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Evaluation of wastewater reuse in commercial laundries: a pilot field study

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ABSTRACT

The commercial laundry industry is a vastly important yet gravely underestimated business area. In the last decades, the evolving chemical restrictions, sustainability-based regulations, and safety standards have strongly affected the commercial laundry sector, especially with environmental consideration rising in demand, that is, wastewater treatment and recycling. This paper addresses a growing need in cost-effective engineering, as well as the application, of wastewater recycling technologies for commercial laundries. This study started from the manufacturing of polypropylene capillary membranes using a combination of polyetherpolyamide (PEBAX®) and titanium dioxide nano-sized particles (nano-TiO_2) for subsequent "flow coating" modification of membrane surfaces. In the next step, the material characteristics of the polymeric membranes were investigated at lab and pre-industrial scales using scanning electron microscopy/energy-dispersive X-ray spectroscopy, contact angle measurements, and defined filtration experiments. The examination of the wastewater reuse potential of novel membranes on a pre-industrial scale was carried out in a field study in a commercial laundry. The treated water has been monitored, for example, by conductometry and surface tension measurements. This study defines the reuse potential of laundry wastewater by using modified polymeric membranes, while at the same time evaluating the critical parameters of this wastewater recycling process in commercial laundries.

Keywords: Wastewater recycling; Polymeric membrane; Commercial laundries; Reuse potential

1. Introduction

The revenues of textile services in Europe grew from 2016 to 2017 by 0.8% [1]. With the steady increase of this industrial branch, its negative environmental impact became critical. Industrial laundries consume a lot of resources (i.e., water, energy, and washing chemicals). Additionally, they produce a significant amount of wastewater, which consists of toxicologically problematic substances (i.e., surfactants, optical brighteners, microplastics, or bleaching agents like chlorine compounds) [2]. The question of whether all alarming substances should be discharged into the drain, removed from wastewater, or kept in closing-loop recycling process, is still strongly driven by economic aspects due to missed regulations and a high degree of the structural heterogeneity of this industrial branch. In keeping with this negative trend, little to no progress was made regarding the adoption of membrane filtration technologies in laundries (i.e., a promising process water reuse strategy). This encompasses both aspects (i) removing of undesired substances from the wastewater via ultra- or nano-filtration processes and via utilization of membrane bioreactors

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and (ii) recycling/reusing of the wastewater by applying micro- and ultra filtration membrane plants.

Several authors describe the toxic potential of laundry wastewater. Sumisha et al. [2] describe the toxicity of different laundry ingredients. Especially anionic surfactants, like linear alkylbenzenesulfonate (LAS), exhibit moderate and high toxicity, and their mean contribution to the overall toxic potential of laundry detergents is estimated to be 40.7%. However, the role of surfactants is critically evaluated embracing both the negative impact on living organisms and their ambiguous role in decomposing and/or removing environmental pollutants [3]. The composition of laundry wastewater varies strongly due to different factors that are applied during the laundering process, that is, structure of textile materials, washing formulations, and process water quality. To embrace the complexity of the laundry wastewater analysis, sum parameters, for example, chemical oxygen demand (COD), is used. As a result, often information is still missing which adverse effects may occur due to the transmission of certain laundry detergent ingredients (e.g., surfactants, optical brightener, etc.) into the environment. Additionally, analytical methods are still under development to precisely quantify the fraction of environmental pollutants. For example, Haap et al. [4] recently developed a real-time monitoring method for the detection of microplastics in effluents of commercial laundries.

Two main strategies exist on how the laundry wastewater can be treated. The first strategy – suitable for laundry companies that drain the laundry effluents directly into the environment – is the wastewater treatment in order to remove any toxic contaminants, for example, toxic heavy metals. Often, reverse osmosis or nanofiltration treatment technologies are used to ensure the complete removal of undesired contaminants. Novel approaches were investigated covering a broad range of methods like precise dosing of coagulants to the effluent fraction, as well as selecting optimal coagulation process [5,6], applying biological treatment, electrocoagulation, flocculation, and sedimentation [7], using up-flow anaerobic sludge blanket (UASB) or expanded granular sludge bed (EGSB) reactors for cost-effective removing of surfactants [8,9], involving intensified Fenton oxidation process in the wastewater treatment cascade [10], different membrane filtration methods [6,11,12], and a combination thereof [13–17]. The second strategy takes into account not only the treatment efficiency to meet the requiring law limits of discharging the laundry effluents, but also the potential of reusing the treated wastewater for some laundry processes [18–21]. Only few studies are focusing on the analytical investigation of such closed-loop processes, where wastewater is frequently treated and reused for washing purposes, as well as an overall analytical monitoring of laundry effluents [21–23]. Ciabatti et al. [11] pointed out the role of a membrane filtration process to achieve process water with appropriate properties for reuse in the washing process. Membrane filtration methods are based on versatile approaches including chemically modified flat-sheet and capillary membranes [24]. Especially for polymeric membranes, different modification strategies have been proposed and are still under investigation. Increasing the efficiency of polymeric membranes by preventing the fouling on the membrane surface is one of the most striving recent goals in this research field. Different modification strategies have been proposed based on physico-chemical treatment methods, that is, plasma deposition, chemical vapor deposition, or wet-chemical functionalization [25–30].

