UNIVERSITY OF TURKU

Microplastic separation based on acoustic manipulation

Department of Mechanical and Materials Engineering

Bachelor's thesis

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26.04.2025

Turku

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Subject: Materials Engineering
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Title: Microplastic separation based on acoustic manipulation
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Number of pages: 30 pages
Date: 26.04.2025

Microplastics - plastic particles smaller than 5 mm - are a major problem for the environment. A wide range of different methods have been developed to separate them, especially from aquatic environments such as oceans and water treatment plants. Currently, no standardized methodology exists for the separation of microplastics, despite the urgent need for one due to the accumulation of microplastics in ecosystems and their harmful effects on living organisms.

Promising methods developed for the separation of microplastics from aquatic environments include the coagulation-flocculation method, various filtration methods or the magnetic separation method. Acoustic manipulation can be considered as promising future separation method for microplastics. Separation by acoustic manipulation has been widely studied as a separation method for different biological particles, such as cells. In this thesis, the applicability of acoustic manipulation for the separation of microplastics is investigated through both a literature review and an experimental part.

The problem with many promising separation methods is their invasiveness. Separation of microplastics by acoustic manipulation is a low-cost, non-invasive and therefore non-toxic and safe method of separation. Separation of microplastic particles with acoustic manipulation has been studied mostly in microfluidic systems. The experimental part of the thesis provided information on the intra-droplet, static acoustic manipulation of microplastics and the possible influences on the efficiency and success of the method. Intra-droplet microplastic particle manipulation is possible but still requires development to be effective on a larger scale. Further experimentation with different aqueous solutions is also needed to ensure the effectiveness of the method.

Key words: microplastic separation, acoustic manipulation, separation methods, non-toxic, intra-droplet manipulation, aquatic environment

Kandidaatin tutkielma

Oppiaine: Materiaalitekniikka
Tekijä: Ellen Vainio
Otsikko: Microplastic separation based on acoustic manipulation
Ohjaaja: Amit Barua
Sivumäärä: 30 sivua
Päivämäärä: 26.04.2025

Mikromuovit, alle 5 mm kokoiset muovihiukkaset, ovat suuri ongelma ympäristölle. Niiden erotteluun erityisesti vesiympäristöistä, kuten meristä ja vedenpuhdistuslaitoksista on kehitetty monenlaisia eri tapoja. Tällä hetkellä standardisoitua metodia mikromuovien erotteluun ei kuitenkaan ole ja sen kehittäminen olisi äärimmäisen tärkeää, sillä mikromuovit kertyvät ekosysteemeihin ja vaikuttavat haitallisesti eliöihin.

Mikromuovien erotteluun vesiympäristöistä on kehitetty useita lupaavia metodeja, kuten esimerkiksi koagulaatio-flokkulaatio-metodi, erilaiset suodatusmetodit tai magneettinen erottelumetodi. Akustinen manipulaatio on myös yksi mahdollisista mikromuovien tulevaisuuden erottelumetodeista. Akustisen manipulaation avulla tapahtuvaa erottelua on tutkittu paljon erilaisten biologisten partikkelien, kuten solujen, erottelumetodina. Tutkielmassa tutkitaan akustisen manipulaation soveltuvuutta mikromuovien erotteluun niin kirjallisuuskatsauksen, kuin kokeellisen osuuden avulla.

Monien lupaavien erottelumenetelmien ongelma on niiden invasiivisuus. Mikromuovien erottelu akustisella manipulaatiolla on edullinen, ei-invasiivinen ja sen kautta myös myrkytön ja turvallinen metodi erotteluun. Mikromuovien akustista erottelua on tutkittu enimmäkseen mikrofluidisissa systeemeissä. Tutkielman kokeellisessa osuudessa saatiin tietoa pisaran sisäisestä mikromuovien akustisesta manipulaatiosta sekä siitä, mikä mahdollisesti vaikuttaa metodin tehokkuuteen ja onnistumiseen. Pisaran sisäinen hiukkasten manipulaatio on mahdollista, mutta vaatii kehitystä vielä suurelta osin, jotta se olisi hyödyllistä suuremmassa mittakaavassa. Myös kokeiden jatkaminen erilaisissa vesiliuoksissa on tarpeen metodin efektiivisyyden varmistamiseksi.

Avainsanat: mikromuovien erottelu, akustinen manipulaatio, erottelumetodi, myrkytön, pisaran sisäinen metodi, manipulaatio, vesiympäristö

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1 Introduction

Plastic particles up to 5 mm in diameter can be defined as microplastics and within that range, particles with a diameter of less than 100 nm can be defined as nanoplastics. Different kinds of microplastics found in wastewater are illustrated in figure 1A. Microplastics are widely found in oceans, from where they also transfer into continental ecosystems where they pose potential threats and contribute to pollution across the entire global ecosystem. [1]. It is estimated that in 2016, 19–23 million tons, 11%, of globally generated plastic waste, ended up in various aquatic ecosystems. It has also been projected that by 2030, annual plastic emissions could potentially reach up to 53 million tons [2]. Figure 1B illustrates the current and possible future quantities of plastic that enter the ecosystem.

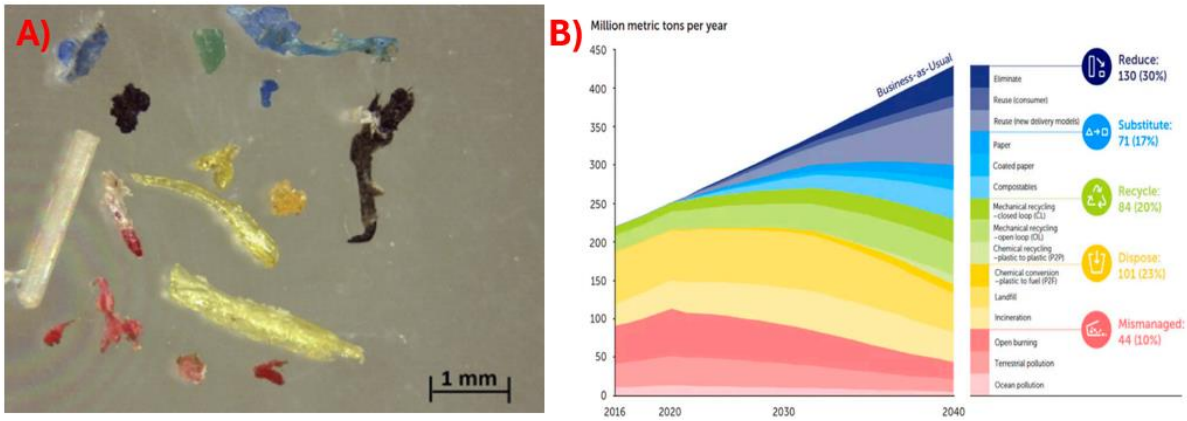

Figure 1. A) Microplastics collected from wastewaters. Image modified with permission from reference [3]. Copyright 2017 Elsevier Ltd. B) Current and potential future quantities of plastic waste. Modified from reference [4].

At present, there are countless studies on microplastics purification and separation methods, but no standard system has yet been developed and there is a particular lack of an effective method for the purification of small-sized microplastics. The development of simple, cost-effective and efficient microplastic removal methods is crucial to prevent the harmful effects microplastics can cause on organisms. [5]. There are various applications for the separation of microplastics from water, some of which still require further research before they can be used effectively on a large scale [6,7]. Many microplastic separation or removal methods can also be combined, in which case they are called hybrid methods [6].

The suitability of acoustic microparticle manipulation has been widely studied in biomedical applications, for example in the separation and aggregation of particles. Acoustic separation has been used in microfluidic systems as a method to separate various types of microparticles

and acoustic manipulation has been used to for example concentrate microparticles in droplets. [8],[9]. Acoustic manipulation as a separation technique has also been applied to the separation of microplastic particles using various devices in flow-based systems and some of the experimental studies have specifically focused on the purification of marine or wastewater. [10],[7],[11].

This thesis presents a literature review on microplastics and the separation methods in aquatic ecosystems and wastewater. The literature review part focuses on commonly used and experimentally promising microplastic separation methods in water environments such as acoustic separation, coagulation-flocculation and electrocoagulation, different filtration methods and magnetic separation method. However, the literature review has a particular emphasis on the acoustic separation method.

