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# Ceramic membrane filtration of natural and synthetic fibers in laundry wastewater

Guangze Qin *, Luuk C. Rietveld, Sebastiaan G.J. Heijman

*Section of Sanitary Engineering, Department of Water Management, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, 2628, CN, Delft, the Netherlands*

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ABSTRACT

The clothes washing industry generates large volumes of laundry wastewater that, in principle, can be well treated by ceramic membrane filtration. However, the fouling of ceramic membranes by fibers/fragments from laundry wastewater could result in a decrease of the water permeance across the membranes. In this study, synthetic wastewater containing cotton, linen, polyester, and nylon fibers and real wastewater were characterized and prepared for the filtration experiments, which were conducted at a flux of 70 $Lm^{-2}$ $h^{-1}$ using an alumina ($Al_2O_3$) membrane and a silicon carbide (SiC)-coated $Al_2O_3$ membrane. Results revealed that natural fabrics, particularly cotton and linen, released higher chemical oxygen demand (COD) loads than synthetic fibers when tested at equal mass, which was further supported by microscopic and SEM imaging. The SiC-coated membrane exhibited a relatively lower reversible and irreversible fouling, attributed to its highly negatively charged surface, which repels the fibers that are negatively charged by negatively charged surfactants. The observed fouling among different fibers corresponded well with the COD levels of the synthetic laundry wastewater containing those fibers. Laser direct infrared imaging (LDIR) analysis confirmed that natural fibers dominate in real laundry wastewater. Treating hot laundry wastewater was more effective in reducing both reversible and irreversible membrane fouling than treating it at room temperature. Moreover, the filtration of hot laundry wastewater could facilitate the recovery and reuse of water, surfactants, and heat, offering a sustainable solution to reduce both water consumption and energy costs. This study underscores the importance of paying closer attention to natural fibers, as they tend to cause more severe membrane fouling compared to synthetic fibers in ceramic membrane-based water treatment systems.

## 1. Introduction

Large flows of laundry wastewater are discharged during the washing of synthetic garments, releasing over five trillion plastic fragments on the ocean's surface [1]. Several authors have studied various treatment technologies to treat laundry wastewater including microfiltration (MF) [2], ultrafiltration (UF) [3], coagulation [4], and advanced oxidation [5]. Yang et al. reported that during the domestic washing of synthetic fabrics, submicrometric particles with sizes ranging from 100 to 600 nm are released [6], thus, UF have been considered to be the most promising approach for removing these submicrometric fibers, making it also an effective option for the reuse of the laundry wastewater [7].

However, fouling remains the primary challenge when using UF membranes for treating laundry wastewater [8]. Ceramic membranes offer several advantages over polymeric membranes, including a higher mechanical, thermal and chemical stability, as well as lower fouling tendencies [9–13]. These benefits make them particularly suitable for treating laundry wastewater in high-temperature and chemically harsh environments [3,7]. The first study on the evolution of the ceramic membranes fouling for laundry wastewater treatment was done by the Kim et al., who reported that ceramic UF membranes have successfully been applied for both the synthetic and real laundry wastewater treatment [3]. Kim et al. also reported that ceramic membranes can be regarded as a potential alternative for the traditional microplastic filter for the treatment of the household washing wastewater [14]. The ceramic UF membrane was effective at removing suspended particulates in real laundry wastewater but less effective in rejecting organic matter [3]. A large amount of microplastic fibers was found in the laundry wastewater [15], having varying shapes, including fibers, films, foam,

* Corresponding author.
*E-mail address:* G.Qin@tudelft.nl (G. Qin).

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and granules [16,17], and sizes from 0.1 μm to 2 mm [17]. FTIR and Raman microspectroscopy are the most commonly used techniques for identifying MPs based on their vibrational spectra, with detection limits of approximately 20 μm and 1 μm, respectively, due to spatial resolution constraints and fluorescence interference [18]. Smaller microplastics could be detected using FlowCam, which allows detection over a broad size range from 0.9 to 1000 μm [19,20]. Apart from that, thermal analysis methods such as pyrolysis gas chromatography mass spectrometry (Py-GC/MS) could quantify microplastics based on mass concentration, independent of particle size [21].

Silicon carbide (SiC) and alumina ($Al_2O_3$) ceramic membranes are commercially available and widely used in wastewater treatment applications, standing out among other ceramic membranes [10,11,22–24]. Our previous studies showed that the SiC-coated $Al_2O_3$ membranes exhibited a lower reversible and irreversible fouling than the $Al_2O_3$ membrane for the filtration of oil-field produced water [25]. Hyeon et al. also found that SiC membranes are more effective than $Al_2O_3$ for laundry wastewater treatment because they have a higher negative zeta potential (−24.3 mV) compared to the $Al_2O_3$ membrane (−4.7 mV) at a pH of 6 [17]. Synthetic fabrics such as nylon and polyester, as well as natural fabrics, including cotton and linen, are commonly used materials in fabric production [26]. It has been reported that the natural fibers can make up 55% of the total fibers found in laundry wastewater and these fibers take 1 to 5 months to fully biodegrade in the natural environment [26,27]. However, most studies have primarily focused on ceramic membrane fouling caused by filtering synthetic laundry wastewater containing synthetic microplastics fibers rather than the natural fibers [3,8,14]. To the best of our knowledge, ceramic membrane fouling caused by natural fiber has not been quantitatively analyzed yet. Therefore, in this study, fouling induced by fabric fibers, especially the natural fibers, using positively charged $Al_2O_3$ membranes and negatively charged SiC ceramic membranes is presented. Filtration experiments were carried out in a constant flux crossflow mode, using both synthetic and real laundry wastewater. The experiments were set up to evaluate how membrane properties, and laundry water characteristics, including temperature and fibric types, influence membrane fouling, thus, giving proper solutions for the membrane fouling mitigation and promoting water reuse and heat recycle in laundry industry.

## 2. Materials and methods

### 2.1. Materials

Fabric materials made of 100% cotton, 100% nylon, 100% linen and 100% polyester were purchased from a local store and used to prepare the synthetic laundry wastewater. The anionic surfactant, sodium dedecyl benzene sulfonate (SDBS, powder, 289957-500G), was purchased from Sigma-Aldrich, the Netherlands.

SiC-deposited $Al_2O_3$ membranes were obtained via low-pressure chemical vapor deposition (LPCVD) using two precursors ($SiH_2Cl_2$ and $C_2H_2$) at a temperature of 860 °C, following the procedure described in our previous work [28]. Tubular $Al_2O_3$ membranes supplied by CoorsTek Co., Ltd., were used as substrates for LPCVD. The membranes without coating and those with a coating time of 20 min were labeled as C0 and C20, respectively. The tubular C0 and C20 membranes have a length of 10 cm each, with an outer diameter of 10 mm and an inner diameter of 6 mm (Fig. S1), corresponding to a total wall thickness of 2 mm. The separation layer of the C0 membrane has a thickness of 24 μm, while that of the C20 membrane is also 24 μm, because the additional SiC coating layer was only approximately 18 nm. These values are confirmed by the cross-sectional morphologies of the C0 and C20 membranes and the EDX net intensity mapping of SiC-coated alumina particles on the top surface of the separation layer (Figs. S2a-b and S3). The EDX line-scan analysis and cross-section SEM images of the C20 membrane revealed that the SiC coating penetrated to a depth of approximately 2.5 μm (Fig. S4). The measured pore sizes were 41 nm for C0 and 33 nm for C20, with corresponding water permeabilities of 360 ± 12 L m$^{-2}$ h$^{-1}$ bar$^{-1}$ and 202 ± 8 L m$^{-2}$ h$^{-1}$ bar$^{-1}$, as reported in our earlier study [28].

### 2.2. Membrane characterization

Surface SEM images of the C0 and C20 membranes were captured using a NovaNanoLab 600 system (FEI, USA), while their zeta potentials were determined with a SurPASS 3 electrokinetic analyzer (Anton Paar, Graz, Austria). The capillary flow porometry (Porolux 500, IBFT GmbH, Germany) was employed to measure the mean pore size, and pore size distribution of the pore size of the C0 and C20 membranes. More information regarding the calculation of the pore size distribution is given in the Supporting Information Text S2. The pore size distribution is shown in the Fig. S5.

### 2.3. Synthetic and real laundry wastewater

To investigate the effect of the charge of the synthetic laundry wastewater on membrane fouling, various synthetic laundry wastewater were prepared. The washing machine (WGG04408, Bosch, Germany) was cleaned by running empty cycles before the preparation of the synthetic laundry wastewater. Linear alkylbenzene sulfonates (LASs) are key anionic surfactants commonly found in detergents, including laundry powders and dishwashing liquids [29]. SDBS, a specific type of LAS, was used as a detergent, with 0.75 g/L added to the 30 L DI water and the 2.5 kg polyester cloth during the washing procedure, based on the work of Hernandez et al. [30]. The same procedure was applied to the preparation of the synthetic laundry wastewater, each containing either 2.5 kg cotton, 2.5 kg nylon, 2.5 kg polyester, or 2.5 kg linen fibers. The real laundry wastewater was collected from a laundry company, Elis B.*V*., located in Uden, the Netherlands. The detergent usage was measured per kilogram of clothing, with an average consumption of 10 ± 1.5 mL per kilogram. The detergent used (Dermasil Plus) has a density of 980 g/L, corresponding to approximately 9.8 ± 1.5 g of detergent per kilogram of fabric, which was comparable to the dosage used in the synthetic wastewater (9 g/kg). The washing process utilized approximately 14 ± 1 L of water per kilogram of clothing. The laundry wastewater was generated from the following washing programs. The prewash was conducted at 45 °C, the main wash at 60 °C, and the cooldown at 40 °C. The particle size distributions of the fabric fibers in the feed water were analyzed with a particle size analyzer (Bluewave, Microtrac, USA). Meanwhile, the particle size distribution of the permeate water and the laundry wastewaters' zeta potential was measured using a Litesizer (DLS 700, Anton Paar, Austria).