For both strategies presented, it is important to include a tailor-made analytical measurement concept of wastewater treatment and reuse process under defined conditions and at the same time extend its use for field applications. Most obstacles that occur during such field studies in commercial laundries are related to dynamical effects (e.g., agglomeration/sedimentation of laundry ingredients in wastewater) of determined process parameters, making the interpretation of the results difficult.

In this study, sophisticated concepts in modification of polymeric capillary membranes were applied and these membranes were investigated in a crossflow filtration pilot plant under practical conditions in an industrial laundry.

Therefore, the main goal of this study was to develop a cost-competitive recycling process for laundry wastewater. For this purpose, commercial microfiltration polypropylene capillary membranes (3M™ capillary membrane MF-PP series, type S6/20) were coated with polyetherpolyamide (PEBAX®) and titanium dioxide nano-sized particles (nano-TiO_2) and utilized in pre-industrial scale experiments in a commercial laundry. The effectiveness of such membrane structures to retain the contaminants and to let through valuable substances (i.e., which can be reused in washing processes) like surfactants was already shown by Polak et al. [31] in a preliminary study that was carried out at laboratory scale. However, here the application of the novel polymer membranes in a field study in a commercial laundry is demonstrated, and the filtration process of laundry wastewater is characterized, in detail. The comparison of filtration performance between lab and pre-industrial scales is important for defining the reuse potential of laundry wastewater by means of different cost-competitive membrane filtration methods.

2. Experimental section

2.1. Manufacturing and characterization of the polymer membranes

The commercial polypropylene (PP) microfiltration capillaries (3M™ capillary membrane MF-PP series, type S6/20) were used in the studies. These membranes have hydrophobic properties, but also good chemical and mechanical strength. Additionally, PP membranes allow us to recover surfactants from laundry wastewater [32]. The internal diameter of the capillary is 1.8 mm, the outer diameter is 2.7 mm and the porosity is 55%. The average pore diameter is 0.2 μm. The PEBAX 2533 (Arkema Inc., Paris, France) was used as a continuous phase for nonorganic particles. The contact angle of PEBAX is about 83°, so it has hydrophilic properties and could improve the wettability of the membranes.

Membranes were modified by the flow coating method. In this method, the modification solution flows along the membrane and is deposited on the membrane surface. After the evaporation of the solvent, a new layer is created on the membrane surface. The modification solution contained 2 wt.% mass of PEBAX and 15 wt.% mass of nano-TiO_2 in relation to the mass of PEBAX. 2-butanol was used as the solvent. The process of modification was conducted with the recirculation of the modification solution for 10 min. The linear velocity of the solution along the capillary was 0.89 m/min.

2.2. Goniometric measurements

The contact angle measurements were performed on membrane surfaces according to the sessile drop technique by using a goniometer device (OCA 25 dataphysics). Water drops (purified by reverse osmosis) were placed on the bulk and modified surfaces via an automated syringe unit. The volume of a water drop was 0.5 µL. This volume provides the setting of drop on the inside membrane surface and prevents a too intensive drop spreading on the surface. The change of wettability properties after the modification was determined by contact angle measurement.

2.3. Filtration coefficient measurement

The filtration coefficient was determined by a typical microfiltration plant. The feed pressure was 2.5 bar and the linear cross-flow was 4 m/s. Reverse osmosis water was used as the feed stream.

The filtration coefficient has been determined using the following equation:

$$\text{FC} = \frac{Q}{S \cdot p_{\text{TM}}} \quad \left[\frac{\text{m}^3}{\text{s} \cdot \text{m}^2 \cdot \text{Pa}}\right] \tag{1}$$

where Q is permeate flow (m^3/s), S is membrane area (m^2) and p_{TM} is transmembrane pressure (Pa).

2.4. Scanning electron microscopy and energy-dispersive X-ray spectroscopy

Scanning electron microscopy and energy-dispersive X-ray spectroscopy (SEM-EDX) investigations were carried out with JSM-IT500LA system (JEOL, Freising, Germany) operating in back-scattering detection mode. The samples were analyzed under low vacuum conditions without applying any conductive coating (which may falsify the interpretation of images). For energy-dispersive X-ray spectroscopy (EDX) measurements, the dry SD30 EDX detector (JEOL, Freising, Germany) was used. All measurements were carried out at an acceleration voltage of 10.0 kV.