The thesis also includes experimental section which utilizes the acoustic separation technique to perform microplastic separation experiment. The experiments demonstrate the accumulation of microplastics at acoustic nodes using two different devices, as illustrated in Figure 2. Additionally, the effect of a surfactant on the efficiency of the method is tested in the experimental section.

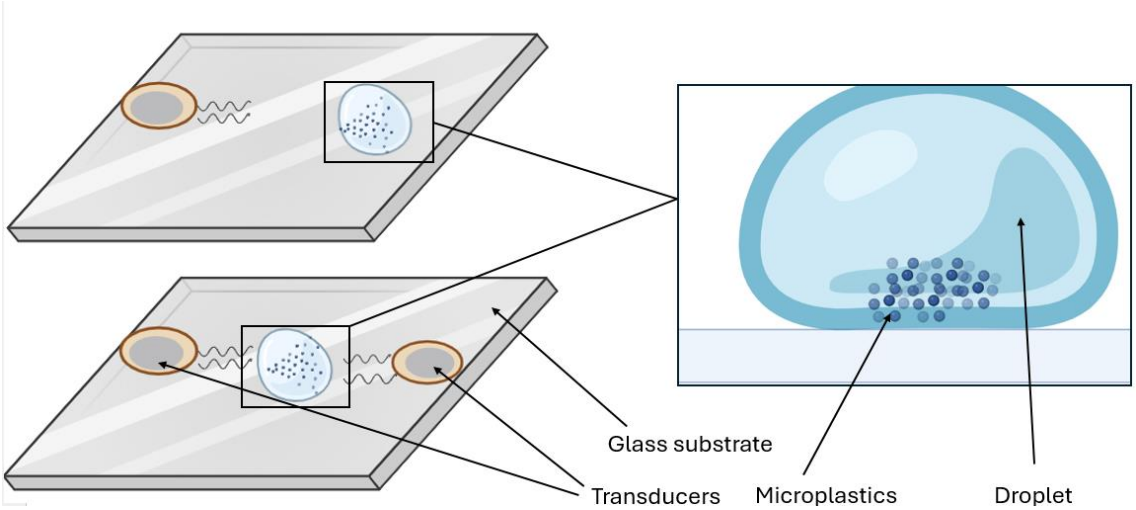

Figure 2. The devices used in the experimental section.

2 Microplastics and separation methods

2.1 Microplastics

Plastic pollution can be seen as a threat to marine ecosystems on a large scale, as the marine species are affected by toxins from the plastics and the problems it causes will persist for many years even if plastic use is reduced or ended in general [12].

Microplastics are often divided into two groups based on the way they are released into the environment, primary and secondary microplastics. Primary microplastics enter marine ecosystems most commonly from cosmetics, cleaning products and the manufacture of larger products. The main source of secondary microplastics in marine ecosystems is the fragmentation of larger plastic products into smaller pieces. The abrasion of plastic-containing products, such as textiles, leads to the development of secondary microplastics [13]. Main sources of primary and secondary microplastics are illustrated in figure 3. The most common types of plastics from which microplastics are found in marine ecosystems are polypropylene (PP), polyethylene (PE), polystyrene (PS), polyethylene terephthalate (PET) and polyesters such as nylon or acrylic [14].

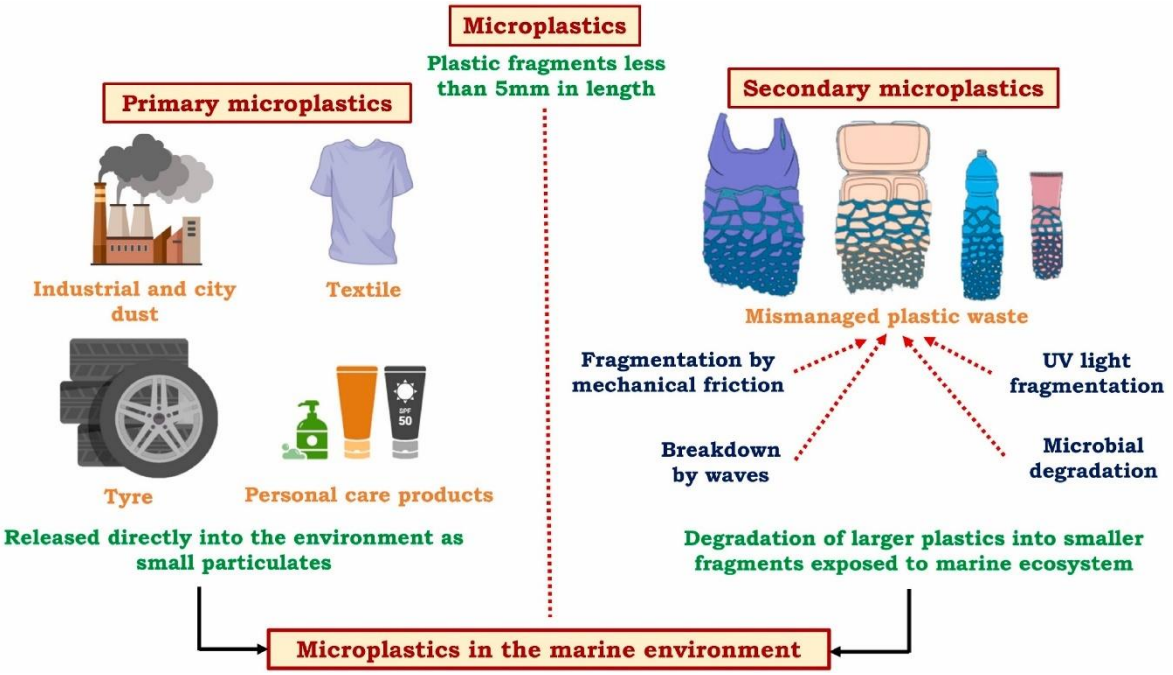

Figure 3. Sources of primary and secondary microplastics in marine environment. Image reproduced with permission from reference [6]. Copyright 2025 Elsevier Ltd.

Microplastics can cause both physical and chemical effects in organisms. Physical effects may result, for example, from the accumulation of microplastics in the digestive systems of organisms, potentially leading to death. This can impact the food chain and cause imbalances in ecosystems. Chemical effects may cause oxidative stress or cause genetic alterations, which can lead to neurotoxicity. Additionally, chemical effects may also interfere with hormonal functions.[15].

Many ways have been developed to remove or capture marine microplastics. Microplastics removal methods can be divided into two types, separation and dispersion. In separation methods, the size, density and hydrophobicity of the microplastics particles can be considered as important classification criteria. Physical removal methods include for example different filtering techniques and density separation. Chemical removal methods can include different oxidation reactions and techniques, flocculation-coagulation and electrocoagulation. Biological removal methods include the use of various biocatalysts, which means they methods may include the use of enzymes or various bacteria [5].

2.2 Coagulation-flocculation

Coagulation-flocculation is a widely used method for the separation and dewatering of contaminants in various industrial processes and wastewater treatment. During coagulation, the energy barriers between particles are overcome by increasing the ionic strength of the system, thereby promoting particle aggregation and sedimentation. Coagulants neutralize the surface charge of suspended particles, facilitating their settling and aggregation. In the flocculation stage, chemical reagents are added following coagulation to enhance the formation of larger flocs, which further improve solid-liquid separation. The process is illustrated in figure 4. Both inorganic and organic compounds, as well as hybrid materials, can be utilized in coagulation-flocculation processes [16].

