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RESEARCH ARTICLE

EXPERIMENTAL INVESTIGATION OF MICROPLASTIC REMOVAL USING A ULP21-4040 MEMBRANE

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Abstract. *The occurrence of microplastics in natural and process waters presents a significant challenge for the design and operation of engineering water treatment and water supply systems in buildings and structures. This study experimentally evaluated the efficiency of a ULP21-4040 reverse osmosis membrane in removing polyethylene terephthalate (PET), polyethylene (PE), and polypropylene (PP) particles of different sizes from artificially contaminated water (hereafter, model water). Experiments were conducted using a pilot-scale HAIAO RO-250 unit operated at 1.3 MPa with a nominal capacity of 250 L/h. Model water was prepared by adding 1 g of each polymer with nominal particle sizes of 0.20 or 0.45mm to 100 L of distilled water. Each polymer–size combination was tested in triplicate. Microplastic particles in the permeate (treated water) and concentrate (water with increased concentrations of retained contaminants) were recovered using Sefar filter cloth with a 100 µm mesh size and quantified gravimetrically. Particle presence was confirmed by digital microscopy. Mean removal efficiency exceeded 97%, ranging from 97.81 ± 0.24% for 0.20 mm PP to 99.87 ± 0.07% for 0.45mm PET. Retention efficiency depended on polymer type and particle size. Mass-balance calculations showed that an average of 0.81% of the initial microplastic mass accumulated inside the membrane module. The results support the potential application of the ULP21-4040 membrane as a final treatment stage in compact engineering water treatment systems. Further research should investigate membrane fouling, pressure losses, energy consumption, cleaning regimes, and long-term performance under actual operating conditions to support integration into building water supply systems and water reuse.*

Keywords: *microplastics; reverse osmosis; ULP21-4040 membrane; membrane filtration; engineering water treatment systems; water supply systems for buildings and structures; polyethylene terephthalate; polyethylene; polypropylene.*

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ҒЫЛЫМИ МАҚАЛА

ULP21-4040 МЕМБРАНАСЫН ҚОЛДАНУ АРҚЫЛЫ МИКРОПЛАСТИКТЕРДІ ЖОЮДЫ ЭКСПЕРИМЕНТТІК ЗЕРТТЕУ

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Аңдатпа. *Табиғи және техникалық суларда микропластиктің таралуы ғимараттар мен құрылыстардың су дайындау және сумен жабдықтау инженерлік жүйелерін жобалау мен пайдалану үшін өзекті мәселе болып табылады. Зерттеудің мақсаты ULP21-4040 кері осмостық мембранасының жасанды түрде ластанған (бұдан әрі – модельдік) судан әртүрлі өлшемдегі полиэтилентерефталат (ПЭТ), полиэтилен (ПЭ) және полипропилен (ПП) бөлшектерін жою тиімділігін эксперименттік тұрғыдан бағалау болды. Сынақтар жұмыс қысымы 1,3 МПа және номиналды өнімділігі 250 л/сағ болатын HAIAO RO-250 пилоттық қондырғысында жүргізілді. Модельдік су зерттелетін әрбір полимердің номиналды өлшемі 0,20 немесе 0,45 мм болатын 1 г бөлшектерін 100 л дистилденген суға қосу арқылы дайындалды. Полимер түрі мен бөлшектер өлшемінің әрбір үйлесімі үш қайталанымда зерттелді. Пермеаттағы (тазартылған судағы) және концентраттағы (ұсталып қалған ластаушы заттардың мөлшері жоғары судағы) микропластик бөлшектері ұяшықтарының өлшемі 100 мкм болатын Sefar сүзгі матасының көмегімен бөлініп алынып, гравиметриялық әдіспен анықталды. Бөлшектердің болуы қосымша цифрлық микроскопия әдісімен расталды. Микропластикті жоюдың орташа тиімділігі 97%-дан жоғары болып, өлшемі 0,20 мм ПП бөлшектері үшін 97,81 ± 0,24%-дан өлшемі 0,45 мм ПЭТ бөлшектері үшін 99,87 ± 0,07%-ға дейін өзгерді. Бөлшектерді ұстап қалу тиімділігіне полимер түрі мен олардың өлшемі әсер ететіні анықталды. Материалдық баланс есебі мембраналық модуль ішінде микропластиктің бастапқы массасының орта есеппен 0,81%-ы жинақталғанын көрсетті. Нәтижелер ULP21-4040 мембранасын ықшам инженерлік су дайындау жүйелерінде тазартудың соңғы сатысы ретінде қолдану мүмкіндігін растайды. Кейінгі зерттеулерде мембрананың ластануын, қысым шығындарын, энергия тұтынуды, жуу режимдерін және қондырғының нақты жағдайлардағы ұзақ мерзімді пайдалану тиімділігін бағалау қажет. Бұл технологияны ғимараттар мен құрылыстардың сумен жабдықтау жүйелеріне интеграциялау жөніндегі ұсынымдарды әзірлеуге мүмкіндік береді.*

Түйінді сөздер: *микропластик; кері осмос; ULP21-4040 мембранасы; мембраналық сүзу; инженерлік су дайындау жүйелері; ғимараттар мен құрылыстарды сумен жабдықтау; полиэтилентерефталат; полиэтилен; полипропилен.*

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НАУЧНАЯ СТАТЬЯ

ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ УДАЛЕНИЯ МИКРОПЛАСТИКА С ИСПОЛЬЗОВАНИЕМ МЕМБРАНЫ ULP21-4040

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Аннотация. *Распространение микропластика в природных и технических водах представляет актуальную проблему для проектирования и эксплуатации инженерных систем водоподготовки и водоснабжения зданий и сооружений. Целью исследования являлась экспериментальная оценка эффективности обратноосмотической мембраны ULP21-4040 при удалении частиц полиэтилентерефталата (ПЭТ), полиэтилена (ПЭ) и полипропилена (ПП) различных размеров из искусственно загрязненной (далее-модельной) воды. Испытания проводились на пилотной установке HAIAO RO-250 при рабочем давлении 1,3 МПа и номинальной производительности 250 л/ч. Модельную воду готовили путём добавления 1 г частиц каждого исследуемого полимера номинальным размером 0,20 или 0,45 мм в 100 л дистиллированной воды. Каждое сочетание типа полимера и размера частиц исследовали в трёх повторностях. Частицы микропластика в пермеате (очищенной воде) и концентрате (воде с повышенным содержанием задержанных загрязняющих веществ) извлекали с использованием фильтровальной ткани Sefar с размером ячеек 100 мкм и определяли гравиметрическим методом. Наличие частиц дополнительно подтверждали цифровой микроскопией. Средняя эффективность удаления микропластика превышала 97% и изменялась от 97,81 ± 0,24% для ПП размером 0,20 мм до 99,87 ± 0,07% для ПЭТ размером 0,45 мм. Установлено влияние типа полимера и размера частиц на эффективность их задержания. Расчёт материального баланса показал, что внутри мембранного модуля накапливалось в среднем 0,81% исходной массы микропластика. Результаты подтверждают возможность применения мембраны ULP21-4040 в качестве заключительной ступени компактных инженерных систем водоподготовки. Дальнейшие исследования должны учитывать загрязнение мембраны, потери давления, энергопотребление, режимы промывки и долговременную эксплуатационную эффективность установки в реальных условиях. Это позволит разработать рекомендации по интеграции технологии в системы водоснабжения зданий и сооружений.*

Ключевые слова: *микропластик; обратный осмос; мембрана ULP21-4040; мембранная фильтрация; инженерные системы водоподготовки; водоснабжение зданий и сооружений; полиэтилентерефталат; полиэтилен; полипропилен.*

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1 INTRODUCTION

Microplastic pollution has become a significant environmental and engineering challenge because of the rapid growth of plastic production and consumption. Global plastic production has reached several hundred million tonnes annually, while a substantial proportion of plastic waste eventually enters natural ecosystems [1]. Microplastics are generally defined as plastic particles smaller than 5 mm. They may be intentionally manufactured at microscopic sizes or formed through the fragmentation of larger plastic materials under ultraviolet radiation, mechanical abrasion, chemical degradation, and other environmental processes [2].