### 2.4. Filtration experiments with synthetic and real laundry wastewater

Fouling experiments were conducted using a constant-permeate-flux crossflow setup (Fig. S6). A constant flux of 50 Lm$^{-2}$ h$^{-1}$ for the real laundry wastewater and 70 Lm$^{-2}$ h$^{-1}$ for synthetic laundry wastewater was selected, based on the threshold flux values determined for the C0 and C20 membranes, respectively. These threshold flux values were determined though the conventional flux stepping method [28,31,32]. Full details of the filtration set up and filtration protocol are provided in the Supporting Information (Text S1). The corresponding membrane permeabilities for both real and synthetic laundry wastewater are summarized in Table S1. For the C0 membranes, the permeability ranged from 288 to 361 Lm$^{-2}$ h$^{-1}$ bar$^{-1}$ for the synthetic laundry wastewater and was 339 Lm$^{-2}$ h$^{-1}$ bar$^{-1}$ for the real laundry wastewater. In contrast, the C20 membranes exhibited lower permeabilities, ranging from 184 to 206 Lm$^{-2}$ h$^{-1}$ bar$^{-1}$ for the synthetic laundry wastewater and 205 Lm$^{-2}$ h$^{-1}$ bar$^{-1}$ for the real laundry wastewater.

### 2.5. Qualitative and quantitative microplastic fiber characterization

Three methods were used to characterize the release of the fabric fibers. In the first method, the fibers in both synthetic and real laundry wastewater, including feed and permeate samples, were analyzed using a digital microscope (VHX-5000, magnification×1000) equipped with a wide-range zoom lens (VH-Z100R). Multiple images with a resolution of 1600 × 1200 pixels with a scale bar of 100 μm were captured for each feed and permeate sample to quantify the number of fibers per milliliter. In the second method, laser direct infrared imaging (LDIR) was used to identify the type and the number concentration of microplastic fibers in the real laundry wastewater [7,33]. The analysis was performed using Agilent Clarity software, which first scanned the sample at a selected wavelength to locate all fibers and then automatically collected a full infrared spectrum for each one [34]. The obtained spectra were compared in real time with a reference spectral library containing both synthetic polymers (Figs. S12 and S13a) and natural fibers (Fig. S13b-c). In the third method, the fabric fibers in the synthetic laundry wastewater were analyzed using Fourier transform infrared (FTIR) spectroscopy (Nicolet™ iS50, Thermo Fisher Scientific, USA). The analysis was conducted in attenuated total reflection (ATR) mode over a wavenumber range of 500–3600 $cm^{-1}$.The scans were performed 60 times with a resolution of 4 $cm^{-1}$, and the data spacing was set at 0.482 $cm^{-1}$. Every FTIR measurement was conducted in duplicate.

## 3. Results and discussion

### 3.1. Synthetic laundry wastewater properties

The FTIR spectra (Fig. 1a) were obtained to confirm the chemical compositions of the commercially purchased fibers and to compare them with reported spectra in literature. Linen and cotton fibers are primarily composed of cellulose, therefore, the key absorption peaks included 1100 $cm^{-1}$ (C—O), 2900 $cm^{-1}$ (C—H), and 3400 $cm^{-1}$ (O—H). For the polyester fibers, the key absorption peaks included 1100&1260 $cm^{-1}$ (C—O), 1600 $cm^{-1}$ (C═C) and 1712 $cm^{-1}$ (C═O), which is in accordance with the absorption peaks given in literature [35,36]. For the nylon fiber, the absorption peak at 3299 $cm^{-1}$ confirms the presence of amine stretching, while the peak at 1633 $cm^{-1}$ indicates amine carbonyl stretching in the structure. These results are in line with the ATR-FTIR spectra of these fibers that have been reported in literature [35,36]. Overall, the results confirm that the fibers used in this study had the expected chemical structures. The particle size distribution of the synthetic laundry wastewater is shown in Fig. 1b. The average particle sizes for cotton, nylon, linen and polyester fibers were 11.35 ± 1.72 μm, 12.62 ± 1.21 μm, 25.45 ± 2.36 μm, 3.97 ± 0.23 μm, respectively. In contrast, Yang et al. reported the release of smaller submicron particles (100–600 nm) during the domestic washing of 12 different polyester fabrics. The washing experiments were carried out using a Gyrowash lab washing machine (James Heal, Model 1615), which contains eight steel containers designed to simulate household washing conditions [6].

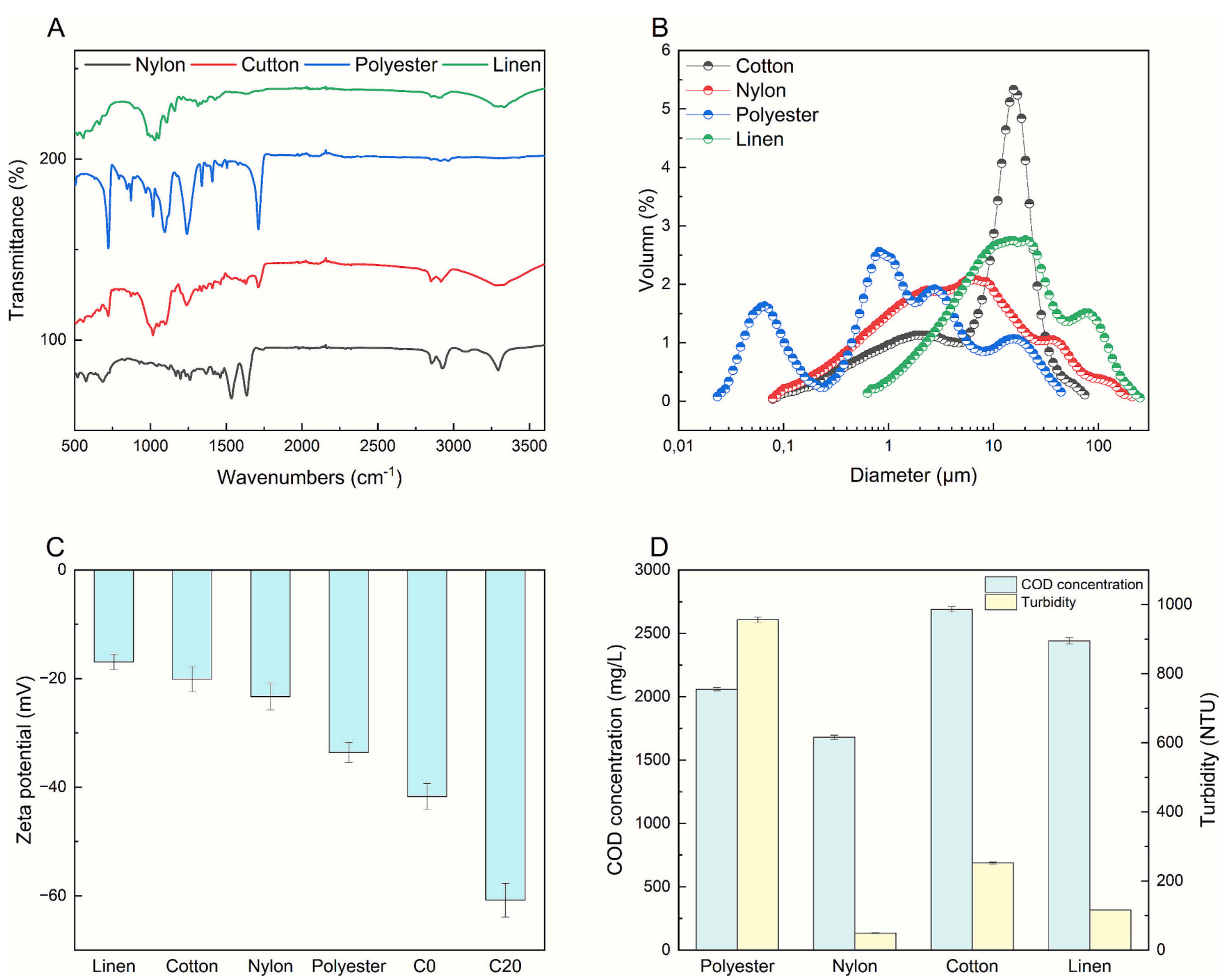


**Fig. 1.** (a): The FTIR spectra of the fabric fibers. (b): The fiber size distribution of the synthetic laundry wastewater. (c): The zeta potential of the synthetic laundry wastewater containing cotton, linen, nylon, polyester fibers and the C0 and C20 membranes soaking into the SDBS solutions. (d): The COD concentration and turbidity of the synthetic laundry wastewater containing cotton, linen, nylon, polyester fibers.

Meanwhile, Barrick et al. reported larger microfiber sizes for cotton, nylon, and polyester, averaging 20.46 ± 5.36 μm, 25.37 ± 5.24 μm, and 30.51 ± 5.09 μm, respectively [37].

Cotton and linen fibers are both cellulose-based and hydrophilic [38], but when soaked in a negatively charged surfactant solution, linen fibers (derived from flax) typically exhibit a less negative zeta potential (−16.9 ± 2.3 mV) than cotton fibers (−20.1 ± 1.4 mV), as shown in Fig. 1c. This difference is attributed to the lower concentration of surface carboxyl groups present on linen fibers, as well as less adsorption of the negatively charged surfactant due to their hydrophilic nature [39,40]. At neutral pH (pH = 7), nylon fibers lose most of their positive charge due to the deprotonation of amide groups, indicating a near-neutral surface [41]. However, when nylon fiber are released from fabric and interact with SDBS surfactant, the negatively charged $SO_3^-$ groups of the SDBS adsorb onto nylon fibers. Additionally, the hydrophobic nature of nylon fiber further promotes adsorption of the SDBS molecules, particularly of the surfactant's hydrophobic tail. This combined adsorption caused a shift in the zeta potential to −23.3 ± 1.2 mV, a more negative value than those observed for cotton fibers and linen fibers. Polyester exhibits an even higher surface hydrophobicity than nylon [42], and tend to adsorb more SDBS surfactants by hydrophobic interactions. Thus, the zeta potential was −33.6 ± 1.8 mV, more negative compared to nylon, cotton, and linen. Ladewig et al. have reported that at a pH of 10, synthetic fibers (polyester) exhibited a higher zeta potential of −69 mV, compared to natural fibers (cotton), having a zeta potential of −24.5 mV [40]. Similarly, Ripoll et al. have reported that at alkaline pH, natural fibers, such as cotton and bamboo, had a lower absolute value of zeta potential, compared to synthetic fibers like polyamide (PA) [43]. This difference has also been attributed to the higher zeta potential of hydrophobic fibers (e.g., PA) compared to the more hydrophilic fibers (e.g., cotton) [43].

