_21	Fenton reagent	Stirring (250 rpm), 3h		2 + discoloration
PP_22	5% wt SDS	Stirring (250 rpm), 1h		4
PP_23	10% wt SDS	Stirring (250 rpm), 1h		4
PP_24	5% wt SDS	Ultrasonic, 30 min		4

PP_25	10% wt SDS	Ultrasonic, 30 min		4
PP_26	1% v/v ECOSurf/ cold tap water solution	Stirring (250 rpm), 1h		4
PP_27	1% v/v ECOSurf/ cold tap water solution	Ultrasonic, 30 min		5

As expected, the cleaning method using only water did not yield any noticeable cleaning effect, as the samples were covered with water-insoluble contaminants. The addition of ultrasonication provided a slight improvement; however, the results remained unsatisfactory, leading to the exclusion of methods 1, 2, 5, 7, 8, and 9 from those selected for subsequent phases. In evaluating the washing efficiency of polypropylene (PP) waste, it was found that combining physical and chemical methods—specifically, ultrasound with the surface-active agents Triton X-100, ECOSurf, and SDS—was highly effective.

Moreover, stronger chemical agents, such as sodium hydroxide and hydrochloric acid solutions, produced the most substantial cleaning results. Notably, these solutions were effective across various concentrations; therefore, to prioritise sustainability and safety, we selected only lower concentrations of 1M NaOH and 1% HCl for further steps.

Hydrogen peroxide also proved effective but required an extended washing time, increasing from 1 hour to 5 hours for optimal results. Conversely, treatments with the organic solvent isopropanol and Fenton's reagent were ineffective. Additionally, the discoloration observed in the PP samples after Fenton's reagent treatment indicated possible degradation, prompting us to exclude both this method and isopropanol from further analysis (methods 10, 11, 12, 19, 20, 21).

To further assess the effectiveness of the cleaning process, we conducted spectroscopic analyses using Raman and FTIR (Fourier Transform Infrared) spectroscopy. The structural monomer of polypropylene is propylene whose structural formula is shown in the image on the side of figure 2. The Raman spectrum of polypropylene consists of a few main bands due to the C-C, CH_3, and CH_2 bonds, as shown in figure 2.

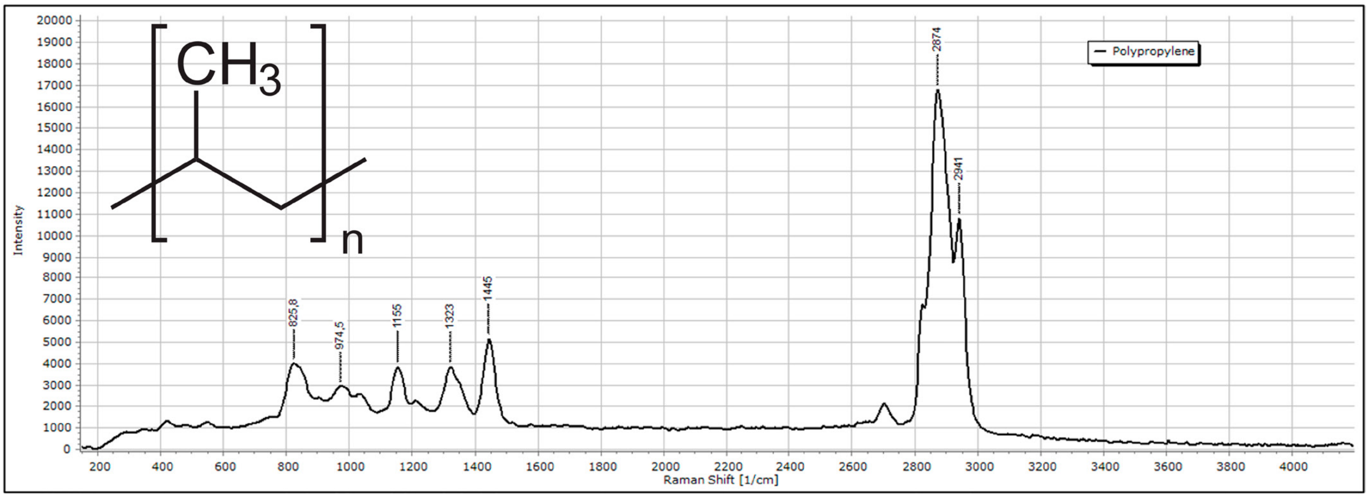


Fig. 2 Polypropylene Raman spectrum (source: https://physicsopenlab.org/2022/05/08/polymer-analysis-using-raman-spectroscopy/)

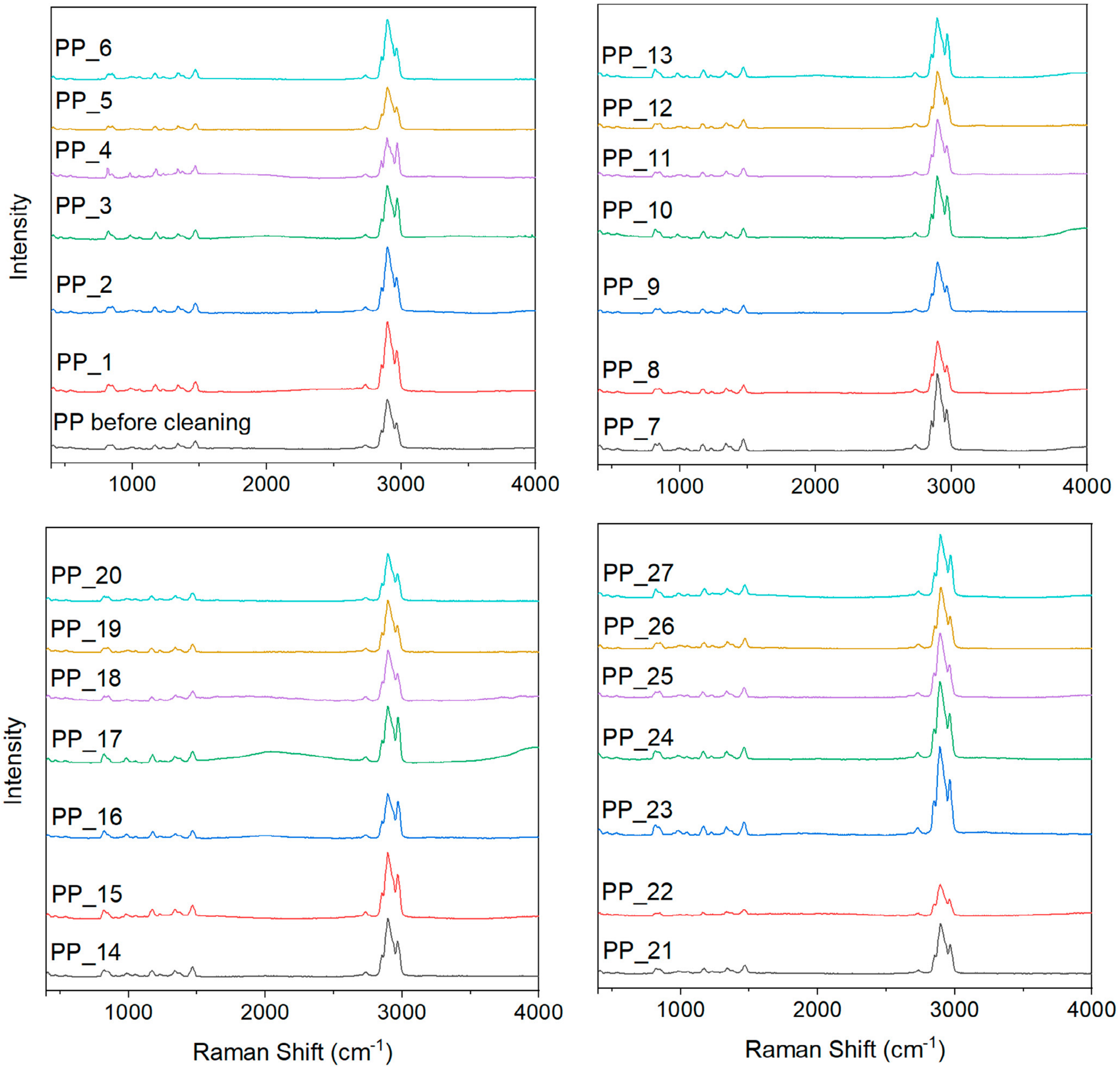


Fig. 3 The Raman spectroscopy results of the PP samples after cleaning

Figure 3 presents the Raman spectra of plastic litter structure, before (PP before cleaning) and after (PP_1-PP_27) cleaning. The PP spectrum typically reveals the presence of a few bands located at 2,800–3,000 cm^{-1}, attributed to the o stretching vibrations of C–H [19][20]. Additionally, the spectrum of polypropylene has characteristic vibrations at 1,105, 810–860 (double peak) cm^{-1}. PP was found to be essentially resistant to all cleaning media used. No new peaks or disappearance of bonds were observed in the Raman spectra of PP even at very high concentrations.

Table 5 FTIR peak assignments for polypropylene [21]

Wave number (cm^{-1})	Vibration type	Assignment
808	Stretching	C-C
840	Rocking	C-H
973	Rocking	CH_3
	Stretching	C-C
996	Rocking	CH_3
1,166	Stretching	C-C
	Wagging	C-H
	Rocking	CH_3
1,376	Symmetrical bending	CH_3
1,456	Symmetrical bending	CH_3
2,870	Stretching	CH_3
2,920	Asymmetrical stretching	CH_2
2,950	Asymmetrical stretching	CH_3

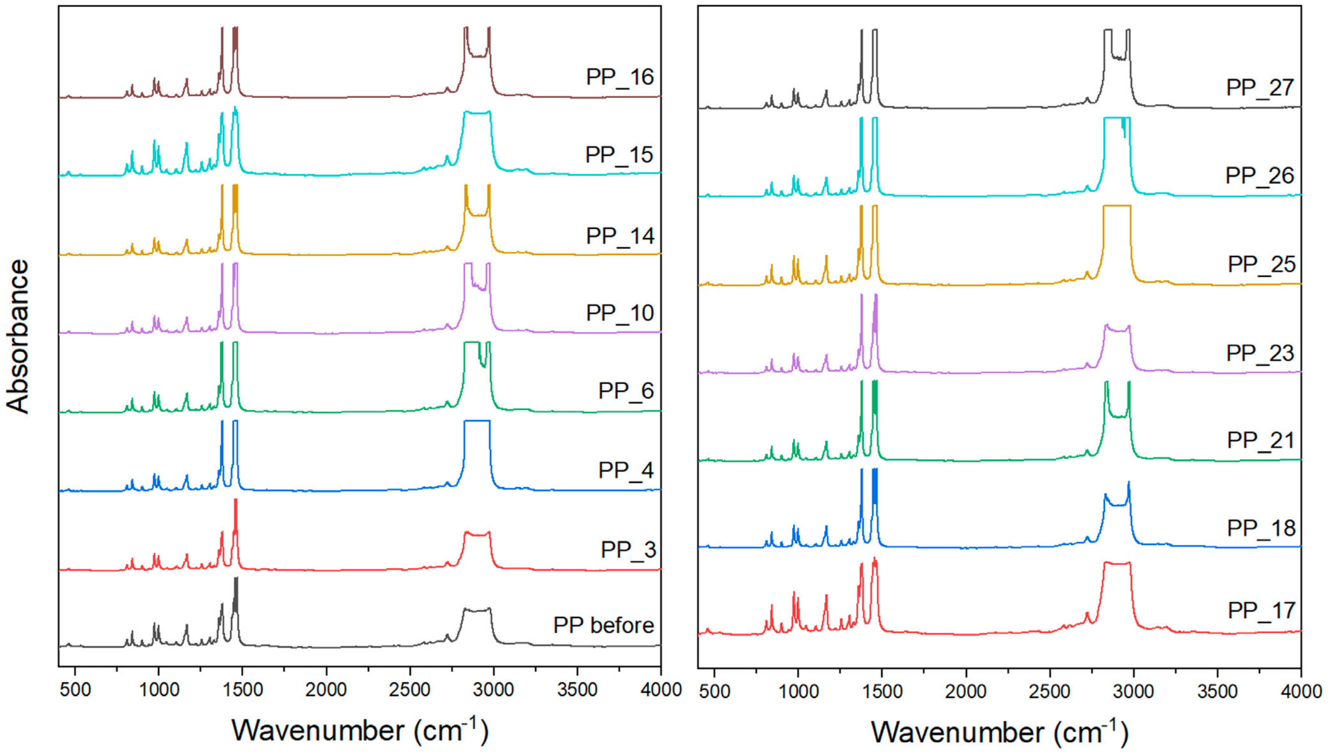


Fig. 4 The FTIR results of the selected PP samples after cleaning

Figure 4 presents the FTIR spectra for selected PP samples, all of which display similar features, including the characteristic peaks of PP listed in Table 5. The FTIR analysis confirmed that even the application of highly concentrated chemicals (10M NaOH, 30% H_2O_2, and 10% HCl) did not alter the polymer's structure. For instance, in oxidative treatments of PP, a change in surface polarity is typically indicated by the appearance of a carbonyl peak around 1,700 cm^{-1} [20].

However, this peak is absent in the spectra of our post-cleaning samples, indicating that no such structural modification occurred. Thus, it can be concluded that using strong chemicals effectively removes contaminants from the polymer surface without compromising its integrity.

When preparing plastic waste for further processing, such as recycling, shredding is a widely used technique. This process involves breaking down larger plastic items into smaller pieces before washing them. Shredding enhances efficiency and improves the quality of the cleaned material, as smaller plastic pieces are easier to wash and rinse thoroughly. Dirt, labels, and adhesives can be more effectively removed from smaller surfaces, and the reduced size allows cleaning agents to penetrate better, ensuring a more uniform cleaning process. Figure 5 illustrates the results of cleaning shredded PP samples using only tap water.

The findings demonstrate that the shredding process itself mechanically removes some contaminants from the PP surface and enables good cleaning efficiency using tap water alone as the cleaning medium. In contrast, cleaning larger plastic pieces proved ineffective using the same approach. However, this method presents challenges in separating the small plastic pieces from the contaminants. It requires the use of filters with pore sizes small enough to retain the plastic particles while allowing contaminants to pass through, which can complicate the process.

Fig. 5 The images of the sample after shredding and cleaning

4.2. Polyethylene terephthalate (PET)

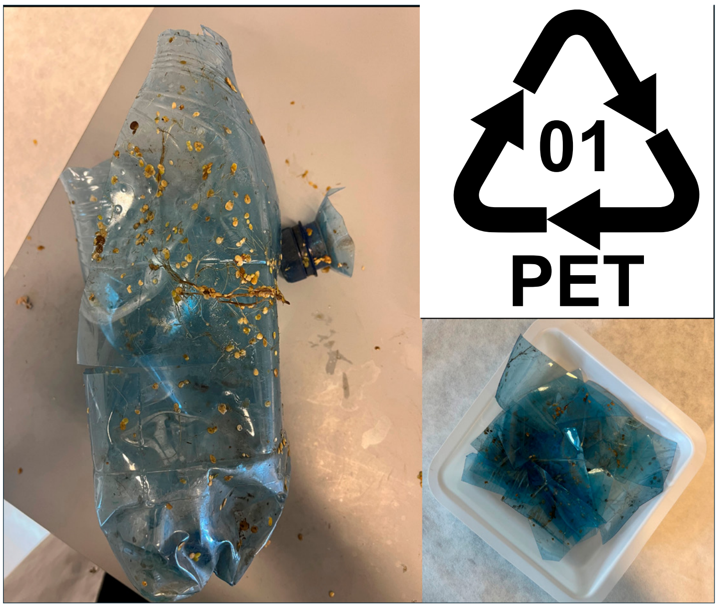


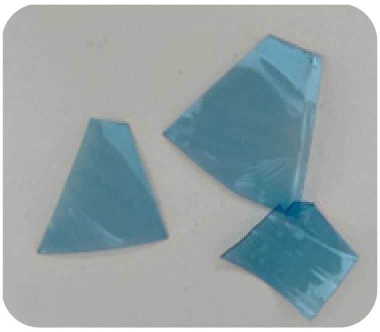
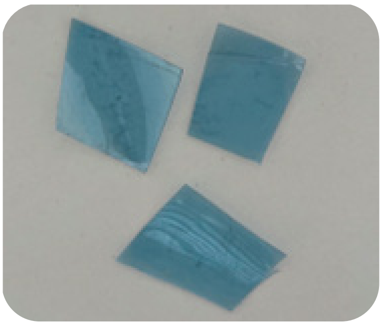
Fig. 6 The photo of plastic (blue PET) litter caught from the Motlawa river, rinsed with water and dried

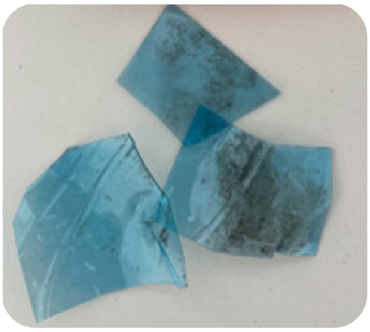
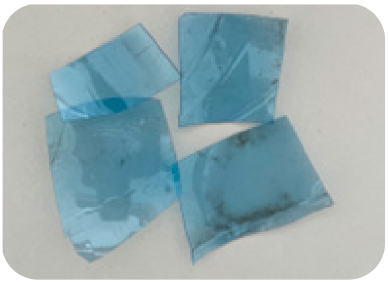
The plastic litter provided by Gdansk Sports Center (GSC) partner consists of PET bottles collected from Gdansk pilot area (fig. 6). For PET cleaning, wassessed 11 cleaning methods that were identified as promising in previous evaluation. Similar to the PP cleaning process, the effectiveness of the methods was evaluated using visual inspection (table 6), Raman spectroscopy, and FTIR spectroscopy. Interestingly, the washing effect was sometimes assessed differently for PET compared to PP. This discrepancy may be attributed to factors such as the different origins of the plastic waste, varying types of contaminants, polymer polarity, distinct interactions between the plastic and contaminants, and/or differences in the duration the plastic spent in the aquatic environment.

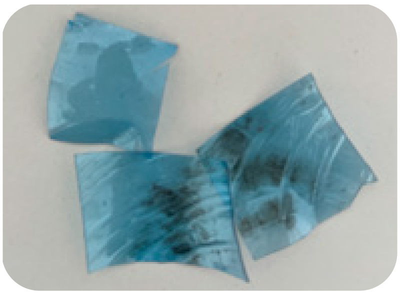
One highly effective cleaning method for PET bottles involved washing them under ultrasonication in a water bath with the addition of Triton X-100 and ECOSurf. This approach successfully removed contaminants without leaving any visible residue on the plastic surface. In this case, Triton X-100 and ECOSurf were found to be more effective compared to another surfactant, SDS, which only resulted in a minor cleaning effect. Therefore, methods 22, 23, 24, 25 were excluded from further analysis. Notably, 1M NaOH also showed promising results, but it was unable to completely remove all visible contaminants from the PET surface. The cleaning results with the hydrochloric acid solution were unsatisfactory. While it was highly effective in removing contamination from Danish PP (Aarhus River), in this case, it resulted in almost no noticeable cleaning effect.

If a contaminant is more effectively removed by a surfactant combined with ultrasonication than by acid or base treatments, it suggests that the substance may be primarily an organic or hydrophobic material, such as biofilm residues or hydrophobic organic particles. In contrast, acids and bases primarily disrupt mineral or ionic contaminants or degrade certain organic materials through hydrolysis, but they may not affect hydrophobic or lipid-based substances as efficiently without the action of a surfactant [16]. Finally, hydrogen peroxide once again required an extended treatment time to effectively address the plastic contaminants, with 5 hours needed for optimal results. As a result, we have excluded the shorter 1-hour hydrogen peroxide treatment (method 13) from further cleaning methodologies.

