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Strategy towards the use of ultrafiltration and reverse osmosis for industrial water recovery and reuse as part of the Green Deal Implementation

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ABSTRACT

In line with the European Parliament's Resolution of February 10th, 2021 on the new action plan for a closed economy, most of the activities undertaken in the wastewater treatment process should focus on the search for new technologies that use wastewater as a source of water and nutrients. The paper reviews the concept of water reuse in industrial installations, with special emphasis on the use of membrane technologies for this purpose. The results of authors' own research on effectiveness of using ultrafiltration (UF) and reverse osmosis (RO) processes to recover process water from brewery wastewater, following pretreatment by the BIOPAQ®-IC process, are presented. Raw wastewater, after averaging the parameters, was digested in an anaerobic reactor, followed by deodorization and oxidation of sulfides to sulfate in an oxidation process in a pretreatment tank. The water recovered from pretreated brewery wastewater by UF and RO membrane techniques was found to be suitable for boiler feed, cooling technology and washing process without directly cleaning beer bottles. The study used a ZeeWeed capillary immersion ultrafiltration module operating under vacuum and a module equipped with a Filmtec XLE 2125 reverse osmosis membrane. The technology improved the efficiency of contaminant removal, yielding purified and high-quality water toward the implementation of the assumptions of Circular Economy and Green Deal Implementation.

Keywords: Green Deal Implementations; Industrial wastewater; Brewery wastewater; Ultrafiltration; Reverse osmosis; Reuse of process water; Circular economy

1. Introduction

Water, although a renewable resource, is becoming a factor limiting economic development due to the uneven distribution of its resources, sewage pollution, climate change and insufficient hydrotechnical and water supply and sewage infrastructure, especially in poorer regions. [1] According to the Global Risks Report [2] published in 2019 at the World Economic Forum in Davos, the decline in water resources is one of the world's most serious risks. The UN's 2021 World Water Development Report WWDR [3] indicates that about 80% of all industrial and municipal

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wastewater is released into the environment without prior treatment. The same report states that more than 2 billion people worldwide live in the areas vulnerable to water scarcity, and about 3.4 billion people, or 45% of the world's population, do not have access to safely managed sanitation. The main users of water are industry and agriculture. Agriculture accounts for 70% of all freshwater withdrawals worldwide, most of which are used for irrigation. Demand for food is projected to increase by 60% by 2050, and this growth will require an increase in arable land and intensification of agricultural production [4]. This will translate into increased water consumption [5]. Another major user of water is industry, which accounts for 22% of global water consumption [6]. Global water demand for industrial production is projected to increase by 400% by 2050 [5]. In addition, the industrial sector is a major polluter of water; Eurostat statistic data indicate that only up to 60% of industrial wastewater is treated before being discharged into the environment [7].

In the face of growing challenges, water management must become more sustainable and resource-efficient [8]. In order to prevent a looming global water crisis, it is necessary to take action on a broader scale to find other ways to obtain water and ensure its supply for current and future generations. Considering the sustainable development goals, the appropriate model to implement in terms of water resources management seems to be the closed-loop economy – CLE. In recent years, the recovery and reuse of water has become an important part of water resources management around the world [9–11]. Among the conventional methods of treating reclaimed wastewater are flocculation, coagulation, adsorption and membrane separation [12–15]. Membrane technologies, particularly reverse osmosis (RO), play an important role in producing highly purified recycled water (RO) [16,17].

The use of membranes in industrial wastewater neutralization processes enables to reduce the amount of pollutants entering the environment together with wastewater and to recover valuable substances dissolved in it [18,19]. The effect of using membrane systems for wastewater treatment is also the possibility of closing water circuits within a production plant [12,20,21]. Industrial applications of membrane methods are quite common in the food and dairy sector [22,23], in the paper industry [24] in dye houses [25,26] and for seawater desalination [27].