2.5. Experimental set-up and experimental conditions in the commercial laundry

The commercial laundry (located in Sierpc, Poland), where all experiments were carried out, operates on an industrial scale; about 25 tons of laundry needs to be cleaned daily. The washed laundry can be divided into two main fractions: from health care and hotel sectors with a ratio of 70%–30%, respectively. For commercial washing processes, an estimated value of 200 m^3 process water is needed per day. The well water utilized for professional laundering operations is softened to 0–4°dH (i.e., 0–0.712 mmol/L) and exhibits a minimum of the microbial load as well as traces of heavy metals. The main amount of laundry in the investigated commercial laundry facility is processed in tunnel washer systems of company Herbert Kannegiesser GmbH (Vlotho, Germany). The systems are well known for high water recovery rates of the utilized process water. For example, nearly the whole fraction of the water used for rinsing processes is collected in so-called water recovery tanks and is used in most cases for prewash (i.e., emulsifying/suspending soil at moderate temperature by addition of detergents) and main wash (i.e., bleaching, disinfection and cleaning processes in a broad temperature range up to 90°C) laundering processes. However, after the prewash and main wash processes, wastewater is generated and drained away. In our study, a mixed fraction of wastewater was used. This wastewater was collected from drainpipes into an intermediate bulk container (IBC) tank. In order to avoid time-dependent changes of the wastewater, the filtration experiments were carried out on-site in the laundry facility, immediately after collecting the necessary amount of the wastewater.

In Fig. 1a, a simplified flow diagram of the used experimental set-up is shown. The IBC container that was used as a feed tank could be easily dewatered and cleaned with pure water using a pump. During the filtration experiment, the wastewater fraction was pre-filtered by filter cartridge with integrated nonwoven with a pore size of about 60 µm. This step was important for removing the fibers from the wastewater and thus maintaining the flux through the membrane. In the next step, the wastewater is entering the membrane filtration module (i.e., PP hollow fiber membranes that were modified by PEBAX/TiO_2). This process is forced by a diaphragm pump. The filtration area of PP hollow fibers was 2 m^2. The filtration process was carried out at a temperature of 30°C–32°C and a transmembrane pressure of 1.5 bar. Sensors were used for measuring volumetric flow, pressure, and temperature during the filtration process. The filtrated process water was collected in the permeate tank (i.e., IBC container). The retentate was also collected in a special vessel. During the filtration experiments, samples were taken out at defined sampling points: (1) upper fraction of the feed tank, (2) bottom fraction of the feed tank, (3) after filtration of approximately 10 L of wastewater, (4) after filtration of 100 L of wastewater, (5) after filtration of 200 L of wastewater, (6) after filtration of 300 L of wastewater, and (7) the retentate tank.

A sequential cleaning procedure was applied to maintain the filtration performance of the pilot plant. At first, the filtration pilot plant was cleaned with pure water, afterwards commercially available alkaline membrane cleaning agents were used to remove hydrophobic pollutants from membrane surface, and in the last step a mechanical removal of fiber contaminations from the filtration system (e.g., prefiltering system) was carried out.

2.6. Analytical methods for characterization of process water compositions

The measurements of COD and surfactant concentration values were performed in laboratory conditions to avoid any cross-contamination. For this purpose, samples were

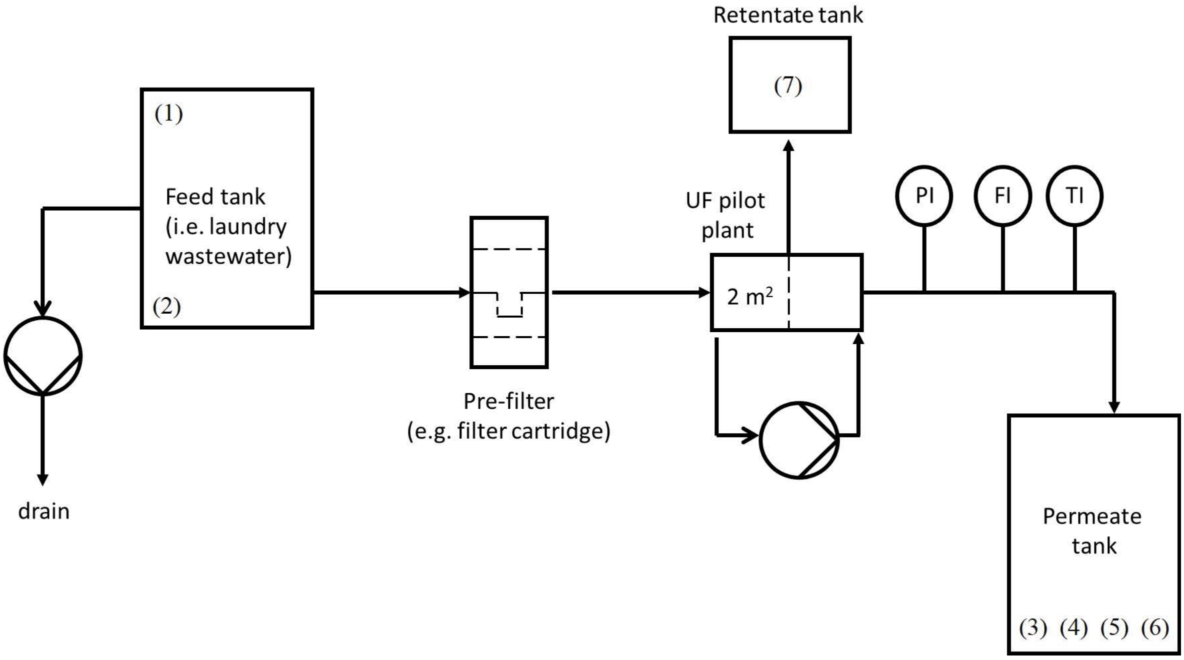

Fig. 1. Schematic flow diagram of MF pilot plant based on ISO 10628-2:2012 nomenclature. The monitoring of the process parameters was evaluated by pressure indicator (PI), flow indicator (FI), and temperature indicator (TI). Numbers in brackets indicate sampling locations.