Table 6 Summary of all PET washing methods (the number in the sample name refers to the cleaning method), photos after washing and visual assessment of washing effectiveness (scale 1-5)

Sample name	Cleaning medium	Physical cleaning	Photo after cleaning	Effectiveness (1-5)
PET_3	Tap water, cold + Triton X-100 (1% v/v)	Stirring (250 rpm), 1h		3-4
PET_6	Tap water, cold + Triton X-100 (1% v/v)	Ultrasonic, 30 min		5
PET_15	1M NaOH	Stirring (250 rpm), 1h		4

PET_17	1% HCl	Stirring (250 rpm), 1h		2
PET_13	30% H_2O_2	Stirring (250 rpm), 1h		2
PET_14	30% H_2O_2	Stirring (250 rpm), 5h		4
PET_22	5% wt SDS	Stirring (250 rpm), 1h		1-2
PET_23	10% wt SDS	Stirring (250 rpm), 1h		2-3

PET_24	5% wt SDS	Ultrasonic, 30 min		1-2
PET_25	10% wt SDS	Ultrasonic, 30 min		3
PET_27	1% v/v ECOSurf/tap water solution, cold	Ultrasonic, 30 min		5

Polyethylene terephthalate (PET) is a thermoplastic polyester resin widely used in food contact applications. The structural formula of its monomer is illustrated in the inset of figure 6.

PET's material properties vary based on production methods, allowing it to exist in either an amorphous (transparent) form or a semi-crystalline (opaque, white) form. Besides its application in food packaging, PET is valued for its excellent electrical properties, chemical resistance, and stability at high temperatures. Figure 7 presents the Raman spectrum of PET.

The spectrum shows distinct peaks, with bands near 3,000 cm^{-1} corresponding to C-H bond stretching frequencies. The prominent peak around 1,700 cm^{-1} represents the C=O bond, while the peak near 1,600 cm^{-1} is associated with the C-C bond within the aromatic ring.

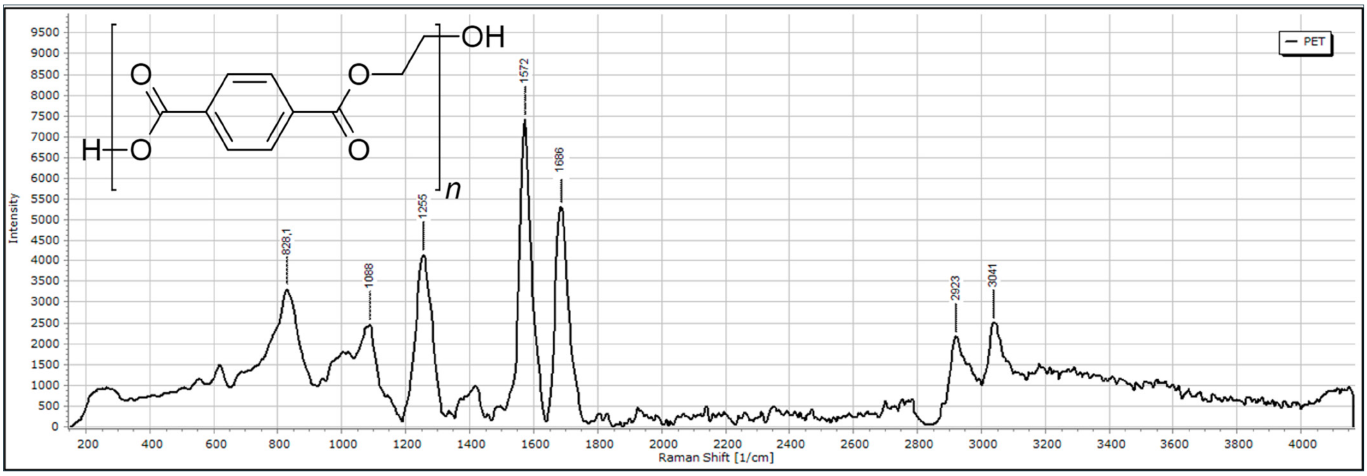


Fig. 7 PET Raman spectrum (source: https://physicsopenlab.org/2022/05/08/polymer-analysis-using-raman-spectroscopy/)

Figure 8 displays a series of Raman spectra for post-cleaning PET samples, and a control one before cleaning. The characteristic peaks of PET are visible across the spectra, indicating similar structural features in each sample. For instance, the prominent peaks, including those near 1,600 cm^{-1} (related to C-C bonds in the aromatic ring) and around 1,700 cm^{-1} (related to C=O stretching in carbonyl group) are consistently visible across samples, signifying that the PET backbone is unchanged, and the PET structure has not been significantly altered by the cleaning methods. If there is a reduction in overall intensity or clarity of peaks post-cleaning, it could suggest a removal of surface contaminants rather than a change in the polymer structure itself. However, these spectra mostly display consistent peak intensities, which implies that surface contaminants may not significantly interfere with the PET signal, or that they were effectively removed without damaging the polymer.

Based on peak clarity and baseline smoothness, samples PET_27, PET_6, PET_15, and PET_14 appear to be the most effectively cleaned, showing clear and distinct spectra.

These treatments likely removed contaminants well without leaving residues. On the other hand samples PET_13, PET_17, and PET_3 exhibit minor spectral distortions, which could indicate the presence of residual contaminants or incomplete cleaning.

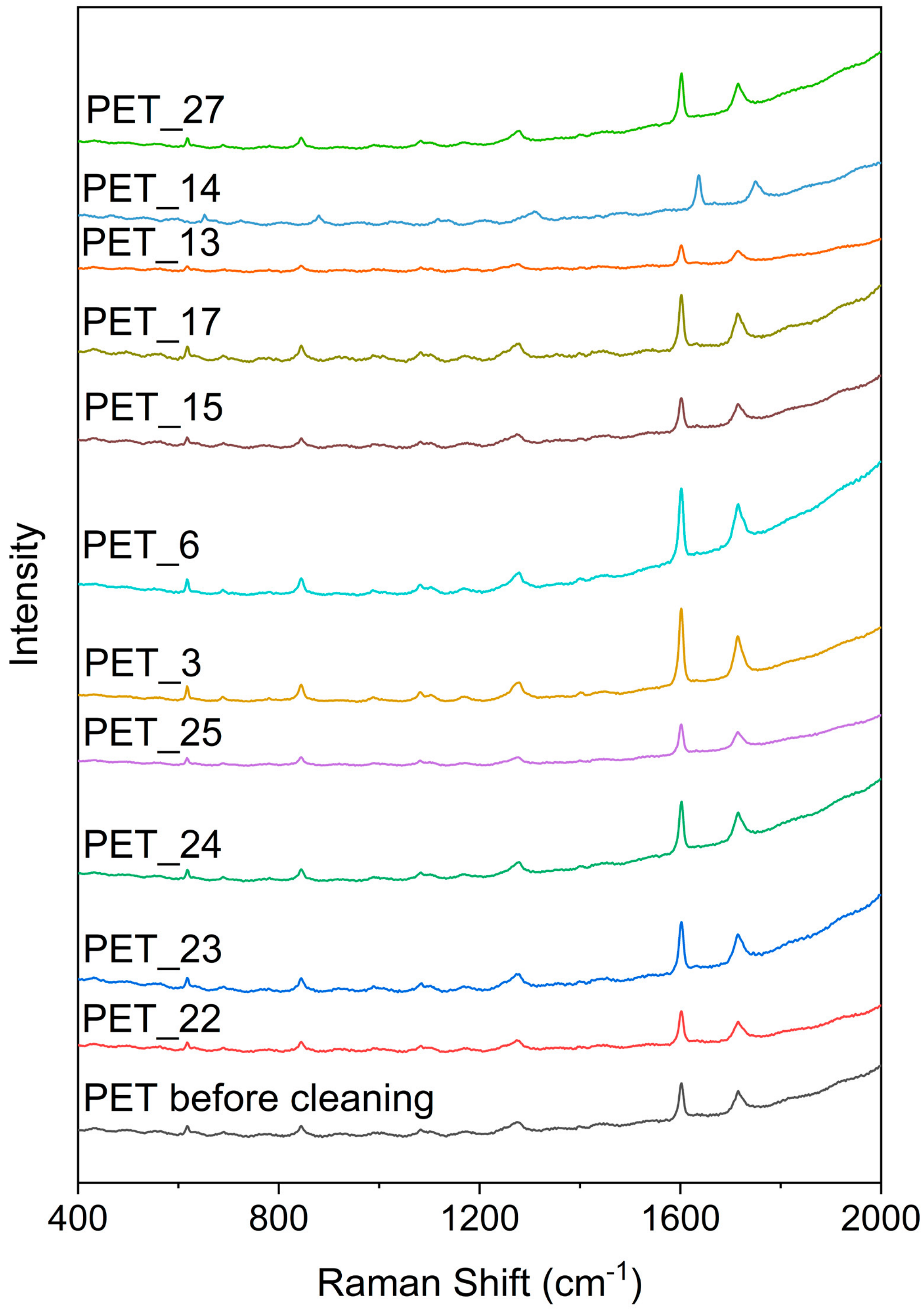


Fig. 8 The Raman spectroscopy results of the PET samples after cleaning

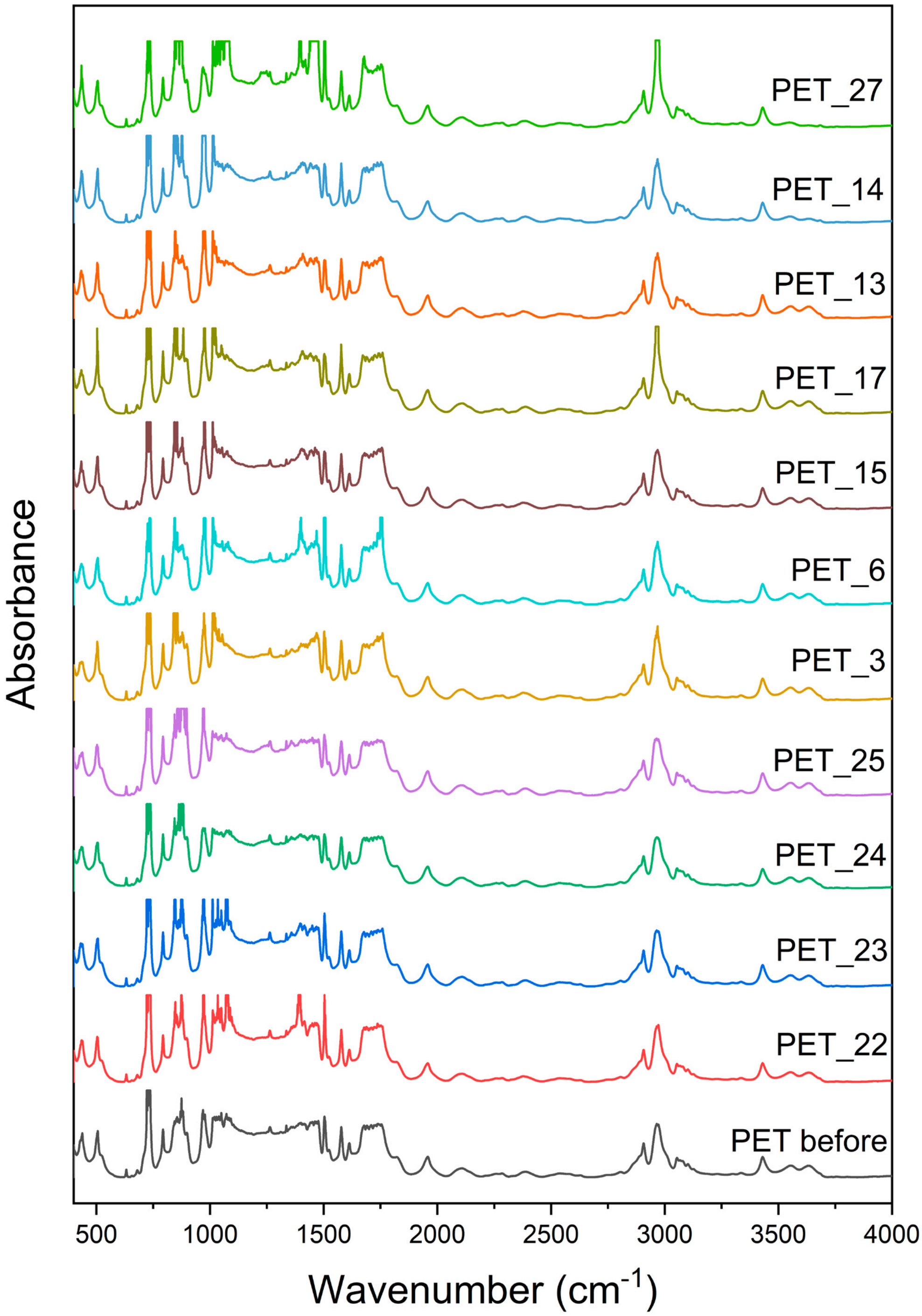


Fig. 9 The FTIR results of the PET samples after cleaning

Figure 9 presents the FTIR spectra for PET samples, all of which display similar features, including the characteristic peaks of PET listed in Table 7.

Table 7 FTIR peak assignments for PET [22][23]

Wave number (cm^{-1})	Vibration type	Assignment
700 - 900	Out-of-plane bending	Aromatic (C-H)
1,000 - 1,200	In-plane bending and stretching	Aromatic (C-C)
1,342	Stretching	C-O
1,453 & 1,410	Bending and wagging	C-H
1,577 & 1,504	Stretching	Aromatic (C=C)
1,730	Stretching	C=O
2,969 & 2,908	Symmetrical stretching	C-H
3,054	Symmetrical stretching	Aromatic (C-H)

In all post-cleaning spectra, the key peaks around 1,700 cm^{-1} (C=O stretch) and 3,000 cm^{-1} (C-H stretch) appear largely unchanged, suggesting that none of the cleaning methods caused degradation to the primary PET structure. PET_27, PET_14, and PET_6 show relatively clean and sharp spectra, suggesting effective removal of contaminants while preserving PET integrity.

Samples like PET_15 and PET_3 have some irregularities in their spectra, which could indicate minor residues or less effective cleaning. As mentioned earlier, surfactants like Triton X-100 and ECOSurf combined with ultrasonication are generally effective in removing organic contaminants without damaging the polymer structure. Samples treated with this method (e.g., PET_27, PET_6) show clean, well-defined spectra. At this stage of the research, we have identified six cleaning methods that consistently deliver the best results, depending on the type of contamination.

These methods include three surfactant-based approaches (methods 3, 6, and 27), an oxidation method (method 14), an alkaline method (method 15), and an acid-based method (method 17). Each of these methods has demonstrated high effectiveness in removing contaminants, making them the most promising candidates for further analysis and potential application.

4.3. Polyethylene (PE)

Fig. 10 The photo of plastic foil caught from the Motlawa river, rinsed with water and dried

Another item of waste retrieved from the Motława River (Gdansk pilot area) for analysis is a thin piece of plastic, which appears to be either a plastic bag or a plastic wrap (fig. 10). Since the sample lacked a Resin Identification Code (RIC), which would typically indicate the type of plastic material, we performed FTIR, Raman, and TGA analyses to identify the material. Plastic wrap is usually made from polyvinyl chloride (PVC), while plastic bags are made usually from polyethylene (PE). However, the type of polyethylene used can vary:

- **Low-Density Polyethylene (LDPE)**: This is used for soft, flexible plastic bags, such as grocery or sandwich bags. LDPE bags are less rigid and stretch easily.

- **High-Density Polyethylene (HDPE)**: This is a tougher material and is often used for thicker, more durable bags, like supermarket or shopping bags. HDPE has a more crinkly feel compared to LDPE.

Using Raman spectroscopy and FTIR, it is possible to determine the material composition of a sample and identify whether it is polyethylene or polyvinyl chloride. Polyethylene, with the chemical formula $(C_2H_4)_n$, exhibits four characteristic peaks in FTIR spectra due to vibrations of the C-H and CH_2 functional groups within its polymer structure. Specifically, these include the C-H asymmetrical stretching vibration at 2,920 cm^{-1}, the C-H symmetrical stretching vibration at 2,850 cm^{-1}, the CH_2 scissoring vibration at 1,460 cm^{-1}, and the CH_2 rocking vibration at 720 cm^{-1} [24]. In contrast, PVC, which is produced through the polymerization of vinyl chloride monomers, has chlorine atoms bonded to carbon in its structure.

This composition results in an FTIR spectrum with peaks similar to those of polyethylene but with additional unique peaks. Notably, PVC displays a peak at 1,250 cm^{-1}, attributed to the bending vibration of C−H near the chlorine atom, and peaks in the range of 600–650 cm^{-1}, which correspond to the C−Cl gauche bond [25]. The FTIR spectra of our samples (fig. 14) display all the characteristic peaks associated with polyethylene and show no peaks associated with carbon-chlorine (C−Cl) bonds.

Based on this spectral analysis, we conclude that the sample is composed of polyethylene. To further determine whether the plastic foil sample is composed of HDPE or LDPE, we conducted thermogravimetric analysis (TGA) to assess its decomposition temperature. The observed decomposition temperature, which begins around 270°C (fig. 11), suggests that the material is more likely to be LDPE. Typically, HDPE decomposes at a higher temperature range, usually beginning around 350–400°C [26]. This difference in thermal stability provides a reliable indicator for distinguishing between LDPE and HDPE. It further confirms that the sample is not PVC, as the thermal degradation exhibited only a single step in the TGA curve, whereas PVC typically shows two distinct degradation steps [27].

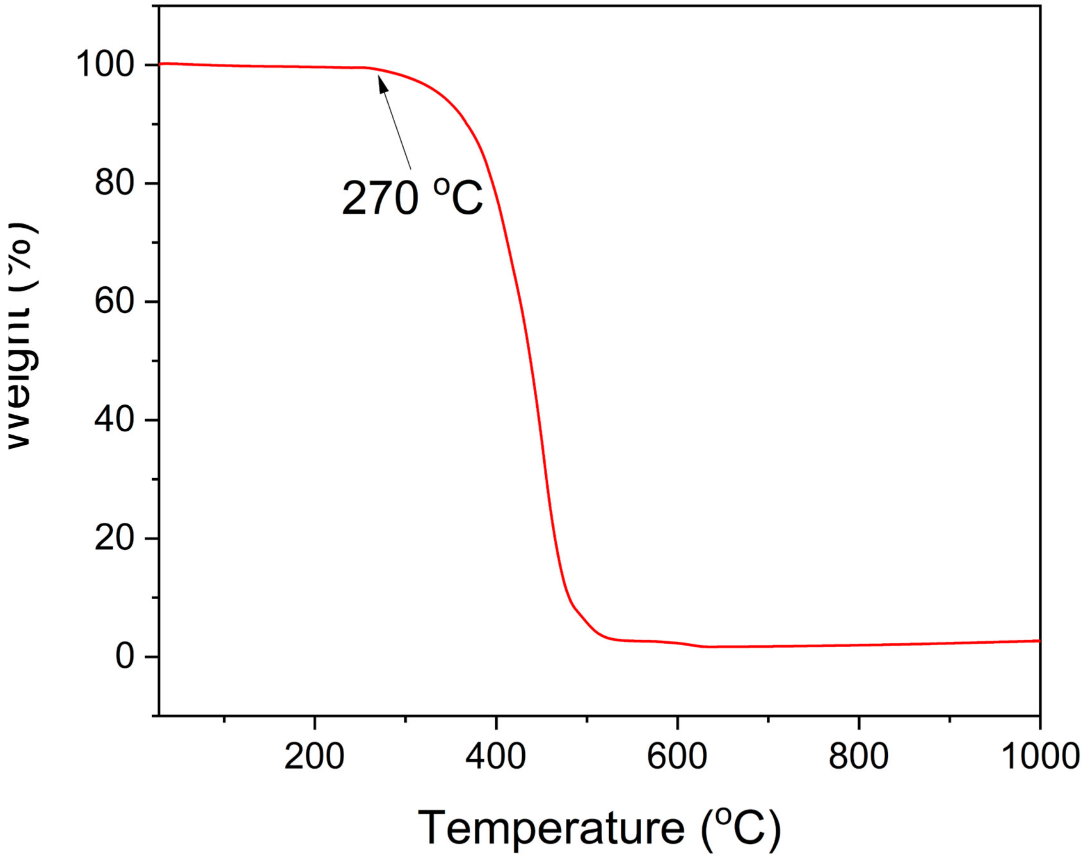


Fig. 11 The TGA curve for the tested plastic sample

Table 8 Summary of all PE washing methods, photos after washing, and visual assessment of washing effectiveness (scale 1-5)

Sample name	Cleaning medium	Physical cleaning	Photo after cleaning	Effectiveness (1-5)
PE_3	Tap water, cold + Triton X-100 (1% v/v)	Stirring (250 rpm), 1h		2
PE_6	Tap water, cold + Triton X-100 (1% v/v)	Ultrasonic, 1 h		4-5
PE_15	1M NaOH	Stirring (250 rpm), 1h		3
PE_17	1% HCl	Stirring (250 rpm), 1h		3

PE_14	30% H_2O_2	Stirring (250 rpm), 5h		4
PE_27	1% v/v ECOSurf/tap water solution, cold	Ultrasonic, 1h		4-5

Firstly, it is important to emphasise that all methods involving ultrasonication were in this case extended to a duration of up to 1 hour, as the initial 30 minutes resulted in only a minimal cleaning effect. Based on visual observations (table 8), the most effective cleaning results for PE were achieved using methods that incorporated ultrasonication (PE_6, PE_27).