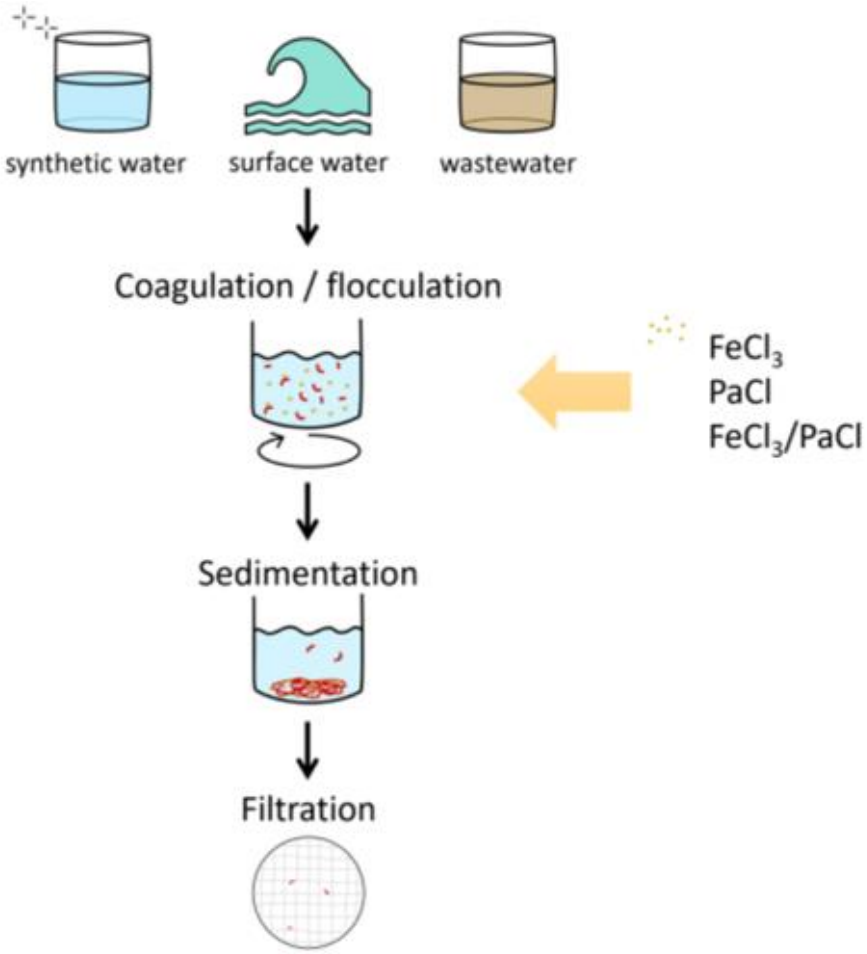

Figure 4. Coagulation-flocculation process with filtration. Modified from Vasiljević et al. [17]. Copyright 2023 by the authors, published by Processes.

In microplastic coagulation-flocculation studies, filtration is often used as a complementary separation technique. Fe- and Al-based coagulants has been used, among other substances, in the coagulation-flocculation method to remove microplastics at a wide range of doses to achieve high removal efficiency. [18], [19]

In addition to the conventional coagulation-flocculation process, electrocoagulation is also utilized as a separation method. The effectiveness of electrocoagulation in the removal of various contaminants, such as strontium or fluorine, from wastewater has been studied [20], [21]. Electrocoagulation has also been investigated as an effective method for the removal of plastic microparticles from wastewater [22].

In electrocoagulation, metal cations are released from the anode and function as micro coagulants, effectively neutralizing the charges of impurities. These micro coagulants subsequently interact with contaminants in the water, such as microplastic particles, facilitating the formation of larger flocs. Over time, these flocs aggregate and precipitate,

ultimately forming a sludge layer. The process of electrocoagulation is illustrated in figure 5. The performance of the electrocoagulation process is influenced by several key factors, including the anode material, pH, electrolyte concentration, applied voltage, and the concentration of microplastic particles. Electrocoagulation offers the flexibility to utilize a diverse range of anode materials; however, the separation efficiency of electrocoagulation using an aluminium anode has been demonstrated to be particularly effective and well-suited for water treatment applications. [22]

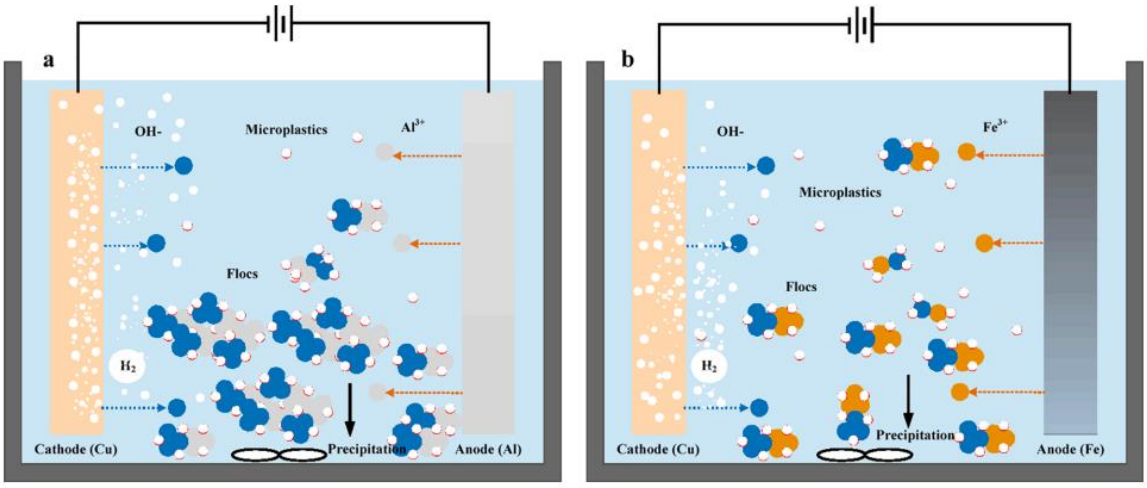

Figure 5. Electrocoagulation process with a) Aluminium cations used as coagulants b) Iron cations used as coagulants. Image reproduced with permission from reference [22]. Copyright 2021 Elsevier B.V.

2.3 Filtration methods

Filtration methods can be roughly divided into two main categories, surface filtration, also known as cake filtration, and depth filtration. In surface filtration, the particles to be filtered are deposited on the surface of the filter material until the deposit is removed. Depth filtration, on the other hand, is based on filters in which particles are deposited not only on the filter surface but also inside the filter, where they penetrate through the porous material and accumulate in the filter-dependent fibres. [23]. An example of deep filtration filter is illustrated in figure 6.

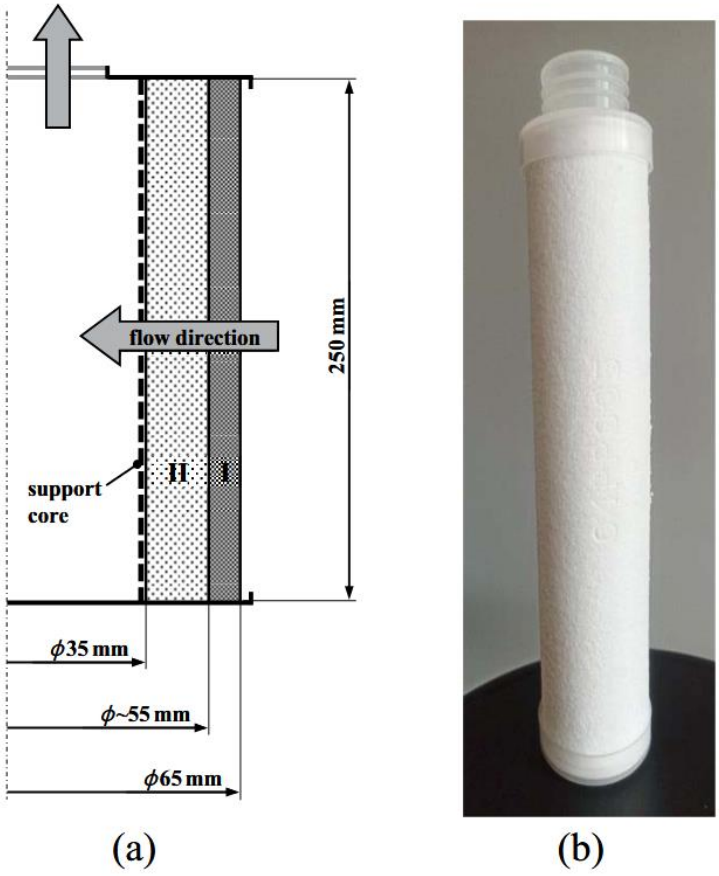

Figure 6. A) Dimensions and representation of different filtering layers used in a filter for deep filtration. B) Picture of a real deep filtration filter. Image reproduced with permission from reference [23]. Copyright 2023 Desalination Publication.