Owing to their persistence and resistance to biodegradation, microplastics have been detected in marine and freshwater environments, rivers, lakes, groundwater, wastewater, soils, atmospheric deposition, drinking water, and living organisms [3,4]. Their environmental impact is associated not only with their long-term persistence but also with their ability to adsorb heavy metals, persistent organic pollutants, pharmaceuticals, and pathogenic microorganisms [3]. Consequently, microplastics may act as carriers of contaminants through aquatic ecosystems and food chains. Their occurrence in drinking water, seafood, and other food products has also raised concerns regarding potential effects on human health [5].

From an engineering perspective, the presence of microplastics in source water, wastewater, and reclaimed water creates additional requirements for the design, construction, and operation of water treatment and water supply systems. Particles that are not completely removed at centralized treatment facilities may enter water distribution networks, storage reservoirs, pumping equipment, and internal engineering systems of buildings and structures. Furthermore, the increasing use of decentralized treatment and water-reuse systems in residential, public, industrial, and infrastructure facilities requires compact and reliable technologies capable of removing residual particulate contaminants.

Wastewater treatment plants are recognized as an important pathway through which microplastics enter aquatic environments. Domestic wastewater contains synthetic fibres released during textile washing, as well as particles originating from cosmetic products, packaging materials, and other household activities. Industrial effluents may contain microplastics generated during plastic manufacturing and other industrial processes [6]. Although conventional wastewater treatment facilities can remove a considerable proportion of these particles, complete removal is rarely achieved. Secondary and tertiary treatment processes have been reported to remove approximately 88% and 94% of microplastics, respectively. Nevertheless, considerable quantities may still be discharged because of the large volumes of wastewater processed daily [7].

The construction of modern wastewater treatment facilities requires an integrated approach to the selection and arrangement of individual technological processes. In addition to achieving the required quality of treated water, the design should account for the hydraulic profile of the facility, treatment capacity, equipment layout, energy consumption, operational reliability, maintenance access, waste generation, and the possibility of future modernization. When microplastics and other persistent contaminants are present, conventional mechanical and biological processes may need to be supplemented with an advanced tertiary treatment stage.

Various technologies have been investigated for microplastic removal, including sedimentation, coagulation–flocculation, dissolved-air flotation, rapid sand filtration, membrane bioreactors, microfiltration, ultrafiltration, nanofiltration, and reverse osmosis [8]. Coagulation and flocculation promote the aggregation of microplastic particles and facilitate their subsequent separation. However, their efficiency depends on particle size, polymer type, surface properties, coagulant dosage, and wastewater composition, while the generation of chemical sludge represents an additional limitation [9]. Research on complex wastewater has demonstrated that multistage physicochemical treatment combining gravitational separation, coagulation–flocculation, filtration, and adsorption can substantially improve contaminant removal [10]. These findings confirm the importance of combining several treatment stages when wastewater contains persistent or difficult-to-separate pollutants.

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Among advanced treatment methods, membrane technologies have attracted considerable attention because of their high separation efficiency, compact configuration, and operational flexibility [11,12]. Microfiltration and ultrafiltration are generally suitable for retaining suspended and relatively large particles, whereas nanofiltration and reverse osmosis provide an additional barrier against smaller particles and dissolved contaminants. Another advantage of membrane separation is the possibility of physically retaining pollutants without continuously introducing chemical reagents into the treated water [11]. These characteristics make membrane processes suitable for both centralized treatment facilities and compact engineering systems installed in buildings and structures.

Reverse osmosis is particularly promising as a final treatment or polishing stage because its dense semipermeable layer can retain dissolved salts, organic pollutants, microorganisms, suspended particles, and microplastics. Available studies demonstrate that pressure-driven membrane processes can provide higher microplastic removal efficiencies than many conventional treatment methods [12,13]. Investigations conducted at seawater reverse-osmosis facilities have shown that more than 97% of detected microplastic particles may be removed during the reverse-osmosis stage, although overall treatment efficiency depends on feed-water properties, pretreatment, and treatment-system configuration [14]. Studies of point-of-use membrane devices have also demonstrated that membranes with smaller separation thresholds generally provide more effective microplastic retention [15].

When planning and constructing new wastewater treatment facilities, a separate reverse-osmosis unit may be incorporated downstream of the biological treatment stage as a modular tertiary treatment block. A similar solution may be applied when reconstructing or modernizing existing treatment facilities. Such a technological configuration can provide an additional barrier against residual microplastics and other contaminants that are not completely removed during mechanical and biological treatment. The modular arrangement also makes it possible to increase treatment capacity gradually and to adapt the technological scheme to changing requirements for treated-water quality.

However, the direct supply of biologically treated wastewater to a reverse-osmosis unit may cause rapid membrane fouling. Appropriate pretreatment should therefore be provided before the reverse-osmosis stage. Depending on feed-water quality, the pretreatment system may include clarification, sand or multimedia filtration, microfiltration, ultrafiltration, cartridge filtration, or other processes intended to reduce suspended solids and protect the membrane modules. The selection of pretreatment equipment should be considered during the technological design of the facility because it influences the required construction area, hydraulic head, capital costs, energy consumption, and operational reliability of the entire treatment system.

The integration of reverse osmosis into an engineered treatment facility also requires specific construction and infrastructure solutions. The design should provide sufficient space for membrane modules, high-pressure pumps, pretreatment equipment, chemical-cleaning systems, pipelines, control and monitoring devices, and permeate-storage tanks. Appropriate electrical capacity, corrosion-resistant pipelines, drainage systems, ventilation, safe access for maintenance, and measures for controlling leakage and pressure should also be included. Particular attention must be given to concentrate collection and discharge because pollutants retained by the membrane are transferred into a smaller wastewater stream rather than destroyed. Consequently, the effectiveness of a reverse-osmosis treatment block should be evaluated together with its energy demand, concentrate-management requirements, cleaning frequency, and expected service life.

For engineering systems in buildings and structures, compact reverse-osmosis units may be incorporated into local water treatment, point-of-entry treatment, and water-reuse systems. Depending on the intended application and the applicable water-quality requirements, treated water may potentially be reused for technical purposes, sanitary systems, irrigation, cleaning, or other non-potable needs. The installation of such units should be coordinated with internal water supply and drainage networks at the building-design stage. This requires consideration of the available installation area, water demand, operating pressure, permeate storage, concentrate discharge, noise and vibration, energy consumption, and access for membrane replacement and maintenance.

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Despite the promising performance of membrane technologies, considerable differences exist among reported microplastic removal efficiencies. Such variability may be associated with membrane characteristics, operating pressure, feed-water composition, particle concentration, particle-size distribution, polymer type, and particle morphology [12]. Polyethylene terephthalate (PET), polyethylene (PE), and polypropylene (PP) are among the polymers frequently detected in aquatic environments [16]. These materials differ in density, hydrophobicity, surface characteristics, and morphology, which may influence their transport, accumulation, and retention during membrane filtration. However, comparative pilot-scale investigations of PET, PE, and PP particles under identical reverse-osmosis operating conditions remain limited.