The method relies on high-frequency sound waves that generate microscopic cavitation bubbles in the cleaning liquid. These bubbles collapse with high energy, creating localised mechanical forces that can effectively dislodge dirt and contaminants even from hard-to-reach areas. Therefore, it seems like ultrasonication is an excellent cleaning option for foil with intricate surfaces, including small nooks and crannies where dirt tends to accumulate.

Additionally, for optimal washing of the foil, it is beneficial to cut it into smaller pieces to improve access to all surfaces. Methods that relied on stirring as a physical aid demonstrated the lowest cleaning effectiveness (PE_3, PE_17, PE_15). Acid treatment (method 17) was therefore excluded from the cleaning methods due to its consistently moderate or weak performance. In contrast, H_2O_2 achieved better results; however, this improvement was likely due to the longer stirring time compared to other methods, rather than the inherent effectiveness of H_2O_2 itself. For this reason, we excluded method 14 from consideration due to the significantly longer time required to achieve a satisfactory cleaning effect. As highlighted in the introduction, time efficiency is one of the critical parameter in our evaluation of cleaning methods.

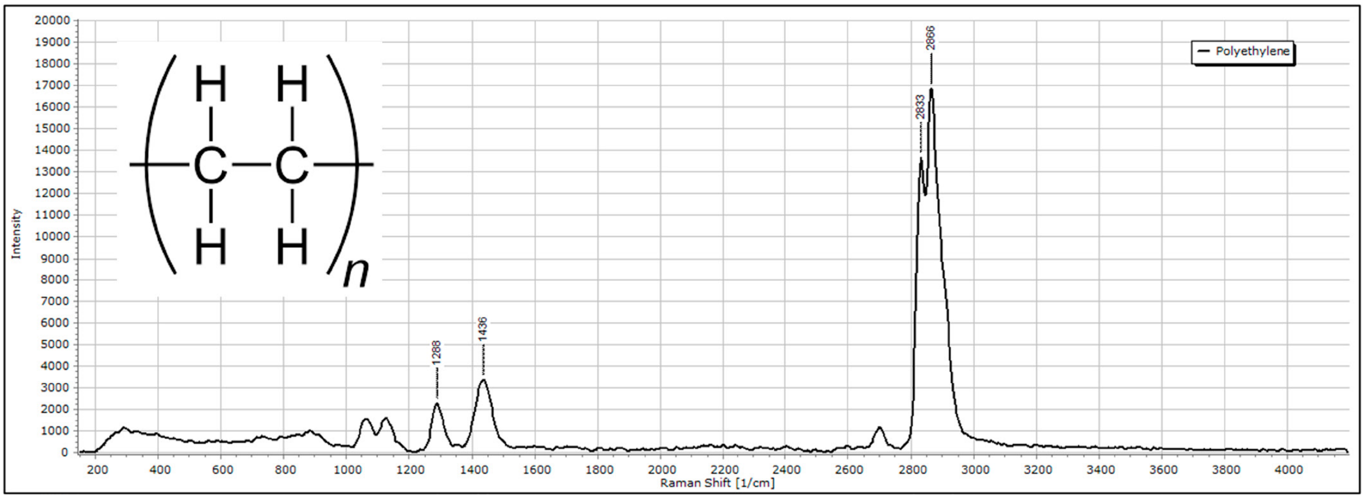


Fig. 12 PE Raman spectrum (source: https://physicsopenlab.org/2022/05/08/polymer-analysis-using-raman-spectroscopy/)

Polyethylene, the simplest synthetic polymer, is the most widely used plastic due to its versatility and cost-effectiveness. Its chemical structure is represented by the formula $(-C2H4-)_n$. The Raman spectrum of polyethylene, shown in figure 12, highlights characteristic vibrational bands. These include the stretching vibrations of C-H bonds around 3,000 cm^{-1}, bending and twisting vibrations of C-H bonds near 1,300 cm^{-1} and 1,400 cm^{-1}, and the stretching vibrations of C-C bonds in the range of 1,000 to 1,200 cm^{-1}[28]. These features are indicative of the polymer's structural and bonding characteristics.

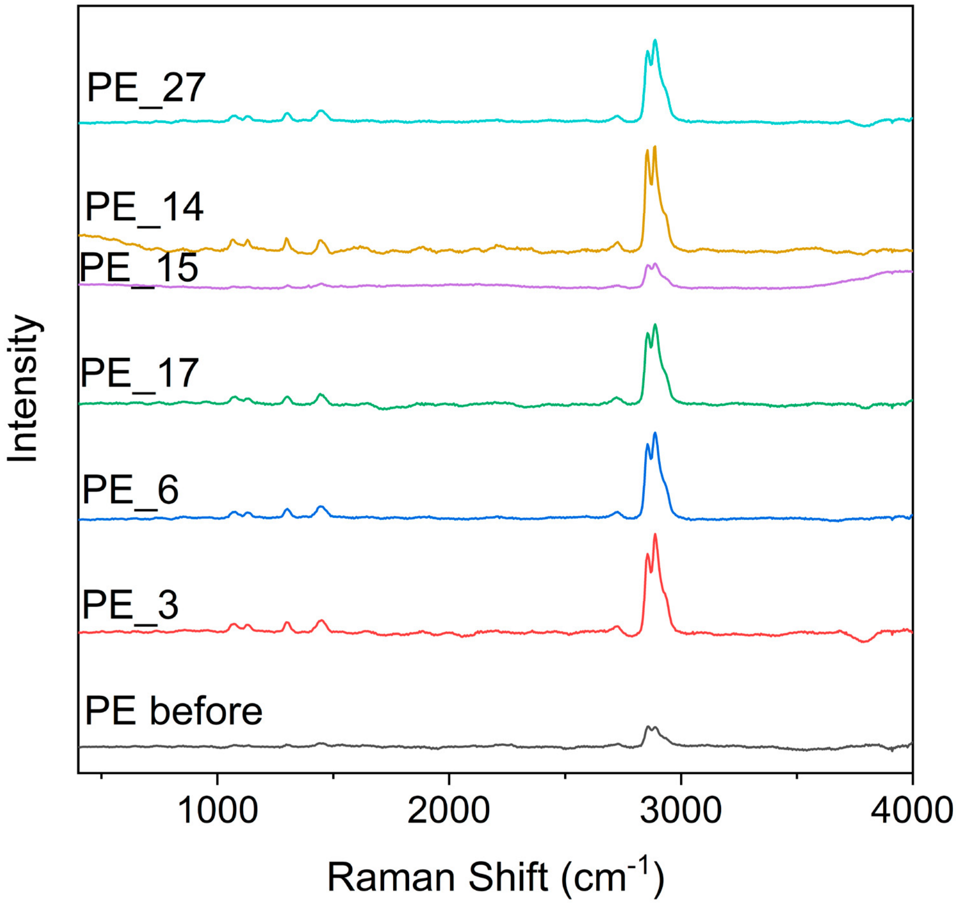


Fig. 13 The Raman spectroscopy results of the PE samples after cleaning

To analyse the cleaning effectiveness based on the Raman spectra, we compared the spectra of each treated polyethylene (PE) sample (PE_3, PE_6, PE_14, PE_15, PE_17, and PE_27) with the one before cleaning (fig. 13). All cleaned samples display improved intensity and clarity of characteristic polyethylene peaks, particularly in the C-H stretching and bending regions. This indicates the effective removal of surface contaminants to varying degrees. The spectrum for PE_6 and PE_27 indicates the best cleaning performance, with sharp and intense peaks corresponding to pure polyethylene.

Table 9 FTIR peak assignments for PE [29]

Wave number (cm^{-1})	Vibration type	Assignment
720 - 730	Rocking	C-CH$_2$
1378	Symmetric bending	C-CH$_3$
1473 &1463	Bending	C-H
2851	Symmetric stretching	C-H
2919	Asymmetric streching	C-H

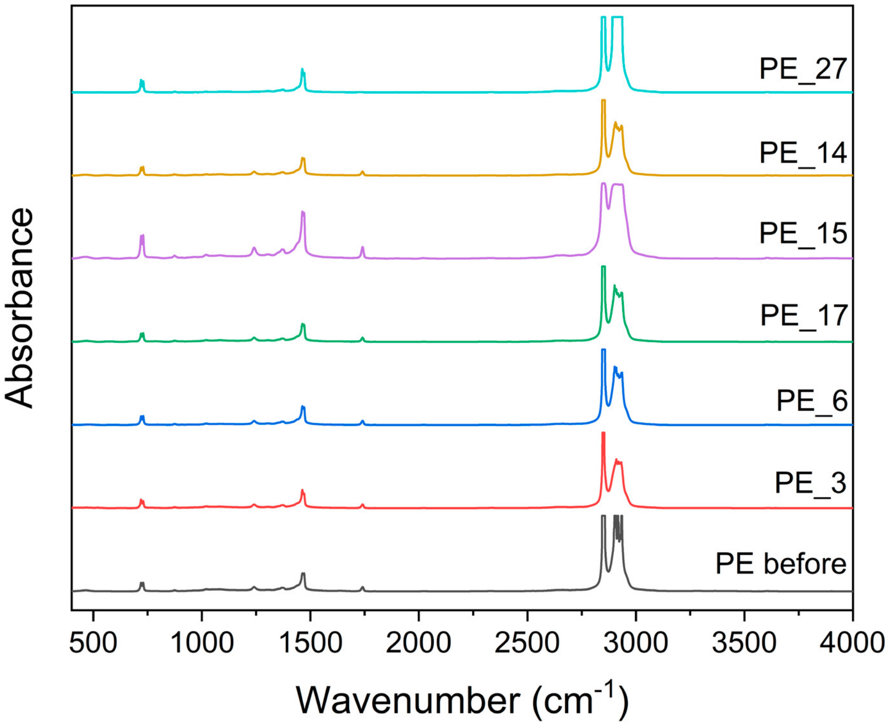


Fig. 14 The FTIR results of the PE samples after cleaning

FTIR spectra are not as distinct as Raman spectra in their ability to differentiate cleaning effectiveness for PE samples. However, method 27 stands out, displaying the sharpest and intense peaks, particularly in the regions around 2,919 cm^{-1} and 720 cm^{-1} (fig. 14). Additionally, this spectrum is free from the interfering signals present in the spectra of other samples (around 1,250 cm^{-1} and 1,750 cm^{-1}). This observation suggests the highest cleaning efficiency, as the spectra closely resemble the restored IR absorption characteristics of pristine polyethylene (table 9).

4.4. Polystyrene (PS)

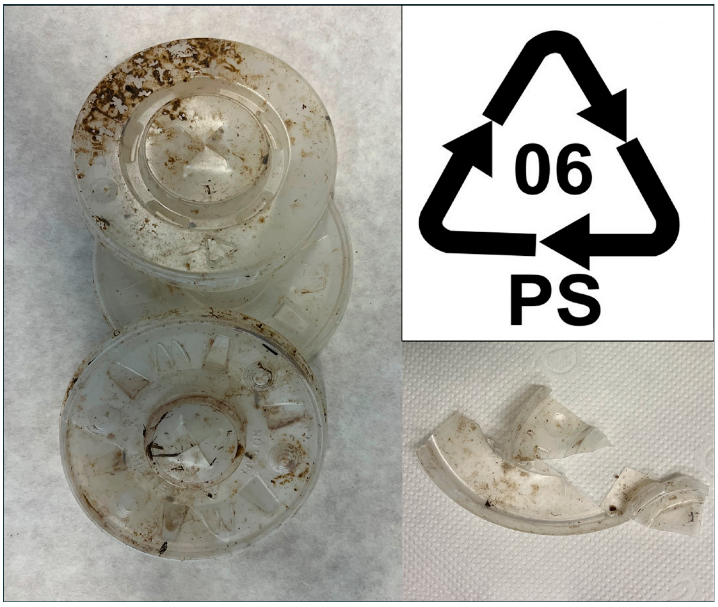
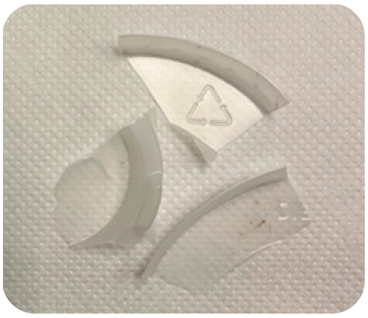


Fig. 15 The photo of plastic cup lid from the Aarhus River rinsed with water and dried

Table 10 Summary of all PS washing methods, photos after washing, and visual assessment of washing effectiveness (scale 1-5)

Sample name	Cleaning medium	Physical cleaning	Photo after cleaning	Effectiveness (1-5)
PS_6	Tap water, cold + Triton X-100 (1% v/v)	Ultrasonic, 30 min		4
PS_15	1M NaOH	Stirring (250 rpm), 1 h		4
PE_27	1% v/v ECOSurf/tap water solution, cold	Ultrasonic, 30 min		4-5

PS samples were collected from Aarhus pilot area (fig. 15). Visual observation indicates a good to very good cleaning effect on the PS samples for all three methods (PS_6, PS_15, PS_27), which were previously identified as the most effective cleaning protocols (table 10). Polystyrene is a polymer derived from styrene, whose structural formula is illustrated in fig. 16. Styrene is an aromatic hydrocarbon characterised by the presence of a highly reactive vinyl group attached to the aromatic ring. Figure 16 presents the Raman spectrum of polystyrene. Carbon-hydrogen (C-H) vibrations appear around 3,000 cm^{-1}. In contrast, low-frequency carbon-carbon (C-C) vibrations are observed near 800 cm^{-1}.

The spectrum also highlights vibrations from double-bonded carbon atoms (C=C) at approximately 1600 cm^{-1}, compared to vibrations of single-bonded carbon atoms (C-C) near 800 cm^{-1}. A detailed examination of the spectrum reveals that the C-H vibrations in polystyrene are split into two bands: one near 2,900 cm^{-1}, corresponding to carbon atoms in aliphatic chains, and another above 3,000 cm^{-1}, associated with carbon atoms in aromatic rings. Additionally, the spectrum features a prominent band around 1,000 cm^{-1}, attributed to the expansion and contraction vibrational modes of the benzene ring. Figure 17 displays Raman spectra for PS (polystyrene) samples before and after cleaning, with data collected for different cleaning conditions labeled as PS_6, PS_15, and PS_27. The “PS before” spectrum has more baseline noise, likely caused by residual materials or impurities. After cleaning, the noise is reduced significantly, indicating a cleaner surface or sample.

The cleaned samples (PS_6, PS_15, and PS_27) show sharper and more defined peaks, indicating an effective cleaning process and better removal of any contaminants that may scatter or absorb light. The peaks appear consistent across all samples in terms of position (cm^{-1}), which suggests the chemical structure of the polystyrene remains intact after cleaning. Similarly to the observations for PE, the FTIR analysis was not particularly helpful in evaluating cleaning efficiency, as the spectra appear very similar (fig. 18).

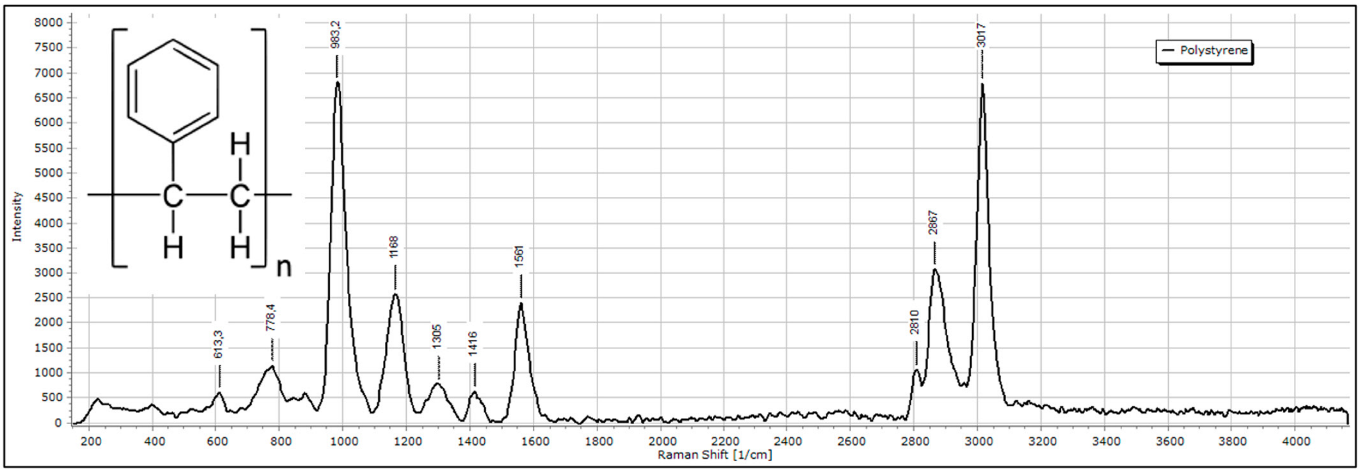


Fig. 16 PS Raman spectrum (source: https://physicsopenlab.org/2022/05/08/polymer-analysis-using-raman-spectroscopy/)