Filtration for the removal of microplastics is usually combined with coagulation-flocculation and their integrated working improves removal efficiency. Methods that have been tested in combination with coagulation-flocculation include sand filtration, granular activated carbon filtration and ultrafiltration. [19], [24],[25].

In the rapid sand filtration, water is purified as it passes through a sand filter composed of gravel and quartz, utilizing gravity-driven filtration. According to a study by Talvitie et al., rapid sand filtration achieved an efficiency of over 95% in removing microplastics larger than 20 μm from wastewater. [3]. Ultrafiltration (UF) is based on the use of different permeable membranes. Ultrafiltration has been shown to be an effective method for removing microplastics particles from wastewater, seawater and drinking water, except in situations where ultrafiltration is used to filter microplastics particles a second time using the same membrane or in situations where external contamination occurs. [26]. The problem with ultrafiltration is the potential for membrane fouling and clogging, which can be prevented by adjusting the amount of coagulant [27].

Granular activated carbon (GAC) filtration is based on the absorption of microplastics [28]. GAC filtration has proven to be very effective, combined with coagulation-flocculation the removal of microplastics was 81%. GAC can be combined with other filtration methods such as sand filtration. [24], [25]. Bogdanowicz et al. demonstrated the performance of polypropylene-based depth filters for the separation of microplastics and compared the performance of surface filters. They found that the performance of depth filters was superior to surface filters, due to the difficulty of the so-called cake layer, which clogs the filter, to accumulate in depth filters. [23].

2.4 Magnetic separation

One of the promising, but still experimental method for the separation of microplastics is the magnetic separation method [6]. The separation of microplastics by the magnetic method is mainly based on the hydrophobicity of the microplastics [29]. The microplastic particles are magnetised by iron nanoparticles, such as Fe_3O_4, that are absorbed by the microplastics. After absorption, the microplastics are collected by a magnet [30]. The process described in figure 7.

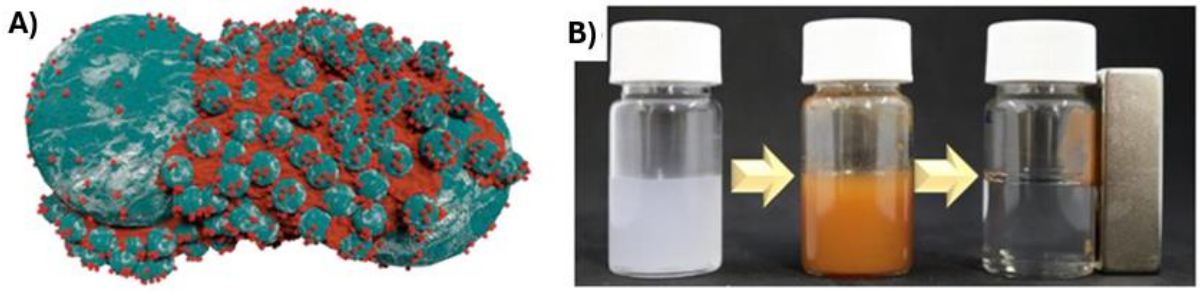

Figure 7. A) Red nanoparticles absorbed on the surface of a microplastic particle. B) The process of magnetic separation. The first container shows only the microplastic particles, the second container has the magnetic nanoparticles added, and the last container has the microplastic particles and nanoparticles gathered in one place by a magnet. Image reproduced with permission from reference [31]. Copyright 2021 Elsevier LTD.

Microplastic particles consisting of common types of plastics such as polypropylene (PP), polyethylene (PE), polystyrene (PS), polyethylene terephthalate (PET) has been successfully separated by magnetic separation. Their removal efficiency differs due to their different degrees of hydrophobicity [30]. It has also been studied that the hydrophobicity of micro- or nano-plastics can be enhanced by forming hydrophobic ligands on the surface of Fe_3O_4 nanoparticles to improve surface absorption. This was performed by mixing octadecyl

phosphonic acid (PAC18) or (12-dodecylphosphonic acid)-N,N-dimethyl-N-octadecyl ammonium bromide (PAC12NC18) with iron oxide. [31].

Magnetic separation using nanoparticles can also be achieved with hydrophilic magnetic nanoparticles. These hydrophilic nanoparticles adsorb onto microplastic particles through hydrogen bonding. After binding, the microplastics can be separated or collected in a specific location using a magnet. The nanoparticles can be reused, as their structure and magnetic properties remain intact during the treatment process. Therefore, the method is both cost-effective and efficient. [32].

While magnetic separation presents several promising advantages, it also has potential limitations. Research on the toxicity of iron nanoparticles has indicated that they can increase oxidative stress and promote the formation of reactive oxygen species, leading to cytotoxic effects. However, the overall number of studies investigating the toxicity of iron nanoparticles remains still limited. [33].

3 Acoustic separation method

Acoustic manipulation enables the separation of various microparticles based on different types of surface acoustic waves (SAW) or bulk acoustic waves (BAW). This technique has been widely used for the separation of biological microparticles such as cells, bacteria, and viruses and it has also been applied to the separation of microplastics. Acoustic manipulation is a non-contact, controllable, and adaptable separation method. [8].

The effectiveness of standing surface acoustic waves (SSAW) in concentrating and patterning various micro- and nanoparticles has been demonstrated [34],[35]. The principle of surface acoustic wave (SAW) particle concentration is based on the interference of two opposing surface acoustic waves from different directions. Their mutual interference causes constructive and destructive interferences, which form a standing surface acoustic wave (SSAW). This standing surface acoustic wave has pressure nodes (minimum pressure amplitude) and anti-pressure nodes (maximum pressure amplitude), resulting acoustic radiation forces on the microparticles in the medium caused by the pressure variation. This forces particles involved to move towards either pressure nodes or anti-pressure nodes, depending on the relative density or compressibility of the medium and the microparticles. [36]. The working principle is illustrated in figure 8.

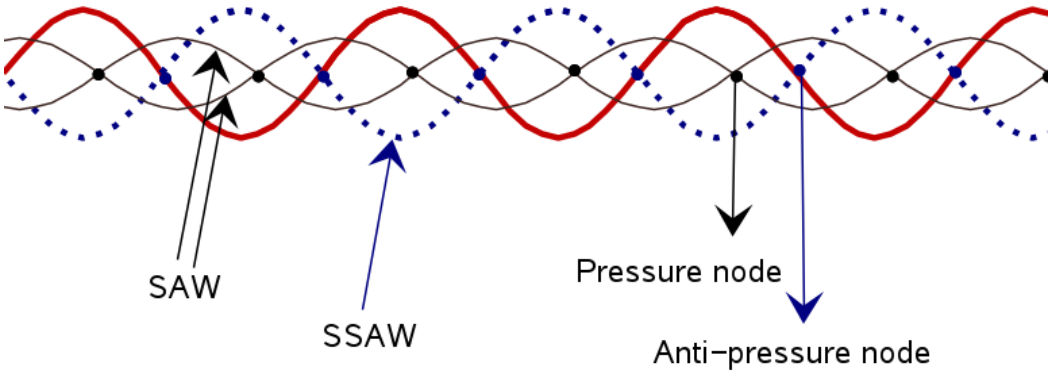

Figure 8. Working principle of the SAW resulting to SSAW and pressure variation.

Travelling surface acoustic waves (TSAWs), are another type of SAW, which, unlike SSAWs, do not form a standing wave but propagate in one direction, radiating away from acoustic sources. TSAWs can also form pressure nodes ant anti-pressure nodes, which makes them also useful for acoustic manipulation applications. [37], [8].

Interdigitated transducers (IDTs) can be used to generate different types of SAWs. By adjusting the arrangement of the ITD, different liquids or particles can be controlled. If only one IDT is used, travelling surface acoustic waves (TSAWs) are usually generated. Two opposing IDTs generate standing surface acoustic waves (SSAWs). Both TSAWs and SSAWs are used for separation in acoustic methods. [8].

SAWs proceed on the surface of the material. A bulk acoustic wave (BAW), on the other hand, is a compression wave in a solid that propagates through a variety of bulk materials.[38]. However, the mechanism by which BAWs facilitate particle assembly closely parallels that of SAWs and is fundamentally based on the formation of a standing wave. BAWs undergo reflection from opposing, parallel surfaces, leading to wave superposition and the establishment of a standing wave pattern. [38],[39].