preserved and handled according to the ISO 5667-3:2012. All other measurements were carried out on-site in the laundry facility. In this study, the following parameters of interest were determined: the values of pH and conductivity were evaluated by "HI2002 edge" pH measurement device and "HI99300" conductivity measurement system (both provided by co. Hanna Instruments, Vöhringen, Germany), respectively. The COD values were measured via AL200 COD Vario system (co. AQUALYTIC, Dortmund, Germany) according to the standard method ISO 15705:2002. For the determination of the dynamic surface tension, SITA pro line f10 bubble pressure tensiometer was utilized. All measurements were carried out at a surface age of 1 Hz (i.e., 1,000 ms). All samples were measured at nearly the same temperature to avoid the fluctuation of the surface tension values. The contents of alkaline and bleaching (i.e., active oxygen compounds) agents were evaluated via simplified titration methods (co. WATER KITS SUPPLY sarl, Juillan, France). The simplified titration for alkalinity determination is based on ISO 9963-1:1994. For evaluation of iron content a colorimetric test was used (VISCOCOLOR Eco, co. Macherey-Nagel GmbH & Co., KG Düren, Germany). The turbidity value was measured with AL250T-IR device (co. AQUALYTIC, Dortmund, Germany) according to the standard method EN ISO 7027. The spectrophotometer NANOCOLOR® VIS II (co. Macherey-Nagel GmbH & Co., KG Düren, Germany) was used to elucidate the surfactant concentration in laundry process water. For the analysis of anionic and nonionic surfactants, NANOCOLOR test 0–47 (co. Macherey-Nagel GmbH & Co., KG Düren, Germany) and NANOCOLOR test 0–32 (co. Macherey-Nagel GmbH & Co., KG Düren, Germany) were applied, respectively.

3. Results and discussion

3.1. Modification of polypropylene capillary membranes by PEBAX/nano-TiO$_2$

The membrane surfaces in the original state, after the modification with PEBAX and nano-TiO$_2$ and after the exploitation in a field study were investigated by SEM-EDX. Fig. 2 shows the SEM images of the membrane surfaces at different magnifications. After the modification of PP hollow fiber membrane, agglomerates of nano-TiO$_2$ cover the inner membrane surface. The EDX analysis (Fig. 2) supports this conclusion by showing that the agglomerates mainly consist of titanium. Further evidence of successful modification of membrane surface by PEBAX/TIO$_2$ coating can be derived from the EDX spectra (Fig. 3). In contrast to the PP hollow fiber membrane in the original state, a peak at 4.53 keV could be detected, which can be clearly correlated with the presence of titanium on the membrane surface. The agglomeration behavior of nano-TiO$_2$ applied to polyethersulfone hollow fiber membranes was studied by Ramzjou et al. [33]. It was found that sophisticated methods like sonication in ethanol or chemical modification of TiO$_2$ particles with silane coupling agents are necessary to inhibit the agglomeration. Even by applying such methods, agglomeration of nano-TiO$_2$ takes place. If the particles are not well dispersed/distributed in the surrounded polymer matrix, it can negatively influence the hydrophilicity and roughness of the surface and therefore reduce the antifouling ability of the membrane. However, in contrast to the results of Razmjou et al. [33], several publications report a more complex correlation between the manufacturing process, that is, load of TiO$_2$, and the resulted morphology of

