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APPLICATION OF THE ULTRAFILTRATION PROCESS IN THE TREATMENT OF BREWERY WASTEWATER

The objective of this study is to evaluate the efficacy of UF treatment of brewery wastewater from a university brewery, employing flat polymer membranes with varying cut-offs. The findings provide substantiation for the viability of the examined UF process for the treatment of brewery wastewater. The study demonstrated that the separation properties of the membranes are contingent on their limiting resolution, with the XT membrane (1000 Da) yielding optimal results. Increasing the transmembrane pressure (TMP) did not yield a substantial enhancement in separation efficiency, particularly for membranes with larger pores. The UF efficiency demonstrated stability over the course of the study, thus suggesting that the membranes exhibited excellent resistance to blockage and did not necessitate frequent regeneration. The transport properties of UF membranes are contingent on TMP, cut-off value, and operating time. An increase in pressure and cut-off value increased permeate flux; however, the hydraulic capacity of the membranes gradually decreased over time.

1. INTRODUCTION

Beer, an alcoholic beverage with a long and storied history, has played an integral role in the cultural and economic landscape of numerous nations for centuries [1]. Despite its foundation in time-honored methods, the production of beer has been undergoing a constant evolution, incorporating modern technologies and innovative approaches [2]. The contemporary beer production process encompasses several pivotal stages, including mashing, fermentation, maturation, and packaging. Each of these stages exerts a substantial influence on the final characteristics of the beverage, including its taste, aroma, and quality [3]. In recent years, there has been a focus on optimizing fermentation processes and implementing modern quality management systems, enabling the production of products with high reproducibility and excellent sensory qualities [4–6].

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In the context of raw materials, brewer's malt, a by-product of the brewing process, is gaining importance as a material with potential prebiotic properties. Research has highlighted its substantial fiber, protein, and fat content, underscoring its potential as a valuable ingredient in animal nutrition and a promising source of nutrients in the human diet [7, 8]. Additionally, beer has been identified as a source of polyphenolic compounds, which have been shown to possess antioxidant activity, potentially conferring health benefits [9]. While excessive alcohol consumption is detrimental to health, moderate beer consumption has been demonstrated to contribute to the body's acquisition of these valuable compounds [10]. In the context of intensifying competition within the beer market, brewers are progressively adopting unconventional brewing malts and pioneering production techniques to distinguish their products and cater to a range of consumer preferences [11].

Despite its long-standing tradition and innovative technological advances, the brewing industry faces significant challenges in managing its water usage and producing wastewater [12]. The processes involved in beer production, such as mashing, fermentation, and cooling, require substantial amounts of water [13]. This makes the brewing industry one of the most water-intensive sectors of the food industry. Depending on the technology and efficiency of the methods used, data indicates that as much as 3–10 dm^3 of water may be used to produce 1 dm^3 of beer [12]. Furthermore, brewing processes generate substantial amounts of wastewater, which contains high concentrations of organic substances such as proteins, starches, fats, and malt and yeast residues [14]. These pollutants can pose a grave threat to the environment if they are not adequately treated. Consequently, there has been a growing focus on the development and implementation of effective wastewater treatment systems and water recovery technologies [15]. These technologies play a pivotal role in reducing the adverse environmental impact of beer production. Innovations in the field of water management, such as water recirculation, heat recovery, and advanced treatment technologies, are becoming imperative for the pursuit of sustainable development in the beer industry. The implementation of these solutions not only contributes to the conservation of natural resources but also results in a reduction in production costs and minimization of environmental emissions [16].

Contemporary technologies have rendered feasible the effective treatment of brewery wastewater, thereby ensuring the complete removal of all contaminants and the production of water that meets stringent chemical and microbiological standards for safe human consumption [17]. In recent years, the development of comprehensive treatment systems has enabled the reuse of water [18]. The reclaimed water can be utilized for various applications, including cleaning rainwater and sewage networks, vehicle washing, irrigating green spaces such as lawns and gardens, or areas surrounding the brewery, washing surfaces and equipment in the brewery, and extinguishing fires. Furthermore, it can support the maintenance of wastewater treatment plants [19, 20]. Additionally, it can be reused in the beer production process itself, for instance, in cooling equipment, rinsing equipment, or preparing water for mashing. This approach enables a substantial reduction in the utilization of fresh water in brewing processes.