With a time-averaged drifting force, a standing wave can position particles in a fluid-filled cavity to a pressure node or anti-pressure node. The acoustic radiation force (F) acting on the particles can be calculated with following equation (1):

$$F = \frac{(\pi p_0^2 V_p \beta_m)}{2\lambda} \phi(\beta, p) \sin 2kx \quad (1)$$

where p_0 is the acoustic pressure amplitude, V_p is the particle volume, $\frac{1}{\lambda}$ is the applied frequency, k is the wave number (is defined by $2\pi/\lambda$), x is the distance from a pressure node and ϕ is the acoustic contrast factor, which can be calculated using following equation (2):

$$\phi(\beta, p) = \frac{5p_p - 2p_m}{2p_p + p_m} - \frac{\beta_p}{\beta_m} \quad (2)$$

where p_p is the density of the particle, p_m is the density of the suspended medium, β_p is the compressibility of the particle and β_m is the compressibility of the medium. [40], [41].

The acoustic wave scattered by the particle causes inter-particle scattering, affecting the particle. However, interparticle scattering and secondary radiation forces on the particles can be interpreted as insignificant when the diameter of the particles is smaller than the wavelength and the distance between the particles is larger than the combined diameter of the two particles. [42]. It can therefore be concluded that equation 1 can only be used in situations where the particles are smaller than the wavelength used. The scattering between the particles of an acoustic wave is not negligible and the diameter of the particle is comparable to the wavelength, which is completely ignored in equation 1. [43].

Akiyama et al. built a bulk acoustic wave-based microparticle collector capable of detecting only particles with a positive acoustic contrast factor (presented in equation 2). The device was a three-axis, and the study demonstrated that it could effectively collect almost all microparticles in the middle section, regardless of the size of the microparticles. The microplastics used in the study were polystyrene (PS), Nylon 6 and polyethylene terephthalate (PET).[10].

Perera and Piyasena investigated the acoustic manipulation of polystyrene (PS), polymethyl methacrylate (PMMA), and polyethylene (PE) within a steel tube device, demonstrating that the primary factors influencing particle behaviour were acoustic frequency and medium density. Their findings indicated that at low medium density and low acoustic frequency, particles consistently accumulated at pressure nodes, irrespective of their size. However, at higher acoustic frequencies, larger microplastic particles of the same material preferentially migrated to anti-pressure nodes instead of pressure nodes, independent of the medium density. [43].

Akiyama et al. studied the separation of microplastic particles using a microfluidic device [10] and Perera and Piyasena studied the separation of mostly large-sized microplastic particles using steel tubes [43]. Tatsuki et Al. developed a device that could effectively enrich various sized microplastic particles without recirculation by serial acoustic separation. The instrument developed for the study was suitable for microparticles between 200 μm and 10 μm. The microparticles were collected at a total collection rate which, using a suitable excitation voltage, exceeded 90 % in individual collection experiments. In mixture experiments based on actual collection rates and total collection rates measured by means of

outlets, the collection rates of microparticles ranged from 70% to 90%. The problem and bias in the study was caused by the adherence of the microparticles onto the walls of the microchannel. However, the study showed that serial acoustic separation of the enrichment furnace is a promising method for the collection or enrichment of microplastic particles from environmental samples.[11].

Mesquita et al. utilized travelling surface acoustic waves (TSAW) to separate microplastic particles in their study. Employing a microfluidic device, they investigated the migration behaviour of microplastics and blood cells under varying acoustic frequencies. The findings indicated that lower flow rates and higher acoustic power enhanced the efficiency of microplastic separation. [44].

4 Experimental Section

4.1 Materials and equipment used

Materials and equipment used in experimental part are listed below:

4.1.1 Materials

- Polystyrene (PS) particles
- Polyethylene glycol (PEG) particles
- Ethanol
- Hexane
- 2-[4-(2,4,4-trimethylpentan-2-yl) phenoxy] ethanol (commercial name Triton X-100)
- Loctite epoxy glue
- Two glass plates (7,5 x 2,5 cm and 7,3 x 2,5 cm)
- Three transducers

4.1.2 Equipment

- Mortar and pestle
- Keysight 33500B Waveform Generator
- Falco Systems WMA-300 high-voltage amplifier
- Euromex bScope optical microscope

4.2 Sample preparation

Three different samples were prepared for testing. Sample 1, shown in figure 9A, contained commercial red polystyrene (PS) particles and surfactant 2-[4-(2,4,4-trimethylpentan-2-yl) phenoxy] ethanol, commercial name Triton X-100. The other samples contained commercial polyethylene glycol (PEG) particles. PEG particles were mechanically reduced in size using a mortar and pestle to achieve dimensions appropriate for microparticle classification as shown in figure 10. Sample 2, shown in 9B, contained 500 mg of larger PEG particles and 5ml of ethanol used as solvent. Sample 3, shown in figure 9C, contained 500mg of smaller, more finely crushed PEG particles and 5ml of hexane used as solvent.

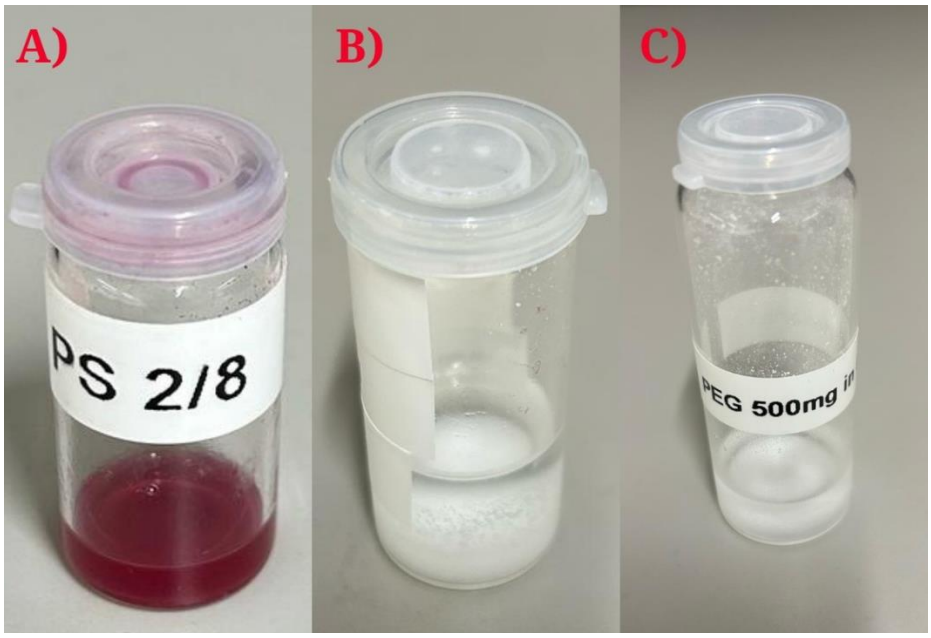

Figure 9. A) PS and surfactant. B) PEG and ethanol. C) PEG and hexane.

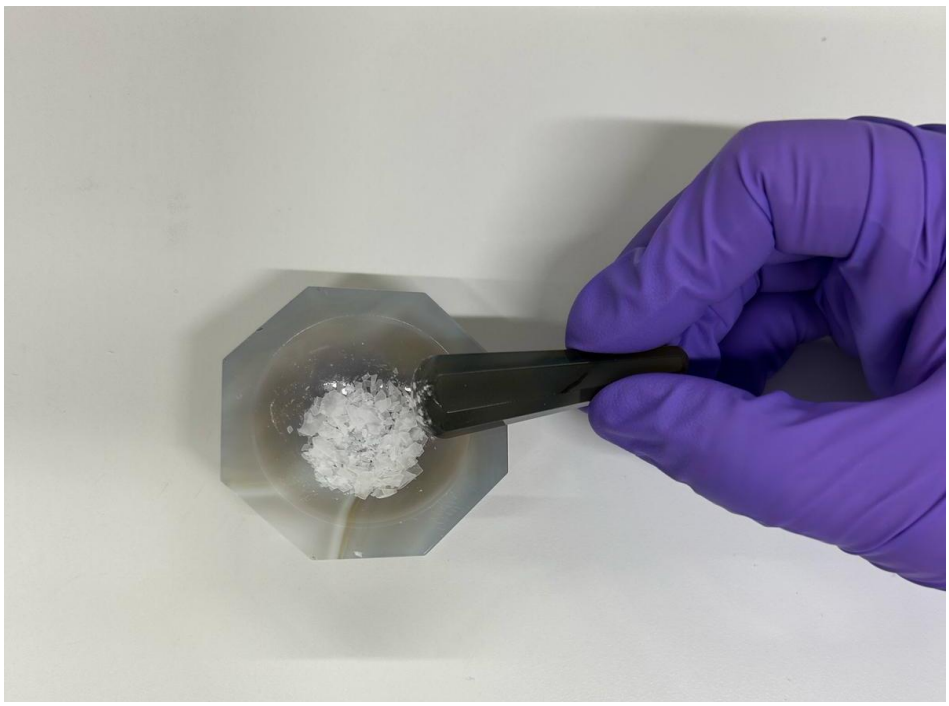

Figure 10. Mortar and pestle were used to mechanically reduce the size of the commercial PEG particles.