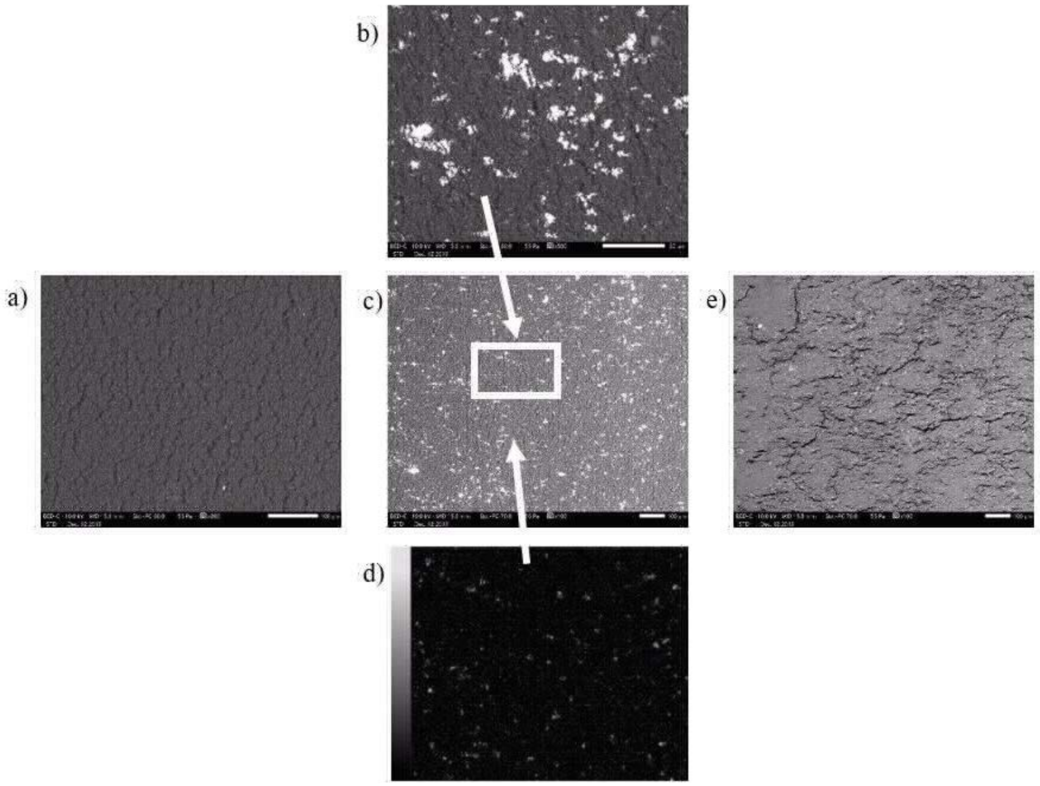

Fig. 2. SEM images of (a) PP membrane surface, (b) membrane surface with PEBAX/nano-TiO_2 modification at a magnification of ×500, (c) the same image at a magnification of ×200, (d) the same image during mapping of titanium via EDX detector, and (e) modified membrane surface with a layer of fouling.

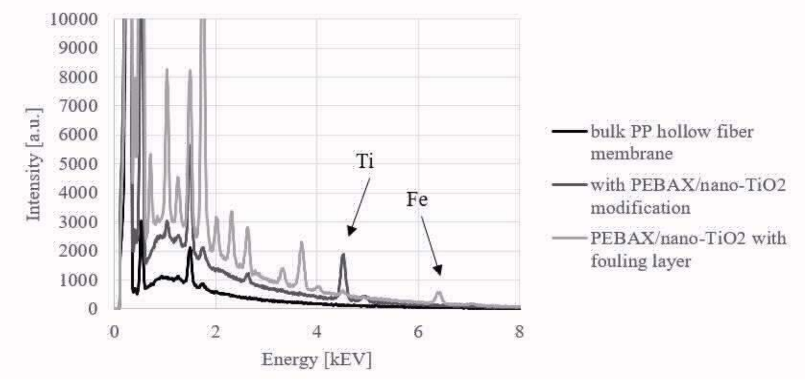

Fig. 3. EDX analysis of the bulk PP membrane surface, membrane surface with PEBAX/nano-TiO_2 modification, and modified membrane after field study (a.u.: arbitrary units).

the membrane surfaces [34]. For example, Rahimpour et al. [34] reported that a strong agglomeration of TiO_2 particles rapidly occurs after reaching a certain loading of coating solution with nano-TiO_2 during the manufacturing process.

On the other hand, our results show that the hydrophobicity (i.e., as evaluated via contact angle measurements) of the PP hollow fiber surfaces was significantly reduced by using the PEBAX/nano-TiO_2 coating (Fig. 4) without applying a complex and cost-intensive mechanical and chemical modification of the coating formulation.

Furthermore, filtration coefficient measurements were carried out under defined process conditions (Fig. 4). The increase in the filtration coefficient indicates that the pollutants adhere less readily to the modified PP surface and thus negatively influence the filtration performance. These results are in good agreement with the contact angle measurements, highlighting the role of surface energy (i.e., hydrophobic and hydrophilic properties) in the filtration process.

However, it should be considered that further mechanical and chemical modification of the dispersibility of nano-TiO_2 and its subsequent application on membrane surfaces are still not well understood and are related to increased effort in terms of costs and time, especially