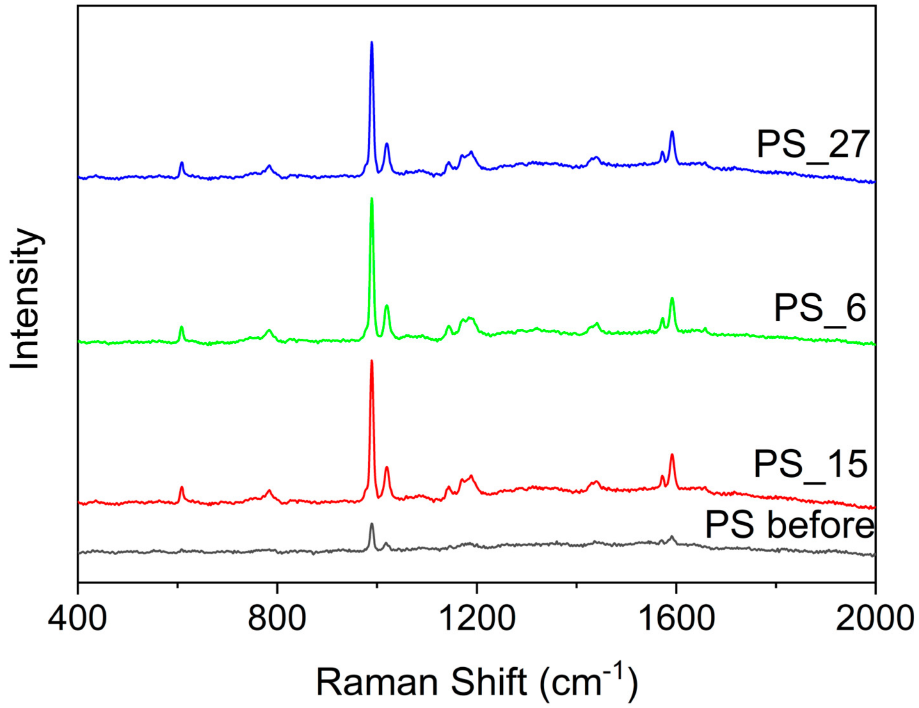


Fig. 17 The Raman spectroscopy results of the PS samples after cleaning

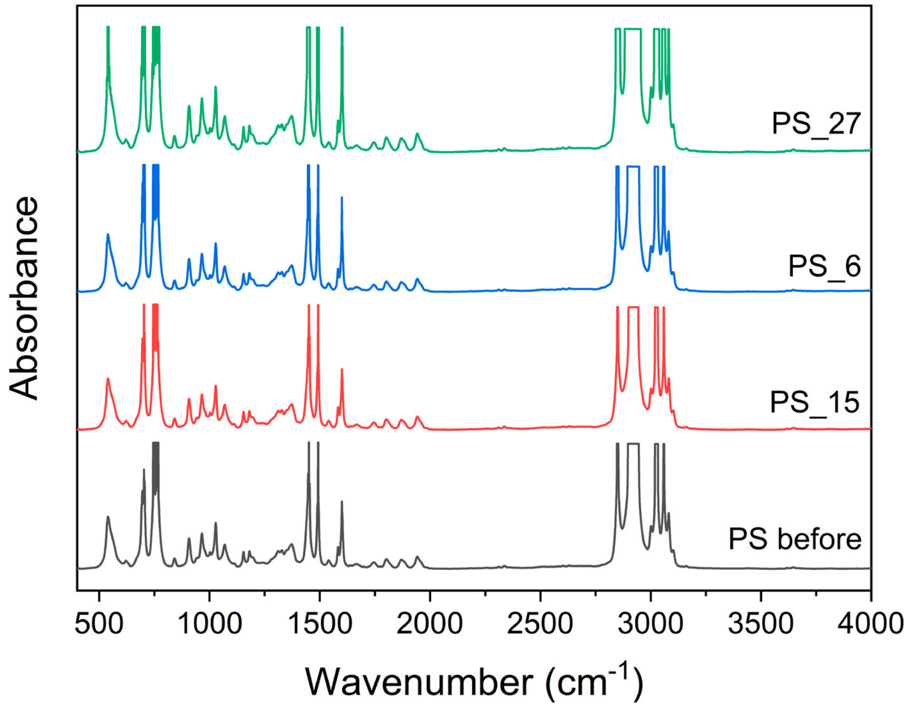


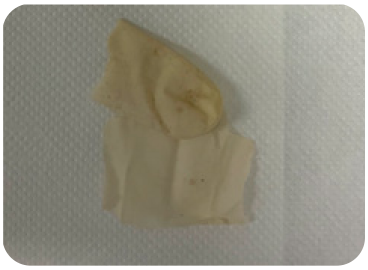
Fig. 18 The FTIR results of the PS samples after cleaning

4.5. Other

Fig. 19 The photo of latex glove from the Motława river rinsed with water and dried

Finally, a random sample representative of OTHER type of plastic was used to assess cleaning efficiency. In this case, a latex glove was selected for evaluation (fig. 19). This sample was collected from Gdansk pilot area. For the contaminants present on this type of litter, the most effective cleaning solution was determined to be an alkaline solution, specifically 1M NaOH (table 11). This finding highlights the adaptability of the cleaning methods to different types of plastic waste and underscores the importance of tailoring cleaning protocols to the specific material and contamination profile.

Table 11 Summary of all latex washing methods, photos after washing, and visual assessment of washing effectiveness (scale 1-5)

Sample name	Cleaning medium	Physical cleaning	Photo after cleaning	Effectiveness (1-5)
LATEX_6	Tap water, cold + Triton X-100 (1% v/v)	Ultrasonic, 30 min		3
LATEX_15	1M NaOH	Stirring (250 rpm), 1 h		4
LATEX_27	1% v/v ECOSurf/tap water solution, cold	Ultrasonic, 30 min		3

5.
Gravimetric analysis
&
6.
Thermogravimetric analysis

5. Gravimetric analysis

Gravimetric analysis was conducted to evaluate the effectiveness of the cleaning methods applied to the samples. This approach involved measuring the weight of the sample before and after each cleaning process to quantify the amount of contaminant removed. By calculating the weight loss percentage after cleaning, we could assess the effectiveness of each cleaning agent and method. The higher the weight loss, the more efficient the method was in removing contaminants from the polymer surface. This quantitative technique provided a straightforward and reliable measure of cleaning efficiency, complementing the qualitative insights obtained from spectroscopic analyses.

Table 12 Percentage Weight Loss for Different Cleaning Methods Across Plastic Types

Cleaning method	PP	PET	PE	LATEX	PS
3 (1% v/v Triton X-100/tap water solution, cold + stirring)	0.42	0.57	4.25	0.12	0.03
6 (1% v/v Triton X-100/tap water solution, cold + ultrasonic)	2.24	0.83	5.70	2.09	1.03
14 (30% H_2O_2 + stirring)	0.16	0.25	3.80	0.78	0.51
15 (1M NaOH + stirring)	1.69	1.33	7.18	0.58	0.51
17 (1% HCl + stirring)	0.03	0.48	1.56	1.44	0.81
27 (1% v/v ECOSurf/tap water solution, cold + ultrasonic)	0.51	0.30	4.11	3.74	0.35

The table 12 presents the percentage of weight loss for five different materials (PP, PET, PE, LATEX, and PS) under various cleaning methods labeled by numbers (3, 6, 14, 15, 17, and 27). The method with the highest weight loss for each material is highlighted in green. Method 3 is characterised with minimal weight loss across all materials. In general, this is a gentle method, likely effective for minor surface contaminants but not for deep or strong chemical interactions. Weight loss increases notably for method 6 compared to method 3. The contaminants on PE (5.70%) and LATEX (2.09%) are significantly affected.

Ultrasonication enhances the cleaning effect of surfactants by introducing cavitation, which can cause physical erosion or intensify chemical interactions. Method 14 exhibits moderate weight loss for all materials. Alkaline cleaning (method 15) strongly interacts with the polymer surface, likely causing hydrolysis or chemical degradation of the surface contaminants. Acidic cleaning appears less aggressive than alkaline cleaning overall.

The combination of Ecosurf (a surfactant) with ultrasonication causes notable effects, particularly for LATEX and PE. Ultrasonication likely exacerbates the chemical action of Ecosurf, causing good cleaning efficiency. These results align with our visual observations and spectroscopic analyses, further supporting the effectiveness of the identified cleaning methods.

6. Thermogravimetric analysis

Thermogravimetric Analysis (TGA) is an analytical technique used to measure changes in the weight of a material as it is heated, cooled, or held at a constant temperature over time. We used this method to evaluate the cleaning effect of plastic samples by assessing the changes in their thermal behavior, composition, and impurity levels before and after the cleaning process. Derivative Thermogravimetry (DTG) is the first derivative of the TGA curve, and it provides additional insight into the decomposition behavior of a material.

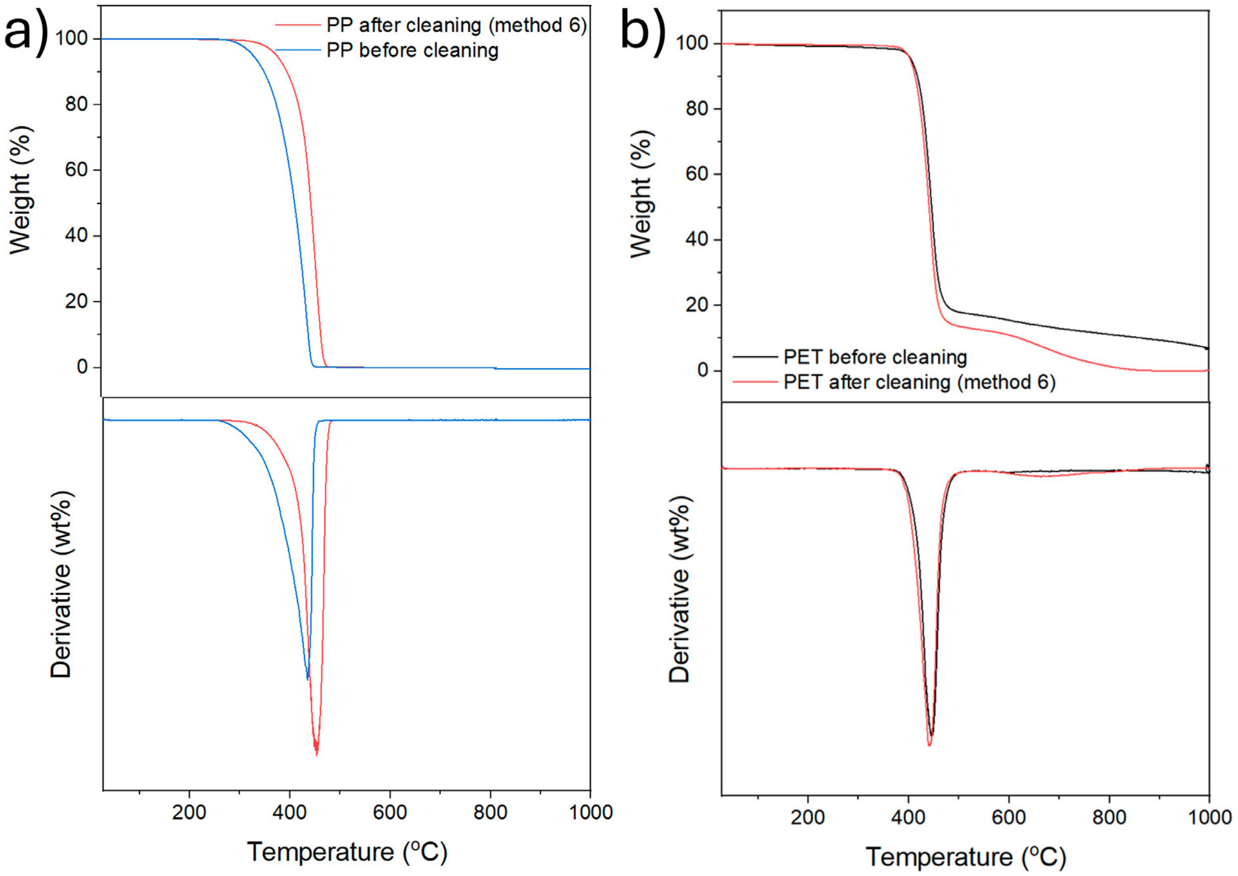


Figure 20 TGA and DTG curves for a) PP samples, b) PET samples.

Figure 20 depicts thermogravimetric analysis (TGA) comparison for PP and PET samples. It shows % weight loss and derivative weight loss as functions of temperature (°C) for samples before cleaning and after cleaning (method 6). For PP (fig. 20a), both curves show a single-step weight loss, indicating uniform degradation. The mass evolution as a function of temperature for both PP samples is described by the usual sigmoid like shape [30][31].

The degradation of the PP sample before cleaning started at 280°C, while the weight loss for the cleaned sample is slightly delayed, suggesting improved thermal stability. No additional mass loss has been noticed as the temperature of the analysis was raised from 500°C to 1,000°C. This may indicate the presence of organic impurities which decompose or volatilize at lower temperatures (<600°C) compared to inorganic contaminants because they are thermally unstable. In order to increase the resolution of TGA analysis, the first derivative of the mass loss versus the degradation temperature has been analyzed. For both samples DTG has a single maximum and is asymmetric. The peak temperature shifts to a higher value after cleaning, confirming increased thermal stability. Moreover, sharper and slightly more intense peak for the cleaned sample suggests a more homogeneous material after cleaning.

TGA weight loss data for PET samples are shown in fig. 20b. Complete conversion of the sample was observed in the case of cleaned PET, whereas degradation reaction ceased at a residue accumulation of around 6.7% for sample before cleaning suggesting the presence of inorganic contaminants (table 13). The DTG plots show similar trend, typical for PET [32][33].

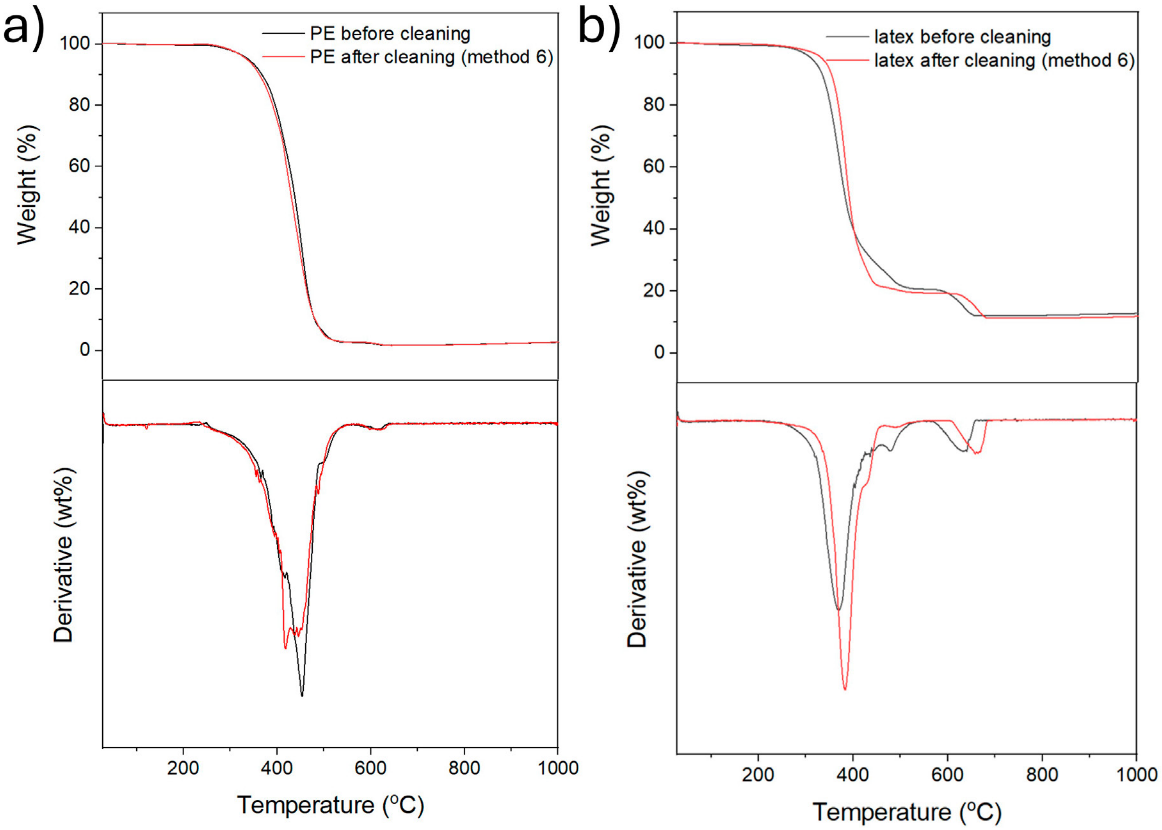


Figure 21 TGA and DTG curves for a) PE samples, b) latex samples.

For PE samples (fig. 21a), both before and after cleaning, the weight loss occurs in a single step, indicating a uniform thermal degradation process, typical for this type of material [34]. The onset and completion of degradation are very close for both samples, suggesting minimal impact of contaminants. However, the DTG curve reveals a more complex composition of the PE sample before cleaning, characterized by a multi-peak signal without a strongly defined maximum. For this sample, the cleaning effect is clearly evident through the intensification of the maximum and the improvement in peak clarity. In the case of latex (fig. 21b), the weight loss appears to occur in two steps, indicating the presence of multiple components or phases.

After cleaning, the second weight loss step is slightly delayed and more gradual, suggesting that the cleaning process may have removed lower-molecular-weight or more thermally unstable components. In this sample, the DTG curves also reveal a sharpening of the main peak and the disappearance of an additional peak around 481°C in the latex after cleaning. This additional peak was clearly associated with impurities or contaminants present in the sample before cleaning. The temperature of the first peak remains similar before and after cleaning, while the second peak shifts to a higher temperature post-cleaning.

Table 13 presents data on the thermal properties and residue percentages of various materials (PP, PET, PE, and LATEX) before and after cleaning. To clarify the column headers: T5% (°C) refers to the temperature at which 5% of the material's mass is lost, T10% (°C) indicates the temperature at which 10% of the material's mass is lost, and Residue (after 1,000°C) represents the amount of material remaining after being heated to 1,000°C, expressed as a percentage. According to the table data PP shows an increase in both T5% and T10%, but no change in residue, while PET shows a slight decrease in T5% and T10%, with a reduction in residue after processing. On the other hand, PE has little change in T5% and T10% and a small residue amount before and after, whereas LATEX shows an increase in both T5% and T10%, with almost no change in residue percentage.

Table 13 Thermal properties and residue percentages of materials before and after cleaning

Sample	T5% (°C)	T10% (°C)	Residue (after 1,000°C)
PP before	329	348	0%
PP after	375	395	0%
PET before	406	419	6.7%
PET after	405	413	0%
PE before	330	370	2%
PE after	328	364	2%
LATEX before	311	332	12%
LATEX after	338	354	11%


500
1000 ml
50
100
150
600
400

7.

Economical and sustainable analysis

7. Economical and sustainable analysis

Analysing economical and sustainable factors, may help businesses or researchers make informed decisions about choosing cleaning chemicals that balance both economic viability and environmental responsibility. Economical analysis focuses on the cost-effectiveness of each chemical. It evaluates the price per unit (e.g., cost per 1,000 L of cleaning solution) and assesses the affordability of using each chemical in cleaning processes. The sustainable part focuses on the environmental impact of the chemicals. It looks at whether the chemicals are biodegradable, their potential to cause harm to ecosystems, and their overall environmental footprint. It also includes any certifications or claims related to green chemistry or eco-friendly formulations.

Table 14 Cost comparison of cleaning solution for various methods

Method	Chemicals (per 1,000 L of cleaning solution)	Amount of chemical per 1 m^3 of cleaning solution	Cost (per 1 m^3 of cleaning solution)	Source
6	Triton X-100	10 L	€986.70	1
15	Sodium Hydroxide	40 kg	€318	2
27	ECOSurf	10 L	€359	3

1. www.scientificlabs.com/en/product/bioreagents/X100-1L
2. www.braumarkt.com/Sodium-hydroxide-caustic-soda-1-kg?srsltid=AfmBOopcPLam972_qF_FfDpTrC_YQVCmN-redb6fnjPqMmJJX3-juXuYA
3. www.carlroth.com/pl/pl/a-to-z/ecosurf%E2%84%A2-sa-9/p/0982.5

Table 14 shows the chemicals used in method 6, 15, and 27 and their cost per 1,000 L of cleaning solution. Sodium hydroxide offers the lowest cost at €318 per 1,000 L, followed by ECOSurf at €359. Triton X-100 is significantly more expensive at €986.70. On the other hand, ECOSurf is the most sustainable choice, as it is biodegradable and designed to reduce environmental impact. Triton X-100, while effective, is less sustainable due to its persistence in the environment and toxicity. Sodium hydroxide is environmentally neutral when handled properly but can be harmful if not disposed of properly.

8.

Conclusion

8. Conclusion

Through both qualitative and quantitative assessments, we have found that the most efficient cleaning techniques are the alkaline-based method (15) and ultrasonication-assisted surfactant cleaning (6 and 27). Our visual inspections consistently indicated that the alkaline cleaning method (15) showed the most significant cleaning effect in surface contamination. Surfaces treated with this method exhibited clear signs of thorough cleaning, with contaminants such as oils, dust, and particulate matter visibly removed. Similarly, the ultrasonication-assisted surfactant cleaning (6 and 27) demonstrated superior efficacy, as evidenced by the enhanced clarity and uniformity of cleaned surfaces.