4.3 Device preparation

Two different devices were prepared for the tests. A 7,5 x 2,5 cm and 7,3 x 2,5 cm glass plates were used as substrate for devices. Transducers with 2,5 cm diameter were attached to the glass plates with Loctite epoxy glue. The first device featured a single transducer positioned on one side of the glass plate, as illustrated in Figure 11A. The second device

incorporated two transducers, symmetrically placed on opposite edges of the glass plate, as shown in Figure 11B.

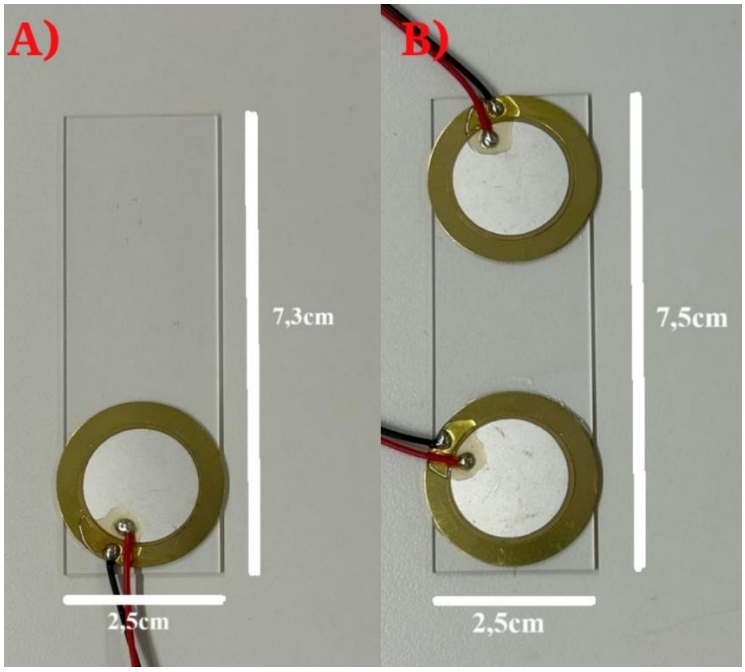

Figure 11. A) Single transducer device. B) Double transducer device. The transducers are mounted on a glass slide using epoxy glue.

Microscope analysis was conducted using a Euromex optical microscope Bscope and the equipment used was attached to the microscope as shown in figure 12A. Additional equipment used in the experiments included a Keysight 33500B Waveform Generator, illustrated in figure 12B, which was used to generate acoustic force at a specified frequency and voltage. A Falco Systems WMA-300 high-voltage amplifier was also used to amplify the applied voltage by a factor of 50, illustrated in figure 12C.

Figure 12. A) Set up for the microscope analysis. B) Waveform generator used in experiments. C) High voltage amplifier used in experiments.

4.4 Results

The first experiment was carried out using a single transducer device. A small layer of water was applied to a thin glass plate and used to attach it on top of the glass substrate in single transducer device. A droplet of approximately 50 μl of sample 1 containing polystyrene particles and a surfactant was pipetted onto the thin glass plate. The polystyrene particles were evenly distributed throughout the droplet as shown in microscopic picture, Figure 13A. The frequency was set to 11 kHz and the power to 4 V_{pp} (peak to peak voltage).

After switching on the power, the polystyrene particles immediately began migrating towards an acoustic node, as can be seen in Figure 13B. The accumulation process continued, with the particles concentrating closer to the centre of the acoustic node, as illustrated in Figure 13C. At the final stage, after the power was switched off, the particles had accumulated at a single point, as shown in Figure 13D. A macro-level view of the accumulated PS particles can be seen in Figure 14.

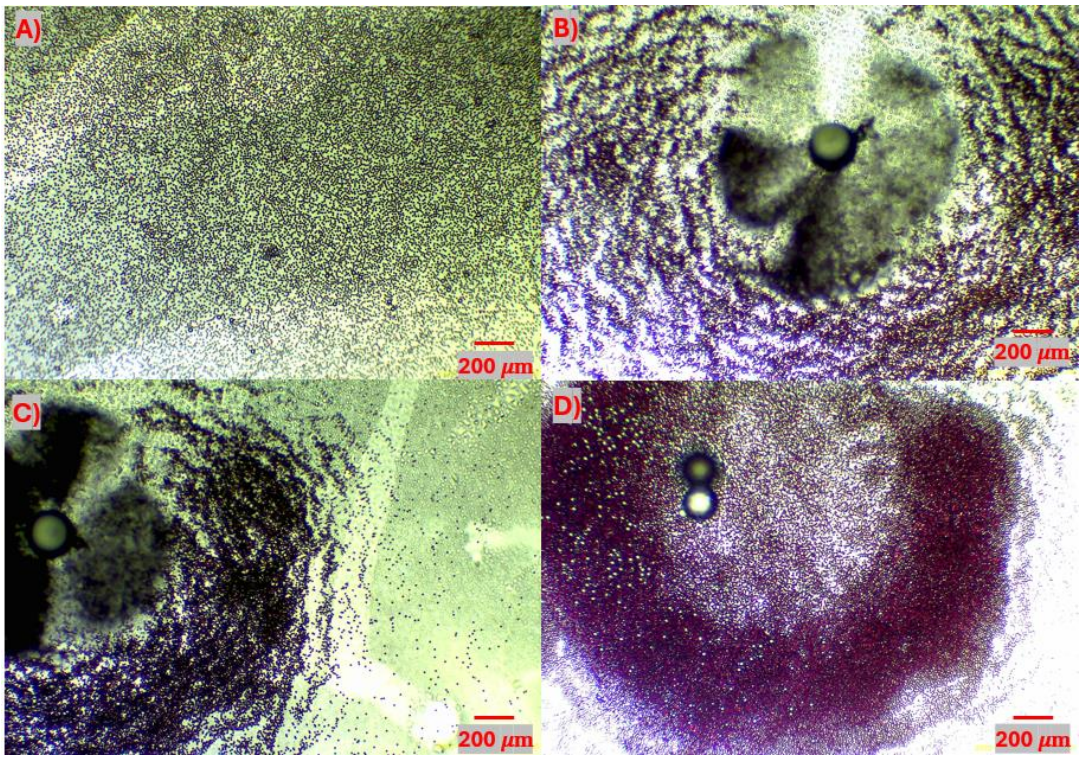

Figure 13. A) PS particles in the droplet before the experiment. B) PS particles immediately after turning on the power. C) PS particles accumulating closer to the centre of the acoustic node. D) PS particles after the experiment.