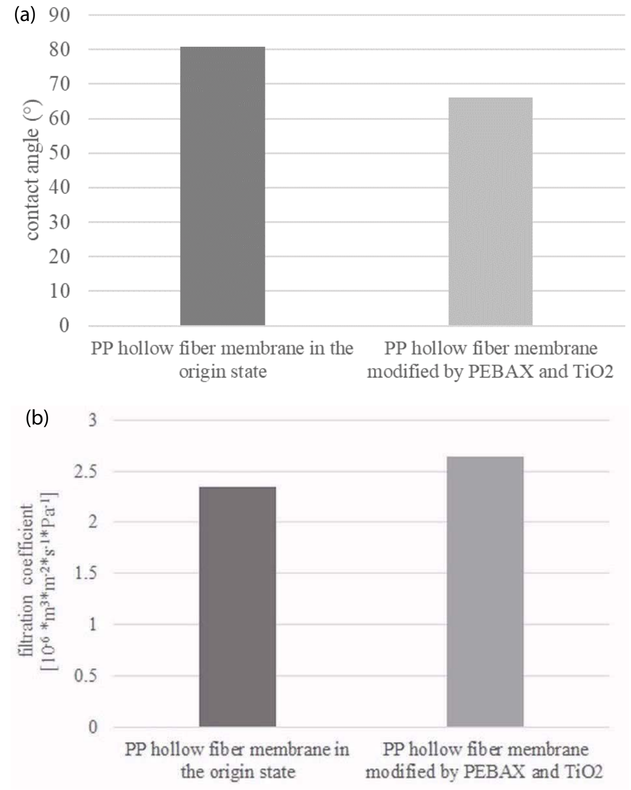

Fig. 4. Changes in wettability behavior with water (expressed as contact angle) and changes of filtration performance (expressed as filtration coefficient) of membrane surfaces after the "flow coating" modification process.

by scaling up the membrane manufacturing process for industrial applications.

The morphology of the PP hollow fibers was investigated after the exploitation in a field experiment (Fig. 3). A thin layer of pollutants is remaining on the membrane surface, even after a cleaning with water and membrane cleaning agents was applied. Furthermore, no significant amount of metals, such as titanium, could be detected by EDX analysis, which is caused by interference of EDX signal with an organic dirt layer. Additionally, partial removal of the coating could take place, which weakens the EDX signal of titanium traces. These questions could not be answered yet and should be investigated in future field experiments in industrial laundries.

3.2. Filtration experiments in a commercial laundry

3.2.1. Evaluation of flux during the filtration process

In the field study in the commercial laundry, the filtration experiments were carried out at nearly constant temperature (i.e., 30°C–32°C) and transmembrane pressure of 1.5 bar. The filtration performance decreases with time due to the adherence of substances contained in the laundry wastewater to the membrane surface (Fig. 5). Furthermore, besides the pre-filtering with 60 μm nonwoven material, agglomerated fiber could be found at the inlet of the membrane. The transmission of fibers could not be avoided by using common pre-filtering methods and especially for treatment of laundry wastewater the prefiltration step should be object of optimization to ensure high flux and minimal maintenance. In the given experiments, a three-stage cleaning protocol was applied to restore the flux to the initial value (Experimental section). However, to the best of our knowledge, the effective removal of fiber content from μm to nm scales is still an object of research. Novel methods were recently published for quantification of fiber release and removal by dynamic image analysis and more cost-effective prefiltration technology were proposed in the scientific literature [5,12]. For example, Ashfaq and Qiblawey [12] compare different pretreatment methods, like sand filtration and/or granular activated carbon filtration, with each other and demonstrate that the combination of those methods may be a reliable strategy for drastically reducing the pollutants load in laundry wastewater.

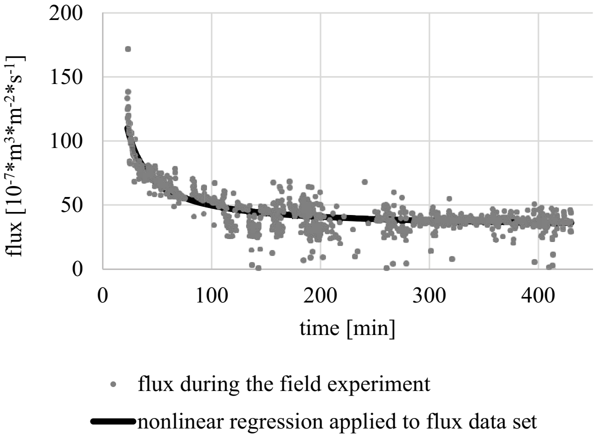

Fig. 5. Decrease of flux with passing in time during the field study experiment.

3.2.2. Investigation of the laundry wastewater recycling process

During the filtration experiments in the laundry, samples were taken at different sampling points and at different stages of the process. Table 1 summarizes the results of the process analytical monitoring done during the field experiment.

In this study, the reuse potential of laundry wastewater was examined and a specific attention was directed to the changes in detergent composition during the filtration experiments. In addition, as part of analytical monitoring the concentration of bleaching agents and iron was evaluated. Table 2 contains the description of typical ingredients of the laundry formulation (i.e., based on ISO 15797) [35]. Their molecular size and physico-chemical abilities (i.e., critical micelle concentration, surface adsorption abilities) vary strongly in dependence on their chemical structure (i.e., polarity, molecular weight, number, and length of branches, etc.). The analytical methods were chosen with respect to the data compiled in Table 2. Only the anionic and nonionic surfactant tend to form at a certain concentration and temperature larger structures, that is, micelles,

Table 1
Monitoring of process parameters at the following sampling points: (1) upper fraction of the feed tank, (2) bottom fraction of the feed tank, (3) permeate after filtration of 10 L of wastewater, (4) permeate after filtration of 100 L of wastewater, (5) permeate after filtration of 200 L of wastewater, (6) permeate after filtration of 300 L of wastewater, and (7) the retentate tank