The visual reduction of surface films and contaminants supports the quantitative findings of our analysis. Spectroscopic techniques, such as FTIR and Raman provided further insight into the molecular changes on the surface before and after cleaning. However, despite the insights provided by spectroscopic methods, they were less successful in evaluating cleaning effectiveness, as the spectra obtained from different cleaning treatments exhibited similar shapes and intensities. This limitation suggests that while spectroscopic techniques are powerful tools for analysing surface composition, they may not always capture the subtle differences in cleaning efficiency, particularly when the contaminant layers are not drastically altered or removed at the molecular level. A similar conclusion was reached by our partners in Denmark, who also explored the use of FTIR for their analysis.

The alkaline method (15) typically works by altering the pH of the cleaning solution, which breaks down greasy or organic contaminants through saponification and chemical degradation. The alkaline solution likely solubilises contaminants, making them easier to remove through physical rinsing or washing. The combination of ultrasonication and surfactants (method 6 and 27) further emphasises the benefits of mechanical and chemical synergy. The ultrasonic waves generate microbubbles that, upon collapsing, impart intense localised energy to dislodge and break up contaminants from the surface. This is particularly effective on materials like polyethylene, which can be difficult to clean through conventional means. The presence of surfactants, such as Ecosurf, aids in the emulsification of oils and dispersal of dirt particles, making them easier to wash away. These findings highlight the importance of selecting the appropriate cleaning technique based on the material type and contamination nature, ensuring optimal cleaning results. The economical analysis comparison highlights the significant cost difference between Triton X-100 and the other two chemicals, with Sodium Hydroxide being the most economical option. Moreover, ECOSurf provides a more environmentally friendly alternative to Triton X-100.

The experimental assessment of the preferred cleaning methods was conducted in collaboration with our partners from Denmark (PCD) and Germany (UROS). Their reports are appended at the end of this document for reference. PCD carried out cleaning analysis on samples collected from SeaProtectorOne, supplied by AllinOnGreen and Aarhus Municipality, using both the alkaline cleaning method (Method 15) and ultrasonication-assisted surfactant cleaning (Triton X-100, method 6). Their research consistently identified NaOH as the superior cleaning agent for polypropylene (PP) and PET samples, outperforming Triton X-100 in all instances. The cleaning efficiency of the alkaline method was rated 4 or 5 on our 5-point scale in most cases. Furthermore, gravimetric analysis revealed a higher weight loss for samples cleaned with NaOH, reinforcing its effectiveness. On the other hand, our partners at the University of Rostock evaluated the effectiveness of methods 15 and 27 in their laboratories. Despite their efforts, the results were not satisfactory, and no alternative solutions were identified to improve the cleaning outcomes. It would be beneficial to further investigate these samples by extending the cleaning duration or increasing the concentration of the chemicals to assess whether these adjustments enhance cleaning efficiency.

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Appendix

Report from Plast Center Danmark

Introduction

This project involves the collection and cleaning of plastic waste collected by SeaProtectorOne and supplied by AllinOnGreen and Aarhus Municipality to Plast Center Danmark. The cleaning methods are derived from techniques developed by our partners at Gdansk University. These methods are designed to clean the plastic in a low-cost and efficient way.

Samples

Three different types of plastics were separated from the litter and cut into small pieces. The samples can be seen in Appendix A.

Sample 1

- Sample 1.1 – 1.4 - Polypropylene – to be washed with tap cold water
- Sample 1.5 – 1.8 - Polypropylene – to be washed with 100 ml of 1M NaOH
- Sample 1.9 – 1.12 Polypropylene – to be washed with 100 ml 1% v/v Triton X-100 / tap cold water

Sample 2

- Sample 2.1 – 2.4 - Polyethylene Terephthalate – to be washed with water
- Sample 2.5 – 2.8 - Polyethylene Terephthalate - to be washed with 100 ml of 1M NaOH
- Sample 2.9 – 2.12 - Polyethylene Terephthalate plastic – to be washed with 100 ml 1% v/v Triton X-100 / tap cold water

Sample 3

- Sample 3.1 – 3.4 - Polyethylene - to be washed with water
- Sample 3.5 – 3.8 - Polyethylene plastic – to be washed with 100 ml of 1M NaOH
- Sample 3.9 – 3.12 - Polyethylene plastic – to be washed with 100 ml 1% v/v Triton X-100 / tap cold water

Methodology:

The analysis of the samples is being conducted utilizing a tripartite methodological approach, ensuring a comprehensive evaluation.

Firstly, the samples are subjected to gravimetric analysis by precise weighing, a method facilitating quantification of mass-related attributes. Secondly, Fourier Transform Mid-Infrared Spectroscopy (FT-MIR) is employed, enabling the examination of molecular compositions through IR spectra, thereby allowing for the identification of functional groups. Lastly, a methodical visual inspection is performed, wherein the standard of cleanliness is systematically graded according to predefined criteria. The grading is between 1 and 5 where 1 means the samples is as dirty in the final state as it was in the initial, whereas 5 means that all impurities have been removed from the samples.

The cleaning process of the samples is shown in the table below:

Table 1: Cleaning process

Day 1	
Steps	Description
Step 1	Sort the plastic into PP, PET and PE
Step 2	Cut the samples as it follows: - 3 samples of 2x2 cm for each material - 1 sample 6x3 cm (so it can be used for the MIR test)
Step 3	Perform MIR test before the samples in their initial stage – MIR test is conducted at every stage of the process to find out if there are any differences
Step 4	Dry the samples at 60 ℃ for 24 H

Day 2	
Step 1	Weigh the samples after the first dry
Step 2	Perform MIR test after the first dry
Step 3	Wash the samples according to the methods (see Table 2)
Step 4	Rins the samples with cold tap water
Step 5	Dry at 60 ℃ for 24 H
Day 3	
Step 1	Weigh the sample in their final stage (washed & dried)
Step 2	Perform MIR test on samples in their final stage (washed & dried)

Table 1 outlines a detailed cleaning process for plastic samples over a three-day period, focusing on sorting, testing, and treating different materials.

On Day 1, the procedure begins with sorting plastics into PP, PET, and PE categories. Samples are then cut into specific sizes: three samples of 2x2 cm for each material and one 6x3 cm sample reserved for MIR testing. A MIR test using the transmission method is conducted to detect differences, followed by drying the samples at 60 ℃ for 24 hours.

On Day 2, the process continues with weighing samples after the initial drying, ensuring consistency in measurements. Another MIR test is performed post-drying. The samples undergo a washing procedure specified in Table 2, followed by rinsing them in cold tap water to ensure thorough cleaning. The samples are then dried again at 60 ℃ for 24 hours, ensuring complete moisture removal.

Day 3 involves weighing the samples after thorough washing and drying, ensuring accuracy in evaluating weight changes. A final MIR test is conducted to verify any alternations in the samples.

The systematic approach across the three days ensures comprehensive cleaning and analysis of the plastic samples, providing essential data on the effectiveness of the cleaning process and material integrity before and after each treatment stage.

The methods used for cleaning the plastic are found in the table below:

Table 2: Methods used for washing

Method Nr.	Cleaning medium	Physical cleaning	Final wash & dry
Method 1	100 ml tap cold water	Stirring at 250 rpm for 1 hour (a magnetic stirrer is added to the beaker, and the mixture was stirred at 250 rpm without heating)	After treatment, the samples are rinsed with water and dried for 24h at 60℃
Method 2	100 ml of 1M NaOH	Stirring at 250 rpm for 1hour (a magnetic stirrer is added to the beaker, and the mixture was stirred at 250 rpm without heating)	After treatment, the samples are rinsed with water and dried for 24h at 60℃
Method 3	100 ml 1% v/v Triton X-100 / tap cold water	Ultrasonication for 30 min (the beaker is placed in an ultrasonic bath and subjected to ultrasonication for 30 minutes)	After treatment, the samples are rinsed with water and dried for 24h at 60℃

The table above displays the washing process for the three types of plastics (PP, PET and PE). Three methods are being used, each detailing the cleaning medium, the physical cleaning process, and the final wash and drying steps.

Results and findings

In this chapter, it is being analysed the results and findings of the washing process. The samples are being analysed from three different angles: the weight, the MIR test and the pictures taken with the samples in the initial and final stage of the process.

Weights results

The weights of the samples together with the percentage of the mass loss between the polypropylene (PP) samples before and after cleaning/washing are shown in Table 3.

Table 3: The weights for the samples 1.1 - 1.12 in the initial stage, after the first dry, and final weight.

Polypropylene samples (PP)			
Sample Nr.	Weight after the first dry (after the first dry & before wash) (g)	Final weight (Weight after wash & dry) (g)	Percentage of mass loss between the dry sample before and after cleaning/washing (%)
Sample 1.1	0.4654	0.4650	0.09
Sample 1.2	0.0592	0.0578	2.36
Sample 1.3	0.0571	0.0570	0.18
Sample 1.4	0.0525	0.0522	0.57
Sample 1.5	0.3222	0.3183	1.21
Sample 1.6	0.0784	0.0776	1.02
Sample 1.7	0.0658	0.0655	0.46
Sample 1.8	0.0604	0.0602	0.33
Sample 1.9	0.1992	0.1986	0.30
Sample 1.10	0.1029	0.1010	1.85
Sample 1.11	0.0479	0.0476	0.63
Sample 1.12	0.1028	0.1028	0

Table 3 presents data of polypropylene (PP) samples, detailing their weights at different stages of the cleaning process, along with the percentage of mass loss between drying and washing. Each sample's weight is listed post-initial drying and again after it has been washed and dried, providing insight into how the washing process affects the sample mass. The samples have been subjected to different washing treatments: tap water, NaOH, and Triton X-100.

Tap Water Treatment:

Samples 1.1 through 1.4 were washed with tap water. The results indicate minimal mass loss, with sample 1.1 showing a decrease of only 0.09% from 0.4654 g to 0.4650 g. Similarly, sample 1.2’s weight reduced from 0.0592 g to 0.0578 g, indicating a 2.36% loss. The results suggest that tap water washing causes relatively low mass loss, potentially due to its mild nature and inability to dissolve or dislodge substantiated residues with the PP matrix significantly.

NaOH Treatment:

Samples 1.5 to 1.8 were washed using NaOH. This alkali solution typically serves as a stronger, more reactive agent, possibly leading to higher rates of surface degradation or detachment of adhered substances. Sample 1.6's weight decreased from 0.1482 g to 0.1462 g, indicating a measurable mass loss over 1%. This trend underscores NaOH's capacity to invoke chemical interactions that result in more substantial mass loss compared to tap water, exemplifying its higher efficacy in reducing contaminants bonded to PP surfaces.

Triton X-100 Treatment:

Samples 1.9 to 1.12 underwent washing with Triton X-100, a non-ionic surfactant renowned for its ability to remove organic residue and clean nonpolar surfaces. Interestingly, these samples displayed varied mass retention characteristics. For instance, Sample 1.11 maintained its weight with no noticeable change, suggesting that Triton X-100's action did not significantly impact this sample's mass. In contrast, other samples revealed slight variations, hinting at the specific interplay between the surfactant's molecular mechanisms and the PP structure.

Overall, the table clearly illustrates that the washing agent impacts the extent of mass loss in PP samples. While tap water displays gentleness, NaOH shows greater efficacy in material removal, and Triton X-100 reveals diverse effects based on sample composition and surfactant action. In most samples, the final weight is slightly lower than both the initial weight and the weight after first drying. This suggests that the washing and drying process leads to a slight reduction in weight, due to the removal of impurities and moisture.

The weights of the samples together with the percentage of the mass loss between the Polyethylene Terephthalate (PET) samples before and after cleaning/washing are shown in Table 4.

Table 4: The weights for the samples 2.1 - 2.12 in the initial stage, after the first dry, and final weight.

Polyethylene Terephthalate (PET) samples			
Sample Nr.	Weight after the first dry (after the first dry & before wash) (g)	Final weight (Weight after wash & dry) (g)	Percentage of mass loss between the dry sample before and after cleaning/washing (%)
Sample 2.1	0.5056	0.5039	0.34
Sample 2.2	0.1323	0.1315	0.60
Sample 2.3	0.1540	0.1509	2.01
Sample 2.4	0.1282	0.1276	0.47
Sample 2.5	0.3226	0.3225	0.03
Sample 2.6	0.1144	0.1135	0.79
Sample 2.7	0.1047	0.1053	0.57
Sample 2.8	0.0914	0.0913	0.11
Sample 2.9	0.5046	0.5050	0.079
Sample 2.10	0.1102	0.1102	0
Sample 2.11	0.1429	0.1430	0.07
Sample 2.12	0.1015	0.1015	0

Table 4 provides an overview of polyethylene terephthalate (PET) samples, outlining their weights at various phases of the cleaning procedure, as well as the percentage of mass loss observed between the drying and washing stages. The weight of each sample is recorded after the initial drying and subsequently after the washing and drying processes, offering valuable information on the impact of washing on the sample's mass. The samples underwent different washing treatments, including tap water, NaOH, and Triton X-100.

Tap Water Treatment:

Samples 2.1 to 2.4 were washed using only tap water. These samples exhibited varying degrees of mass loss, with sample 2.3 experiencing the highest at 2.01% and others showing minor weight changes. This indicates that simple tap water can influence the mass of the PET samples, possibly by removing small impurities or loose particles.

NaOH Treatment:

Conversely, samples 2.5 to 2.8 were treated with NaOH, a strong base. These treatments resulted in more consistent and minor mass changes, with sample 2.6 displaying a negligible loss of 0.03%. The use of NaOH seems to offer a more predictable washing effect, likely due to its ability to break down certain impurities or residues on the surface without significantly altering the mass of the PET.

Triton X-100 Treatment:

Finally, samples 2.9 to 2.12 were cleaned using Triton X-100, a non-ionic surfactant. These samples generally maintained their original weights, with variations between 0% and 0.079%. The results suggest that Triton X-100 is effective for surface cleaning without inducing substantial mass loss, making it suitable for applications requiring minimal alteration to the sample's weight.

Most samples experience a reduction compared to their initial weights. Sample 2.1’s final weight is 0.5039 grams, showing a slight decrease from its initial weight. There are two samples which had the most weight reduction; Sample 2.3 has a decrease of 0.0031 grams and Sample 2.1 has a decrease of 0.0017 grams, indicating that samples washed with water had the biggest change. Samples washed with NaOH have a minimal weight reduction, while samples washed with Triton have a minimal or non-existent weight reduction.

The weights of the samples together with the percentage of the mass loss between the Polyethylene Terephthalate (PET) samples before and after cleaning/washing are shown in Table 5.

Table 5: The weights for the samples 3.1 - 3.12 in the initial stage, after the first dry, and final weight.

Polyethylene samples			
Sample Nr.	Weight after the first dry (after the first dry & before wash) (g)	Final weight (Weight after wash & dry) (g)	Percentage of mass loss between the dry sample before and after cleaning/washing (%)
Sample 3.1	0.1050	0.1046	0.38
Sample 3.2	0.0129	0.0127	1.55
Sample 3.3	0.0112	0.0111	0.89
Sample 3.4	0.0097	0.0097	0
Sample 3.5	0.0283	0.0278	1.77
Sample 3.6	0.0060	0.0059	1.67
Sample 3.7	0.0058	0.0057	1.72
Sample 3.8	0.0133	0.0133	0
Sample 3.9	0.0338	0.0339	0.30
Sample 3.10	0.0082	0.0082	0
Sample 3.11	0.0081	0.0081	0
Sample 3.12	0.0096	0.0096	0

Table 5 presents the data for polyethylene terephthalate (PET) samples, outlining their weights at various stages of the cleaning process, as well as the percentage of mass loss observed between the drying and washing phases. The weight of each sample is recorded after the initial drying and subsequently after it has undergone washing and drying, offering an understanding of the impact of the washing process on the sample's mass. The samples have been treated with different washing agents, including tap water, NaOH, and Triton X-100.

Tap Water Treatment:

Samples 3.1 to 3.4 were washed using tap water. The weights of these samples showed minimal change, illustrating that tap water washing maintained the integrity of the samples with only slight weight losses, ranging from 0% (Sample 3.4) to 1.55% (Sample 3.2). This suggests that tap water may be effective for light surface cleaning without causing significant material loss.

NaOH Treatment:

In contrast, the samples washed with NaOH (Samples 3.5 to 3.8) exhibited a higher percentage of mass loss, with Sample 3.5 showing the highest reduction at 1.77%. The corrosive nature of NaOH likely contributed to the increased weight loss, indicating its effectiveness in removing surface material but potentially compromising the sample's mass integrity.

Triton X-100 Treatment:

Samples washed with Triton X-100 (Samples 3.9 to 3.12) largely maintained their weight, with slight variations observed, such as a minor increase in Sample 3.9 at 0.30%. Triton X-100 appears to facilitate effective cleaning while preserving the material mass, making it suitable for applications requiring thorough surface cleaning without degradation.

Overall, the data highlights the varying impacts of different washing treatments on polyethylene samples.

In conclusion, after analysing Table 3, Table 4, and Table 5, it could be mentioned that each sample undergoes predictable weight alterations, validating the methodology for assessing the impact of drying and washing of polypropylene samples. The highest weight reduction belongs to the sample 1.5 washed with NaOH, with a change of 1.21%. Three samples washed with water have the next highest weight reduction, sample 2.3 (2.01%), sample 2.1 (0.34%), and sample 1.2 (2.36%). The samples washed with Triton X-100 have minimal weight reduction, beside samples 1.10 which has a weight reduction of 1.85%. This does not necessarily mean that the samples washed with water have lost the most weight because they are the cleanest in the end of the washing process. The samples washed with NaOH or Triton X-100 could have minimal weight reduction since the solution used for washing have not been washed off during the rinsing process. Therefore, an MIR analysis has been conducted to find out if there is a difference in the samples. Moreover, pictures with the samples before and after the wash, are being rated in regards with how clean they are in the end of the process.

FT-MIR Test

FT-MIR test is conducted on the samples to find out if there is a difference in the peaks before and after the washing and drying of the samples.

The data for IR – Transmission method for the samples before drying & washing is shown in the table below. The IR spectrum of the samples in their initial stage, after being dried for 24 hours at a temperature of 60 ℃, and after being washed and dried, are to be found in Appendix B.

The percentages presented in Table 6 were derived from the OMNIC spectral library. The analysis involves comparing the spectral data of each sample against a comprehensive library dataset. This comparison allows for the identification and matching of each sample with the closest spectral library entry. The match percentage indicates the degree of similarity between the sample spectrum and the library spectrum, providing a quantitative measure of how closely they align. The values reflect the accuracy of the identification process, as demonstrated by the variations observed before and after the sample treatment stages, including drying and washing.

Table 6: Match Percentage for the Samples in their initial stage, after being dried, and after being washed and dried

Samples	Compound name	Match percentage before the first dry) (%)	Match percentage before the wash (%)	Match percentage after wash (%)
Sample 1.1	Polypropylene	77.20	74.13	76.61
Sample 1.5	Polypropylene	73.33	82.00	80.63
Sample 1.9	Polypropylene	66.58	75.19	68.14
Sample 2.1	Polyethylene Terephthalate	46.14	47.78	46.92
Sample 2.5	Polyethylene Terephthalate	58.60	58.41	58.19
Sample 2.9	Polyethylene Terephthalate	41.53	39.01	41.95

Sample 3.1	Polyethylene	85.48	85.86	80.26
Sample 3.5	Polyethylene	90.35	96.75	97.10
Sample 3.9	Polyethylene	97.59	87.82	94.03

Table 6 presents data on the match percentage of different samples before and after undergoing various washing treatments. Samples 1.1, 2.1, and 3.1 were cleaned using tap water, samples 1.5, 2.5, and 3.5 with NaOH, while samples 1.9, 2.9, and 3.9 were treated with Triton X-100. Each sample type includes three types of compounds: polypropylene, polyethylene terephthalate, and polyethylene.

In the case of polypropylene samples, those washed with NaOH (samples 1.5) exhibited a notable improvement, with match percentages increasing from 73.33% before the wash to 80.63% after. Conversely, samples washed with Triton X-100 (samples 1.9) showed a decrease in match percentage post-wash from 75.19% to 68.14%. The tap water method (samples 1.1) maintained relatively stable performance, with percentages staying near 76.61%.