When the membranes were soaked in the SDBS solution, the zeta potentials of the C0 and C20 membranes were − 41.7 ± 2.4 mV and − 60.8 ± 3.1 mV, respectively. This indicates the presence of electrostatic repulsion between the membrane surfaces and the fibers.

The COD concentrations of the synthetic laundry wastewater, after the washing of 2.5 kg of the respective clothes, containing polyester, nylon, cotton and linen, were 2059 ± 13 mg/L, 1680 ± 16 mg/L, 2689 ± 21 mg/L, 2440 ± 25 mg/L, respectively (Fig. 1d). The possible explanation for the differences in COD is that natural fibers are more prone to abrasion and damage and, thus, when subjected to friction and mechanical forces, they are more likely to release fibers [44]. However, the synthetic laundry wastewater containing polyester had a higher turbidity than the feed water containing nylon, cotton, and linen, probably due to the higher presence of smaller, suspended particles and fine fibrous fragments that scatter light (Fig. 1d) [45].

The fabric fibers had elongated and irregular shapes, and particularly those with a high aspect ratio (length/diameter) were long with a narrow diameter, being potentially able to penetrate membrane pores (Fig. 2). The microscopic image of the cotton shows the relatively small and uniformly distributed fibers, suggesting the release of finer fibers, which contributed to the highest COD levels. In contrast, microscopic image of nylon displays a clean appearance with minimal visible residues, corresponding to its lowest COD concentration (1680 ± 16 mg/L), indicating limited nylon fiber release. The microscopic image of the linen shows the clearly visible fibrous fragments, corresponding to its second highest COD concentration. Polyester shows scattered but noticeable fibrous structures and small particles, aligning with a moderate COD value (2059 ± 13 mg/L).

### 3.2. Real laundry wastewater properties

The fabric fibers had an average particle size of 15.81 ± 0.67 μm, with a maximum size of 104.7 μm (Table 1 and Fig. 3). The small sizes of the fibers can be attributed to the potential degradation of natural fabric fibers or the desorption of their adsorbed contaminants, which may release smaller substances (e.g., dyes, monomers, finishing chemicals) [40]. This process could deteriorate water quality and accelerate

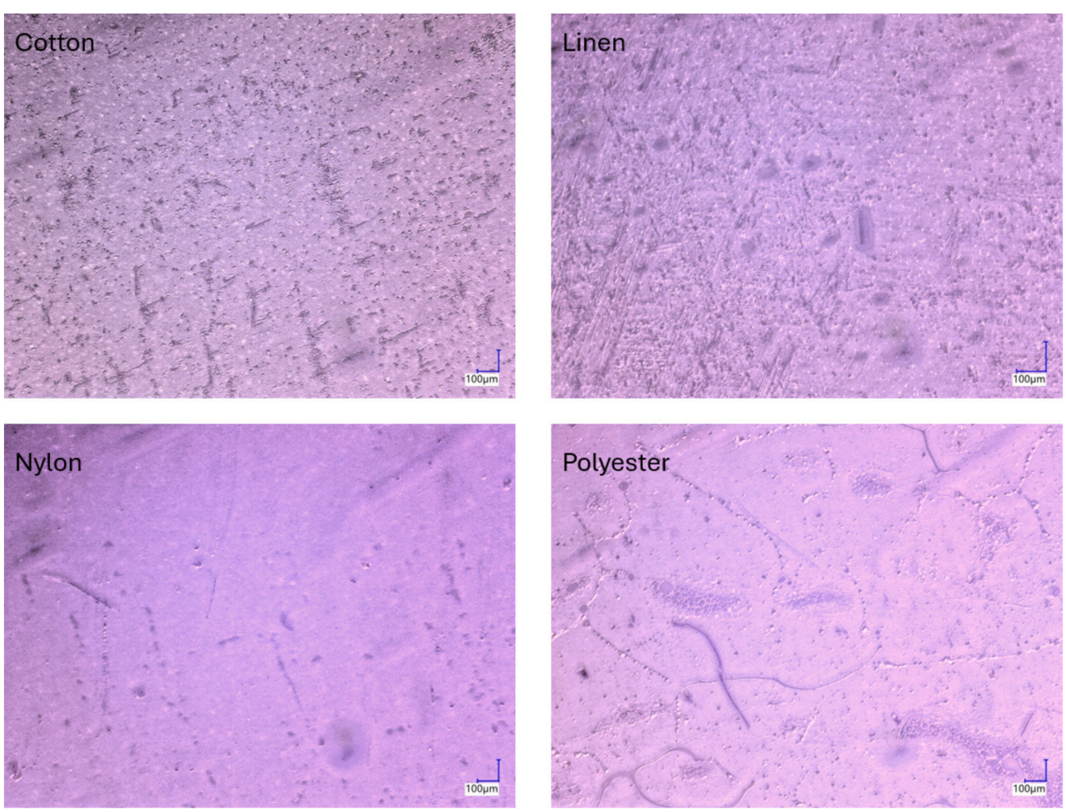


**Fig. 2.** Microscopic images of the cotton, polyester, nylon and linen fibers in the feed water.

**Table 1**
Characteristics of the real laundry wastewater.

| Parameters | Real laundry wastewater |
|---|---|
| Turbidity (NTU) | 318 ± 11 |
| pH | 7.91 ± 0.29 |
| Conductivity (mS/cm) | 1.23 ± 0.02 |
| COD (mg/L) | 4014 ± 154 |
| Zeta potential (mV) | −30.77 ± 0.42 |
| Mean particle size (μm) | 15.81 ± 0.67 |

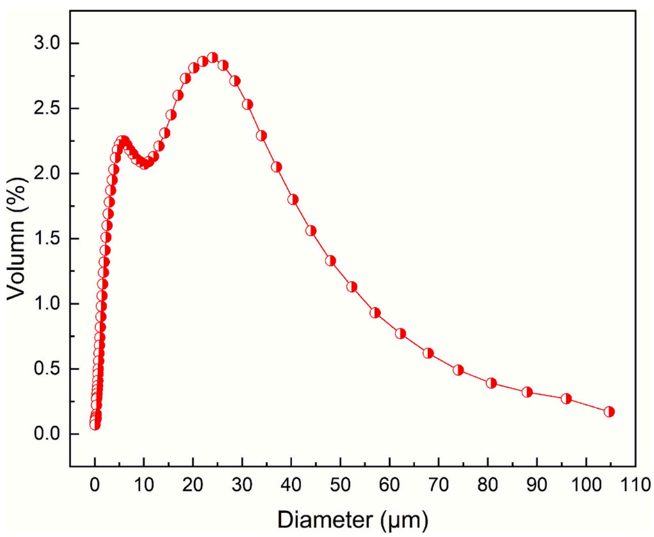


**Fig. 3.** The particle size distribution of the real laundry wastewater.

membrane fouling. The zeta potential of the laundry wastewater was −30.77 ± 0.42 mV (Table 1), due to the presence of anionic and non-ionic surfactants [46].

In order to accurately distinguishing and identifying the percentage and species of synthetic and natural fibers in real laundry wastewater, the LDIR technique was used to analyse the real laundry wastewater sample. Out of the 722 ± 17 particles detected, the composition of 656 ± 21 particles was successfully identified by matching their FTIR spectra with reference spectra from the software library, using a minimum confidence threshold of 65%. Fig. 4a shows the fiber length distribution, and Fig. 4b shows the fiber material distribution of the real laundry wastewater. The fiber identification spectra from the LDIR software are shown in Fig. S12. According to the Fig. 4a, the majority of the fibers have lengths ranging from 0 to 50 μm, as indicated by the particle size distribution results. The LDIR analysis (Fig. 4b) revealed that 67.8% ± 1.6% of the fibers in the sample were natural, including 49.8% ± 0.9% cellulose-derived fibers (e.g., cotton and linen) and 18.9% ± 1.8% natural PA fibers, which including wool and silk [47]. Natural and synthetic polyamides were distinguished by their characteristic infrared absorption bands (Fig. S13a-b), particularly in the amide I (1600–1800 $cm^{-1}$) and amide II (1450–1570 $cm^{-1}$) regions. The remaining fibers were synthetic, consisting of 9.8% ± 1.2% polyethylene terephthalate (PET), 6.4% ± 0.7% acrylates, 5.6% ± 0.8% PA, and 4.0% ± 0.7% Polyurethane (PU), along with smaller fractions of 4.2% ± 0.6% methylcellulose, and 2.3% ± 0.4% polytetrafluoroethylene (PTFE). These results indicated that natural fibers dominate in real laundry wastewater. It is reported that the natural fibers such as cotton and linen could make up 55% of the total fibers in the laundry wastewater [27]. These cellulose-based fibers serve as an easily accessible carbon source for microorganisms. In contrast, polyester and nylon, due to their hydrophobic nature and non-sugar-based composition, are not biodegradable [48]. With the number of fabrics fiber in the real laundry wastewater and the volume of the feed water, an total fiber concentration of $4.23 \times 10^4$ $L^{-1}$ including $2.86 \times 10^4$ $L^{-1}$ natural fibers and $1.37 \times 10^4$ $L^{-1}$ synthetic microplastic fibers was calculated.