The treatment of wastewater from beer production necessitates a range of methodologies that efficaciously remove organic contaminants, including malt residues, proteins, fats, and dissolved substances. These contaminants can lead to elevated chemical oxygen demand (COD) and biochemical oxygen demand (BOD_5) [21]. A predominant approach in the treatment of brewery wastewater is biological treatment, which utilizes microorganisms to degrade organic contaminants [22]. This process can be executed in sludge reactors and activated sludge systems, which effectively remove dissolved substances from the water. These systems are frequently employed in conjunction with other treatment methods, such as sedimentation, which removes larger solids. Coagulation, a process that involves the addition of chemicals to neutralize electrical charges on pollutant particles, allowing them to be agglomerated and more easily removed by sedimentation, is also increasingly used [23]. Conversely, advanced oxidation processes (AOPs), such as ozonation and photocatalysis, employ potent oxidants to degrade organic pollutants, thereby facilitating the reduction of COD and BOD_5, thus enhancing water quality and safety for the environment [24]. In addition to conventional treatment methodologies, novel technologies, including pressure-driven membrane processes, have been developed in recent years. These technologies enable the efficient removal of contaminants of diverse sizes. These processes utilize semi-permeable membranes through which water is transported by TMP, while retaining dissolved substances and suspended solids [25].

Microfiltration and ultrafiltration (UF) are primarily employed for the removal of particulates, bacteria, and macromolecules [26]. Conversely, nanofiltration (NF) and reverse osmosis (RO) facilitate the elimination of ions, heavy metals, and organic pollutants with smaller molecular weights [27, 28]. The selection of the most suitable process is contingent upon the composition of the water to be treated and the desired quality of the permeate obtained. Due to their high separation efficiency, membrane technologies are widely used in the treatment of water for human consumption and in the treatment of industrial and municipal wastewater [29].

In the context of brewery wastewater treatment, UF emerges as a particularly salient technology, achieving notable efficacy in the removal of suspended solids, organic macromolecules, and microorganisms [12]. Fundamentally, UF utilizes membranes with a pore size ranging from 0.01 to 0.1 μm, which function as a mechanical barrier, effectively capturing larger particles while permitting the passage of water and substances of lower molecular weight dissolved therein [30]. Due to its high separation efficiency, UF is employed as a pivotal step in advanced treatment systems, both before and in conjunction with further purification processes, as well as in technologies for reusing reclaimed water. The integration of UF into brewery wastewater treatment systems enables a substantial reduction in organic loading, thereby promoting more efficient operation of subsequent treatment stages, such as NF and RO [31].

The objective of this study was to examine the efficiency of UF, a sophisticated technological approach, in the treatment of brewery wastewater. The research endeavored to ascertain the efficiency of organic matter removal and the impact of process parameters on permeate quality. The study's innovation lies in the utilization of advanced polymeric membranes with distinct separation properties. Furthermore, the study encompassed an analysis of susceptibility to fouling, a critical consideration for the practical implementation of UF in the brewing industry. The findings of the study offer invaluable insights into the viability of integrating UF as a component of a sustainable water management system for breweries, with the objective of reducing freshwater consumption and minimizing the environmental impact of wastewater.

2. METHODS AND MATERIALS

A wastewater sample was obtained from a research brewery operated at Wroclaw University of Technology (Poland). This facility replicates the processes of a real brewing plant, thereby enabling the research and simulation of authentic brewing processes. However, due to the academic nature of the facility, the entire installation was designed on a significantly smaller scale, adapted to university conditions and teaching needs.