Polyethylene terephthalate samples demonstrated inconsistency across the treatments. NaOH washing (samples 2.5) resulted in consistent values before and after the wash (58.41% to 58.19%). However, Triton X-100 (samples 2.9) slightly decreased the match percentage post-wash (39.01% to 41.95%). The samples washed with tap water (samples 2.1) displayed minimal improvement, ending with a match percentage of 46.92%, up from 47.78%.

Finally, polyethylene samples treated with NaOH (samples 3.5) showed a substantial increase from 90.35% to 97.10%, indicating effective washing. Triton X-100 (samples 3.9) slightly reduced the match percentage from 87.82% to 94.03%. Tap water (samples 3.1) led to a modest decrease from 85.86% to 80.26%.

Overall, the data indicate that the effect of washing varies across different compounds and even within the same compound type. Polypropylene and Polyethylene demonstrate some resilience, while PET is more susceptible to decreases in match percentage. The data suggests that NaOH generally enhances sample quality across different compounds, as evidenced by the increase in post-wash match percentages. In contrast, Triton X-100 tends to result in decreased match percentages, and tap water maintains or slightly reduces them, indicating its limited effectiveness in improving sample match quality.

The FT-MIR spectral analysis of the samples—before the first drying, after the first drying and before washing, and post-washing—reveals minimal spectral differentiation among them. Despite undergoing distinct preparatory stages, the consistent spectral profiles suggest negligible alteration at the molecular level across these treatments. This uniformity implies robust stability or invariant chemical composition throughout the drying and washing processes.

Washing results

The results of PP, PET and PE samples wash test provide insights into the effectiveness of water, NaOH, and Triton X-100 as cleaning agents. The washing process aimed to evaluate how well the samples could be cleaned merely by washing with water, NaOH, or Triton X-100.

Visually, prior washing, all samples exhibited considerable dirt accumulation. Post-wash images reveal varying degrees of cleanliness, highlighting the effectiveness of the three different agents in removing surface dirt and debris. However, the extent to which dirt was eliminated differed across the samples.

The effectiveness rating offers a numeric summary of the washing outcome.

The visual effectiveness of water as a cleaning agent and the rating scale of the finished products after being washed is found in the table below:

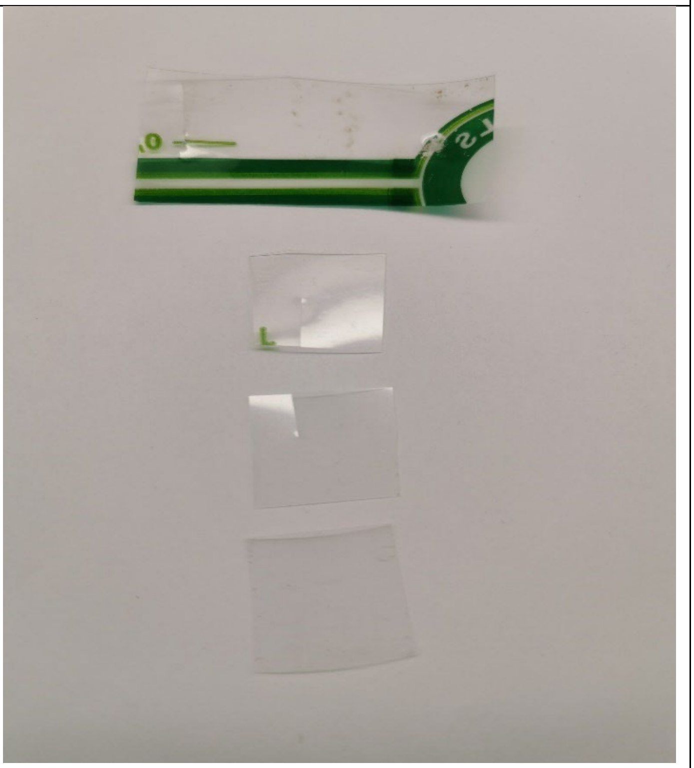
Table 7: Initial and Final stage of the PP samples washed with Water

<table>
<tr><th colspan="2">Polypropylene Samples 1.1 – 1.4</th></tr>
<tr><td>Initial stage of the samples</td><td>Final stage of the samples</td></tr>
<tr><td></td><td></td></tr>
<tr><td colspan="2">Effectiveness/scale:
Sample 1.1 = 3
Sample 1.2 = 2
Sample 1.3 = 3
Sample 1.4 = 3</td></tr>
</table>

Table 7 displays images and effectiveness ratings of polypropylene samples before and after being washed with water. Samples 1.1, 1.3, and 1.4 all received a rating of 3, indicating a moderate level of dirt removal. The samples showed visible improvement, with a substantial amount of surface grime removed. The consistency in their ratings suggests a reliable level of performance for water as a washing medium across these samples. Sample 1.2, however, stands out with a significantly lower rating of 2. This score indicated a minimal cleaning effect, with the sample remaining visibly dirty despite the wash.

The visual effectiveness of NaOH as a cleaning agent and the rating scale of the finished products after being washed is found in the table below:

Table 8: Initial and Final stage of PP samples washed with NaOH

<table>
<tr><th colspan="2">Polypropylene Samples 1.5 – 1.8</th></tr>
<tr><td>Initial stage of the samples</td><td>Final stage of the samples</td></tr>
<tr><td></td><td></td></tr>
<tr><td colspan="2">Effectiveness/scale:
Sample 1.5 = 4
Sample 1.6 = 5
Sample 1.7 = 5
Sample 1.8 = 5</td></tr>
</table>

The results presented in Table 8 demonstrate the effectiveness of NaOH washing on polypropylene samples, with an effectiveness ranging from 4 to 5. As seen in the left image, these samples exhibited considerable surface contamination.

Upon washing with NaOH, notable improvements were observed. The final stage images on the right reveal a drastic reduction or complete elimination of the contaminants, with samples appearing significantly cleaner. These outcomes suggest that NaOH is an effective agent for cleaning polypropylene surfaces.

The visual effectiveness of Triton X-100 as a cleaning agent and the rating scale of the finished products after being washed is found in the table below:

Table 9: Initial and Final stage of PP samples washed with TRITON X-100

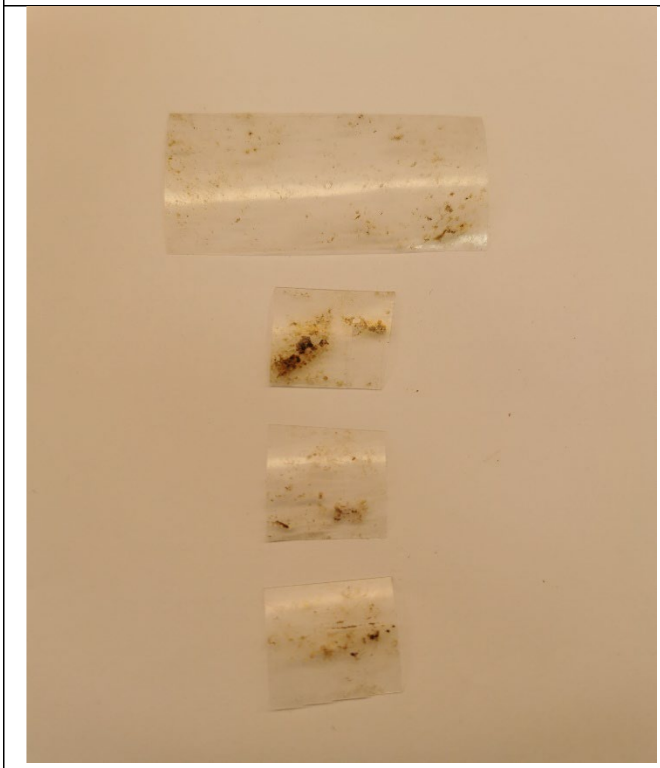
<table>
<tr><td colspan="2">Polypropylene Samples 1.9 – 1.12</td></tr>
<tr><td>Initial stage of the samples</td><td>Final stage of the samples</td></tr>
<tr><td></td><td></td></tr>
<tr><td colspan="2">Effectiveness/scale:
Sample 1.9 = 4
Sample 1.10 = 2
Sample 1.11 = 3
Sample 1.12 = 3</td></tr>
</table>

Table 9 demonstrates the effectiveness of using Triton X-100 for cleaning PP samples. In the initial stage, all samples displayed visible contamination. After treatment with Triton X-100, the final stage of the samples shows a noticeable reduction in contamination across all samples.

According to the effectiveness scale provided, Sample 1.9 received the highest score of 4, suggesting it had the most significant improvement post-treatment. Meanwhile, Sample 1.10 received a score of 2, indicating a less pronounced but still noticeable cleaning effect. Samples 1.11 and 1.12 both scored 3, showing a moderate level of cleaning efficiency.

The visual effectiveness of water as a cleaning agent and the rating scale of the finished products after being washed is found in the table below:

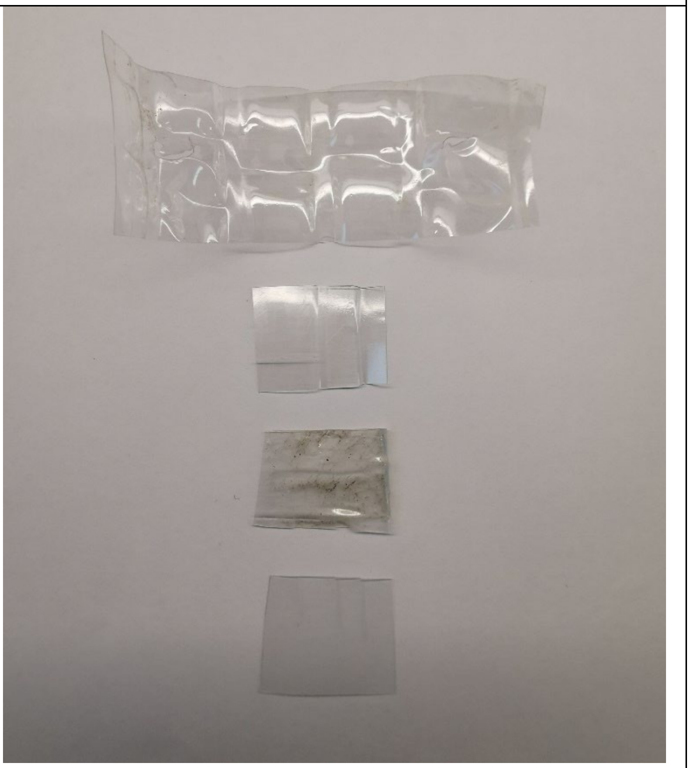
Table 10: Initial and Final stage of the PET samples washed with Water

Polyethylene Terephthalate Samples 2.1 – 2.4	
Initial stage of the samples	Final stage of the samples
	
Effectiveness/scale: Sample 2.1 = 1 Sample 2.2 = 2 Sample 2.3 = 2 Sample 2.4 = 1	

Table 10 displays images and effectiveness ratings of PET samples before and after being washed with water. Samples 2.1, and 2.4 received a rating of 1, indicating a minimal cleaning effect, with the samples remaining visibly dirty despite the wash. Samples 2.2, and 2.3 showed a slight visible improvement, however still not being enough to conclude that it is enough to wash PET samples only with water.

The visual effectiveness of NaOH as a cleaning agent and the rating scale of the finished products after being washed is found in the table below:

Table 11: Initial and Final stage of PET samples washed with NaOH

Polyethylene Terephthalate Samples 2.5 – 2.8	
Initial stage of the samples	Final stage of the samples
	
Effectiveness/scale: Sample 2.5 = 5 Sample 2.6 = 5 Sample 2.7 = 2 Sample 2.8 = 4	

The results presented in Table 11 demonstrate the effectiveness of NaOH washing on PET samples. The effectiveness is ranging from 2 to 5. As seen in the left image, these samples exhibited considerable surface contamination.

Upon washing with NaOH, notable improvements were observed for sample 2.5, 2.6 and 2.7 where there is a substantial reduction or complete elimination of the contaminants, with samples appearing significantly cleaner. These outcomes suggest that NaOH is an effective agent for cleaning polypropylene surfaces.

Sample 2.7, however, stands out with a significantly lower rating of 2, which indicates a minimal cleaning effect, with the sample remaining visibly dirty despite the wash.

The visual effectiveness of Triton X-100 as a cleaning agent and the rating scale of the finished products after being washed is found in the table below:

Table 12: Initial and Final stage of PET samples washed with TRITON X-100

Polyethylene Terephthalate Samples 2.9 – 2.12	
Initial stage of the samples	Final stage of the samples
	
Effectiveness/scale: Sample 2.9 = 3 Sample 2.10 = 4 Sample 2.11 = 1 Sample 2.12 = 3	

Table 12 demonstrates the effectiveness of using Triton X-100 for cleaning PET samples. In the preliminary phase, all samples exhibited clear signs of contamination. Following treatment with Triton X-100, the concluding phase of the samples reveals a significant decrease in contamination levels across the board.

According to the effectiveness scale provided, Sample 2.10 received the highest score of 4, suggesting it had the most significant improvement post-treatment. A less pronounced but still noticeable cleaning effect for Samples 2.9 and 2.12, which both scored 3. Meanwhile, Sample 2.11 received a score of 1, indicating a minimal cleaning effect, with the sample remaining visibly dirty despite the wash.

The visual effectiveness of water as a cleaning agent and the rating scale of the finished products after being washed is found in the table below:

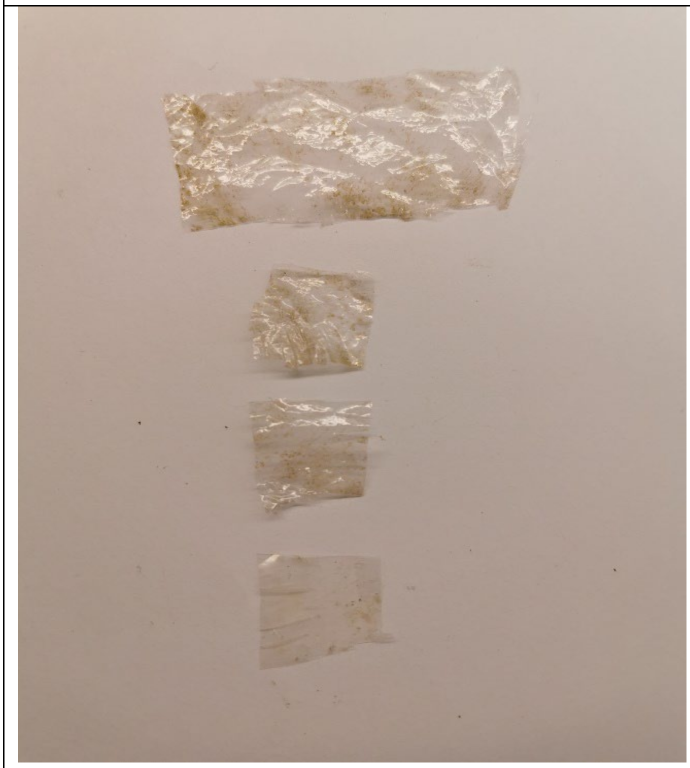
Table 13: Initial and Final stage of the PE samples washed with Water

Polyethylene Samples 3.1 – 3.4	
Initial stage of the samples	Final stage of the samples
	
Effectiveness/scale: Sample 3.1 = 1 Sample 3.2 = 1 Sample 3.3 = 1 Sample 3.4 = 1	

Table 13 displays images and effectiveness ratings of polyethylene samples before and after being washed with water. All samples received a rating of 1, suggesting no improvement in the amount of removed dirt. The consistency in their ratings suggests that additional agents are required to complement the water in order to have more effective results.

The visual effectiveness of NaOH as a cleaning agent and the rating scale of the finished products after being washed is found in the table below

Table 14: Initial and Final stage of PE samples washed with NaOH

Polyethylene Samples 3.5 – 3.8	
Initial stage of the samples	Final stage of the samples
	
Effectiveness/scale: Sample 3.5 = 5 Sample 3.6 = 5 Sample 3.7 = 5 Sample 3.8 = 5	

The findings illustrated in Table 14 highlight the efficacy of NaOH washing on polyethylene samples, showing an effectiveness level of 5. The left image indicates that these samples initially displayed significant surface contamination. Following the NaOH washing process, substantial enhancements were noted. The final stage images on the right demonstrate a marked decrease or total removal of the contaminants, resulting in samples that appear considerably cleaner. These results indicate that NaOH serves as an effective cleaning agent for polypropylene surfaces.

The visual effectiveness of Triton X-100 as a cleaning agent and the rating scale of the finished products after being washed is found in the table below:

Table 15: Initial and Final stage of PE samples washed with TRITON X-100

Polyethylene Samples 3.9 – 3.12	
Initial stage of the samples	Final stage of the samples
	
Effectiveness/scale: Sample 3.9 = 3 Sample 3.10 = 2 Sample 3.11 = 2 Sample 3.12 = 1	

Table 15 demonstrates the effectiveness of using Triton X-100 for cleaning PE samples. In the preliminary phase, all samples exhibited clear signs of contamination. Following treatment with Triton X-100, the concluding phase of the samples reveals a significant decrease in contamination levels across all specimens. According to the effectiveness scale provided, Sample 1.9 received the highest score of 3, suggesting it had the most significant improvement post-treatment. Meanwhile, sample 3.10 and 3.11, received a score of 2, indicating a less pronounced but still noticeable cleaning effect. Sample 3.12 scored 1, showing no change at all for the sample post-wash. The table below represents the effectiveness of PP, PET and PE after undergoing the washing process:

Table 16: Effectiveness after the wash

PP Water	PET Water	PE Water
1.1 = 3	2.1 = 1	3.1 = 1
1.2 = 2	2.2 = 2	3.2 = 1
1.3 = 3	2.3 = 2	3.3 = 1
1.4 = 3	2.4 =1	3.4 = 1
Average = 2.75	Average =1.5	Average = 1
STDEV = 0.5	STDEV = 0.6	STDEV = 0
PP NaOH	PET NaOH	PE NaOH
1.5 = 4	2.5 = 5	3.5 = 5
1.6 = 5	2.6 = 5	3.6 = 5
1.7 = 5	2.7 = 2	3.7 = 5
1.8 = 5	2.8 = 4	3.8 = 5
Average = 2.75	Average = 4	Average = 5
STDEV = 0.5	STDEV = 1.4	STDEV = 0
PP Triton X-100	PET Triton X-100	PE Triton X-100
1.9 = 4	2.9 = 3	3.9 = 3
1.10 = 2	2.10 = 4	3.10 = 2
1.11 = 3	2.11 = 1	3.11 = 2
1.12 = 3	2.12 = 3	3.12 = 1
Average = 3	Average = 2.75	Average = 2
STDEV = 0.8	STDEV = 1.3	STDEV = 0.8

Table 16 displays the results of the cleaning efficiency of three different plastic samples – Polypropylene (PP), Polyethylene Terephthalate (PET), and Polyethylene (PE) - employed three treatment methods: water alone, NaOH solution, and Triton X-100.

When washed with water, PP and PET samples presented moderate cleaning efficiencies. The average effectiveness for PP samples was 2.75 with a standard deviation of 0.5, indicating a consistent performance. In contrast, PET showed a lower average effectiveness of 1.5 with a slightly higher variability (standard deviation of 0.6). On the other hand, PE samples exhibited the least effectiveness with a steadfast average of 1 and no deviation, suggesting water washing did not enhance their cleanliness significantly. Overall, all three types of plastics with water provided consistent but mediocre results. The results vary between 1 and 3 which shows that the water was effective in removing loose surface contaminants, showcasing a uniform baseline level of cleanliness across the samples. However, the overall results underscore that while washing with water can achieve moderate cleanliness for some samples, like polypropylene samples, it is insufficient for others, like PET and PE. The inherent limitation of water as a cleaning agent becomes apparent as it solely addresses superficial debris, leaving behind ingrained dirt and oil residues. These findings suggest that for optimal results, especially in industrial applications where PP, PET and PE are frequently used, additional cleaning methods or agents may be required to complements water, particularly for these three materials.