### 3.3. Membrane fouling with synthetic laundry wastewater

The UF ceramic membranes were selected for the fouling experiments because, based on the fiber size distribution of synthetic laundry wastewater containing polyester, approximately 18% of the particles

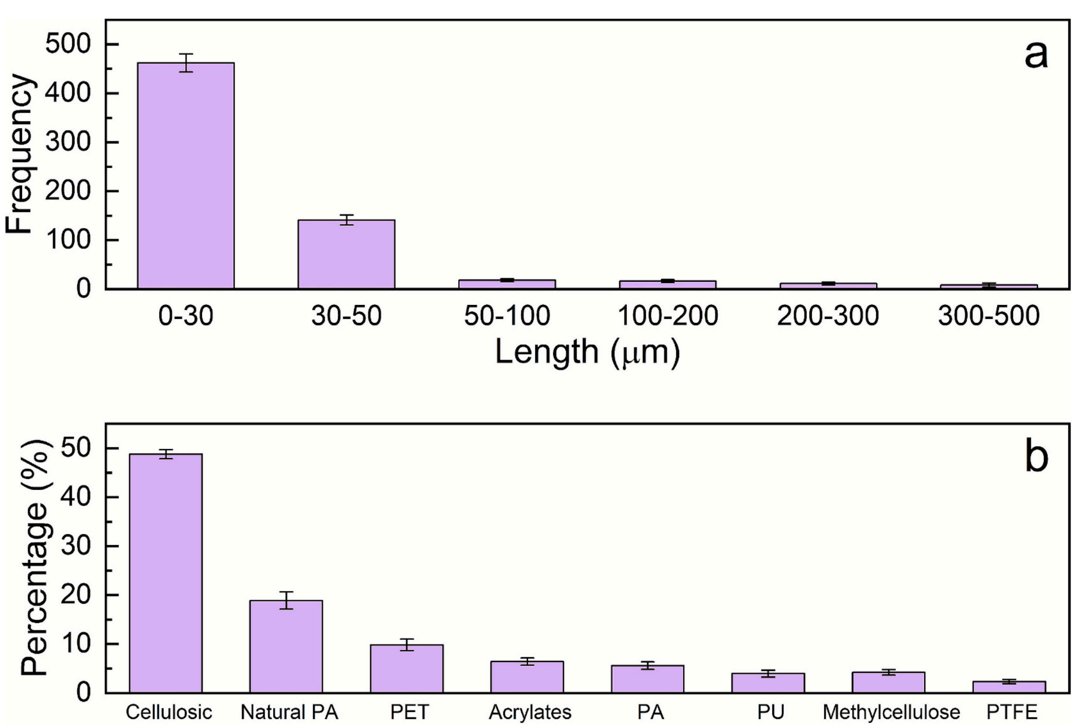


**Fig. 4.** (a) Fiber length distribution and (b) fiber material distribution of the real laundry wastewater.

were smaller than 100 nm (Fig. 1b). The normalized TMP fouling curves, shown in Fig. 5, indicate that cotton fibers caused the most severe membrane fouling, followed by the linen, polyester and nylon. Among them, linen fibers resulted in the highest irreversible fouling, probably due to the lower zeta potential of linen fibers (−16.9 ± 2.3 mV), which reduces the electrostatic repulsion between the fibers and the C0 and C20 membranes, promoting stronger adhesion and irreversible deposition.

The trend of membrane fouling is consistent with the COD concentrations, which is in the order of cotton > linen > polyester > nylon (Fig. 5a-e). As shown in Fig. 5e, reversible fouling resistance was dominant for both the C0 and C20 membranes, indicating that cake layer formation is the primary fouling mechanism. Further details on the thickness of the cake layer are provided in Fig. S11. The normalized permeance curve showed similar fouling trend as indicted in the normalized TMP curve (Fig. S7a-d). To evaluate whether surfactants contribute to membrane fouling, pure SDBS surfactant solutions were filtered. The results showed that the surfactants did not cause either

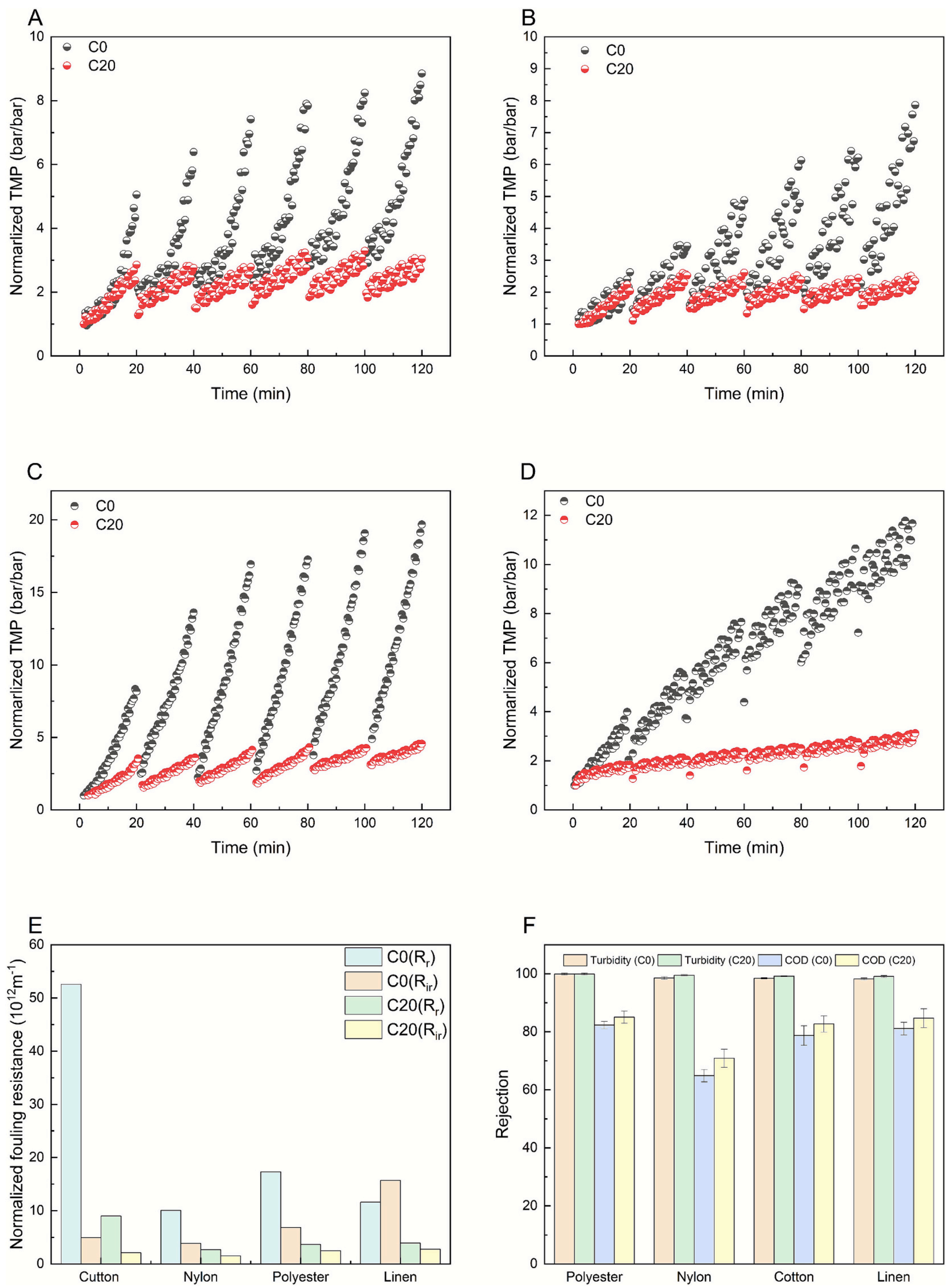


**Fig. 5.** The normalized TMP curve of C0 and C20 membranes for different types of laundry wastewater including (a): Polyester, (b): Nylon, (c): Cotton, (d): Linen; (e): Normalized fouling resistance of C0 and C20 membranes for different types of synthetic laundry wastewater. (f): Turbidity and COD rejection of C0 and C20 membranes for various types of synthetic laundry wastewater.

reversible or irreversible fouling of the C0 or C20 membranes, as indicated by the unchanged TMP with the increase in filtration time at the flux of 70 $Lm^{-2}$ $h^{-1}$ (Fig. S8). Fig. S9a shows the increase in the normalized TMP over time during filtration of SDBS solution at 100 $Lm^{-2}$ $h^{-1}$. Both membranes exhibited a gradual increase in TMP; however, the C0 membrane showed a higher TMP increase compared to the C20 membrane. Correspondingly, Fig. S9b presents the normalized permeability ($P/P_o$), which decreased over time for both membranes, with the C0 membrane experiencing a larger decline (from 100% to 70%) than the C20 membrane (79%). These trends can be explained by the combined effects of micelle formation and electrostatic interactions. The SDBS concentration used (750 mg/L, 2.15 mM) exceeded the critical micelle concentration (1.2 mM) [49], indicating that micelles (2–20 nm) were present in solution and can accumulate near the membrane surface [46], partially obstructing the pores. In addition, as shown in Fig. S9c, the C0 membrane had a slightly positive zeta potential (+3 mV), which favored electrostatic attraction of the negatively charged SDBS molecules, enhancing adsorption and fouling resistance. In contrast, the C20 membrane exhibited a strongly negative zeta potential (−55 mV), which repelled SDBS molecules and minimized adsorption. Therefore, the larger TMP increase and permeability decline observed for the C0 membrane reflect the combined effects of micelle-induced pore blockage and electrostatic adsorption, whereas the C20 membrane was less affected due to electrostatic repulsion.