In engineering applications, treatment efficiency cannot be assessed exclusively on the basis of permeate quality. Microplastic particles may also accumulate in feed channels, membrane spacers, pipelines, and other internal components. Such accumulation can increase hydraulic resistance, contribute to membrane fouling, reduce permeate production, increase operating pressure, and shorten the service life of the equipment. Consequently, mass-balance analysis covering the permeate, concentrate, and membrane-module retention fractions is important for evaluating both treatment efficiency and operational risks. The resulting information can support the selection of pretreatment processes, membrane-cleaning intervals, hydraulic operating conditions, and equipment-maintenance procedures.

Another limitation of existing studies concerns the analytical methods used for microplastic identification and quantification. Fourier-transform infrared spectroscopy and Raman spectroscopy provide detailed information about polymer composition but may require expensive equipment, specialized sample preparation, and considerable analysis time [17]. Gravimetric measurements combined with microscopic observations provide a complementary approach for controlled experiments in which the initial polymer type and introduced particle mass are known. This method makes it possible to evaluate the distribution of microplastic mass between the permeate (treated water) and concentrate (water with increased concentrations of retained contaminants) and to estimate the fraction potentially retained within the membrane module.

In Kazakhstan, the planning and construction of water-management facilities must also consider the safety, durability, and operational reliability of engineering infrastructure. Previous studies have examined the multifactor assessment of hydraulic structures located in seismically active areas [18], degradation mechanisms and repair technologies for concrete hydraulic structures [19], the influence of surfactants on the abrasion resistance of hydraulic concrete [20], and the reconstruction and modernization of reservoir facilities [21]. These studies demonstrate that the performance of water-management facilities depends not only on treatment technology but also on the structural reliability, durability, maintainability, and adaptability of the infrastructure. In this context, the introduction of membrane-based tertiary treatment should be considered as part of an integrated engineering solution covering technological equipment, hydraulic systems, building structures, energy supply, automation, and long-term maintenance.

Several research gaps therefore remain. First, information on the comparative removal efficiencies of PET, PE, and PP particles by reverse-osmosis membranes under identical operating conditions is limited. Second, the influence of particle size on membrane retention and internal particle accumulation requires further experimental investigation. Third, combined gravimetric, microscopic, and mass-balance approaches have not been widely applied to evaluate the distribution of different microplastic polymers among permeate, concentrate, and membrane-module retention fractions. Finally, the available experimental data remain insufficient for substantiating engineering decisions concerning the inclusion of reverse-osmosis blocks in newly constructed or modernized wastewater treatment facilities.

The aim of this study was to experimentally evaluate the efficiency of microplastic removal from model water using a pilot-scale reverse-osmosis system equipped with a ULP21-4040 membrane. PET, PE, and PP particles with nominal sizes of 0.20 and 0.45 mm were selected as representative microplastic pollutants. Six polymer–size combinations were investigated, with three replicate experiments conducted for each combination. Removal efficiency was determined by

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gravimetric analysis, while digital microscopy was used to confirm the presence of particles recovered from the permeate (treated water) and concentrate (water with increased concentrations of retained contaminants) streams.

The scientific novelty of this study lies in obtaining a directly comparable pilot-scale dataset on the retention of PET, PE, and PP microplastics of two nominal particle sizes by a ULP21-4040 reverse-osmosis membrane under identical feed-water and operating conditions. Unlike assessments based exclusively on permeate quality, the present study evaluated the distribution of the introduced microplastic mass among the permeate, concentrate, and membrane-module retention fractions. This approach makes it possible to consider not only the quality of the treated water but also the potential accumulation of particles inside the membrane module. The results may be used when evaluating the feasibility of incorporating a modular reverse-osmosis block after biological treatment during the design, construction, reconstruction, or modernization of wastewater treatment facilities. They are also relevant to the selection of pretreatment processes, membrane-protection measures, cleaning regimes, concentrate-management solutions, and operating conditions for compact engineering water treatment systems used in buildings and structures.

2 MATERIALS AND METHODS

The experimental program was designed to systematically evaluate the retention of representative microplastic particles by the ULP21-4040 reverse-osmosis membrane under controlled pilot-scale conditions. The study comprised four main stages: (1) preparation of model water containing polyethylene terephthalate (PET), polyethylene (PE), or polypropylene (PP) particles with nominal sizes of 0.20 or 0.45 mm; (2) pilot-scale reverse-osmosis filtration at a constant operating pressure of 1.3 MPa; (3) recovery and gravimetric determination of the mass of microplastic particles in the permeate (treated water that passed through the membrane) and concentrate (water that did not pass through the membrane and contained increased concentrations of retained contaminants), followed by mass-balance calculations to estimate the fraction of microplastics remaining within the membrane module; and (4) digital-microscopy examination to confirm the presence and evaluate the morphological characteristics of the recovered particles. Six combinations of polymer type and particle size were investigated, and each combination was tested in triplicate. A total of 18 experimental runs were conducted, enabling the repeatability of the results to be evaluated and subsequent statistical analysis to be performed.

2.1 Design and characteristics of the custom-built reverse osmosis system

The experimental tests were conducted using a pilot-scale reverse-osmosis unit assembled from the main components of a HAIAO RO-250 system. The unit was evaluated for its ability to retain microplastic particles from aqueous streams under controlled operating conditions. The system had a nominal treated-water production capacity of 250 L/h and was configured to reproduce conditions relevant to advanced membrane water treatment.

The pilot system comprised a feed-water tank, a pretreatment unit, a high-pressure pumping system, a central reverse-osmosis membrane module, a treated-water collection system, and a concentrated reject-water discharge line. As shown in the process-flow diagram (Figure 1), the feed water was continuously circulated through the membrane system. The operating pressure was maintained at 1.3 MPa and continuously monitored using pressure gauges installed upstream and downstream of the membrane module. Inside the module, the feed-water stream was separated into two fractions: treated water that passed through the membrane and a concentrated reject stream containing the contaminants and microplastic particles retained by the membrane.

From an engineering perspective, reverse-osmosis systems of this configuration can be incorporated into water-treatment systems for buildings and structures as a final polishing stage. Depending on the required water quality, such units may be used in centralized or decentralized systems for drinking-water treatment, technical-water preparation, and non-potable water reuse. Their compact and modular configuration allows them to be installed during the construction of new

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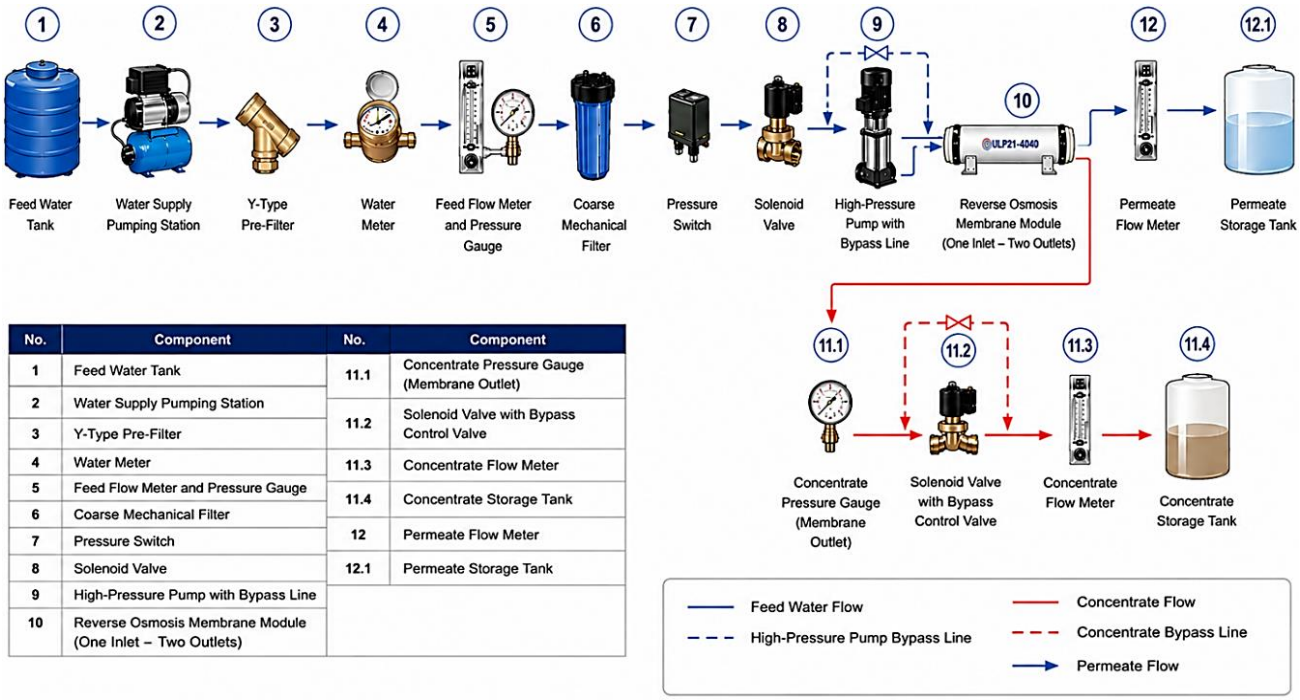
engineering facilities or incorporated into existing water-treatment systems during reconstruction and modernization.