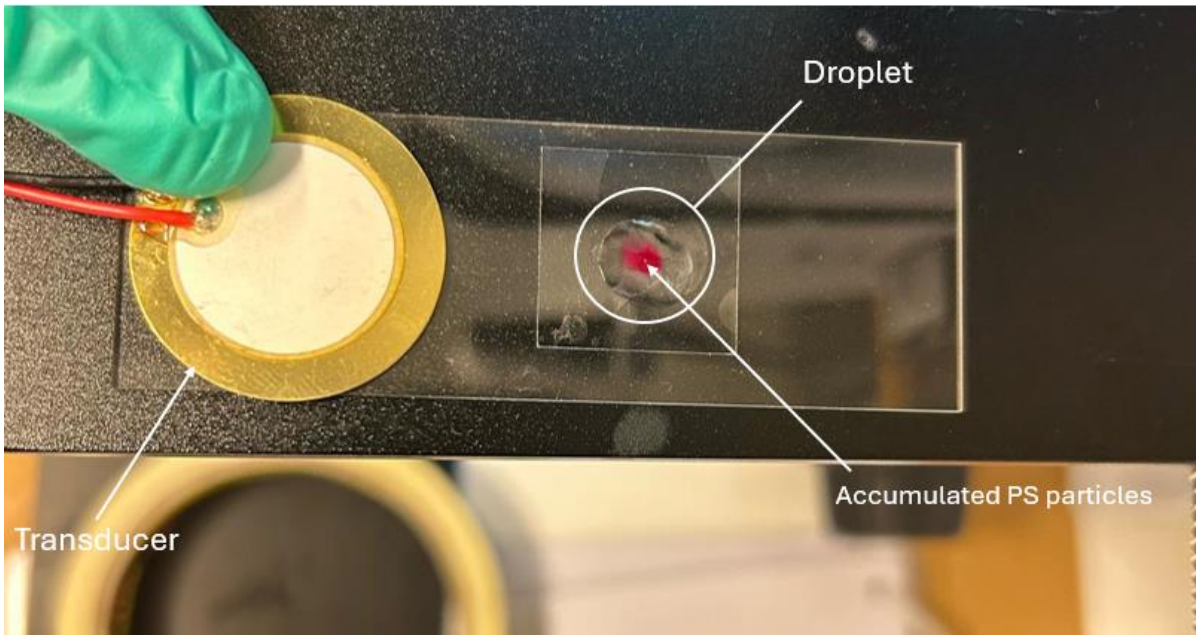

Figure 14. PS particles (red colour) accumulated in the middle of the droplet after the first experiment done with single transducer device with a thin glass plate added on top.

Next two experiments were carried out with the single transducer device, without the additional glass plate on top. Second experiment was done with sample 2 containing large PEG particles and ethanol. Approximately 50 μL droplet was pipetted to the glass surface. The position of the particles at the start is shown in figure 15A. At the start, the frequency was set to 10 kHz and the power to 2 V_{pp}. After the power was turn on, the particles did not start to accumulate despite the change in frequency or power. The final situation of the particle is presented in figure 15B.

Third experiment was done with sample 3 containing smaller PEG particles and hexane. Approximately 50 μl droplet was pipetted to the glass surface. The positions of the particles at the start point are shown in figure 15C. The frequency was set to 10 kHz and the power to 3 V_{pp}. After the power was activated, the particles began to accumulate. However, the process was not entirely efficient, as some particles remained dispersed throughout the solution. The final situation of the particles accumulated at the acoustic node is shown in figure 15D.

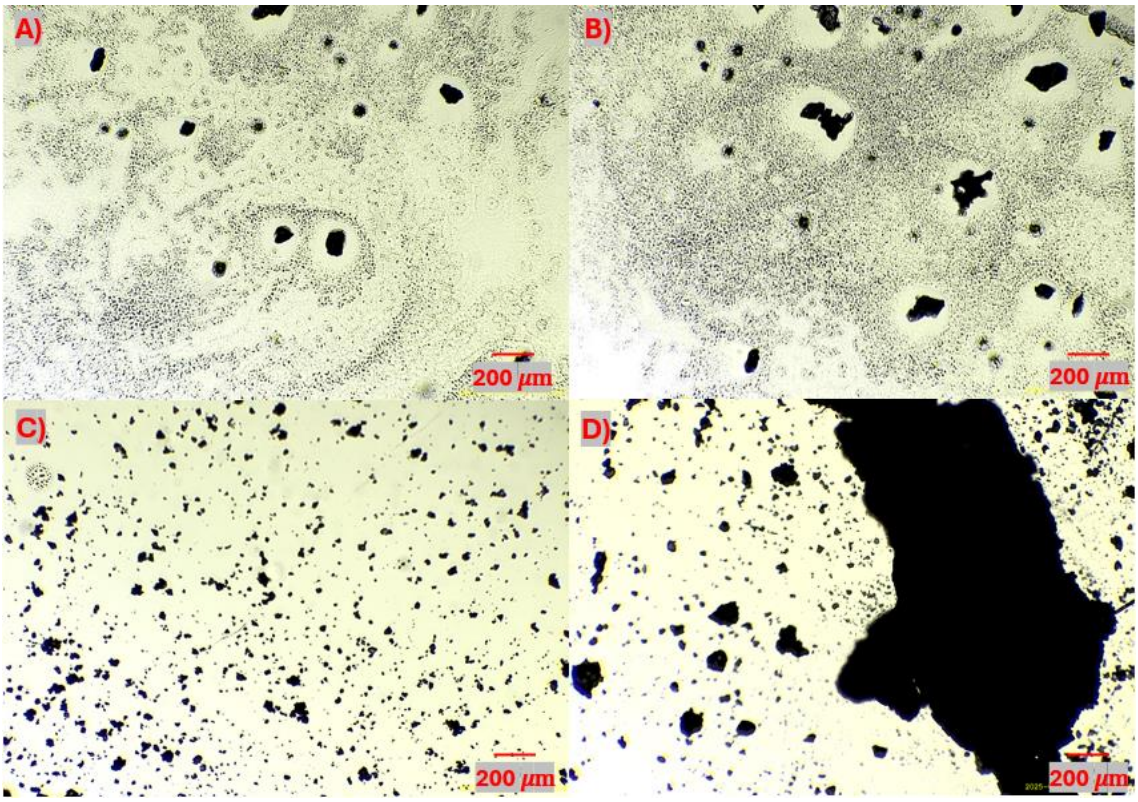

Figure 15. A) Large PEG particles in ethanol before beginning of the experiment. B) Large PEG particles in ethanol after the experiment. C) Small PEG particles in hexane before the experiment. D) Accumulated small PEG particles in hexane after the experiment.

Next three experiments were done with the double transducer device. Approximately 50 μl droplet of PS and surfactant was pipetted on the glass surface of the device. The positions of the PS particles at the beginning, before applying acoustic force, is illustrated in figure 16A. The frequency was set to 10 kHz and power to 3 V_{pp}. After applying acoustic force, the particles moved but did not accumulate to a certain acoustic node. The positions of the PS particles in surfactant after the experiment is illustrated in figure 16B.