Therefore, the fouling observed is attributed to the presence of fibers. Natural fibers thus caused more membrane fouling than the synthetic fibers, probably due to the lower absolute values of zeta potential of the natural fibers and higher COD load. In literature, natural fibers have largely been overlooked, with research primarily focusing on synthetic fibers. This is likely due to the assumption that natural fibers, being

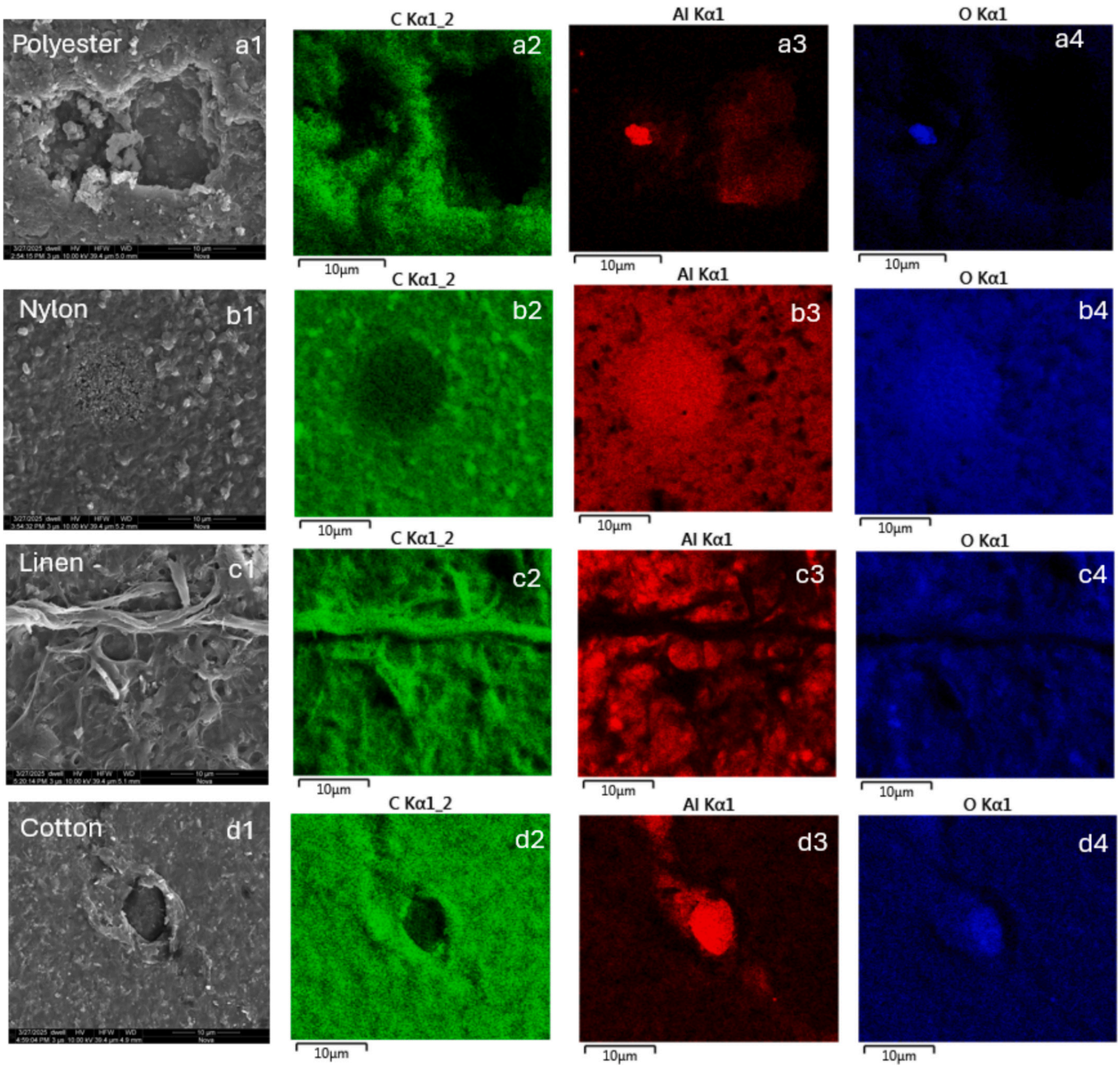


**Fig. 6.** SEM images of the fouled C0 membrane, along with the corresponding element mapping (C, Al and O) after treating the synthetic laundry wastewater containing (a) Polyester, (b) Nylon, (c) Linen, and (d) Cotton.

organic and biodegradable, pose a minimal environmental risk [37]. For example, natural fibers, such as cotton and silk, have not exhibited toxicity toward *Daphnia magna*, whereas synthetic fibers like nylon caused acute toxic effects on the organism [37]. However, it has also been reported that natural fibers could serve as carriers for harmful substances, as fabrics made from organic fibers are often treated with chemicals such as chemical colorants and finishes [40]. These chemical additions could also slow down the biodegradation process of natural fibers [50].

As shown in Fig. 5f, the COD removal efficacies of the C0 and C20 membranes were highest for polyester fibers, reaching 82.3 ± 0.8% and 85.1 ± 1.4%, respectively. A possible explanation is that all the fibers were removed, and only the small molecules, such as surfactants, and monomers, contributed to the COD measured in the permeate. In contrast, the nylon fabrics released the lowest amount of fibers, thus, resulting in less adsorption of surfactant onto the fibers and a higher concentration of surfactant in the permeate. This led to low COD rejection by the C0 membrane and C20 membranes, at 64.9 ± 2.1% and 70.9 ± 3.1%, respectively. Because the COD, present in the permeate, mainly originated from the SDBS surfactant, it could be recovered and reused if the wastewater were recycled. Additionally, all fibers released from the fabrics were completely rejected by the membranes, as confirmed by the microscopic images (Fig. S10).

As can be observed from Fig. 6, the surface morphology and elemental mapping confirm that different fabric fibers in synthetic laundry wastewater led to varying degrees of membrane fouling on the C0 membrane. The fouling layer on the C20 membrane was not studied since the carbon in the SiC membrane influences the carbon distribution of the foulants (fiber) on the membrane surface. Among all tested fibers, cotton resulted in the most developed cake layer, covering approximately 91% of the membrane surface, as evidenced by the strong and widespread carbon signal and the near absence of aluminum signal. The cross-sectional SEM image further shows that the fouling layer thickness for cotton reached 8–10 μm, indicating severe deposition and cake buildup (Fig. S11a). The polyester led to the second largest fouling, with about 65% of the alumina signal obscured and a fouling layer thickness of 6–8 μm (Fig. S11b), also suggesting the formation of a substantial cake layer. The observed fouling appeared to be dominated by foulant-foulant interactions, particularly hydrophobic interactions, rather than membrane-foulant interaction. With the increase in the filtration time, these interactions promote the accumulation and growth of the cake layer and the porosity of the cake layer initially increases during the early stage of filtration and then reaches a plateau [51]. Enfrin et al. have reported a similar fouling mechanism, where polyester fibers produced via electrospinning and cryosectioning, with a diameter of 13 ± 7 μm, led to a combination of internal pore blockage and cake layer formation [52].When treating synthetic laundry wastewater containing linen fibers, the fibers were clearly deposited as cake layer on the membrane surface with average thickness of 2–6 μm (Fig. S11c). In the case of nylon fibers, the elemental carbon mapping showed a homogeneous but faint distribution of carbon across the membrane surface, however, the aluminum signal remained clearly visible, indicating that only a thin and sparse fouling layer (1–2 μm) with minimal surface coverage (Fig. S11d). This suggests that nylon caused the least reversible fouling, which is related to cake layer formation, consistent with the low COD value (1680 ± 16 mg/L).

### 3.4. *Membrane fouling with real laundry wastewater*

#### 3.4.1. *The threshold flux of the membranes*

The threshold fluxes for the C0 and C20 membranes were 48 Lm$^{-2}$ h$^{-1}$ and 56 Lm$^{-2}$ h$^{-1}$, respectively (Fig. 7), thus, a constant flux of 50 Lm$^{-2}$ h$^{-1}$ was selected for filtering the real laundry wastewater.

#### 3.4.2. *The effect of the temperature and flux on membrane fouling*

At the flux of 50 LMH (Fig. 8a), a rapid increase in the normalized TMP for the C0 membrane indicates a higher fouling rate than the C20 membrane, which may be attributed to the lower electrostatic repulsive forces between the C0 membrane and fabric fibers. It has been reported that fabric fibers, including natural and synthetic (microplastics) fibers, are primarily rejected by membranes based on size-exclusion, with fibers smaller or larger than the membrane pores potentially causing irreversible or reversible fouling, respectively [14]. In order to further study the effect of flux on irreversible fouling, the flux was increased to 70 Lm$^{-2}$ h$^{-1}$, being higher than the threshold flux of the both membranes (Fig. 8b). A higher irreversible and reversible fouling was observed for both C0 and C20 membranes. The increased irreversible fouling can be attributed to the increased TMP, which likely resulted in the compaction of the fiber cake layer and facilitated the penetration of smaller fibers and foulants into the membrane pores, thereby exacerbating irreversible fouling in both membranes (Fig. 8d) [25]. However, the C20 membrane still outperformed the C0 membrane, with a lower fouling tendency. The performance gap between the two membranes became more noticeable at this higher flux (70 Lm$^{-2}$ h$^{-1}$) compared to the low flux of 50 Lm$^{-2}$ h$^{-1}$.

In cloth washing industry, large volumes of reusable hot laundry wastewaters are being discharged [53]. To evaluate membrane performance under realistic conditions, the filtration experiments were conducted at the temperature of 20 °C and 60 °C (Fig. 8c). At higher temperatures, ceramic membranes usually exhibit a higher permeability due to the lower water viscosity at higher temperature, potentially resulting in less fouling. Similarly, Paula et al. have also observed an increased membrane fouling at lower temperatures during flux step experiments [54]. Due to the stronger convective forces, because of