No.	Component	No.	Component
1	Feed Water Tank	11.1	Concentrate Pressure Gauge (Membrane Outlet)
2	Water Supply Pumping Station	11.2	Solenoid Valve with Bypass Control Valve
3	Y-Type Pre-Filter	11.3	Concentrate Flow Meter
4	Water Meter	11.4	Concentrate Storage Tank
5	Feed Flow Meter and Pressure Gauge	12	Permeate Flow Meter
6	Coarse Mechanical Filter	12.1	Permeate Storage Tank
7	Pressure Switch		
8	Solenoid Valve		
9	High-Pressure Pump with Bypass Line		
10	Reverse Osmosis Membrane Module (One Inlet – Two Outlets)		

Figure 1 - Process flow diagram of the reverse osmosis pilot system [Authors' material].

The central filtration element of the constructed system is a commercial ULP21-4040 reverse osmosis membrane manufactured by Haiao (China). This ultra-low-pressure thin-film composite polyamide membrane was selected due to its high selectivity and widespread application in water treatment systems. It is specifically designed to deliver high rejection efficiency under relatively low operating pressures. The primary technical specifications of the integrated membrane are summarized in Table 1.

Table 1 - Technical specifications of the ULP21-4040 membrane.

Parameter	Value
Membrane type	ULP21-4040
Membrane material	Thin-film composite polyamide
Salt rejection	99.5%
Water production	9.1 m³/day
Nominal pressure	1.0 MPa
Maximum pressure	4.0 MPa
Operating temperature	2–45°C
Maximum TDS	1500 mg/L

2.2 Preparation of model water and experimental filtration protocol

Model feed solutions were prepared using distilled water to eliminate baseline particulate and ionic interference. For each experimental run, 1 g of target microplastic particles - polyethylene terephthalate (PET), polyethylene (PE), or polypropylene (PP) in discrete particle size fractions of 0.20 mm or 0.45 mm - was added to 100 L of distilled water in the feed tank to achieve an initial concentration of 10 mg/L. Continuous mechanical agitation was applied to maintain dynamic suspension homogeneity prior to and throughout the filtration process.

Filtration experiments were conducted using the HAIAO RO-250 pilot unit operated at a constant operating pressure of 1.3 MPa. Each trial was performed independently for a specific polymer type and particle size combination. During operation, the feed stream was separated within

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the ULP21-4040 membrane module into two fractions: permeate (treated water) and concentrate (retentate containing rejected microplastics). Representative volumetric samples from both output streams were collected at steady-state operating conditions for subsequent gravimetric quantification and morphological analysis

2.3 Gravimetric analysis

The gravimetric method was used to quantify microplastic particles remaining in permeate and concentrate samples.

A Sefar sieve cloth with a mesh size of 100 µm was selected as the filtration medium. The sieve cloth was initially dried and weighed using an analytical balance.Following sample filtration, the cloth was dried again to constant mass and reweighed.

The mass of retained microplastic particles was calculated according to Equation (1):

$$\Delta m = m_2 - m_1 \quad (1)$$

where: Δm – retained microplastic mass (mg);
m_1 – mass before filtration (mg);
m_2 – mass after filtration (mg).

The removal efficiency was determined using Equation (2):

$$R = \frac{M_o - M_p}{M_o} \times 100 \quad (2)$$

where: R – removal efficiency (%);
M_o – initial microplastic mass (mg);
Mp – microplastic mass detected in permeate (mg).

2.4 Microscopic and morphological characterization

Qualitative visual confirmation and morphological evaluation of microplastic particles recovered from the permeate and concentrate streams were conducted using a Levenhuk MED D30T LCD digital biological microscope equipped with an integrated digital imaging system. Following filtration, microplastics retained on the Sefar sieve cloth (100 µm mesh size) were inspected under transmitted light.

Digital micrographs were captured to evaluate key physical characteristics, including particle geometry, surface morphology, size distribution, and spatial accumulation behavior on the filter matrix. This analysis provided direct qualitative verification of the gravimetric mass-balance determinations and allowed physical assessment of particle behavior within the output streams.

2.5 Preparation and Structural Characterization of Microplastics

To prepare model microplastic (MP) solutions, commercially available polymer samples that frequently contact water were selected: polypropylene (PP) and polyethylene (PE) water pipes, along with polyethylene terephthalate (PET) plastic water bottles. All plastics were crushed manually and subsequently processed using laboratory mills to mimic the particle shapes typically found in wastewater. The comminuted microplastics were fractionated by sieving through a cascade of screens to isolate particle fractions of 0.20 mm and 0.45 mm.

The chemical structure of the pristine polymer samples was analyzed via Fourier-transform infrared (FTIR) spectroscopy using a Shimadzu IR-Prestige 21 spectrophotometer (Japan) in the wavenumber range of 400-4000 cm^{-1}. The analysis was conducted without prior sample preparation using a Smiths DuraSamplIR II single-reflection attenuated total reflection (ATR) accessory equipped with a diamond-on-ZnSe internal reflection element. Polymer identification based on the obtained IR spectra was performed using the IRs Polymer2, Polymer, T-Polymer, and T-Organic reference libraries, as well as by analyzing absorption bands corresponding to the stretching and bending vibrations of functional groups characteristic of specific polymer types.

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The structural characteristics of the microplastic samples, which were subsequently evaluated in the wastewater treatment process, are shown in Figures 2-4.