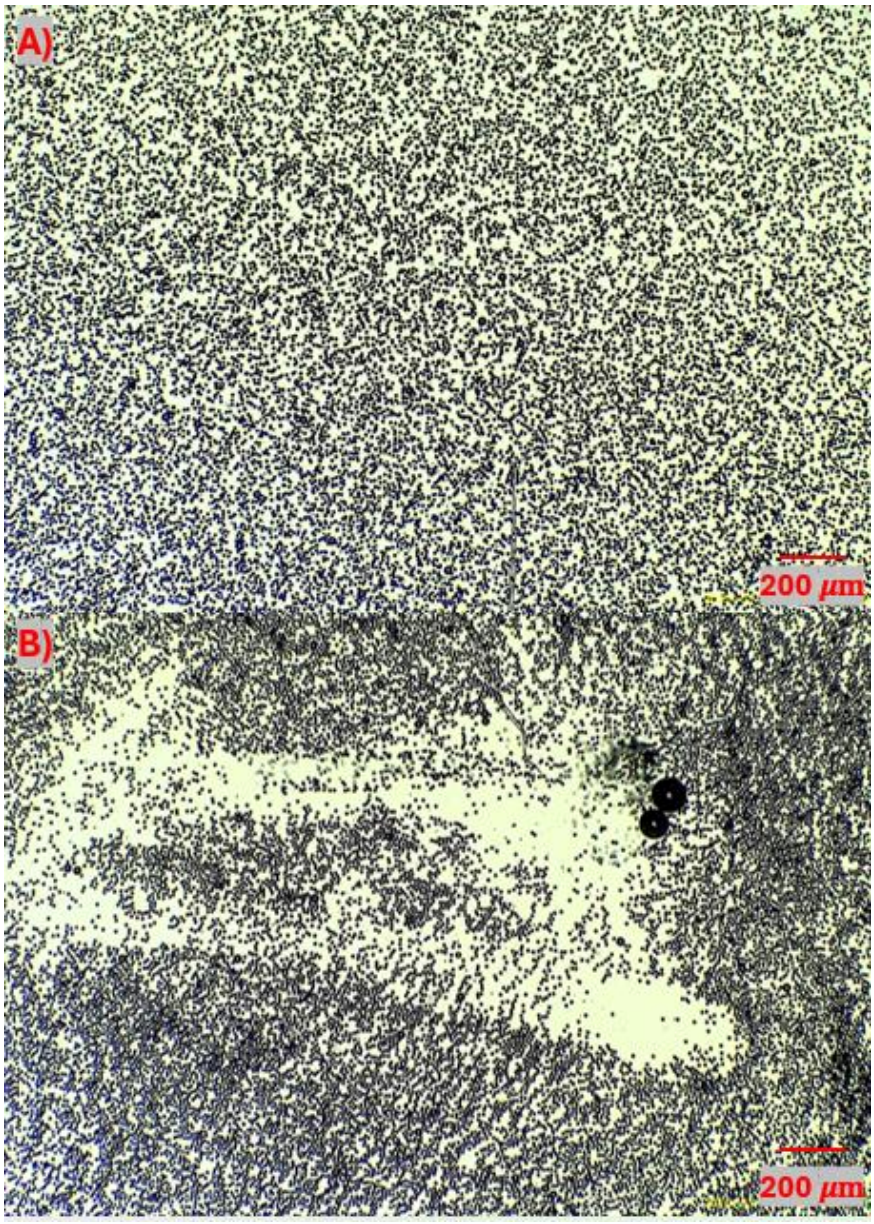

Figure 16. A) PS particles in surfactant before applying acoustic force. B) PS particles in surfactant after applying acoustic force from two opposite transducers.

Second experiment with the double transducer device was done with large PEG particles in ethanol. Approximately 50 μl droplet was pipetted to the glass surface. The positions of the PEG particles before starting the experiment are illustrated in figure 17A. After applying acoustic force with 10 kHz frequency and 3 V_{pp} power, the particles started to accumulate to multiple nodes. The changes in frequency or in power did not affect the accumulation process of the particles. The positions of the particles accumulated at multiple acoustic nodes are shown in figure 17B.

Third experiment with the double transducer device was done with smaller PEG particles in hexane. Approximately 50 μl droplet was pipetted to the glass surface. The positions of the

smaller PEG particles before the experiment can be seen in figure 17C. The frequency was set to 10 kHz and power to 3 V_{pp}. The particles started to accumulate to single node, but the accumulation process was not efficient, as large proportion of the particles did not accumulate. The amount and positions of the accumulated particles are illustrated in figure 17D. It should be noted that in the experiments involving hexane and PEG, the rapid dissipation of hexane posed challenges in conducting the study.

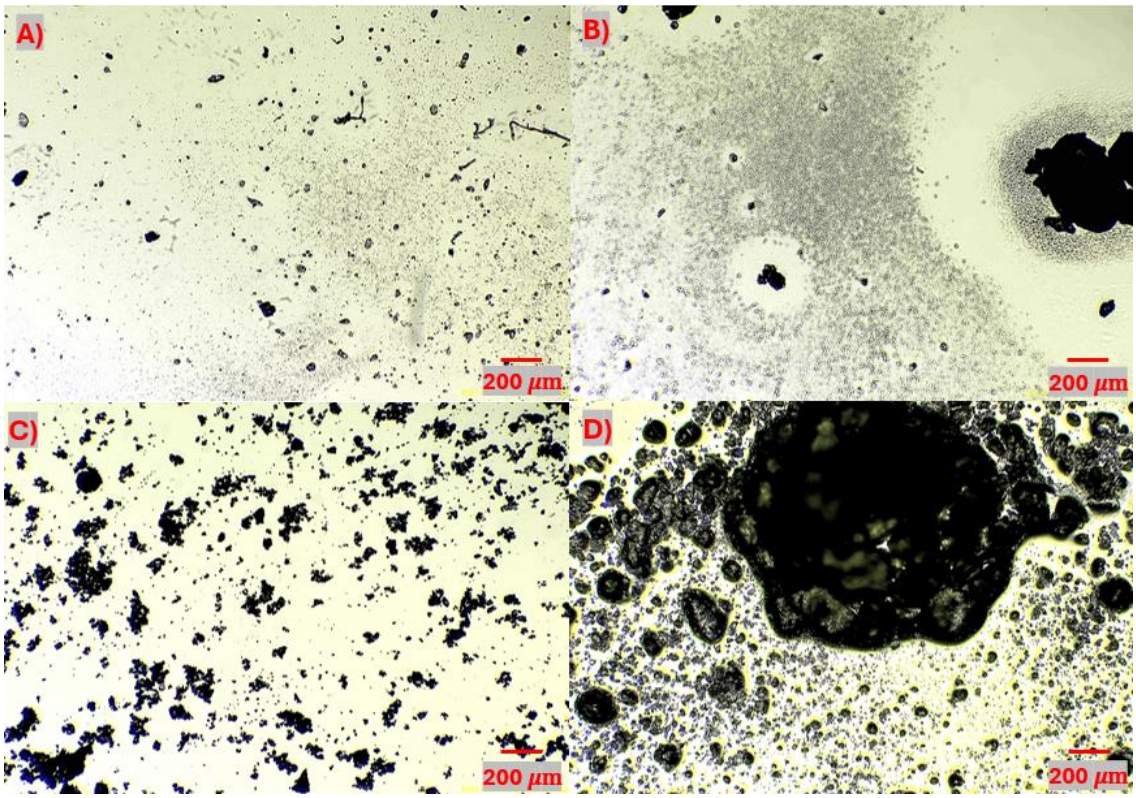

Figure 17. A) PEG particles in ethanol before the experiment. B) PEG particles in ethanol, accumulated in multiple nodes. C) PEG particles in hexane before the experiment. D) PEG particles in hexane, accumulated to one node.

The effect of the surfactant on the movement of PEG particles by acoustic manipulation was to be further tested during the experiments. However, when Triton X -100 (2-[4-(2,4,4-trimethylpentan-2-yl)phenoxy]ethanol) surfactant was added to samples 2 and 3, the PEG particles dissolved, preventing the experiments from being conducted.

5 Conclusions

Microplastics, both primary and secondary, are a major issue in the world's oceans, water bodies and waste waters. Several different methods have been developed to separate microplastics from water and wastewater. The general methods presented in this thesis i.e. acoustic separation method, coagulation-flocculation and electrocoagulation, various filtration methods and magnetic separation are all promising and most have been proven effective in their own applications.

However, the problem with most of the general separation methods is the mandatory addition of chemicals or particles to the water to make the separation method of microparticles effective. The separation of microplastics by the acoustic method is possible to be carried out non-invasively, making it a possible non-toxic and safe alternative method compared to invasive methods, as the invasive methods can be using possibly toxic substances or materials.

The separation of microplastics using acoustic manipulation has been studied to some extent in flow-based methods. Experimentally, microplastic separation has been tested using devices based on both bulk acoustic waves (BAW) and traveling surface acoustic waves (TSAW). While these devices have demonstrated the capability to separate microplastics, achieving precise separation based on characteristics such as particle size or type is challenging, which is why the acoustic frequency should be adjustable in real time to optimize separation efficiency. The adhesion of microplastic particles to the walls of microfluidic devices is also a challenge. Therefore, the devices should incorporate a flushing mechanism or a design feature to prevent the accumulation of microplastic particles on the walls.

Based on the experiments, the accumulation of microplastics to a specific location within a droplet is possible. However, significant improvements are required to enhance its efficiency. The use of surfactants may potentially improve the accumulation process, but their application would change the non-invasive nature of the method. Further research should focus on utilizing more efficient transducers and higher frequencies to achieve better results. In the experimental section, no significant difference was observed between the devices with one or two transducers. However, the installation of a hydrophobic pedestal notably improved the results.

In the experimental section, only two different polymers and three different solvents were used. Further studies should be conducted using common types of microplastics found in natural waters and wastewater, comparing how their varying masses, sizes or structures influence the effectiveness of the method. Additionally, tests should be performed with authentic or artificial seawater, as well as with water in general.

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