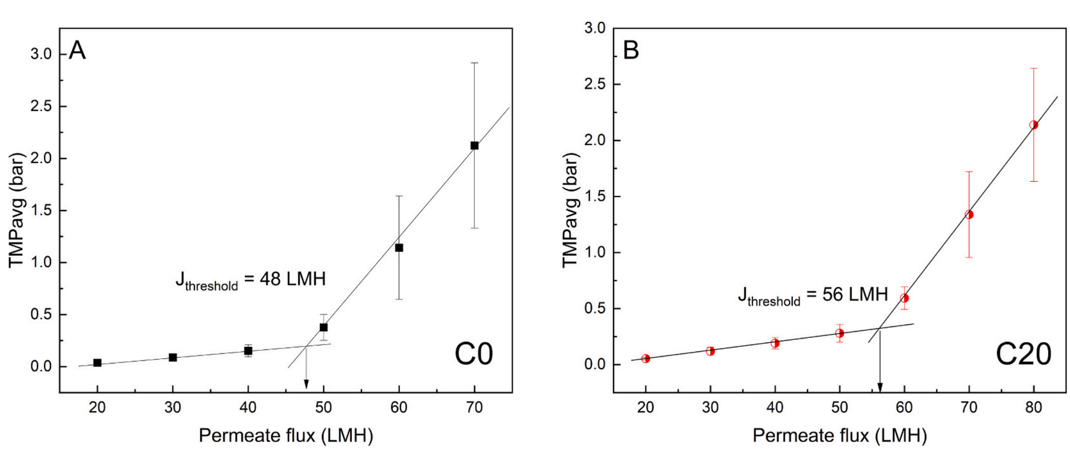


**Fig. 7.** The threshold flux of the C0 and C20 membranes for the real laundry wastewater treatment.

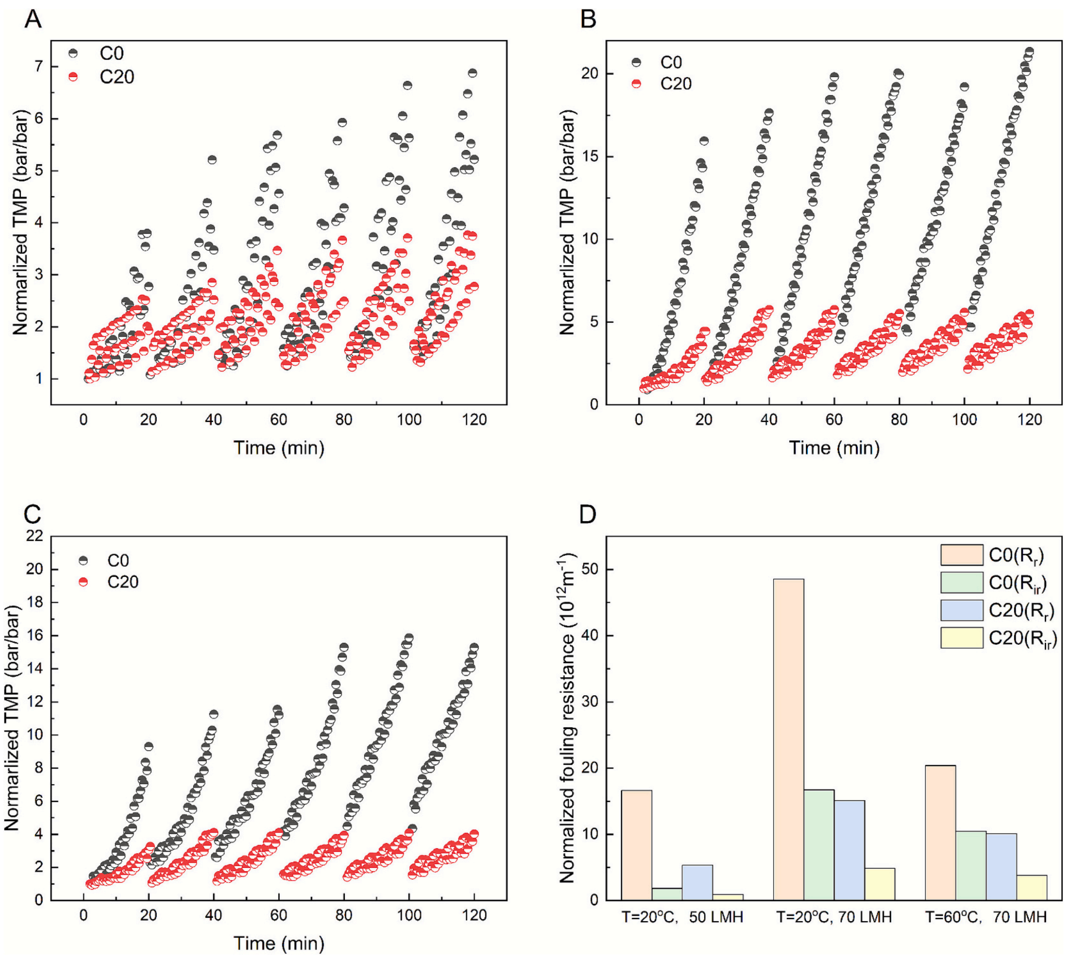


**Fig. 8.** The normalized TMP curve of C0 and C20 membranes under different conditions (a):$T = 20$ °C, 50 $Lm^{-2}$ $h^{-1}$; (b): T = 20 °C, 70 $Lm^{-2}$ $h^{-1}$; (c): $T = 60$ °C, 70 $Lm^{-2}$ $h^{-1}$; (d):The normalized fouling resistance for the C0 and C20 membranes under different conditions.

decreased viscosity, at higher temperatures, the formation of the cake layer on the membrane surface is probably slowed down, leading to a decreased reversible fouling. This finding is also confirmed by the increase in the initial permeance of the C20 membrane in the sixth cycle, from 42% at 20 °C to 61% at 60 °C (Fig. S7f-g). By comparison, increased temperatures can increase fouling in oily wastewater treatment, as the reduced viscosity of oil leads to droplet deformation and greater potential for pore blockage in ceramic membranes [55]. From an economic perspective, treating real laundry wastewater at 60 °C not only mitigates the membrane fouling, but also enables the recovery and reuse of both water and heat, potentially reducing water consumption and associated energy costs.

The COD concentration in the permeate was 1179 ± 42 mg/L for the C0 membrane and 1128 ± 25 mg/L for the C20 membrane. Based on these values, the calculated COD rejection rates were 70.6% and 71.9%, respectively (Table 2). The particles in the permeate (Fig. 9) can be explained by the presence of spherical micelles of the surfactant ranging from 2 to 20 nm [46].

**Table 2**
Characteristics of the permeate water.

| Parameters | Permeate water (C0) | Permeate water (C20) |
|---|---|---|
| pH | 7.88 ± 0.12 | 7.82 ± 0.08 |
| Conductivity (mS/cm) | 1.16 ± 0.04 | 1.18 ± 0.05 |
| COD (mg/L) | 1179 ± 42 | 1128 ± 25 |
| Zeta potential (mV) | −19.41 ± 0.32 | −18.66 ± 0.47 |
| Mean particle size (nm) | 12.38 ± 0.34 | 12.13 ± 0.56 |

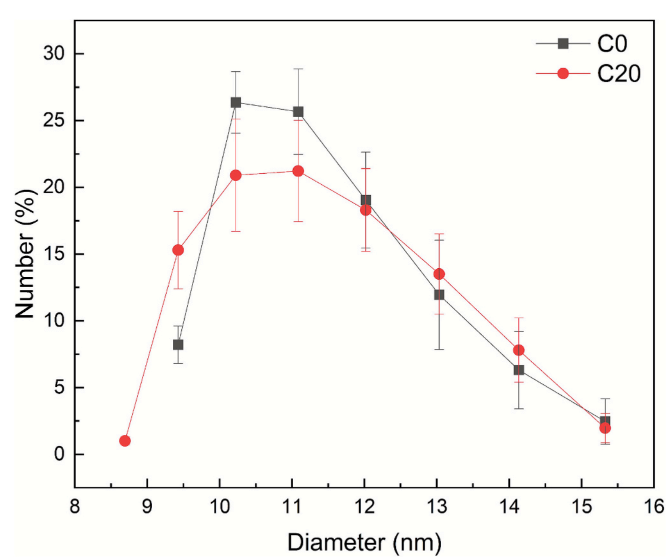


**Fig. 9.** The particle size distribution in the permeate water of the C0 and C20 membranes.

To further analyse the fibers in the real laundry wastewater, their morphologies were examined using microscopic images (Fig. 10). The contaminants in the feed water exhibited various shapes, including fibers, films, fragments and chips [16,17]. In contrast, microscopic

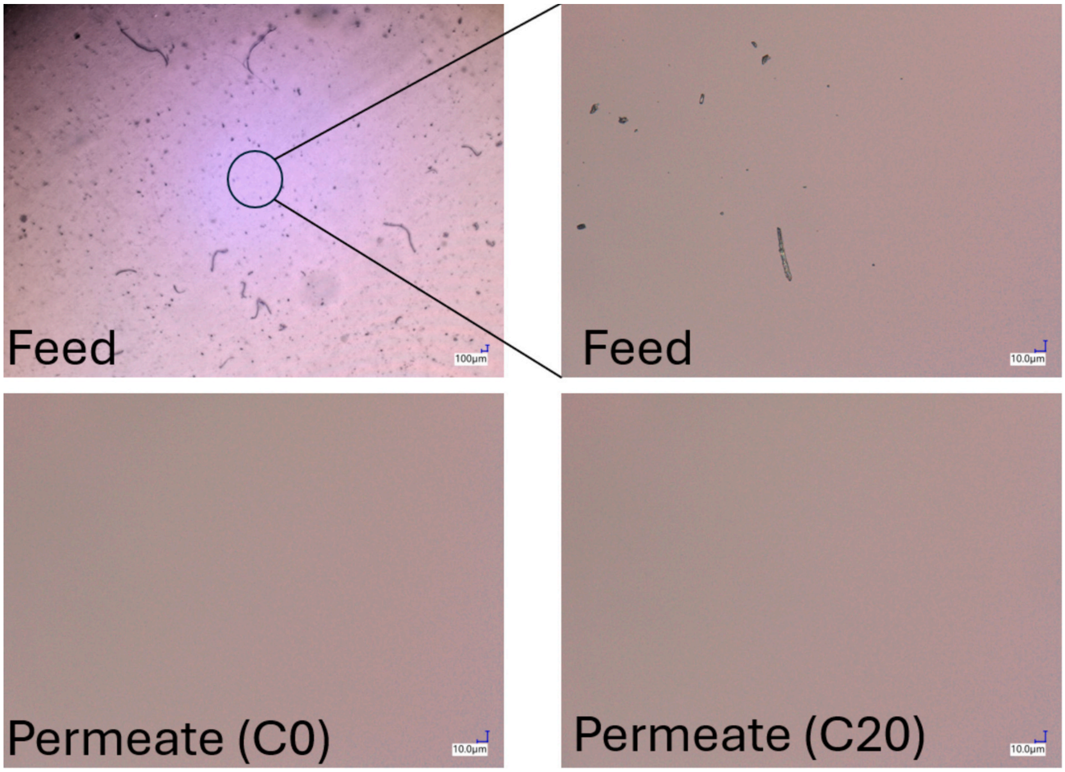


**Fig. 10.** Microscopic characterization of the feed and permeate of real laundry wastewater after treatment with C0 and C20 membranes.

analysis of the permeate water revealed no visible fibers and particles, with only small surfactant micelles (2–20 nm) present, confirming the high rejection (100%) performance of the ceramic membranes. Lastly, the results obtained in this study were compared with those reported in literature. Zhang's group studied the treatment of real laundry wastewater using SiC MF membranes (350 nm) and UF $ZrO_2$ membranes (55 nm) obtained from a tent laundry outlet. The threshold flux of the UF $ZrO_2$ membrane was reported as 50 L $m^{-2}$ $h^{-1}$, which is slightly higher than that of the C0 membrane (48 L $m^{-2}$ $h^{-1}$) but lower than that of the C20 membrane (56 L $m^{-2}$ $h^{-1}$) in this study. The COD removal efficiency achieved with the $ZrO_2$ UF membrane was 83.8% [56], which exceeds the values obtained in this work (70.6% for C0 and 71.9% for C20). The same research group also examined hospital laundry wastewater treatment, where a COD rejection of 35% was reported. They noted that only moderate COD removal was achieved because a substantial portion of the organic content originated from surfactants, which can be beneficially reused in the washing process if the treated water is recycled [7]. Therefore, while the SiC-coated membrane demonstrated a high performance compared to the commercial ceramic membrane in terms of threshold flux, the COD rejection efficiency strongly depends on the characteristics of the feedwater. In particular, a high proportion of surfactant molecules, contributing to the COD, can lead to lower rejection by ceramic UF membranes.