Table 1

Physical and chemical characteristics of the studied brewery wastewater

Parameter	Value	Standard or documented testing procedure
pH	4.36	PN-EN ISO 10523:2012
Specific conductivity, mS/cm	2088	PN-EN 27888:1999
Dry residue, g/m^3	35 303	PN-78 C-04541
Dissolved substances, g/m^3	34 782	PN-78 C-04541
Mineral substances, g/m^3	863	PN-C-04541:1978
Volatile substances, g/m^3	33 969	PN-EN ISO 15680:2008
Total suspended solids, g/m^3	1284	PN-EN 872:2007
COD, g O_2/m^3	58 800	Standard methods 5220 D
BOD_5, g O_2/m^3	59 853	PN-EN 1899-1:2002
DOC, g/m^3	13 960	PN-EN 1484:1999
NH_4^+-N, g/m^3	4.4	Standard methods 4500-NH_3 C
NO_2^--N, g/m^3	14	PN-EN ISO 13395:2001
NO_3^--N, g/m^3	102	PN-EN ISO 10304-2001
PO_4^{3-}, g/m^3	47	PN-EN ISO 3946:2000
SO_4^{2-}, g/m^3	1070	PN-EN ISO 10304-1:2009
P_{total}, g/m^3	15.4	PN-EN ISO 6878:2006

Table 2

The results of bacteriological analysis

Parameter	Value [cfu/cm^3]	Standard or documented testing procedure
Total number of microorganisms at 36±2 °C after 48 h	4600	PN-EN ISO 6222
Total number of microorganisms at 22±2 °C after 72 h	1000	PN-EN ISO 6222
Coliform bacteria at 36±2 °C after 24 h	30	PN-EN ISO 9308-1
Fecal streptococci at 36±2 °C after 48 h	2720	PN-EN ISO 7899-2
Fungi 26±2°C after 5 d	2570	Surface method

The wastewater analyzed was a mixture of wastewater from the first stage of the plant's flushing. The physical and chemical properties, along with the results of the bacteriological analysis of the wastewater mixture, are presented in Tables 1 and 2, respectively. The properties of the test solution were evaluated in accordance with the guidelines outlined in *Standard Methods for the Examination of Water and Wastewater* [32].

In this study, five commercial polymeric membranes made of polyethersulphone (PES) were utilized, with each membrane exhibiting a distinct molecular weight cut-off value (MWCO). These membranes were all manufactured by Sterlitech (USA). The employment of membranes with varying MWCOs enabled the assessment of their efficacy in the separation process and the investigation of the impact of membrane parameters on purification efficiency. The utilized membranes are distinguished by their conventional asymmetric configuration, comprising an epidermal layer and a more substantial support layer. The characteristics of these membranes are enumerated in Table 3.

Table 3

Characteristics of the membranes used in the experiments [33]

Type	Synder flat sheet membrane				
	XT	MT	ST	MK	MQ MAX
pH range	1–11				1–10
Redistilled water flux at 0.4 MPa, $m^3/(m^2 \cdot d)$[a]	1.27	1.76	1.94	2.02	3.59
MWCO, Da	1000	5000	10 000	30 000	50 000
Active filtration area, cm^2	38.5				

[a]Authors' measurements.

The transport and separation properties of flat membranes were studied using a system shown in Fig. 1. The main component of the system was an Amicon 8400 UF chamber from Millipore. This chamber allows the dead-end filtration process to be performed and was designed to work with flat membranes. The membranes tested had a diameter of 76 mm, and the working volume of the filtration chamber was 350 cm^3. To maintain a uniform concentration of the substance throughout the solution volume, the chamber was placed on an OMC Envag ARE magnetic stirrer. In the experiments performed with this type of chamber, TMP was applied in the range of 0.1 to 0.4 MPa. All experiments were performed in duplicate to verify the results obtained.