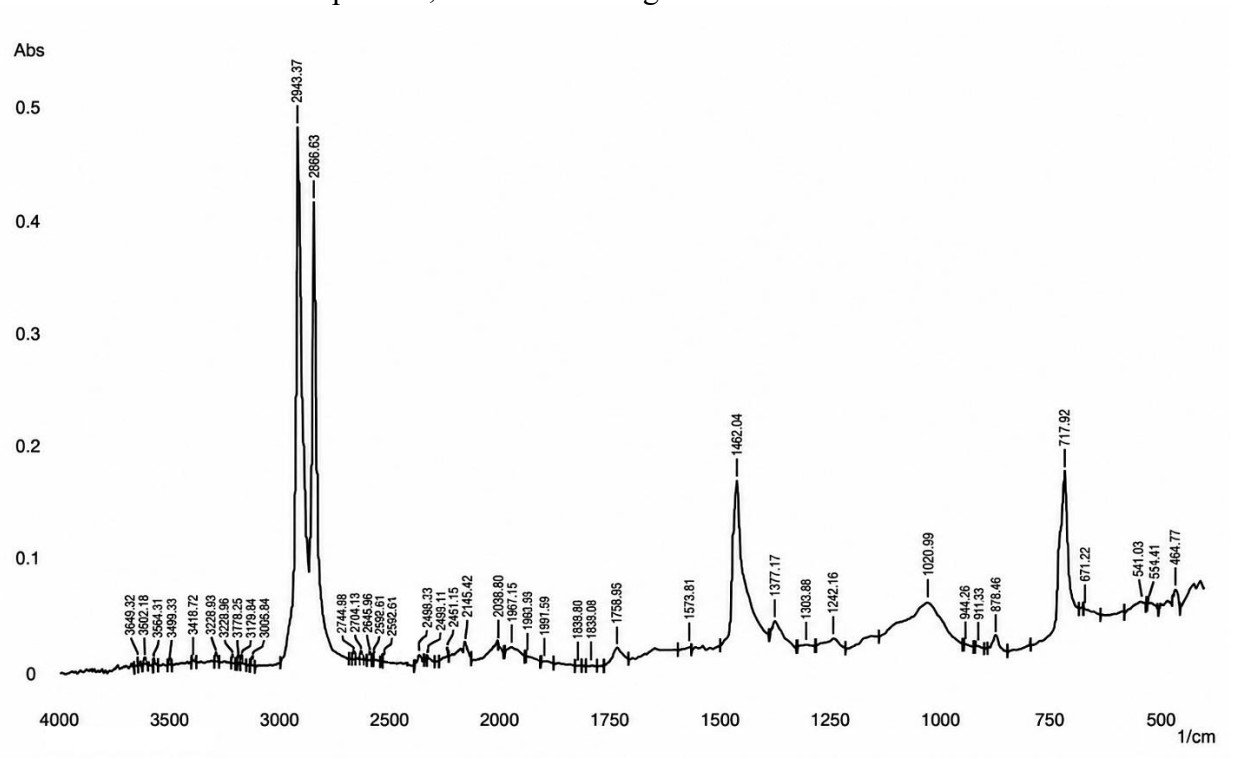

Figure 2 – FTIR spectrum of polyethylene (experimental sample) [Authors' material].

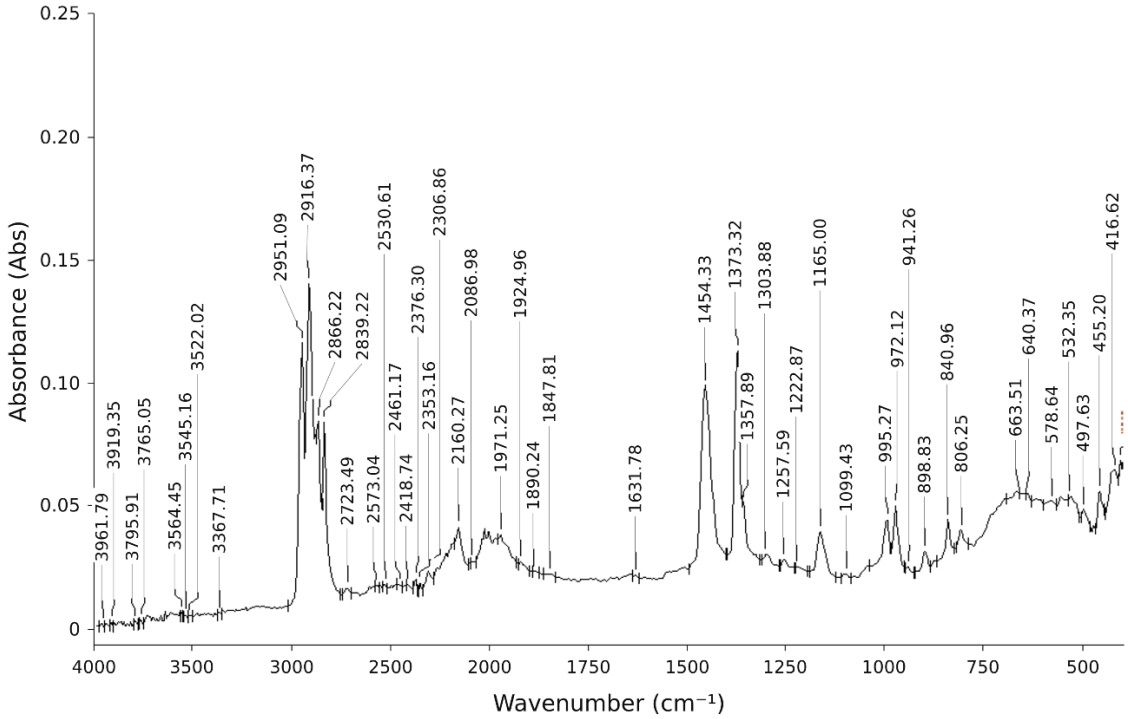

Figure 3 - FTIR spectrum of polypropylene (experimental sample) [Authors' material].

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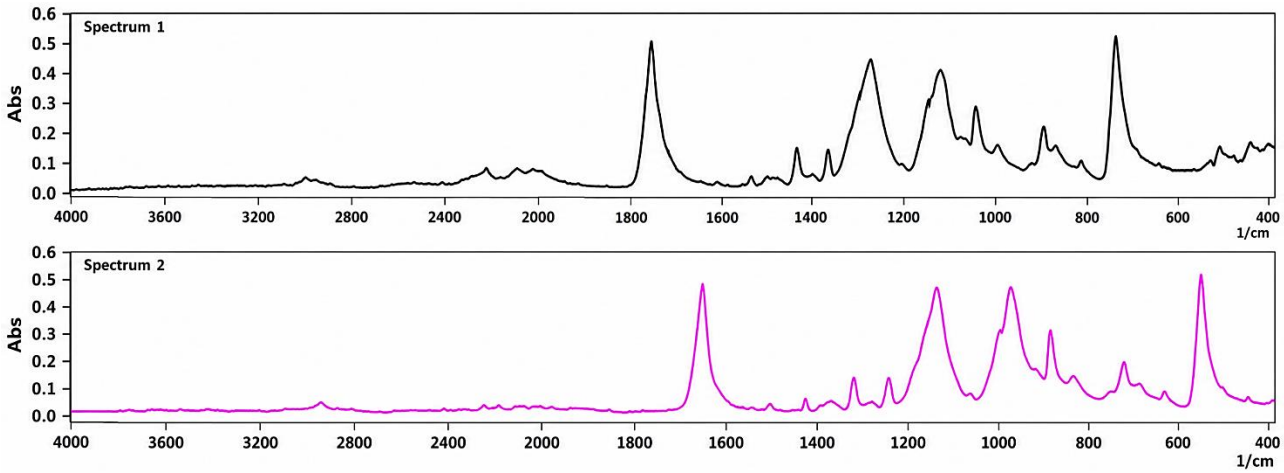

Figure 4 – Identification of polyethylene terephthalate by the FTIR spectrum of the polymer library database [Authors' material].

The FTIR analysis confirmed the identification of the target polymers based on their characteristic absorption bands. Polyethylene (PE) and polypropylene (PP**)** were identified via their classic aliphatic peaks. The PE spectrum (Figure 2) exhibits intense stretching vibration doublets of C–H bonds in the 2916-2840 cm^{-1}region, alongside bending vibrations near 1454 cm^{-1} and 720 cm^{-1}. The PP spectrum (Figure 3) is characterized by distinct methyl group CH_3- bands at 1373 cm^{-1} and 1165 cm^{-1}.