Recent publications provide positive data on the use of membrane processes for water recovery. Partal et al. [28] developed an integrated membrane process for recovering water and salt from textile wastewater. In their study, they used a pilot brine treatment system including ozone oxidation, nanofiltration (NF), RO and ion exchange (IEX) to recover high-quality process water and salt solution for reuse in dyeing processes. The conducted process recovered 77% of the water and 66% of the salt solution (in terms of NaCl). When operating the system at full scale for 1 y, savings of $176,256 can be achieved with 115,000 m^3 of reused water and $37,000 with 680 tons of recovered NaCl. Brine recovery enables the concept of sustainable production and zero liquid discharges. Bouchareb et al. [26] investigated the performance of electrochemical oxidation (EO), nanofiltration (NF) and reverse osmosis (RO) membrane processes in the treatment of yarn fabric dyeing wastewater (YFDW) in terms of COD removal, color, salinity reduction and conductivity. Experimental results showed that both NF membranes tested were ineffective in removing COD, color and conductivity. In contrast, the EO and RO membranes were effective in reducing COD and color concentrations in the analyzed wastewater. In both processes, there was a complete elimination of color and a COD reduction of 80% and 98% for the EO and RO processes, respectively. However, the conductivity removal efficiency of the EO process was not as significant as that of the RO membrane filtration process (conductivity re-education of 97%). Therefore, the water treated by the RO membrane can be reused in processes such as washing and dyeing, thus offering economic benefits by reducing water consumption and wastewater treatment costs. In their long-term study, Toran et al. [29] compared the effectiveness of two different membrane processes, UF + RO and O_3 + Coagulation + MF + RO, in treating secondary wastewater from the brewing industry. They found that both UF and ceramic MF units produced treated water of a quality that complied with the national regulatory framework for reuse in industrial services. However, while the MF membrane showed higher elimination of suspended solids and organic matter, the UF membrane gave better results in terms of nitrate and dissolved salt removal. The RO membranes, in addition to their ease of use and reliability, showed a very high capacity to treat UF and MF wastewater streams to the water quality standards suitable for potable water reuse. Hernández et al. [30] have produced clean water for reuse as a result of using the UF-RO process to treat food wastewater. Chandrasekhar et al. [31] used an integrated bioreactor membrane system (IMBR)-UF-RO to treat wastewater from coffee production. The water recovered from the process was of high enough quality to be reused again in the process plant. Łaskawiec et al. [32] conducted research using membranes in multi-stage treatment systems for swimming pool rinse. In their study, they used a two-stage ultrafiltration process (UF I – UF II), in which membranes with different mass limits were used, followed by a nanofiltration (NF) process. The UF I process enabled to significantly reduce the parameters tested and reduce the transport of contaminants to the membrane used in UF II. The turbidity of the permeate from UF II did not exceed 0.45 NTU, and the concentration of total organic carbon ranged from 1.64 to 2.69 mg·C/dm^3. In order to prevent elevated concentrations of harmful low-molecular-weight organic compounds in closed water circuits, it made sense to apply a third treatment step in the form of the NF process. The high separation capacity of the tested nanofiltration membranes made it possible to reduce the turbidity of the washings below 0.10 NTU.

The literature data presented here clearly indicate that the use of membrane technology in process plants enable the recovery of difficult-to-treat waters, making them technologies compatible with the idea of a closed-loop economy. The purpose of this article is to evaluate the effectiveness of using ultrafiltration (UF) and reverse osmosis (RO) processes to recover process water from brewery wastewater.

2. Materials and methods

As it results from the review of the literature, membrane processes are characterized by high efficiency in the treatment of various types of wastewaters. However, in order to achieve the goal of water treatment and recovery, it is necessary to design and study the system to select the appropriate operations and process conditions that will provide data to scale the process and improve membrane efficiency. An integrated UF/RO membrane process was designed and evaluated to provide an efficient solution for treating wastewater from the brewing industry for water recovery.

2.1. Characteristics and configuration of the pilot plant: ultrafiltration module UF and reverse osmosis RO

The study was carried out using a ZeeWeed ultrafiltration (UF) and reverse osmosis (RO) pilot plant, which used BIOPAQ®-I fermentation pretreated wastewater from the brewing industry [33]. This wastewater, taken from the bottom section of the treatment tank, was characterized by a variation in physicochemical parameters and provided the feed for the membrane process. During the research, daily water samples (6 in total) were taken for laboratory analysis, including two additional samples (after the 2nd and 3rd degree of RO). The characteristics of the wastewater are shown in Table 1.

Raw wastewater (after pretreatment in the digestion process) was subjected to preliminary preparation consisting of dosing the oxidant $KMnO_4$ and NaOCl and PIX coagulant $Fe_2(SO_4)_3$ to the wastewater stream. The wastewater prepared in this way flowed through the contact coagulation tank directly to the process tank with ZeeWeed membrane, where the separation of contaminants from the filtrate took place.