Observations differed substantially when samples were washed with NaOH. The most effective cleaning results emerged from the samples treated with NaOH (sodium hydroxide). Both PP and PET samples demonstrated marked improvements in cleaning performance. PP’s effectiveness scores ranged from 4 to 5, indicating enhanced performance compared with water and Triton X-100. PP maintained an average effectiveness of 2.75, consistent with water washing, yet with a notable outcome of higher individual ratings (4and 5). PET also showed improvement, reaching scores of 2 to 5. PET samples saw considerable enhancement, achieving an average effectiveness of 4, despite displaying greater variation (standard deviation of 1.4). PE’s effectiveness significantly increased, with consistent high scores of 5, suggesting that PE benefits greatly from the NaOH wash. PE samples substantially improved with NaOH washing, attaining full effectiveness (average of 5) across all trials, 0 standard deviation, indicating uniform cleaning success. The NaOH treatment resulted in the highest level of cleanliness for all three plastic types, particularly with PE (which had maximum grading of 5 for all). The success with NaOH can be attributed to its ability to saponify fatty acids and remove embedded impurities, making it ideal for applications where a high degree of cleanliness is crucial. NaOH's alkaline nature allowed it to break down organic stains and contamination more thoroughly, providing a deep clean that surpassed both water and Triton X-100 treatments.

Subsequently, the application of Triton X-100, yielded improved cleaning results across all plastic types compared with the samples washed with water, however not as good as the samples washed with NaOH. Triton X-100 enhanced the removal of stains and organic residues. The results suggest that Triton X-100 is generally effective at reducing contamination, with varying degrees of success depending on the sample.

Washing the samples with Triton X-100 presented varied results. PP exhibited mixed effectiveness, scoring between 2 and 4. PP samples achieved the highest average effectiveness (3), although with increased variability (standard deviation of 0.8), showing improved but less consistent results. PET demonstrated variable scores of 1 to 4, indicating some consistency. PET samples had an average effectiveness of 2.75, reflecting similar variability to NaOH (standard deviation of 1.3). PE's effectiveness ranged narrowly between 1 and 3, suggesting limited improvement compared to other washing methods. PE samples averaged an effectiveness of 2 with a standard deviation of 0.8, suggesting moderate improvement in cleanliness but not as effective as NaOH washing. The difference in effectiveness could be attributed to factors such as the initial contamination level, or the distribution and application of the cleaning agent. The samples showed a significant improvement post-treatment with Triton X-100, indicating that this surfactant interacted more effectively with their surface properties compared to simple water wash.

Overall, the efficacy of the washing method depended markedly on the type of plastic, with NaOH emerging as the most effective for all three types, particularly for PE.

Comparison Results

The FT-MIR spectral analysis of the samples—those processed before the first drying, after the first drying and before washing, and after washing—revealed negligible differences in their molecular structures. This observation suggests that the spectroscopic technique employed may not be sensitive enough to detect subtle chemical variations or alterations that might exist among the samples. Consequently, this necessitates an alternative evaluative approach for the study. Therefore, the comparison will be focused on the variations in weight and washing results, which might provide more distinct and measurable differences between the samples. This approach appears to offer a more reliable metric for understanding the impact of processing conditions on the samples' characteristics, allowing for a comprehensive analysis that aligns with the overall research objectives.

Table 7 provides a comparative examination of different washing techniques applied to polypropylene samples (PP).

Table 17: Comparison Results Polypropylene Samples (PP): % of mass loss between the dry sample before and after cleaning/washing vs Effectiveness after the wash

Polypropylene samples (PP)		
Sample Nr.	% of mass loss between the dry sample before and after cleaning/washing	Effectiveness after the wash
Sample 1.1	0.09	3
Sample 1.2	2.36	2
Sample 1.3	0.18	3
Sample 1.4	0.57	3
Average	0.8	2.75
STDEV	1.06	0.5
Sample 1.5	1.21	4
Sample 1.6	1.02	5
Sample 1.7	0.46	5
Sample 1.8	0.33	5
Average	0.76	4.75
STDEV	0.43	0.5
Sample 1.9	0.30	4
Sample 1.10	1.85	2
Sample 1.11	0.63	3
Sample 1.12	0	3
Average	0.7	3
STDEV	0.81	0.8

Table 17 presents a comparative analysis of various washing methods on polypropylene samples (PP). The effectiveness of the washing process was evaluated based on the percentage of mass loss and visual inspection ratings, which ranged from 1 (still dirty) to 5 (no impurities). Samples 1.1 to 1.4

were washed using tap water, samples 1.5 to 1.8 with sodium hydroxide (NaOH), and samples 1.9 to 1.12 with Triton X-100.

For tap water-washed samples, the mass loss ranged from 0.09% to 2.36%, with an average effectiveness score of 2.75. The effectiveness varied slightly, indicating moderate impurity removal, but the standard deviation of 0.5 suggested consistency among samples.

In contrast, the NaOH-washed samples exhibited a mass loss between 0.46% and 1.21%. These samples achieved an average effectiveness score of 4.75, indicating a higher cleaning efficacy. The lower standard deviation of 0.43 highlighted uniform results across this group, suggesting that NaOH washing significantly improves impurity removal.

Lastly, samples washed with Triton X-100 showed mass losses from 0.30% to 1.85%, with a slightly lower average effectiveness of 3. Although effective, Triton X-100's performance varied more than NaOH, as indicated by a standard deviation of 0.8, suggesting that while Triton X-100 was capable of cleaning, its results were less consistent compared to the NaOH method.

These findings suggest that NaOH is particularly effective for cleaning polypropylene samples, providing superior and consistent results compared to tap water and Triton X-100.

Table 18 presents a comparative analysis of various washing methods on Polyethylene Terephthalate (PET) samples.

Table 18: Comparison Results Polyethylene Terephthalate (PET) samples: % of mass loss between the dry sample before and after cleaning/washing vs Effectiveness after the wash

Polyethylene Terephthalate (PET) samples		
Sample Nr.	% of mass loss between the dry sample before and after cleaning/washing	Effectiveness after the wash
Sample 2.1	0.34	1
Sample 2.2	0.60	2
Sample 2.3	2.01	2
Sample 2.4	0.47	1
Average	0.86	1.5
STDEV	0.78	0.6
Sample 2.5	0.03	5
Sample 2.6	0.79	5
Sample 2.7	0.57	2
Sample 2.8	0.11	4
Average	0.09	4
STDEV	0.56	1.4
Sample 2.9	0.079	3
Sample 2.10	0	4
Sample 2.11	0.07	1
Sample 2.12	0	3
Average	0.04	2.75
STDEV	0.04	1.3

Table 18 presents the effectiveness of different washing methods on Polyethylene Terephthalate (PET) samples, measured by the percentage of mass loss and a visual inspection scale ranging from 1 (still dirty) to 5 (no impurities).

Samples 2.1 to 2.4, washed with tap water, showed minimal effectiveness with an average visual inspection score of 1.5. The percentage of mass loss varied, with Sample 2.3 losing the most mass at 2.01%. This group's higher standard deviation of 0.78 indicates significant variability in mass loss results, suggesting inconsistent cleaning.

Samples 2.5 to 2.8 were treated with NaOH and showed a substantial improvement in cleaning effectiveness, achieving an average effectiveness score of 4. The mass loss for these samples was negligible, with an average of 0.09%, and a slightly lower standard deviation of 0.56, indicating more consistent outcomes. Samples 2.5 and 2.6, each with an effectiveness score of 5, highlight NaOH's superior ability to remove impurities effectively.

Samples 2.9 to 2.12, washed with Triton X-100, demonstrated moderate effectiveness, with an average visual score of 2.75 and the least variation in mass change, averaging 0.04% mass loss with a standard deviation of 0.04. The results suggest Triton X-100 is effective but not as consistent or powerful in cleaning compared to NaOH.

In conclusion, NaOH proved to be the most effective and consistent washing agent among the three, followed by Triton X-100. Tap water demonstrated the least effectiveness, indicating that chemical agents are necessary for enhanced cleaning of PET samples.

A comparative examination of different washing techniques applied to Polyethylene samples (PE).

Table 19: Comparison Results Polyethylene (PE) samples: % of mass loss between the dry sample before and after cleaning/washing vs Effectiveness after the wash

Polyethylene samples		
Sample Nr.	% of mass loss between the dry sample before and after cleaning/washing	Effectiveness after the wash
Sample 3.1	0.38	1
Sample 3.2	1.55	1
Sample 3.3	0.89	1
Sample 3.4	0	1
Average	0.07	1
STDEV	0.67	0
Sample 3.5	1.77	5
Sample 3.6	1.67	5
Sample 3.7	1.72	5
Sample 3.8	0	5
Average	1.29	5
STDEV	0.86	0
Sample 3.9	0.30	3
Sample 3.10	0	2
Sample 3.11	0	2
Sample 3.12	0	1
Average	0.075	1
STDEV	0.15	0.8

Table 19 provides data on the effectiveness of different washing methods for polyethylene (PE) samples, focusing on mass loss and visual inspection ratings. Samples 3.1 to 3.4 were washed with tap water, whereas samples 3.5 to 3.8 and 3.9 to 3.12 were treated with NaOH and Triton X-100, respectively. The effectiveness of each washing method was evaluated on a scale from 1 to 5, where 1 indicates still dirty and 5 represents no impurities left.

The tap water group (samples 3.1 to 3.4) showed minimal mass loss with an average of 0.07%. However, the effectiveness rating was consistently 1, indicating that this method failed to clean the samples thoroughly. The standard deviation (STDEV) of mass loss was 0.67, suggesting moderate variability within the group.

NaOH-treated samples (3.5 to 3.8) displayed a higher average mass loss of 1.29%, with a perfect effectiveness score of 5. This indicates a successful removal of impurities and consistency in performance, as reflected in the STDEV of 0.86. The higher mass loss suggests that NaOH may have a more aggressive cleaning action, effectively removing contaminants.

Triton X-100 samples (3.9 to 3.12) had the lowest mass variability with an average mass loss of 0.075% and a STDEV of 0.15. However, the effectiveness scores varied, averaging at 1.8. This suggests that while Triton X-100 is gentle in terms of mass preservation, it is less effective at cleaning compared to NaOH.

Overall, NaOH emerged as the most effective cleaning agent, offering the highest cleanliness levels with a consistent mass loss. Conversely, while Triton X-100 minimised mass loss, its cleaning effectiveness varied, making NaOH the preferable choice for thorough cleaning applications.

Conclusion

In conclusion, while water washes offer basic consistency across various plastics, they fall short in delivering a comprehensive clean. Triton X-100 improves upon this by targeting oil-based stains more effectively, making it suitable for moderate cleaning needs. However, for applications demanding the most thorough purification, NaOH emerges as the superior agent, especially for cleaning environments involving PP, PET, and PE materials.

In analysing the weight differences of the material samples pre- and post-wash, the data revealed that the weight variances remain minimal. Nevertheless, in a comparative analysis of cleaning agents, it was observed that NaOH was most effective in removing the dirt from the samples. The post-wash weight loss measurements indicated that the polypropylene (PP) samples lost 0.00188 grams of dirt when washed with NaOH. In contrast, the Triton X-100 solution resulted in a maximum weight loss of only 0.00078 grams for the same sample type, underscoring NaOH's superior cleaning capability in this context. This demonstrates NaOH's efficacy in eliminating residues compared to Triton X-100.

The analysis of match percentages resulted from IR tests across the various samples indicates minimal change. Moreover, the IR spectrum of the samples can be found in Appendix B for further considerations. The results imply that the washing process does not substantially affect the material properties of the tested samples.

The evaluation of washing agents reveals that NaOH is the superior choice for effective cleaning. It achieved a perfect score of 5 for all PE samples, three 5s and one 4 for PP samples, and two 5s, a 2, and a 4 for PET samples. These results highlight NaOH's robust cleaning performance across different materials. Conversely, Triton X-100, despite improving sample cleanliness, fell short compared to NaOH. Its best score was only a 4, and it also had two scores of 1, indicating poor cleaning effectiveness.

Additionally, rinsing the samples is easier after using NaOH compared to Triton X-100, given that Triton X-100 is a more toxic cleaning agent. Hence, NaOH stands out as the optimal, safer choice for effective cleaning across all tested materials.

Overall, the research clearly indicates that NaOH is the superior cleaning agent for both polypropylene and PET samples, consistently outperforming Triton X-100 and tap water. Its capacity to deliver thorough cleaning with a predictable mass loss makes it the preferred option when cleanliness is crucial. Although Triton X-100 offers reduced mass loss, its variable effectiveness limits its reliability as a consistent cleaning solution. These findings underscore the importance of selecting appropriate chemical agents to achieve optimal cleanliness, as reliance on tap water alone is insufficient for effective cleaning of PE materials. Overall, NaOH's consistent performance establishes it as the best choice for comprehensive and reliable cleaning applications in industrial and research settings.

Prepared on 21st of October 2024, by:

APPENDIX A

IR Spectrum of the samples in the initial stage (before first drying), after first drying, and in the final stage (after washing and drying) are found in Figure 10 – Figure 45.

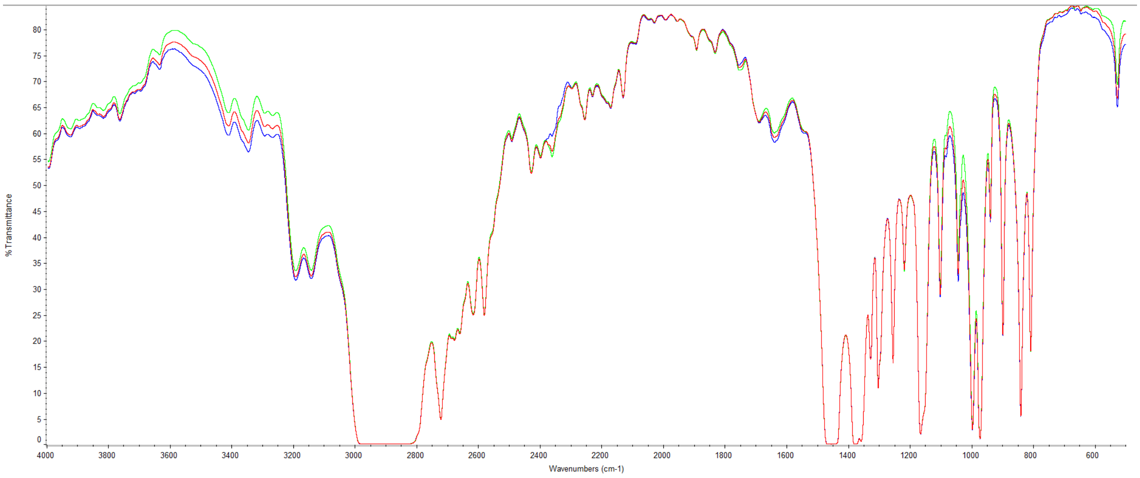


Figure 1: MIR Spectrum Sample 1.1 (PP) Water: Blue line – Initial sample; Red line – after first dry and before wash sample; Green line – Final sample

Table 20: Match Percentage for the Sample 1. in their initial stage, after being dried, and after being washed and dried

Samples 1.1 (PP-Water)	Compound name	Match percentage (%)	Index	Library Name
Before first drying	Polypropylene	77.20	496	HR Hummel Polymer and Additives
After first drying	Polypropylene	74.13	496	HR Hummel Polymer and Additives
Final	Polypropylene	76.61	496	HR Hummel Polymer and Additives

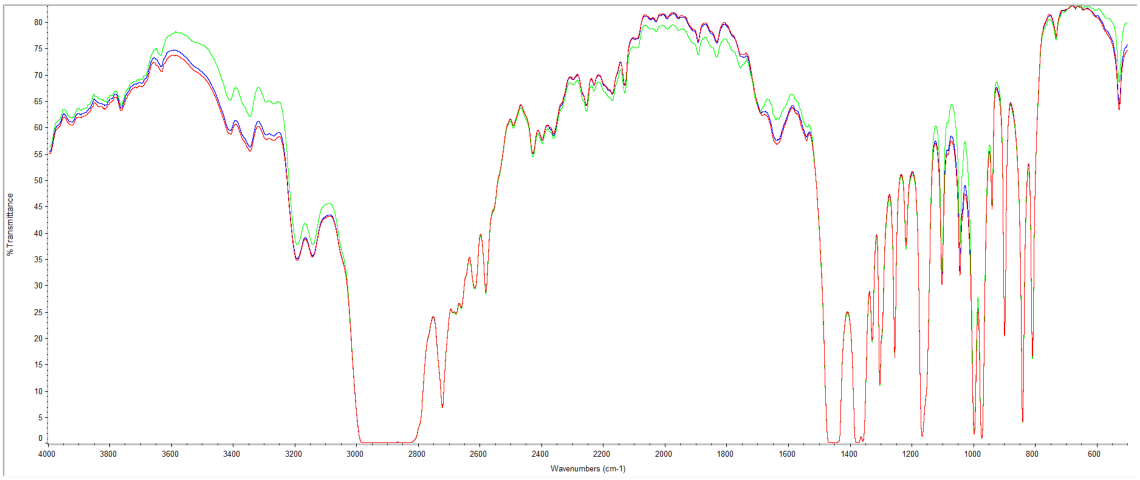


Figure 2: MIR Spectrum Sample 1.5 (PP) NaOH: Blue line – Initial sample; Red line – after first dry and before wash sample; Green line – Final sample

Table 21: Match Percentage for the Sample 1.5 in their initial stage, after being dried, and after being washed and dried

Samples 1.5 (PP-NaOH)	Compound name	Match percentage (%)	Index	Library Name
Before first drying	Polypropylene	73.33	496	HR Hummel Polymer and Additives
After first drying	Polypropylene	82.00	496	HR Hummel Polymer and Additives
Final	Polypropylene	80.63	496	HR Hummel Polymer and Additives

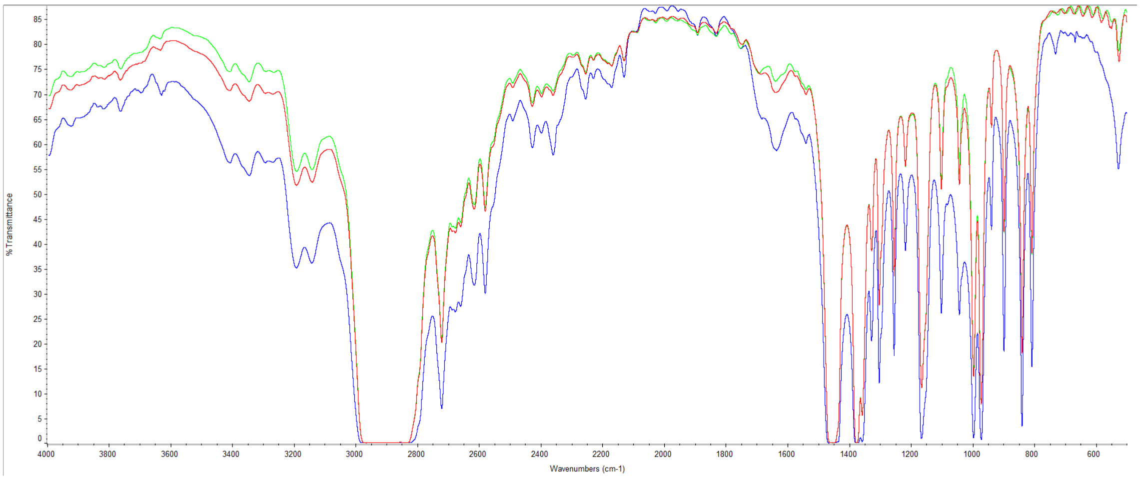


Figure 3: MIR Spectrum Sample 1.9 (PP) Triton X-100: Blue line – Initial sample; Red line – after first dry and before wash sample; Green line – Final sample with water sample

Table 22: Match Percentage for the Sample 1.9 in their initial stage, after being dried, and after being washed and dried

Samples 1.9 (PP-Triton X-100)	Compound name	Match percentage (%)	Index	Library Name
Before first drying	Polypropylene	66.58	38	HR Hummel Polymer Sample Library
After first drying	Polypropylene	75.19	38	HR Hummel Polymer Sample Library
Final	Polypropylene	68.14	38	HR Hummel Polymer Sample Library