Due to its more complex chemical structure containing ester groups and aromatic rings, polyethylene terephthalate (PET) was verified by direct comparison with reference library databases, showing a high match score (Figure 4). Concurrently, the experimental spectrum reveals the typical diagnostic peaks of PET, most notably the sharp, intense carbonyl (C=O) stretching band around 1720 cm^{-1} and the characteristic (C–O) stretching multiplets in the 1250-1100 cm^{-1} range.

2.6 Data processing and statistical analysis

All experimental trials were performed in triplicate (n = 3) for each combination of polymer type (PET, PE, PP) and particle size fraction (0.20 mm and 0.45 mm) to ensure reproducibility and evaluate statistical variability.

Experimental data were processed using descriptive statistical methods. The removal efficiency (%) across output streams (permeate and concentrate), as well as the residual microplastic fraction accumulated within the membrane module, were calculated based on gravimetric measurements. Results for each experimental condition are presented as the mean ± standard error of the mean (M ± SEM), given in equation (3):

$$\text{SEM} = \frac{SD}{\sqrt{n}} \tag{3}$$

where SD is the sample standard deviation and n = 3 is the number of independent replicates.

The total average residual microplastic accumulation within the membrane module was determined from the mass balance between the initial input mass (M_0) and the cumulative mass recovered in the permeate and concentrate streams. Statistical processing, mean calculations, and graphical visualizations were performed using Microsoft Excel and OriginPro software. Digital micrographs were analyzed to provide qualitative visual verification of particle retention and morphological characteristics.

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3 RESULTS AND DISCUSSION

The experimental results demonstrated the high efficiency of the ULP21-4040 reverse osmosis membrane for eliminating microplastic (MP) particles from model aqueous solutions. The system effectively retained particles of polyethylene terephthalate (PET), polypropylene (PP), and polyethylene (PE) across both investigated size fractions (0.20 and 0.45 mm). The primary quantitative datasets capturing these filtration indicators are summarized in Tables 2 and 3.

Table 2 summarizes the obtained removal efficiencies for different polymer types and particle size fractions.

Table 2 - Microplastic removal efficiency during reverse osmosis filtration [Authors' material].

Polymer	Particle size, mm	Experiment number	Removal efficiency, %	M ± SEM
PET	0.45	1	99.97	
PET	0.45	2	99.93	99.87 ± 0.07
PET	0.45	3	99.71	
PET	0.20	1	99.89	
PET	0.20	2	99.35	99.34 ± 0.32
PET	0.20	3	98.78	
PP	0.45	1	99.64	
PP	0.45	2	98.12	98.59 ± 0.53
PP	0.45	3	98.01	
PP	0.20	1	98.12	
PP	0.20	2	97.98	97.81 ± 0.24
PP	0.20	3	97.34	
PE	0.45	1	99.63	
PE	0.45	2	98.63	98.75 ± 0.48
PE	0.45	3	97.98	
PE	0.20	1	99.78	
PE	0.20	2	99.35	99.42 ± 0.19
PE	0.20	3	99.12	

The evaluation of reverse osmosis performance indicates excellent microplastic (MP) rejection for all studied polymer types (PET, PP, PE). The rejection efficiency consistently remains above 97%, validating the robust barrier capacity of the membrane process. The peak rejection was achieved for 0.45 mm polyethylene terephthalate (PET) particles, reaching 99.87 ± 0.07%. Conversely, a marginal decline in rejection efficiency to 97.81 ± 0.24% was noted for smaller polypropylene (PP) fractions (0.20 mm). This trend may be explained by the hydrodynamic behavior of finer, lower-density polymer particles within the membrane boundary layer.

Table 3 demonstrates the efficiency indicators for MP removal from the membrane system through permeate (treated water) and concentrate (water with increased concentrations of retained contaminants) and allows for a preliminary assessment of the membrane module fouling.

Table 3 - Microplastic removal rates from the membrane module [Authors' material].

Polymer	Particle size, mm	Experiment number	Removal efficiency, %	M ± SEM
PET	0.45	1	99.91	
PET	0.45	2	99.88	99.92 ± 0.03
PET	0.45	3	99.98	
PET	0.20	1	99.61	
PET	0.20	2	99.77	99.74 ± 0.07
PET	0.20	3	99.84	
PP	0.45	1	99.42	
PP	0.45	2	99.75	99.06 ± 0.53
PP	0.45	3	98.01	
PP	0.20	1	98.78	98.21 ± 0.37

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PP	0.20	2	97.51	
PP	0.20	3	98.34	
PE	0.45	1	99.12	
PE	0.45	2	99.46	99.05 ± 0.26
PE	0.45	3	98.57	
PE	0.20	1	98.78	
PE	0.20	2	99.55	99.15 ± 0.22
PE	0.20	3	99.12	

To provide a comprehensive holistic view of the separation mechanics, the mass balance variables-incorporating both the purification efficiency and the subsequent particle recovery rate from the concentrate stream-were synthesized into a single reference matrix (Figure 5).

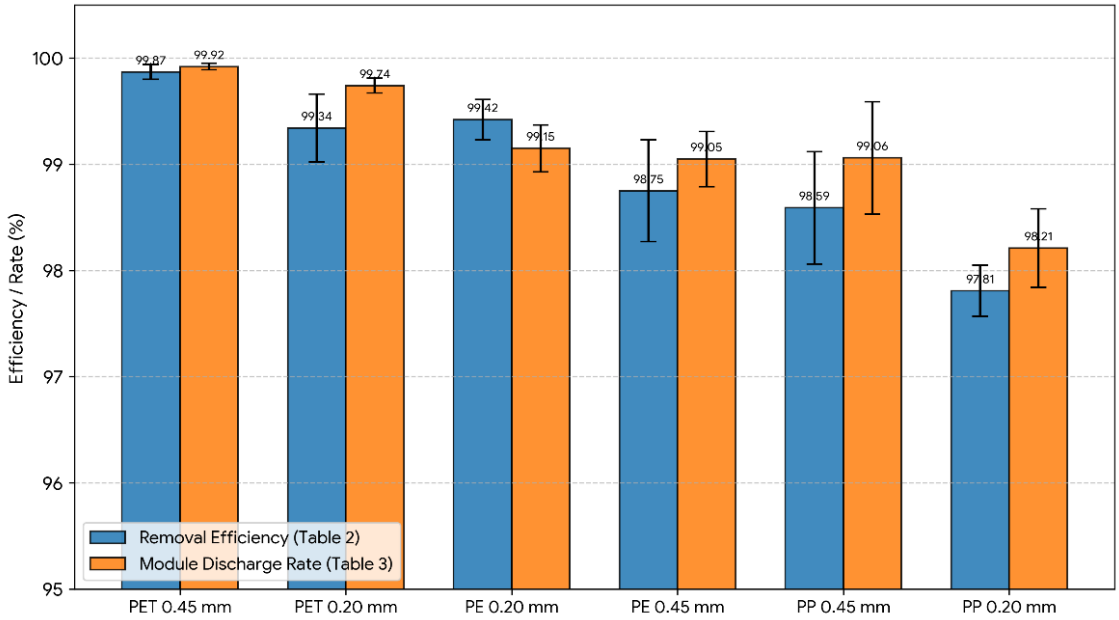

Figure 5 – Rejection efficiency and mass-balance distribution of microplastics (PET, PE, PP) in the output streams of the ULP21-4040 reverse osmosis system

The results presented in Tables 2 and 3, as well as Figure 5, allow for the conclusion that the operational performance of the membrane module demonstrates comparably high microplastic rejection rates, thereby confirming data consistency. For the PET fractions (0.45 mm and 0.20 mm), the average removal efficiencies reach 99.92% and 99.74%, respectively. For polypropylene (PP) and polyethylene (PE), the efficiency varies from 98.21% to 99.15%, demonstrating the module's versatility toward polymers of different chemical nature and shapes.