The pilot plant consisted of two parts: a pretreatment module and a UF and RO membrane module. A schematic of the combination of the two installations – UF ultrafiltration and RO reverse osmosis is shown in Fig. 1. The ZeeWeed membrane process tank was continuously aerated. During the filtration cycle, the filtrate was pumped via a process pump to a flow tank (BP) equipped with an overflow. During backwashing, the accumulated filtrate was taken from the BP tank by means of a process pump and pumped in the opposite direction to the membrane to remove solids accumulated there from the membrane surface. Excess filtrate was discharged outside the pilot plant via an overflow in the BP tank. During the pilot study, flow-through raw wastewater tanks with a total volume of about 300 dm^3 were used. The purpose of such a supply system was to reduce the risk of raw wastewater flow disturbances, and thus achieve stable operation of the pilot installation. The flow rate during the pilot tests was for raw wastewater, filtrate and backwash was: Q = 36, 30 and 45 dm^3/h, respectively. The priority for the UF plant used in the study was to prepare RO feed water free of mechanical suspended solids and, above all, colloids. It was crucial to obtain a filtrate with the lowest

Table 1
Characteristics of the pretreated wastewater that is the feed for the membrane process [34]

Parameter (Unit)	Value
pH	5.2–8.0
Conductivity (cm)	2.0–2.6
Color (mg·Pt/dm^3)	120–360
Turbidity (NTU)	90–780
Total suspended solids (TSS) (mg/dm^3)	700–1,800
Total nitrogen (TN) (mg·N/dm^3)	30–50
Total phosphorus (TP) (mg·P/dm^3)	11–12
BOD_5 (mg·O_2/dm^3)	150–700
COD (mg·O_2/dm^3)	350–1,050
Total organic carbon (TOC) (mg·C/dm^3)	90–310

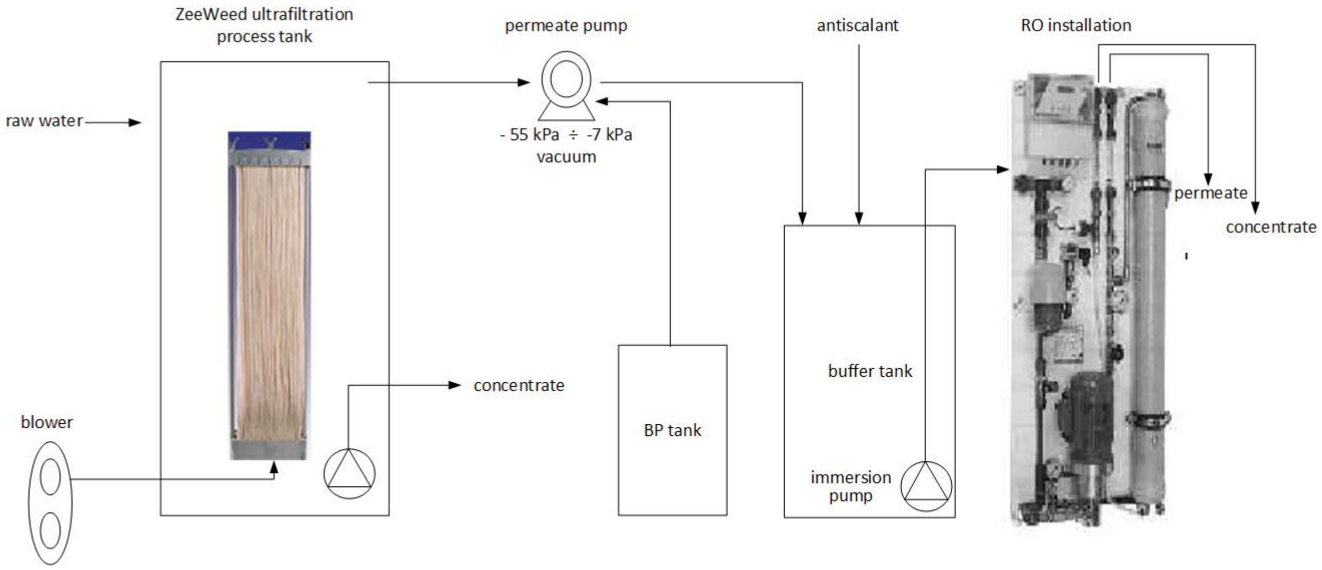

Fig. 1. Schematic of the combination of the two installations - UF ultrafiltration and RO reverse osmosis installation [34].

possible value of the sediment density index SDI and related parameters, such as COD, TOC.

The RO pilot plant was connected to the ultrafiltration pilot installation via a 100 dm^3 buffer tank, where an antiscalant with the trade name "Polifostex" was dosed to chemically deprive the filtrate of its ability to form sludge. The basic UF module was a ZW10 MEM membrane module with a ZW10 PRE pretreatment module based on the ZeeWeed technological solution (vacuum ultrafiltration) with the following parameters: material – PVDF, pore size – 0.04 μ, TMP range – 55 to 55 kPa, max. operating temperature – 40°C, operating pH range – 5.0–9.5. The treated water after ultrafiltration was then drawn from a buffer tank via an immersion pump and further fed to a RO 40 K reverse osmosis pilot installation, preceded by a carbon filter used to remove any free chlorine. The permeate obtained after the RO station membrane constituted the test material for laboratory analysis. The maximum permeate capacity at 15°C feed water was 40 L/h.