No. of sampling location	pH	Conductivity (µS/cm)	Turbidity (NTU)	Surface tension (mN/m)	Alkalinity (mg/L)	Active oxygen compounds (mg/L)	Iron compounds (mg/L)
1	8.97	507	86.5	59.8	500	10	0
2	9.08	535	96.1	62.3	400	10	1–3
3	9.07	490	0.99	70.3	400	10	0.15
4	8.99	526	1.14	66.8	500	10	0.20
5	8.94	514	7.06	66.2	500	10	0.30
6	8.70	548	9.59	67.3	400	20	0.20
7	8.92	523	1,020	63	500	20	1–3

Table 2
Composition of laundry formulation in accordance with ISO 15797

Ingredients in laundry formulation	Percentual amount in the composition (wt.%)
Linear alkyl benzene sulfonate (average length of the carbon backbone is 12 atoms)	0.425
Nonionic surfactant (average length of the carbon backbone is 13–15 atoms and it consists of seven ethylene oxide units)	6.0
Sodium citrate dihydrate	5.0
Hydroxyethanediphosphonic acid salt (HEDP)	1.0
Metasilicate anhydrous	42.3
Polymer (polymaleic acid)	2.0
Foam inhibitor (phosphoric acid ester)	3.0
Sodium carbonate	39.5
Optical brightener	0.3
Remaining water from raw material	0.475

and to be adsorbed/filtered out, in significant amounts, at the membrane surface; obviously, these phenomena promote their retention during the filtration process.

Only relatively small changes of salt concentration, expressed by the parameters such as conductivity, pH, and alkalinity, were maintained during the filtration process. As anticipated, this indicates that the main fraction of alkaline salts passes through the PP hollow fiber capillaries without adhering to the membrane surface. The monitoring of the concentration of surfactants was performed by bubble pressure tensiometry and photometric determination of surfactant compounds (Table 1 and Fig. 6). The tensiometric measurements clearly demonstrate that the concentration of surfactant compounds in the permeate strongly decreases due to, among others, adsorption phenomena. However, the concentration of both anionic and nonionic surfactants changes abruptly after the filtering of the first 10 L of laundry wastewater, as indicated by photometric measurements (Figs. 6a–c) as well as bubble pressure tensiometry (Table 1). Interestingly, a clearly higher content of surfactants was detected in the retentate, which supports the hypothesis that large surfactant aggregates were held back by the membrane. Similarly behaves the COD value, it drops after filtrating the first fractions of wastewater. Although it is evident – these findings indicate a fouling process on the membrane surface. After the formation of a fouling layer the rejection of surfactants and organic matter became more efficient through the alteration of the surface energetic profile, that is, became more hydrophobic, and the decrease in an inner diameter of the PP pores. On the other hand, the flux drops significantly as well, which negatively influences the filtration performance itself.

However, the fouling phenomenon cannot be avoided by the PEBAX/nano-TiO_2 and more efficient strategies of surface modification need to be found. Interestingly, the deposition of pollutants was clearly stronger in a field experiment in the laundry facility, and the importance of such investigation for deriving the reuse potential of wastewater in industrial laundries was demonstrated. To the best of our knowledge, only few studies in the scientific literature embrace different scales of investigation, that is, from lab scale to experiments in industrial laundries and investigating novel cost-competitive wastewater treatment technologies under practical conditions. Sumisha et al. [2] report a dramatic decrease in flux during experiments due to deposition of the fouling cake on the membrane surface. In our opinion, the complex composition of the wastewater under practical conditions in laundries promotes the fouling behavior and that process water composition needs to