A detailed analysis of the graphical trends reveals a clear correlation between the physicochemical properties of the polymers and their hydrodynamic behavior within the membrane boundary layer. The highest retention and removal rates were recorded for the 0.45 mm PET fraction (99.87% and 99.92%, respectively). Due to the high density of polyethylene terephthalate (~ 1.34-1.40 g/cm³), these particles are easily swept away by the cross-flow velocity into the concentrate stream, demonstrating minimal deposition on the active membrane surface.

Conversely, an opposite trend is observed for the fine polypropylene (PP) fraction (0.20 mm), where the removal efficiency drops to the experimental minimum of 97.81 ± 0.24%. Possessing a density lower than that of water (~ 0.90 g/cm³) along with a pronounced hydrophobicity, the PP particles are prone to intensive flotation and entrapment within the laminar boundary layer of the membrane. This induces micro-penetration of the fine PP fraction.

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Despite the high overall filtration performance, complete 100% particle retention is not achieved. Based on the performed calculations, the total average residual amount of microparticles accumulated within the membrane module across all experiments was 0.81%.

Although the fraction of residual particles is minimal, their gradual accumulation and deposition will inevitably affect the hydraulic characteristics of the system. For a comprehensive substantiation of the proposed technology, further studies on the clogging and fouling dynamics of the membrane module are required. Detailed monitoring of pore clogging will allow for an objective evaluation of the system's temporal operational capacity, determination of the optimal backwashing or chemical cleaning intervals, and prediction of the total service life of the filter elements.

3.1. Microscopic analysis of retained microplastics

Microscopic observations confirmed the accumulation of microplastic particles on the Sefar sieve cloth with a mesh size of 100 μm used during sample preparation and gravimetric analysis.

Samples collected from the concentrate stream contained significantly larger numbers of retained particles compared with permeate samples.

Microscopic images revealed irregular particle morphologies, including fragments, flakes, and elongated structures. PET particles generally exhibited angular shapes, whereas PE and PP particles displayed smoother and more flexible structures.

Microscopic examination was performed to complement the quantitative results presented in Table 2 and to provide qualitative visual confirmation of microplastic particles recovered from the two output streams. The particles observed in the treated-water (permeate) sample (Figure 6) confirm that a small residual fraction of microplastics remained after filtration, indicating that removal was highly effective but not complete. The particles recovered from the concentrate (Figure 7) provide visual evidence of their separation into the concentrate stream. In addition, a fraction of the microplastics may have been retained within the experimental system through deposition on the membrane surface, pretreatment components, pipelines, and other internal surfaces. Because these internal components were not examined separately, such retention is considered a possible explanation rather than a directly confirmed result. Overall, the microscopic observations support the separation mechanism of the reverse osmosis process and complement the quantitative removal-efficiency data.

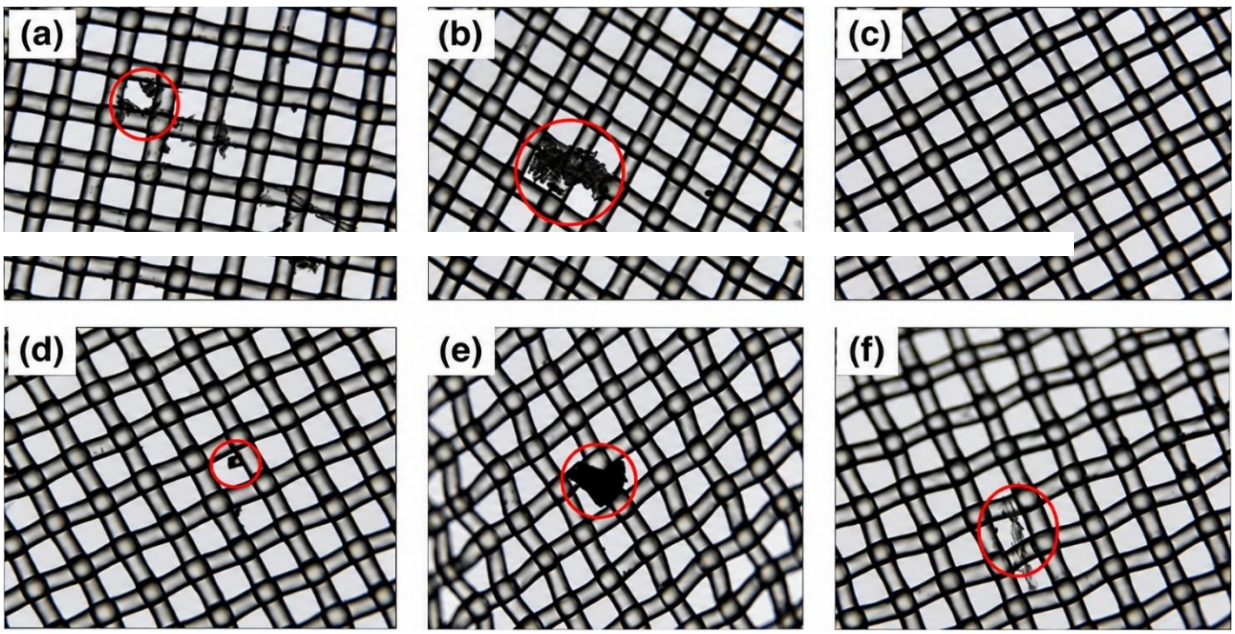

Figure 6 – Representative micrographs of microplastic particles recovered from the permeate stream after reverse osmosis filtration: (a) PET, 0.45 mm; (b) PET, 0.20 mm; (c) PP, 0.45 mm; (d) PP, 0.20 mm; (e) PE, 0.45 mm; and (f) PE, 0.20 mm. The particles were collected on Sefar sieve cloth with a nominal mesh opening of 100 μm [Authors' material].

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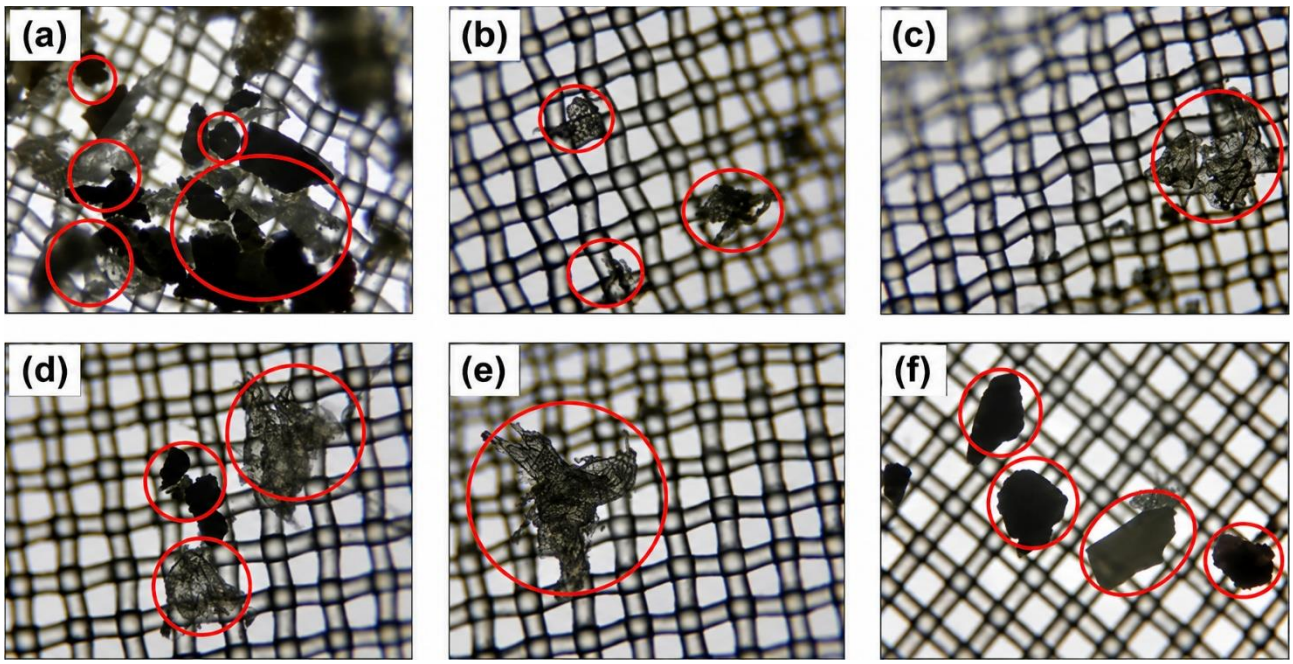