The RO 40 K type reverse osmosis pilot installation used for the study was equipped with an optical information system, consisting of indicators of operating parameters, including: flow rate, permeate quality, disturbance indication (supply water pressure too low), and indication of the upper and lower levels of desalinated water in the permeate tank. In addition, the RO installation had an output for remote control and a conductivity meter with a digital indicator and the ability to set a limit value. In addition, the installation had a fine pre-filter (5 μm) on the inlet and a self-priming rotary pump.

2.2. Experimental research

During the course of the study, daily water samples (6 in total) were taken for laboratory analysis, including an additional two (after stage II and III of RO). Total and organic suspended solids were measured using the gravimetric method according to Polish Standard PN-72/C-04559 [35]. Chemical oxygen demand (COD$_{Cr}$) was determined using the bichromate method. Other parameters, including: TOC, TP, TN were determined by cuvette tests on a Dr. 5000 spectrophotometer (Hach GmbH, Germany). The analytical procedures used in the experimental study, adapted from Hach GmbH, were based on APHA standard methods [36]. In addition, water analysis equipment was used, among others (pH meters, conductivity meters, water hardness testers, SDI tests).

The process of determining SDI was based on measuring the time required to pass 100 mL of test water through a 0.45 μm filter under a pressure of 0.21 MPa during the initial measurement phase (t_1) and 15 min later (t_2). The measured values of time t_1 and t_2 were substituted into Eq. (1):

$$\mathrm{SDI} = 100 \times \frac{\left(1 - \frac{t_1}{t_2}\right)}{T} \tag{1}$$

where: t_1 – time required to fill a measuring cylinder to a volume of 100 mL, t_2 – time required to fill a measuring cylinder to a volume of 100 mL after filtering water for 15 min, T – total measurement time (always 15 min).

For SDI < 3 – the probability of membrane blocking is negligible, for SDI = 3–5 membrane blocking by solid and colloidal particles is likely, for SDI > 5 the probability of membrane blocking is almost certain.

Due to the variable and high concentration of suspended solids in the raw water, the first stage of the process was pre-sedimentation, which was designed to prevent sedimentation and facilitate the operation of the entire system. The second stage of the water production process was based on a technological solution from ZENON SYSTEMS (currently: GE – Water, so-called vacuum ultrafiltration). The method of conducting the process included coagulation with iron(VI) sulfate(III) and disinfection and oxidation of organic compounds. Sodium(I) chlorate NaOCl and potassium(VII) manganate $KMnO_4$ were used for disinfection and oxidation. During the study, the doses of reagents were modified to finally determine the most optimal values, which were: PIX – 10 mg·Fe/dm^3, NaOCl – 3 mg/dm^3 and $KMnO_4$ – 0.25 mg/dm^3. The residue from the disinfection process is the presence of free chlorine in the ultrafiltration permeate, the concentration of which ranged from 0 to 0.25 mg·Cl_2/dm^3, depending on the NaOCl dose used. In the situation of increasing NaOCl doses, the ultrafiltration permeate was filtered on activated carbon before being fed to RO membranes to protect them from possible oxidation by free chlorine. The third stage was a reverse osmosis process, carried out in one-, two- or three-stage variants. During the study, the process was conducted with a 50% recovery from each stage. This means that in order to obtain a permeate of 20–30 m^3/h, as much as 80–120 m^3/h of ultrafiltration permeate must be fed. Running the process in this way makes necessitates increasing the capacity of the plant on the ultrafiltration side; however, it protects the membranes from the adverse phenomenon of biofouling. During the pilot study, no periodic chemical cleaning of the UF and RO membrane module was performed, which are routine maintenance activities during the operation of industrial-scale membrane plants.

3. Results and discussion

Knowing the course of UF/RO processes after the pilot studies, it is possible to assume that water production will generate streams of wastewater unused from the coagulation/ultrafiltration and reverse osmosis processes (Fig. 2). Therefore, the obtained test results were considered in the following aspects: the suitability of the UF/RO plant to obtain water with the desired parameters for boiler purposes, the service life (possible maximum lifetime) of the UF/RO membranes, as well as the quantity and quality of wastewater discharged to the municipal sewer system.