## 4. Conclusion

The behavior of fiber release, membrane fouling, and fouling mitigation during the treatment of synthetic laundry wastewater using pristine $Al_2O_3$ and a SiC-coated ceramic membranes was presented. The fiber size distribution was characterized using light scattering-based techniques, and the fouling experiments were conducted at a constant flux of 70 $Lm^{-2}$ $h^{-1}$. Results revealed that natural fabrics, particularly cotton and linen, released higher COD loads than synthetic fabrics, when tested at equal mass, in the trend of cotton > linen > polyester > nylon, which was further supported by microscopic and SEM images. The SiC-coated membrane showed lower reversible and irreversible fouling than the $Al_2O_3$ membrane due to its highly negatively zeta potential. The fouling order of the fibers in line with the COD concentration of the synthetic laundry wastewater containing these fibers. Further, it was found that during treatment of hot (60 °C) real laundry wastewater by the ceramic membranes, not only membrane reversible and irreversible fouling was mitigated, but it also enabled the simultaneous recovery and reuse of water, surfactants, and thermal energy, potentially offering a sustainable strategy to reduce both water consumption and energy costs. The LDIR results showed that natural fibers is dominant in the real laundry wastewater with number concentration of $2.86 \times 10^4$ $L^{-1}$. This study highlighted the importance of paying greater attention to natural fibers, as they can cause more severe fouling of ceramic membranes compared to synthetic fibers during the laundry wastewater treatment process.

## CRediT authorship contribution statement

**Guangze Qin:** Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Luuk C. Rietveld:** Writing – review & editing, Supervision. **Sebastiaan G.J. Heijman:** Conceptualization, Methodology, Formal analysis, Funding acquisition, Supervision, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seppur.2025.136027.

## Data availability

Data will be made available on request.

## References


[1] M.A. Browne, P. Crump, S.J. Niven, E. Teuten, A. Tonkin, T. Galloway, R. Thompson, Accumulation of microplastic on shorelines woldwide: sources and sinks, Environ. Sci. Technol. 45 (21) (2011) 9175–9179, https://doi.org/10.1021/es201811s.

[2] B. Ghalami Choobar, M.A. Alaei Shahmirzadi, A. Kargari, M. Manouchehri, Fouling mechanism identification and analysis in microfiltration of laundry wastewater, J. Environ. Chem. Eng. 7 (2) (2019), https://doi.org/10.1016/j.jece.2019.103030.

[3] S. Kim, C. Park, Potential of ceramic ultrafiltration membranes for the treatment of anionic surfactants in laundry wastewater for greywater reuse. Journal of water, J Water Process Eng 44 (2021) 102373, https://doi.org/10.1016/j.jwpe.2021.102373.

[4] A.K. Huang, M.T. Veit, P.T. Juchen, G.d.C. Gonçalves, S.M. Palácio, C.s.O. Cardoso, Sequential process of coagulation/flocculation/sedimentation- adsorption - microfiltration for laundry effluent treatment, J. Environ. Chem. Eng. 7 (4) (2019), https://doi.org/10.1016/j.jece.2019.103226.

[5] V.V. Patil, P.R. Gogate, A.P. Bhat, P.K. Ghosh, Treatment of laundry wastewater containing residual surfactants using combined approaches based on ozone, catalyst and cavitation, Sep. Purif. Technol. (2020), https://doi.org/10.1016/j.seppur.2020.116594. **239**, Article 116594.

[6] T. Yang, Y. Xu, G. Liu, B. Nowack, Oligomers are a major fraction of the submicrometre particles released during washing of polyester textiles, Nature Water 2 (2) (2024) 151–160, https://doi.org/10.1038/s44221-023-00191-5.

[7] F.E. Bortot Coelho, S.I. Sohn, V.M. Candelario, N.I.B. Hartmann, C. Hélix-Nielsen, W. Zhang, Microplastics removal from a hospital laundry wastewater combining ceramic membranes and a photocatalytic membrane reactor: fouling mitigation, water reuse, and cost estimation, J. Membr. Sci. (2025), https://doi.org/10.1016/j.memsci.2024.123485. **715**, Article 123485.

[8] S. Kim, C. Park, Fouling behavior and cleaning strategies of ceramic ultrafiltration membranes for the treatment and reuse of laundry wastewater, J Water Process Eng 48 (2022) 102840, https://doi.org/10.1016/j.jwpe.2022.102840.

[9] B. Hofs, J. Ogier, D. Vries, E.F. Beerendonk, E.R. Cornelissen, Comparison of ceramic and polymeric membrane permeability and fouling using surface water, Sep. Purif. Technol. 79 (3) (2011) 365–374, https://doi.org/10.1016/j.seppur.2011.03.025.

[10] Y. Wei, Z. Xie, H. Qi, Superhydrophobic-superoleophilic SiC membranes with micro-nano hierarchical structures for high-efficient water-in-oil emulsion separation, J. Membr. Sci. 601 (2020) 117842, https://doi.org/10.1016/j.memsci.2020.117842.

[11] Z. Wu, Z. Ma, T. Zhu, Y. Wang, N. Ma, W. Ji, P. Nian, N. Xu, S. Zhang, Y. Wei, Engineering of ceramic membranes with superhydrophobic pores for different size water droplets removal from water-in-oil emulsions, Sep. Purif. Technol. 353 (2025) 128293, https://doi.org/10.1016/j.seppur.2024.128293.

[12] G. Qin, H. Zhou, B. Tanis, L.C. Rietveld, S.G.J. Heijman, Impact of ionic strength and surface charge on ceramic membrane fouling by oil-in-water emulsions: a quantitative analysis using DLVO and XDLVO models, Sep. Purif. Technol. 372 (2025) 133424, https://doi.org/10.1016/j.seppur.2025.133424.

[13] Q. Jiang, Y. Wang, Y. Xie, M. Zhou, Q. Gu, Z. Zhong, W. Xing, Silicon carbide microfiltration membranes for oil-water separation: pore structure-dependent wettability matters, Water Res. 216 (2022) 118270, https://doi.org/10.1016/j.watres.2022.118270.

[14] S. Kim, Y. Hyeon, H. Rho, C. Park, Ceramic membranes as a potential high-performance alternative to microplastic filters for household washing machines, Sep. Purif. Technol. 344 (2024) 127278, https://doi.org/10.1016/j.seppur.2024.127278.

[15] M. Dreillard, C.F. Barros, V. Rouchon, C. Emonnot, V. Lefebvre, M. Moreaud, D. Guillaume, F. Rimbault, F. Pagerey, Quantification and morphological characterization of microfibers emitted from textile washing, Sci. Total Environ. 832 (2022) 154973, https://doi.org/10.1016/j.scitotenv.2022.154973.

[16] H. Kamani, M. Ghayebzadeh, A. Azari, F. Ganji, Characteristics of microplastics in a hospital wastewater treatment plant effluent and Hazard risk assessment, Environ. Process. 11 (1) (2024), https://doi.org/10.1007/s40710-024-00694-7.

[17] Y. Hyeon, S. Kim, E. Ok, C. Park, A fluid imaging flow cytometry for rapid characterization and realistic evaluation of microplastic fiber transport in ceramic membranes for laundry wastewater treatment, Chem. Eng. J. 454 (2023) 140028, https://doi.org/10.1016/j.cej.2022.140028.

[18] A. Kappler, D. Fischer, S. Oberbeckmann, G. Schernewski, M. Labrenz, K. J. Eichhorn, B. Voit, Analysis of environmental microplastics by vibrational microspectroscopy: FTIR, Raman or both? Anal. Bioanal. Chem. 408 (29) (2016) 8377–8391, https://doi.org/10.1007/s00216-016-9956-3.

[19] Y. So, S.Y. Kim, S. Kim, C. Park, Innovative approaches to high-speed ceramic membrane filtration for microplastic mitigation in urban wastewater treatment facilities, Sep. Purif. Technol. 363 (2025) 132013, https://doi.org/10.1016/j.seppur.2025.132013.

[20] Y. Hyeon, S. Kim, C. Park, Exploring the transformation of polyethylene and polyamide microplastics during membrane filtration through FlowCam analysis, Sep. Purif. Technol. 334 (2024) 126036, https://doi.org/10.1016/j.seppur.2023.126036.

[21] Y. Xu, Q. Ou, X. Wang, F. Hou, P. Li, J.P. van der Hoek, G. Liu, Assessing the mass concentration of microplastics and Nanoplastics in wastewater treatment plants by pyrolysis gas chromatography-mass spectrometry, Environ. Sci. Technol. 57 (8) (2023) 3114–3123, https://doi.org/10.1021/acs.est.2c07810.

[22] M.B. Asif, Z. Zhang, Ceramic membrane technology for water and wastewater treatment: a critical review of performance, full-scale applications, membrane fouling and prospects, Chem. Eng. J. 418 (2021) 129481, https://doi.org/10.1016/j.cej.2021.129481.

[23] E. Eray, V. Boffa, M.K. Jørgensen, G. Magnacca, V.M. Candelario, Enhanced fabrication of silicon carbide membranes for wastewater treatment: from laboratory to industrial scale, J. Membr. Sci. 606 (2020) 118080, https://doi.org/10.1016/j.memsci.2020.118080.