Figure 7 – Representative micrographs of microplastic particles recovered from the concentrate stream after reverse osmosis filtration: (a) PET, 0.45 mm; (b) PET, 0.20 mm; (c) PP, 0.45 mm; (d) PP, 0.20 mm; (e) PE, 0.45 mm; and (f) PE, 0.20 mm. The particles were collected on Sefar sieve cloth with a nominal mesh opening of 100 µm [Authors' material].

3.2. Comparison with previous studies and discussion of removal mechanisms

The obtained results are consistent with previously reported removal efficiencies for reverse osmosis membranes. Previous studies have demonstrated microplastic removal efficiencies exceeding 95% for membrane-based treatment systems.

The slightly higher efficiencies observed in the present study can be explained by the relatively large particle sizes used in the experiments (0.20–0.45 mm), which are substantially larger than the effective pore size of the reverse osmosis membrane.

The primary removal mechanisms include:

1. Size exclusion (sieving effect);
2. Surface deposition and particle accumulation;
3. Concentration polarization near the membrane surface;
4. Formation of a secondary filtration layer by retained particles.

The concentrate stream contained the majority of retained microplastic particles, confirming that reverse osmosis effectively separates particulate contaminants from treated water.

Overall, the results demonstrate that reverse osmosis membranes can provide an effective barrier against microplastic pollution and may serve as a promising tertiary treatment technology for advanced wastewater reclamation and drinking water production.

4 CONCLUSIONS

This study evaluated the removal of polyethylene terephthalate (PET), polyethylene (PE), and polypropylene (PP) microplastic particles from model water using a pilot-scale reverse-osmosis system equipped with a ULP21-4040 membrane. In addition to evaluating particle-removal efficiency, the study considered the distribution of microplastic mass within the system and the potential engineering implications of integrating membrane treatment into wastewater treatment facilities and the water-engineering systems of buildings and structures. Based on the experimental results, the following conclusions can be drawn:

1. The ULP21-4040 reverse-osmosis membrane demonstrated high microplastic removal efficiency for all investigated polymer types and particle sizes, with mean values consistently

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exceeding 97%. The highest mean efficiency was obtained for 0.45-mm PET particles (99.87 ± 0.07%), whereas the lowest was recorded for 0.20-mm PP particles (97.81 ± 0.24%). These results confirm the ability of the membrane system to provide an effective physical barrier against the tested microplastic particles under the selected operating conditions.

2. Under identical feed-water and operating conditions, the membrane demonstrated polymer- and size-dependent retention behaviour. PET particles showed the highest numerical removal values, while the lowest efficiency was observed for 0.20-mm PP particles. These differences may be associated with variations in particle density, hydrophobicity, surface properties, and behaviour within the membrane module. However, because each experimental condition was tested in only three replicates, the observed differences should not be regarded as statistically significant without confirmation by an appropriate inferential statistical test.

3. The principal quantitative contribution of this study is the determination of microplastic distribution among the treated-water stream, reject-water stream, and membrane-module retention fraction. Mass-balance calculations showed that an average of 0.81% of the introduced microplastic mass remained within the membrane module. Therefore, assessment based exclusively on the treated water and reject water may underestimate the fraction of particles retained within the filtration system.

4. The detected internal retention demonstrates that high microplastic removal efficiency does not necessarily indicate the absence of particle accumulation within the membrane equipment. Even a relatively small retained fraction may become operationally important during long-term operation because particles can accumulate in feed channels, membrane spacers, pipelines, and other internal components. Such accumulation may increase hydraulic resistance, reduce membrane productivity, increase operating pressure, and affect cleaning frequency and membrane service life. The measured 0.81% fraction therefore provides an experimental basis for further studies of membrane fouling and operational reliability.

5. From the perspective of wastewater-treatment engineering, the obtained results support consideration of a modular reverse-osmosis unit as a tertiary treatment stage downstream of biological treatment. This arrangement may be incorporated into the technological scheme when constructing new treatment facilities or reconstructing and modernizing existing plants. However, the reverse-osmosis unit should be protected by an appropriate pretreatment stage, which may include clarification, sand filtration, microfiltration, ultrafiltration, or cartridge filtration, depending on the quality of the biologically treated wastewater. Pretreatment is required to reduce suspended solids, limit membrane fouling, and maintain stable system performance.

6. The incorporation of a reverse-osmosis block affects both the technological design and the construction requirements of a wastewater treatment facility. The design documentation should provide sufficient space for pretreatment equipment, membrane modules, high-pressure pumps, chemical-cleaning systems, monitoring devices, pipelines, and treated-water storage tanks. It should also address electrical power demand, equipment foundations, corrosion-resistant piping, ventilation, drainage, noise and vibration control, safe maintenance access, and the collection and disposal or further treatment of the concentrated reject stream. These factors should be considered when determining the capital and operating costs of the facility.

7. The results are also relevant to compact engineering water-treatment systems installed in residential, public, industrial, and infrastructure facilities. Reverse-osmosis units may potentially be incorporated into local water-treatment systems or non-potable water-reuse systems in buildings and structures. Their integration should be coordinated with internal water supply and drainage networks and should account for water demand, operating pressure, treated-water storage, reject-water discharge, energy consumption, automation, and access for membrane replacement and maintenance. The suitability of the treated water for a specific reuse purpose must nevertheless be confirmed through a comprehensive water-quality assessment and compliance with applicable regulatory requirements.

8. The experiments were conducted using model water, two relatively large microplastic size fractions, a single membrane type, and one operating pressure. Therefore, the results should not be directly extrapolated to full-scale wastewater treatment plants or building water systems without

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additional validation. Future research should include real biologically treated wastewater, smaller microplastic particles, different membrane and pretreatment configurations, longer operating periods, and continuous monitoring of pressure loss, permeate flow, energy consumption, particle accumulation, membrane cleaning, and concentrate characteristics.

Overall, the results demonstrate the high efficiency of the ULP21-4040 membrane in removing the tested microplastic particles and provide an experimental basis for evaluating its use in advanced engineering water-treatment systems. The findings may support the development of technological solutions for integrating modular reverse-osmosis units into newly constructed or modernized wastewater treatment facilities, as well as into local water-treatment and reuse systems for buildings and structures. Nevertheless, engineering implementation requires pilot testing with real wastewater and a comprehensive assessment of pretreatment requirements, membrane fouling, energy consumption, concentrate management, operational reliability, and life-cycle costs.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

ARTIFICIAL INTELLIGENCE STATEMENT

During the preparation of this manuscript, the authors used artificial intelligence tools solely for language editing, grammar checking, and text improvement. All scientific content, interpretations, analyses, and conclusions remain the responsibility of the authors.

AUTHOR CONTRIBUTIONS

M.N.Berdali – Formal Analysis, Validation, Writing – Original Draft, Investigation.
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N.S.Salikova – Conceptualization, Formal Analysis, Methodology, Writing – Original Draft.
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