3.1. Suitability of UF and RO installations for water recovery

The values of water parameters, produced in the various stages of treatment, are shown in Table 2 in the form of retention coefficients R (2) of individual substances (minimum and maximum values of concentration reduction obtained during multiple measurements are included). The value of the retention factor corresponds to the percentage decrease in the concentration of a given substance as a result of the treatment process, taking the treated wastewater

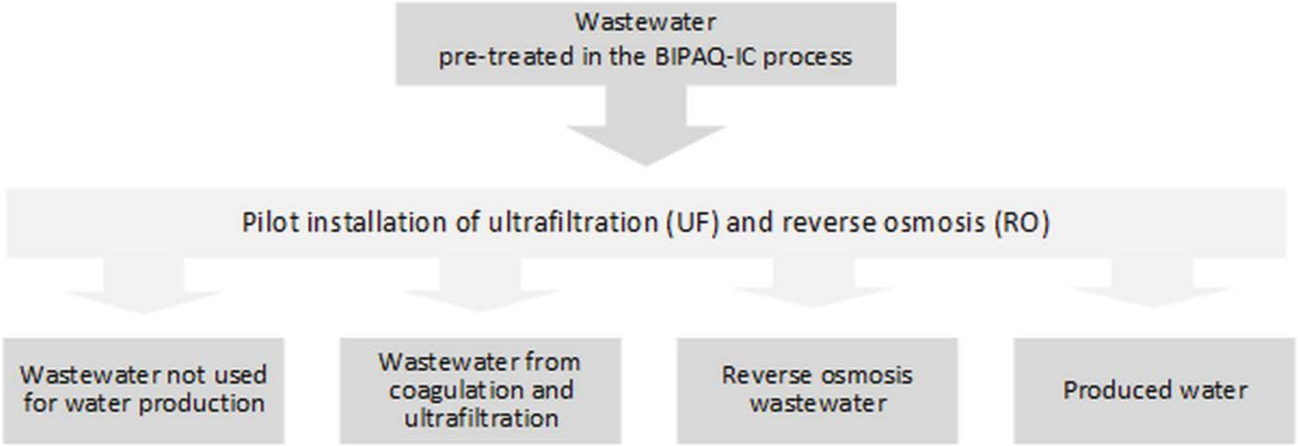

Fig. 2. Wastewater treatment products (after pre-treatment by BIOPAQ®-IC process) at the UF/RO pilot installation.

Table 2
Values of retention coefficients *R* (%) of selected substances and final parameters of water produced using two-stage RO process [34]

Parameter (Unit)	R_1 decrease in concentration after UF		R_2 decrease in concentration after stage I of UF		R_3 decrease in concentration after UF, as well as I and II stage of RO	R_4 decrease in concentration after UF, as well as stage I, II and III of RO	Final value after stage II of RO
	Min.	Max.	Min.	Max.			
COD_{Cr}	86.10	94.58	96.46	98.67	96.27	97.13	13.3 mg·O_2/dm^3
TOC	76.78	93.27	98.00	100	100	100	BDL*
TP	10.00	58.47	97.58	98.75	98.52	98.70	0.17 mg·P/dm^3
TN	5.14	57.17	85.84	93.58	96.91	98.15	0.92 mg·N/dm^3
TSS	96.86	99.81	Approx. 100		100	100	BDL*
Conductivity	3.13	4.00	94.53	96.89	99.40	99.91	0.014 mS/cm
Color	13.06	75.40	97.63	98.80	98.40	99.92	5 mg·Pt/dm^3
Turbidity	74.08	99.60	98.88	99.92	98.75	98.99	1.15 NTU

*BDL – none or below detection limit.

as the starting point and the water after a given treatment stage as the end point. The maximum values of the retention coefficients were obtained by optimizing the doses of chemicals used in the UF process.

$$R = \frac{c_n - c_p}{c_s} \tag{2}$$

where c_p – concentration of a substance/parameter value in permeate, c_n – concentration of a substance/parameter value in inflow, c_s – concentration in treated wastewater/parameter value.

The results of the study (Table 2) except for isolated cases, the values of pollutants in the wastewater flowing into the UF/RO pilot installation remained at similar levels, for which similar percentages of reduction in the listed parameters observed during the conduct of the study were also obtained.

The average values of selected parameters (COD, TOC, TN, TP, conductivity, Color, turbidity) obtained throughout the study period were compared after UF and stage I, II, III of RO and are presented in Table 3.

As indicated by the results shown in the table (Table 3) the concentrations of COD and TOC after UF and stage III of RO were recorded at 10 mg·O_2/dm^3 and below 0.1 mg·C/dm^3, respectively (achieving 97% to even 100% reduction). On the other hand, the content of nitrogen and total phosphorus remained on average above 98% reduction in the concentration range from 0.55 mg·N/dm^3 to 0.15 mg·P/dm^3. Similarly, in the case of analyzed color and turbidity, a very high degree of reduction of up to 99% was obtained in the particular stages of treatment in UF and stage I, II, III of RO.