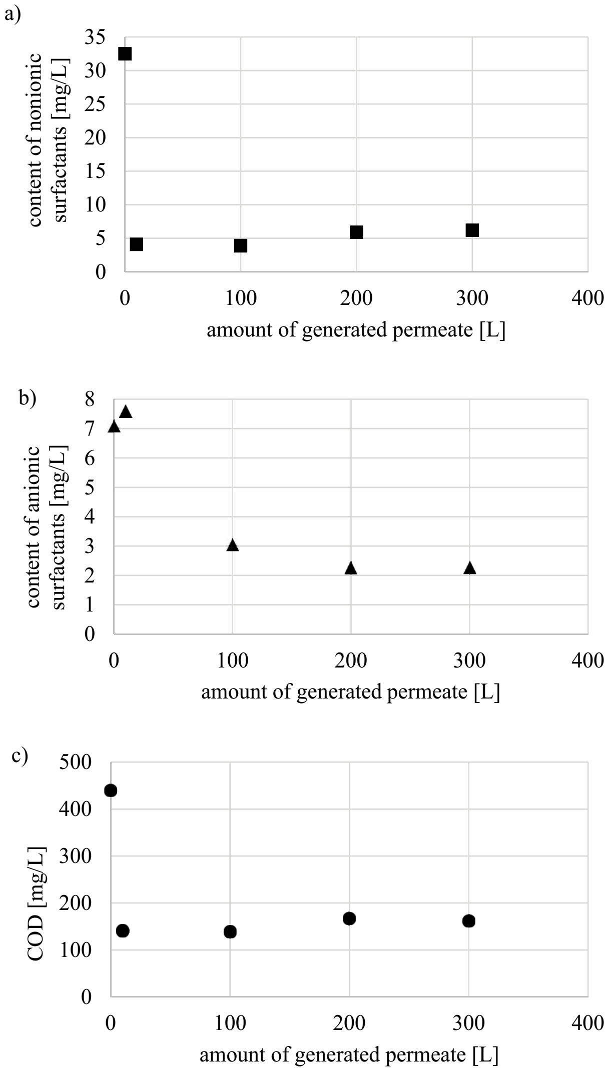

Fig. 6. Concentration of (a) nonionic surfactant in the permeate, (b) anionic surfactant in the permeate, and (c) chemical oxygen demand (COD) as function of generated permeate.

be captured to ensure the long-term utilization of filtration plants based on novel technological approaches. In addition, the enrichment of bleaching/disinfection agents and iron during the filtration process were studied. On the one hand, the presence of traces of peracetic acid (expressed in terms of active oxygen compounds) could have a positive effect by inhibiting the microbial growth in the filtration system. On the other hand, the enrichment of such substances as iron could have a negative influence on the washing performance, because in the presence of iron traces the bleaching agents tend to decompose rapidly, which causes so-called catalytic damages on the textile materials and reduces the cost-efficiency of the wastewater reuse technology. To avoid the latter one, the content of iron should not exceed 0.2 mg/L; this was not the case during the filtration experiments especially due to sedimentation and enrichment of the iron compounds in the lower fraction of the wastewater collection tank. The enrichment of iron was also found in the retentate reflecting the effective rejection of unfavorable substances (Table 1).

The aforementioned findings are useful to derive the economic reasoning for the utilization of wastewater recycling technology. For the investigated commercial laundry, the use of well water is accompanied by low costs. In this case, the main costs linked to the use of process water are caused by taxes for disposal of wastewater. The reuse of this wastewater may be economically beneficial by applying a cost-competitive wastewater recycling technology.

However, the results (i.e., decrease in surfactant concentration) show clearly the changes in the process water composition and thus the limitation to reuse it for laundering processes. To be more precise, several quality assurance concepts (e.g., RAL-GZ 992) and recommendations for commercial laundries define certain washing conditions, among others the amount of added laundry detergents. It could be clearly shown in this study that the laundry formulation changes during the filtration process. Especially, both anionic and nonionic surfactants are rejected due to their ability to form micelles and adhere to interfaces. The latter one has an important role as shown by Kaya et al. [36], who investigate the rejection of anionic and nonionic surfactants below their critical micelle concentration. As a result, despite the useful characteristics of the wastewater reuse technology, some physico-chemical properties of the reused process water (i.e., changed composition of laundry formulation), as well as properties of the exploited polymeric membranes (i.e., fouling), limit its applications in industrial laundries. One of the possible options is to add the recycled process water as additional fraction to certain laundering processes (e.g., rewash processes or laundering processes with high soil load). To enhance the quality of the professional laundering processes through an additional amount of process water and detergent ingredients, the recycled water can be added at different stages in the laundering process (i.e., in the water recovery tank, to prewash or main wash processes).

4. Conclusions

In this study, novel polymeric membranes were investigated in a field study in commercial laundry facility (located in Sierpc, Poland) to determine the reuse potential and the obstacles of the implementation of wastewater recycling technologies. The following key information can be concluded from our study:

- A completely homogenous distribution of filler particles, such as nano-TiO_2, is difficult to achieve without using sophisticated dispersing methods. The filler particles exhibit an agglomerated morphology, which may influence their effectiveness and stability. When considering only the data from the filtration experiments under defined laboratory conditions, the antifouling coating shows beneficial effects. However, by extension of the experiments to pre-industrial scale the picture may change.
- Agglomeration of undesired substances, like iron, in the wastewater recycling process may lead to detrimental effects on washing quality, as iron compounds catalyze

the decomposition of bleaching agents, which can cause damage of fiber structure. These results show that the analytical monitoring of closed-loop recycling processes should not only focus on process parameters, but also the washing quality should be included in the evaluation of the reuse potential. However, especially in a field study, it could be a challenging task due to strong fluctuation of process conditions.
- Furthermore, the decrease of nonionic and anionic surfactants in the permeate (i.e., the enrichment of these substances in the concentrate) could be clearly shown during the filtration process, due to specific abilities of surfactants to form micelles. As surfactants are one of the most important substances for ensuring the adequate performance of the washing process, the changes in the composition of washing chemicals may adversely influence or limit the reuse potential of the laundry process water.

It can be assumed that from a technological point of view, due to different obstacles described in this publication, the implementation of closed-loop wastewater reuse plants is low as the unexpected costs for prototyping, exploitation and maintenance may occur, and negatively influence the laundering process. On the other hand, novel technologies as on-line monitoring sensor systems, softsensors based on artificial intelligence, and augmented reality tools for more effective maintenance of complex wastewater treatment plants may alter the situation and the reuse potential become more reliable, from a technological point of view.

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