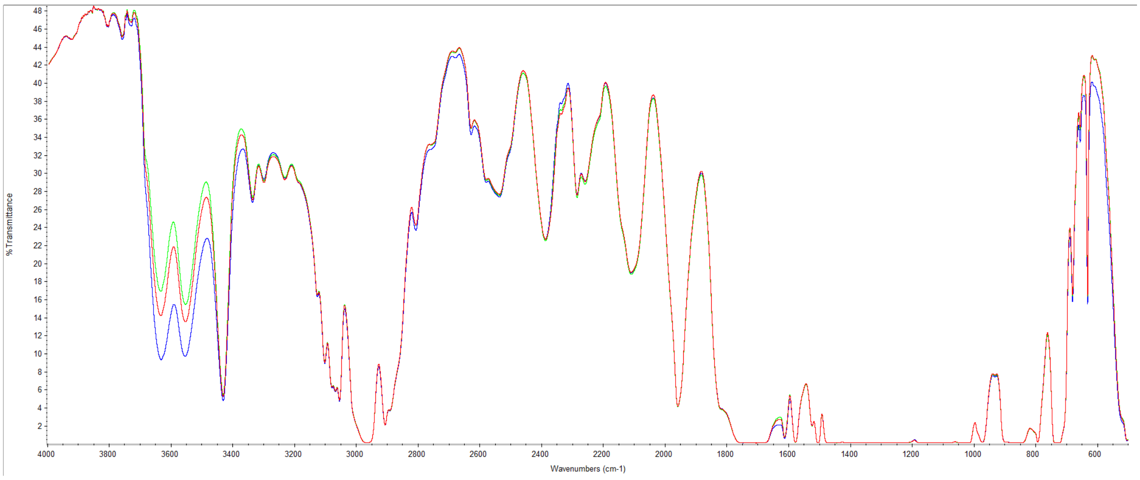


Figure 4: MIR Spectrum Sample 2.1 (PET) Water: Blue line – Initial sample; Red line – after first dry and before wash sample; Green line – Final sample with water sample

Table 23: Match Percentage for the Sample 2.1 in their initial stage, after being dried, and after being washed and dried

Samples 2.1 (PET-Water)	Compound name	Match percentage (%)	Index	Library Name
Before first drying	Polyethylene Terephthalate	46.14	496	HR Hummel Polymer and Additives

After first drying	Polyethylene Terephthalate	47.78	496	HR Hummel Polymer and Additives
Final	Polyethylene Terephthalate	46.92	496	HR Hummel Polymer and Additives

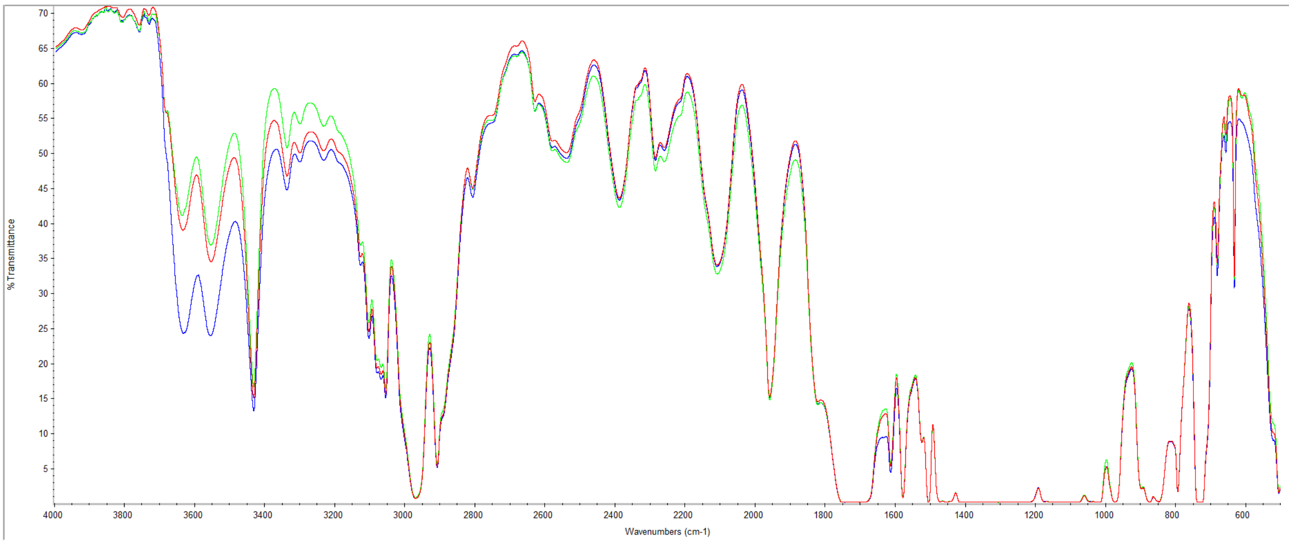


Figure 5: MIR Spectrum Sample 2.5 (PET) NaOH: Blue line – Initial sample; Red line – after first dry and before wash sample; Green line – Final sample with water sample

Table 24: Match Percentage for the Sample 2.5 in their initial stage, after being dried, and after being washed and dried

Samples 2.5 (PET-NaOH)	Compound name	Match percentage (%)	Index	Library Name
Before first drying	Polyethylene Terephthalate	58.60	496	HR Hummel Polymer and Additives
After first drying	Polyethylene Terephthalate	58.41	496	HR Hummel Polymer and Additives
Final	Polyethylene Terephthalate	58.19	496	HR Hummel Polymer and Additives

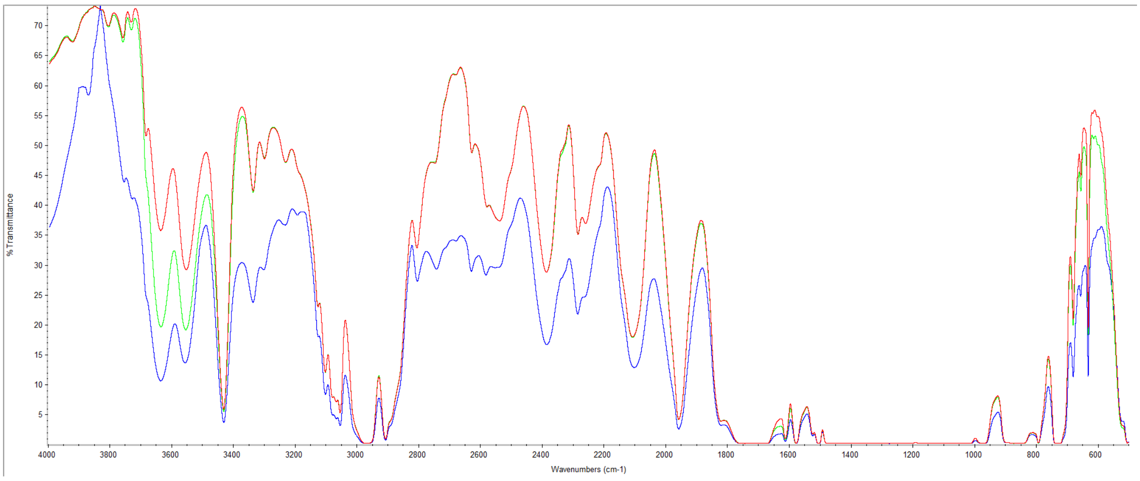


Figure 6: MIR Spectrum Sample 2.9 (PET) Triton X-100: Blue line – Initial sample; Red line – after first dry and before wash sample; Green line – Final sample with water sample

Table 25: Match Percentage for the Sample 2.9 in their initial stage, after being dried, and after being washed and dried

Samples 2.9 (PET-Triton X-100)	Compound name	Match percentage (%)	Index	Library Name
Before first drying	Polyethylene Terephthalate	41.53	543	HR Hummel Polymer and Additives
After first drying	Polyethylene Terephthalate	39.01	543	HR Hummel Polymer and Additives
Final	Polyethylene Terephthalate	41.95	543	HR Hummel Polymer and Additives

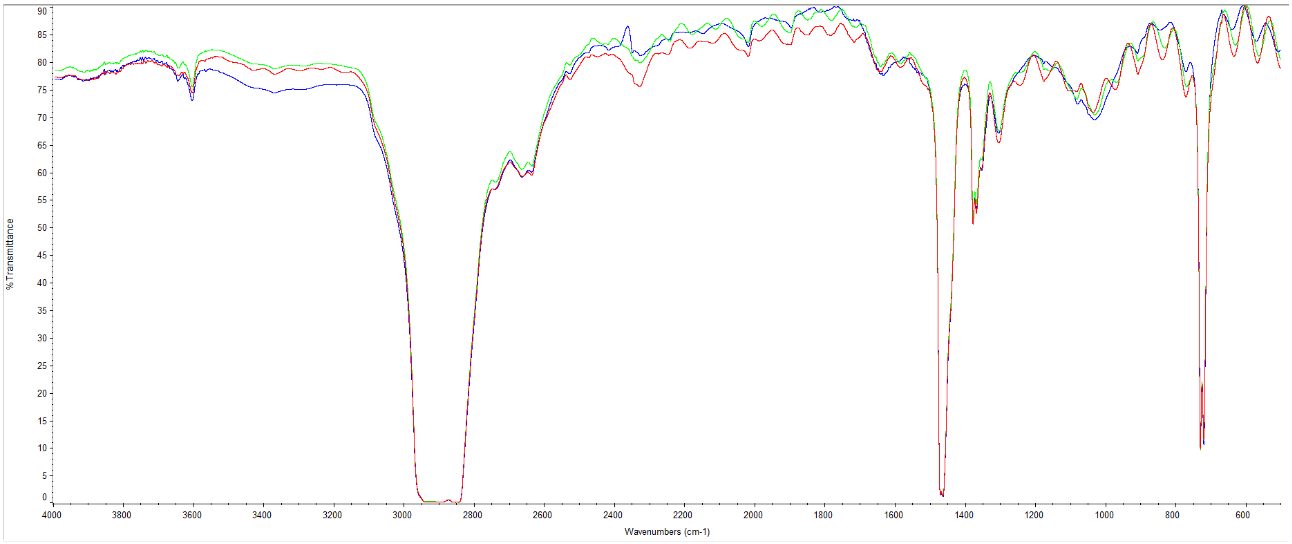


Figure 7: MIR Spectrum Sample 3.1 (PE) Water: Blue line – Initial sample; Red line – after first dry and before wash sample; Green line – Final sample with water sample

Table 26: Match Percentage for the Sample 3.1 in their initial stage, after being dried, and after being washed and dried

Samples 3.1 (PE-Water)	Compound name	Match percentage (%)	Index	Library Name
Before first drying	Polyethylene	85.48	7	Hummel Polymer Sample Library
After first drying	Polyethylene	85.86	7	Hummel Polymer Sample Library
Final	Polyethylene	80.26	7	Hummel Polymer Sample Library

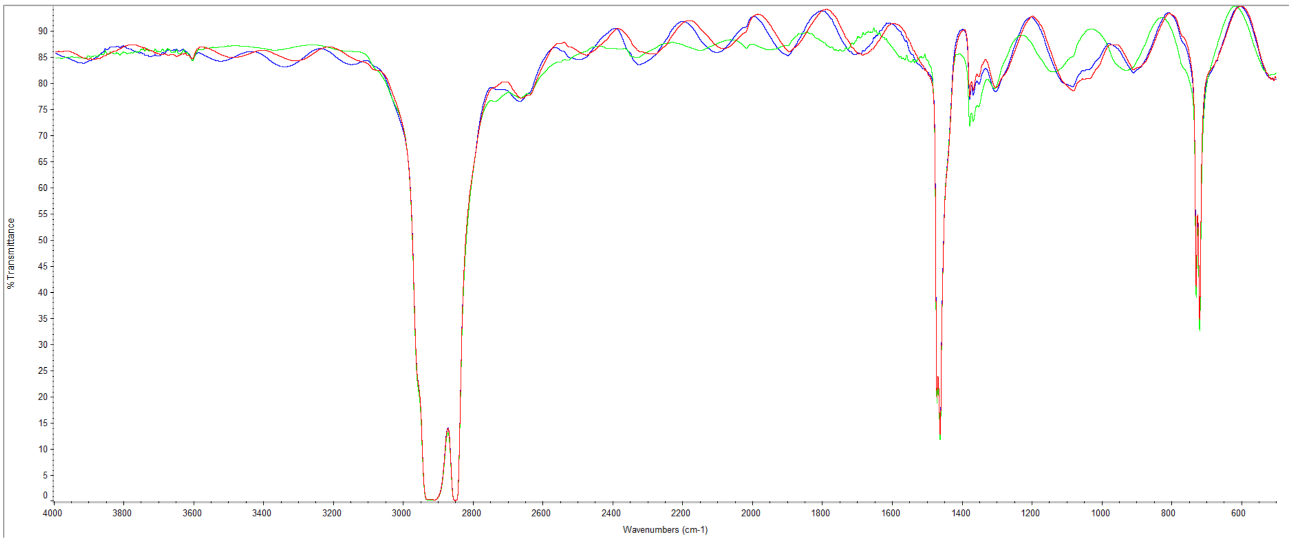


Figure 8: MIR Spectrum Sample 3.5 (PE) NaOH: Blue line – Initial sample; Red line – after first dry and before wash sample; Green line – Final sample with water sample

Table 27: Match Percentage for the Sample 3.5 in their initial stage, after being dried, and after being washed and dried

Samples 3.5 (PE-NaOH)	Compound name	Match percentage (%)	Index	Library Name
Before first drying	Polyethylene	90.35	7	Hummel Polymer Sample Library
After first drying	Polyethylene	96.75	7	Hummel Polymer Sample Library
Final	Polyethylene	97.10	7	Hummel Polymer Sample Library

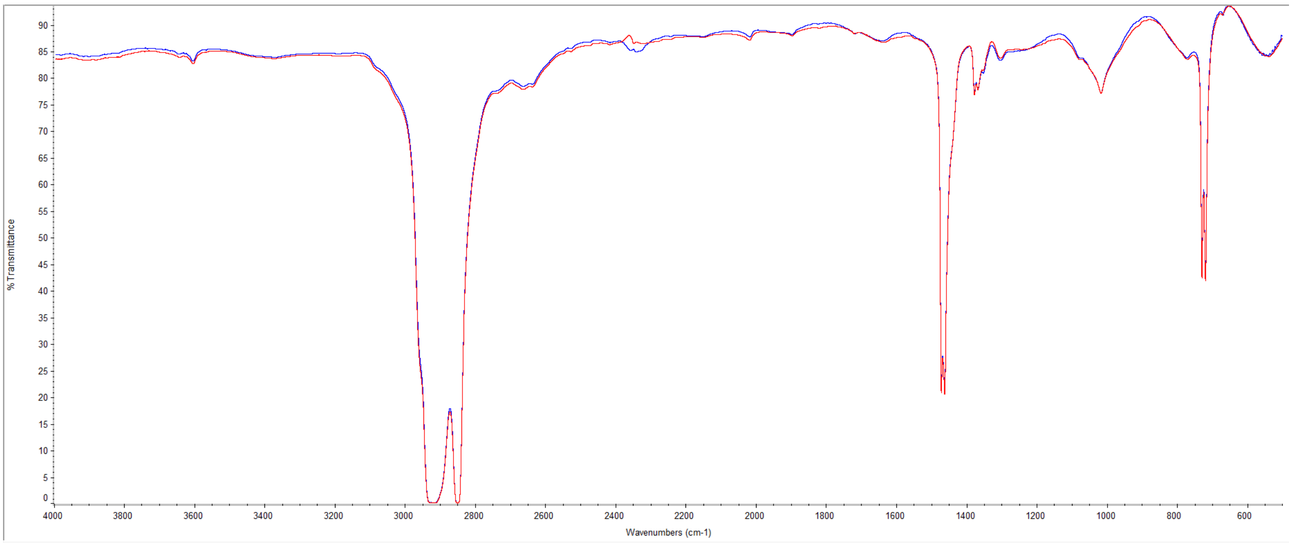


Figure 9: MIR Spectrum Sample 3.9 (PE) Triton X-100: Blue line – Initial sample; Red line – after first dry and before wash sample; Green line – Final sample with water sample

Table 28: Match Percentage for the Sample 3.9 in their initial stage, after being dried, and after being washed and dried

Samples 3.9 (PE-Triton X-100)	Compound name	Match percentage (%)	Index	Library Name
Before first drying	Polyethylene	97.59	7	Hummel Polymer Sample Library
After first drying	Polyethylene	87.82	32	Hummel Polymer Sample Library
Final	Polyethylene	94.03	32	Hummel Polymer Sample Library

Report from University of Rostock

Methodology:

The plastic samples collected from the water were first sorted, cut into pieces, and dried. The dried samples were placed in a beaker and fully submerged in the appropriate cleaning solution (~ 100 ml). When using a 1M NaOH solution, a magnetic stirrer was added to the beaker, and the mixture was stirred at 1000 rpm without heating. For samples treated with a surfactant, the beaker was placed in an ultrasonic bath and subjected to ultrasonication for 30 minutes. After treatment, the samples were rinsed with water and dried.

1. PP

Sample name	Cleaning medium	Physical cleaning	Photo-after	Effectiveness/scale
PP_27	Tap cold water + Ecosurf	Ultrasonication (30 min)		3

COP Circular Ocean-bound Plastic
Interreg South Baltic
Co-funded by the European Union

PP_15	1M NaOH	Stirring (1000 rpm)		2

2. PET

Sample name	Cleaning medium	Physical cleaning	Photo-after	scale
PET_27	Tap cold water + Ecosurf	Ultrasonication (30 min)		3

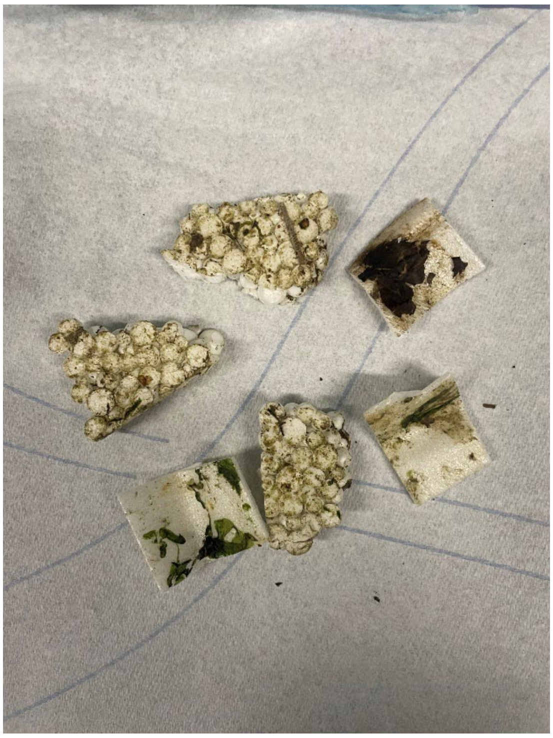
PET_15	1M NaOH	Stirring (1000 rpm)		4

3. PE foil

Sample name	Cleaning medium	Physical cleaning	Photo-after	scale
PE_27	Tap cold water + Ecosurf	Ultrasonication (30 min)		2

PE_15	1M NaOH	Stirring (1000 rpm)		2

4. PS



Sample name	Cleaning medium	Physical cleaning	Photo-after	scale
PS_27	Tap cold water + Ecosurf	Ultrasonication (30 min)		2

				
PS_15	1M NaOH	Stirring (1000 rpm)		2

Cleaning time: The cleaning time was not extended beyond the set parameters in the initial protocol. However, this could be an interesting avenue to explore further to see if it impacts the results. It will be considered for future experiments.

Sample exposure and contaminants: The samples were immersed in water for durations ranging from some hours to a few days, after which they were stored for periods ranging from weeks to months. They are primarily contaminated with organic matter, such as algae, which had significantly desiccated by the time of analysis.

Cleaning effectiveness: At this stage, formal analyses to evaluate the cleaning effectiveness have not been conducted.