In general, the amount of retained labeled substances on the RO membrane after stage III is not much greater than after stage II, and therefore running a three-stage RO process is possible, but not economically efficient. The parameters of the water after RO stage I indicate that it is possible to run – more efficiently – stage II, with more than 50% recovery. This will significantly contribute to a reduction in the demand for UF permeate, and this in turn will affect the amount of investment and operating costs. Studies

Table 3
Average values of selected parameters (COD, TOC, TN, TP, conductivity, color, turbidity, SDI) obtained after UF and stage I, II, III of RO during the study period [34]

Parameter (Unit)	Wastewater	UF	UF and stage I of RO	UF and stage I, II of RO	UF and stage I, II, III of RO
COD_{Cr} ($mg{\cdot}O_2/dm^3$)	805.50	61.50	18.20	13.40	10.30
TOC ($mg{\cdot}C/dm^3$)	247.10	20.70	6.20	0.10	0.00
TP (mg/dm^3)	11.80	6.80	0.20	0.17	0.15
TN (mg/dm^3)	38.20	27.30	3.60	0.92	0.55
Conductivity (mS/cm)	2.50	2.41	0.11	0.015	0.014
Color ($mg{\cdot}Pt/dm^3$)	143.60	69.30	4.80	5.00	3.00
Turbidity (NTU)	451.30	37.00	1.10	1.15	0.93
SDI	15.40	5.60	1.00	1.60	1.20

have confirmed that by running stage II of RO with 75% recovery, the demand for UF permeate will decrease from 80–120 m^3/h to 54–80 m^3/h.

Considering the use of the produced water for boiler purposes, analysis of the treated water for the removal of hardness-causing compounds had to be considered. The study examined treated water after the UF process, which averaged about 124.6 $mg{\cdot}CaCO_3/L$ and a conductivity of 2,229 μS/cm. The high-water hardness and conductivity necessitated using an antiscalant with the trade name "Polifostex", which was dosed manually at a ratio of 50–100 mL per 100 dm^3 of permeate after ultrafiltration in the buffer tank. After a one-step RO process, the treated water was deprived of general hardness according to the analyses, and the measured conductivity was at 0.11 mS/cm. If residual hardness is found in the water that will be produced on a technical scale, it is advisable to divert part of the boiler feed water stream through an ion softener, while in the case of trace amounts it will be advisable to dose trisodium orthophosphate to the boiler water.

3.2. Influence of studied water on the life of UF and RO membranes

The ability of membranes to separate certain substances, at the same time, can sometimes cause membrane fouling, which in extreme cases can make water production impossible. Therefore, it is important to properly manage the process, both in terms of chemical correction of the water fed to the membranes (proper pH, use of antiscalants), its disinfection and frequency of chemical cleaning of the membranes.

To some extent, ultrafiltration membranes protect coagulation and oxidation processes. However, the ultrafiltration permeate is not free of contaminants, as evidenced by both SDI values, fairly high turbidity, color, and the number of microorganisms in the samples tested. The cultures taken during the study indicate the presence of an incalculable number of aerobic bacteria in 1 mL of the test sample, as well as occasional mold colonies. In this situation, it is necessary to apply a suitable biocide to the ultrafiltration permeate. In order to select a suitable preparation, it is proposed to perform culture tests to determine its effectiveness. The effect on changes in UF and RO membrane capacity (permeate flux) depended on the coagulant used: some coagulants have no influence on permeate flux, another enables a 20% increase in permeate flux whereas another coagulant leads to a decrease of 50%. Flocs formed with ferric chloride do not resist shear stress and consequently have no influence on permeate flux. These results show the necessity to create large flocs, but the size is not sufficient to explain membrane performance. Even if flocs show a good resistance to shear stress, a high compactness (*Df* = 3) will lead to a dramatic decrease of permeate flux by increasing the mass transfer resistance of the cake. On the contrary, flocs less resistant to shear stress, then smaller and also more open have no effect on permeate flux. An optimum was quantified for large flocs, resistant enough to shear stress facilitating flow between aggregates. SDI values were around 5, and in some measurements slightly above, which is a limiting value, but still qualifies the water to be fed to RO membranes. A significant influence on the coagulation process is the pH, which, if necessary, should be adjusted – in the case of the use of coagulant $Fe_2(SO_4)_3$ and the presence of organic compounds in the test water towards lower values or – in the case of the presence of multivalent metals – towards higher values. The optimal pH range for coagulant $Fe_2(SO_4)_3$ is: 4–7 and above 8.5. Trials were conducted at pH 8, which is outside this range. The pretreated wastewater, which is the feed for the process, is characterized by high TOC concentrations and high COD_{Cr} values, so it would be advisable to conduct laboratory trials to select the optimal coagulant dose at lower pH values. Lower pH values also prevent the deposition of mineral impurities in the form of so-called membrane scale.