[24] Q. Gu, T.C.A. Ng, Y. Bao, H.Y. Ng, S.C. Tan, J. Wang, Developing better ceramic membranes for water and wastewater treatment: where microstructure integrates with chemistry and functionalities, Chem. Eng. J. 428 (2022) 130456, https://doi.org/10.1016/j.cej.2021.130456.

[25] G. Qin, Y. Liu, L.C. Rietveld, S.G.J. Heijman, Oilfield-produced water treatment with SiC-coated alumina membranes, Sep. Purif. Technol. 362 (2025) 131841, https://doi.org/10.1016/j.seppur.2025.131841.

[26] L.T. Le, K.N. Nguyen, P.T. Nguyen, H.C. Duong, X.T. Bui, N.B. Hoang, L.D. Nghiem, Microfibers in laundry wastewater: problem and solution, Sci. Total Environ. 852 (2022) 158412, https://doi.org/10.1016/j.scitotenv.2022.158412.

[27] J. Talvitie, A. Mikola, O. Setala, M. Heinonen, A. Koistinen, How well is microlitter purified from wastewater? - a detailed study on the stepwise removal of microlitter in a tertiary level wastewater treatment plant, Water Res. 109 (2017) 164–172, https://doi.org/10.1016/j.watres.2016.11.046.

[28] G. Qin, A. Jan, Q. An, H. Zhou, L.C. Rietveld, S.G.J. Heijman, Chemical vapor deposition of silicon carbide on alumina ultrafiltration membranes for filtration of microemulsions, Desalination 582 (2024) 117655, https://doi.org/10.1016/j.desal.2024.117655.

[29] M. Bradai, J. Han, A.E. Omri, N. Funamizu, S. Sayadi, H. Isoda, Effect of linear alkylbenzene sulfonate (LAS) on human intestinal Caco-2 cells at non cytotoxic concentrations, Cytotechnology 68 (4) (2016) 1267–1275, https://doi.org/10.1007/s10616-015-9887-4.

[30] E. Hernandez, B. Nowack, D.M. Mitrano, Polyester textiles as a source of microplastics from households: a mechanistic study to understand microfiber release during washing, Environ. Sci. Technol. 51 (12) (2017) 7036–7046, https://doi.org/10.1021/acs.est.7b01750.

[31] P. Le Clech, B. Jefferson, I.S. Chang, S.J. Judd, Critical flux determination by the flux-step method in a submerged membrane bioreactor, J. Membr. Sci. 227 (1–2) (2003) 81–93, https://doi.org/10.1016/j.memsci.2003.07.021.

[32] S.P. Beier, G. Jonsson, Critical flux determination by flux-stepping, AICHE J. 56 (7) (2009) 1739–1747, https://doi.org/10.1002/aic.12099.

[33] X. Tian, F. Been, P.S. Bauerlein, Quantum cascade laser imaging (LDIR) and machine learning for the identification of environmentally exposed microplastics and polymers, Environ. Res. 212 (Pt D) (2022) 113569, https://doi.org/10.1016/j.envres.2022.113569.

[34] B. Pagliaccia, M. Ascolese, E. Vannini, E. Carretti, C. Lubello, R. Gori, Methodologic insights aimed to set-up an innovative laser direct InfraRed (LDIR)-based method for the detection and characterization of microplastics in wastewaters, Sci. Total Environ. 967 (2025) 178817, https://doi.org/10.1016/j.scitotenv.2025.178817.

[35] P. Peets, I. Leito, J. Pelt, S. Vahur, Identification and classification of textile fibres using ATR-FT-IR spectroscopy with chemometric methods, Spectrochim. Acta A Mol. Biomol. Spectrosc. 173 (2017) 175–181, https://doi.org/10.1016/j.saa.2016.09.007.

[36] S. Ghosh, S. Roy, K. Singh, Effect of pH on antibacterial activity of textile fibers, Journal of the Institution of Engineers (India): Series E 102 (1) (2021) 97–104, https://doi.org/10.1007/s40034-020-00202-0.

[37] A. Barrick, A.J. Boardwine, N.H.A. Nguyen, A. Sevcu, J. Novotna, T.C. Hoang, Acute toxicity of natural and synthetic clothing fibers towards Daphnia magna: influence of fiber type and morphology, Sci. Total Environ. 967 (2025) 178751, https://doi.org/10.1016/j.scitotenv.2025.178751.

[38] T. Grethe, T. Kick, B. Mahltig, Sustainable controlling of hydrophilic properties of cotton and linen by application of amino acids, The Journal of The Textile Institute 108 (3) (2016) 436–439, https://doi.org/10.1080/00405000.2016.1169664.

[39] B.D. Lazic, S.D. Janjic, M. Korica, B.M. Pejic, V.R. Djokic, M.M. Kostic, Electrokinetic and sorption properties of hydrogen peroxide treated flax fibers (Linum usitatissimum L.), Cellulose 28 (5) (2021) 2889–2903, https://doi.org/10.1007/s10570-021-03686-0.

[40] S.M. Ladewig, S. Bao, A.T. Chow, Natural fibers: a missing link to chemical pollution dispersion in aquatic environments, Environ. Sci. Technol. 49 (21) (2015) 12609–12610, https://doi.org/10.1021/acs.est.5b04754.

[41] P. Čapková, A. Čajka, Z. Kolská, M. Kormunda, J. Pavlík, M. Munzarová, M. Dopita, D. Rafaja, Phase composition and surface properties of nylon-6 nanofibers prepared by nanospider technology at various electrode distances, J. Polym. Res. 22 (6) (2015), https://doi.org/10.1007/s10965-015-0741-3.

[42] L.L. Schramm, L.L. Schramm, Surfactants: Fundamentals and Applications in the Petroleum Industry, Cambridge university press, 2000.
[43] L. Ripoll, C. Bordes, P. Marote, S. Etheve, A. Elaissari, H. Fessi, Electrokinetic properties of bare or nanoparticle-functionalized textile fabrics, Colloids Surf. A Physicochem. Eng. Asp. 397 (2012) 24–32, https://doi.org/10.1016/j.colsurfa.2012.01.022.
[44] M. Wang, J. Yang, S. Zheng, L. Jia, Z.Y. Yong, E.L. Yong, H.H. See, J. Li, Y. Lv, X. Fei, M. Fang, Unveiling the microfiber release footprint: guiding control strategies in the textile production industry, Environ. Sci. Technol. 57 (50) (2023) 21038–21049, https://doi.org/10.1021/acs.est.3c06210.
[45] D.G. Bowers, K.M. Braithwaite, W.A.M. Nimmo-Smith, G.W. Graham, Light scattering by particles suspended in the sea: the role of particle size and density, Cont. Shelf Res. 29 (14) (2009) 1748–1755, https://doi.org/10.1016/j.csr.2009.06.004.
[46] K.C. Ho, Y.H. Teow, J.Y. Sum, Z.J. Ng, A.W. Mohammad, Water pathways through the ages: integrated laundry wastewater treatment for pollution prevention, Sci. Total Environ. 760 (2021) 143966, https://doi.org/10.1016/j.scitotenv.2020.143966.
[47] T. Schiller, T. Scheibel, Bioinspired and biomimetic protein-based fibers and their applications, Communications Materials 5 (1) (2024) 56, https://doi.org/10.1038/s43246-024-00488-2.
[48] M.C. Zambrano, J.J. Pawlak, J. Daystar, M. Ankeny, J.J. Cheng, R.A. Venditti, Microfibers generated from the laundering of cotton, rayon and polyester based fabrics and their aquatic biodegradation, Mar. Pollut. Bull. 142 (2019) 394–407, https://doi.org/10.1016/j.marpolbul.2019.02.062.
[49] M. Duan, Z. Ding, H. Wang, Y. Xiong, S. Fang, P. Shi, S. Liu, Evolution of oil/water interface in the presence of SDBS detected by dual polarization interferometry, Appl. Surf. Sci. 427 (2018) 917–926, https://doi.org/10.1016/j.apsusc.2017.09.054.
[50] T. Stanton, A. James, M.T. Prendergast-Miller, A. Peirson-Smith, C. KeChi-Okafor, M.D. Gallidabino, A. Namdeo, K.J. Sheridan, Natural fibers: why are they still the missing thread in the textile Fiber pollution story? Environ. Sci. Technol. 58 (29) (2024) 12763–12766, https://doi.org/10.1021/acs.est.4c05126.
[51] I.H. Ozofor, V.V. Tarabara, A.R. Da Costa, A.N. Morse, Analysis of microstructural properties of ultrafiltration cake layer during its early stage formation and growth, J. Membr. Sci. 620 (2021), https://doi.org/10.1016/j.memsci.2020.118903.
[52] M. Enfrin, C. Hachemi, D.L. Callahan, J. Lee, L.F. Dumée, Membrane fouling by nanofibres and organic contaminants – mechanisms and mitigation via periodic cleaning strategies, Sep. Purif. Technol. 278 (2021) 119592, https://doi.org/10.1016/j.seppur.2021.119592.
[53] M. Dilaver, S.M. Hocaoğlu, G. Soydemir, M. Dursun, B. Keskinler, İ. Koyuncu, M. Ağtaş, Hot wastewater recovery by using ceramic membrane ultrafiltration and its reusability in textile industry, J. Clean. Prod. 171 (2018) 220–233, https://doi.org/10.1016/j.jclepro.2017.10.015.
[54] P. van den Brink, O.A. Satpradit, A. van Bentem, A. Zwijnenburg, H. Temmink, M. van Loosdrecht, Effect of temperature shocks on membrane fouling in membrane bioreactors, Water Res. 45 (15) (2011) 4491–4500, https://doi.org/10.1016/j.watres.2011.05.046.
[55] M. Chen, S.G.J. Heijman, L.C. Rietveld, Ceramic membrane filtration for oily wastewater treatment: basics, membrane fouling and fouling control, Desalination 583 (2024) 117727, https://doi.org/10.1016/j.desal.2024.117727.
[56] B.D.P. Luogo, T. Salim, W. Zhang, N.B. Hartmann, F. Malpei, V.M. Candelario, Reuse of water in laundry applications with Micro- and ultrafiltration ceramic membrane, Membranes (Basel) 12 (2) (2022), https://doi.org/10.3390/membranes12020223.