The problem of using useless membranes is very current. Due to the low profitability, the recovery and reuse of material from used membranes is currently quite rarely used on an industrial scale. Used membranes are most often stored on site or collected by specialized companies for disposal. Of course, this is not in line with the principles of the circular economy. Therefore, for almost two decades, intensive research has been carried out on the reuse of biopolymers, which are the main component in membranes, and their possible recovery [37,38]. Nowadays a large portion of biopolymer-based material in Membranes literature focused on proton exchange membrane research, and idea for utilization of useless membranes. It is highly recommended that more attention should be shifted towards exploring biopolymer-based anion exchange membranes taking into consideration effective strategies that address the balance between swelling and performance in membranes processes as well as their utilization and material recovery in future perspectives. However, there are some good examples of utilization of useless membranes, but still more research should be carried on in this field to find the best solution of this problem. The technical barriers that must be overcome for utilization of membranes over conventional technologies are discussed, along with the benefits offered by membrane technologies.

3.3. Impact of the process on the quality of wastewater discharged into municipal sewer system

Wastewater – once clean water is produced from it – will become concentrated, that is, the concentrations of the substances in it will increase. The amount of wastewater will decrease by the amount of water produced, minus the amount of water required for the production process. In addition, as a result of coagulant dosing, an increase in conductivity, total iron and sulfate(VI) concentrations can be expected. The concentration of suspended solids will also increase, as some of the impurities will be captured in the coagulation process. It will only be possible to determine these concentrations once the coagulant dosage needed to run the process on a technical scale has been carefully refined. The increase in non-coagulant concentrations can be roughly estimated from the mass balance of the plant (Fig. 2). Knowledge of the process flow allows assuming that the effluent stream at the end of the process ($\dot{m}_{\mathrm{SK}}$) will consist of the streams of wastewater not used in the water production process ($\dot{m}_{S2}$) and wastewater from coagulation/ultrafiltration ($\dot{m}_{\mathrm{SUF}}$) and reverse osmosis ($\dot{m}_{\mathrm{SRO}}$).

$$\dot{m}_{\mathrm{SK}} = \dot{m}_{S2} + \dot{m}_{\mathrm{SUF}} + \dot{m}_{\mathrm{SRO}} \tag{3}$$

Using Eq. (4):

$$c = \frac{\dot{m}}{\dot{V}} \tag{4}$$

where $\dot{m}$ – mass flow (kg/s), $\dot{V}$ – volumetric flow rate (m^3/s) and assuming that the water production will be 30 m^3/h, the retention rates for all contaminants present in the water will be approx. 99%, and the wastewater pre-treatment plant will operate at full capacity, that is, 8,000 m^3/d, or 333 m^3/h, the following equation can be written:

$$c_{\mathrm{SK}} = \frac{\dot{m}_{S1} - \dot{m}_{\mathrm{H_2O}}}{\dot{V}_{\mathrm{SK}}} \tag{5}$$

where $\dot{m}_{S1}$ – mass streams of wastewater pre-treated in the BIOPAQ®-IC process (kg/s), $\dot{m}_{\mathrm{H_2O}}$ – mass streems of produced water for technical purposes (kg/s).

That is, the concentration of substances in the wastewater discharged into the sewage system will be:

$$c_{\mathrm{SK}} = c_{S1} \frac{\dot{V}_{S1} - \dot{V}_{\mathrm{H_2O}}}{\dot{V}_{\mathrm{SK}}} \tag{6}$$

where $\dot{V}_{S1}$ – volumetric flow rate of wastewater pre-treated in the BIOPAQ®-IC process (m^3/s), $\dot{V}_{\mathrm{H_2O}}$ – volumetric flow rate of produced water for technical purposes (m^3/s), $\dot{V}_{\mathrm{SK}}$ – volumetric flow rate of effluent at the end of the process (m^3/s).

Finally:

$$c_{\mathrm{SK}} = 1.10 \times c_{S1} \tag{7}$$

This means that the concentration of substances present in the pretreated wastewater that do not coagulate will not increase by more than 10% after being concentrated by the water production process.

The water obtained can be used both for boiler purposes and for the current needs of the plant, such as sprinkling of deposits in sewage treatment plants, replenishment of the cooling system, or washing floors. In addition, some of the retentate from the reverse osmosis could be returned to the beginning of the wastewater treatment plant system and reused by ultrafiltration and reverse osmosis to produce water for technical-technological purposes. The amount of this retentate would have to be optimized in such a way as to not lead to significant compaction of the feed. A certain portion could be used for purposes related to the day-to-day operation of the wastewater treatment plant, that is, cleaning of sludge.

4. Conclusions

Membrane technologies are widely used in industrial circuit water and wastewater treatment processes. As part of authors' own research, an integrated UF/RO membrane process was designed and evaluated to create an efficient solution for treating wastewater from the brewing industry in order to recover water for process purposes. The proposed method of using the treated industrial wastewater to produce process water makes the most sense, both from a technological and economic point of view, as well as keeping in mind the ecological considerations inherent in the principles of a closed loop economy. As the literature review shows, a significant part of freshwater resources in Poland and Central European countries is consumed for industrial purposes; hence, there is a great need to implement modern technological solutions for closing water circuits and recovering water in process installations. Taking into account the decrease in the price of membranes and the cost of their operation, the simultaneous increase in their efficiency and resistance to various process conditions, as well as the lower values of the required transmembrane pressure (which reduces the demand for electricity), it can be said that the proposed solution perfectly fits into the framework of a modern, sustainable economy and the Green Deal. However, in order for the water recovery process to be carried out in the most efficient manner, it would be advisable to follow the recommendations:

- While designing the installation, the pre-sedimentation stage must not be overlooked. Excessive concentration of suspended solids in the ZeeWeed ultrafiltration process tanks can become the cause of operational problems in this part of the installation.

- In order to increase the efficiency of the pre-coagulation process, it is recommended to apply pH correction, which will contribute to improving the chemical parameters of the ultrafiltration feed, and thus the permeates obtained in subsequent stages of water production.
- It is necessary to carry out dechlorination of water to avoid oxidation of the reverse osmosis membrane material, and thus damage to it.
- Due to the fact that the process feed is anaerobic activated sludge treated wastewater, it is proposed to use membranes of the BW – FR (fouling resistant) group. These membranes are coated with a layer of substance that hinders the adhesion of microorganisms to their surface, making them more resistant to "biofouling".
- The thickening of wastewater, caused by the process of water preparation and clean water recovery, not exceeding a 10% increase in the concentration of non-coagulating contaminants, should not significantly deteriorate the parameters of wastewater discharged into the sewer system. However, a larger increase will be observable in the concentration of suspended solids.
- To achieve the goal of treated and recovered process water, it is necessary to properly design and even pre-test the system under pilot conditions to determine the appropriate operations and process conditions that will improve membrane utilization as well as provide data for process scaling.
- The membrane technology might be used for the efficiency improvement of contaminant removal, yielding purified and high-quality water toward the implementation of the sustainable development assumptions of Circular Economy and Green Deal Implementation.

Symbols

R — Retention coefficients, %

c_p — Concentration of a substance/parameter value in permeate, mg·O_2/dm^3 [COD], mg/dm^3 [TOC], mg·N/dm^3 [TN], mg·P/dm^3 [TP], g/dm^3 [TSS], mS/cm [conductivity], Pt/dm^3 [color], NTU [turbidity]

c_n — Concentration of a substance/parameter value in inflow permeate, mg·O_2/dm^3 [COD], mg/dm^3 [TOC], mg·N/dm^3 [TN], mg·P/dm^3 [TP], g/dm^3 [TSS], mS/cm [conductivity], Pt/dm^3 [color], NTU [turbidity]

c_s — concentration in treated wastewater/parameter value permeate, mg·O_2/dm^3 [COD], mg/dm^3 [TOC], mg·N/dm^3 [TN], mg·P/dm^3 [TP], g/dm^3 [TSS], mS/cm [conductivity], Pt/dm^3 [color], NTU [turbidity]

$\dot{m}$ — Mass flow, kg/s

$\dot{V}$ — Volumetric flow rate, m^3/s

$\dot{m}_{\mathrm{SK}}$ — Effluent mass stream at the end of the process, kg/s

$\dot{m}_{\mathrm{S2}}$ — Mass streams of wastewater not used in the water production process, kg/s

$\dot{m}_{\mathrm{UFK}}$ – Mass streams of wastewater from coagulation/ultrafiltration, kg/s

$\dot{m}_{\mathrm{ROK}}$ – Mass streams of wastewater from reverse osmosis, kg/s

$\dot{m}_{\mathrm{S1}}$ — Mass streams of wastewater pre-treated in the BIOPAQ®-IC process, kg/s

$\dot{m}_{\mathrm{H_2O}}$ — Mass streems of produced water for technical purposes, kg/s

$\dot{V}_{\mathrm{S1}}$ — Volumetric flow rate of wastewater pre-treated in the BIOPAQ®-IC process, m^3/s

$\dot{V}_{\mathrm{H_2O}}$ — Volumetric flow rate of produced water for technical purposes, m^3/s

$\dot{V}_{\mathrm{SK}}$ — Volumetric flow rate of effluent at the end of the process, m^3/s

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