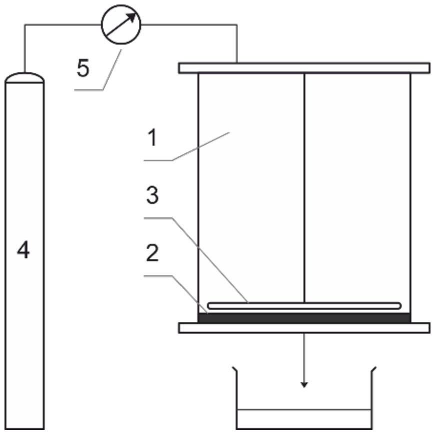

Fig. 1. Laboratory kit diagram with an Amicon 8400 chamber from Millipore: 1 – Amicon 8400 chamber, 2 – membrane, 3 – stirrer, 4 – pressurized nitrogen tank, 5 – regulator

Prior to the actual membrane filtration process, the membranes under test were subjected to a conditioning procedure designed to stabilize them and ensure reproducible measurement conditions. In this process, redistilled water was gradually passed through the membranes at gradually increasing TMP ranging from 0.1 to 0.4 MPa. Conditioning was continued until the volumetric flux values were stable, indicating that the membrane had fully adapted to the operating conditions.

To restore the filtration properties of the membranes, a membrane regeneration procedure was performed after the completion of the UF process, as recommended by the manufacturer. The process took 15 min and consisted of rinsing the membranes with a 0.1 mol/dm^3 NaOH solution (Avantor Performance Materials Poland S.A., Gliwice, Poland) while maintaining the TMP at 0.2 MPa. The membranes were then thoroughly rinsed with redistilled water at the same pressure to remove residual chemicals. After a further 15 minutes, the volumetric flux of distilled water was measured to assess the efficiency of regeneration and any changes in membrane structure.

The efficiency of the separation process was evaluated by determining the contaminant concentration in both the feed solution and the filter after the purification process. On this basis, the value of the retention factor R was calculated according to the following equation:

$$R = \left(1 - \frac{c_p}{c_n}\right) \times 100\%$$

where: c_n, c_p – contaminant concentrations before and after treatment, respectively, g/cm^3.

The values of the *R* factor above 90% were determined with an uncertainty of less than 1%.

The efficiency of the process was evaluated by measuring the concentration of organic compounds, expressed as chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), and dissolved organic carbon (DOC). The determination of COD and BOD_5 was conducted in accordance with standard methods, employing the bichromate and dilution techniques, respectively [32]. The dissolved organic carbon concentration was measured using a HACH IL550 brand TOC-TN (total organic carbon and total nitrogen) analyzer (Hach, Ames, IA, USA).

During the UF process, the volume of the obtained permeate was measured, enabling the determination of the values of the redistilled water flux (J_0) and permeate flux (J). The transport properties of the tested membranes were evaluated based on the value of the permeate flux, which was determined according to the following equation:

$$J = \frac{V}{At}$$

where: V – permeate volume, m^3, A – membrane surface, m^2, t – filtration duration, d.

Membrane fouling was determined by calculating the relative membrane permeability J/J_0, where J is the permeate flux and J_0 is the redistilled water flux of the new membrane.

3. RESULTS

3.1. MEMBRANE SEPARATION PROPERTIES

The retention coefficients of individual indicators, i.e., DOC and COD concentrations, obtained for the tested membranes are shown in Fig. 2. The findings of this study indicate that the efficacy of brewery wastewater treatment is contingent on the membrane's type and its specific pore diameter. The XT membrane (1000 Da) exhibited the highest efficiency in the removal of DOC and COD, due to its smallest pore diameter. The smaller pore diameter of the membrane restricts the penetration of small organic molecules, enhancing separation efficiency. The values of DOC and COD retention rates for this membrane in treated beer wastewater samples were in the range 50.9–55.8% (reduction from 13 960 to 6175–6855 g C/m^3) and 84.0–84.4% (reduction from 58 800 to 9200–9400 g O_2/m^3), respectively. The MT and ST membranes, with larger pore diameters, also demonstrate satisfactory performance, though their efficiency is marginally lower than that of the XT membrane. Conversely, the MQ MAX membrane (50 000 Da) exhibits the least efficient performance in treating brewery wastewater. This is attributable to its large pore diameter, which fails to effectively impede the reduction in values of DOC and COD retention factors. This outcome aligns with the expectation that an increase in pore diameter permits the passage of larger organic molecules through the membrane. Consequently, it can be concluded that membranes with larger pore diameters, such as MK and MQ MAX, are not effective in removing organic matter.

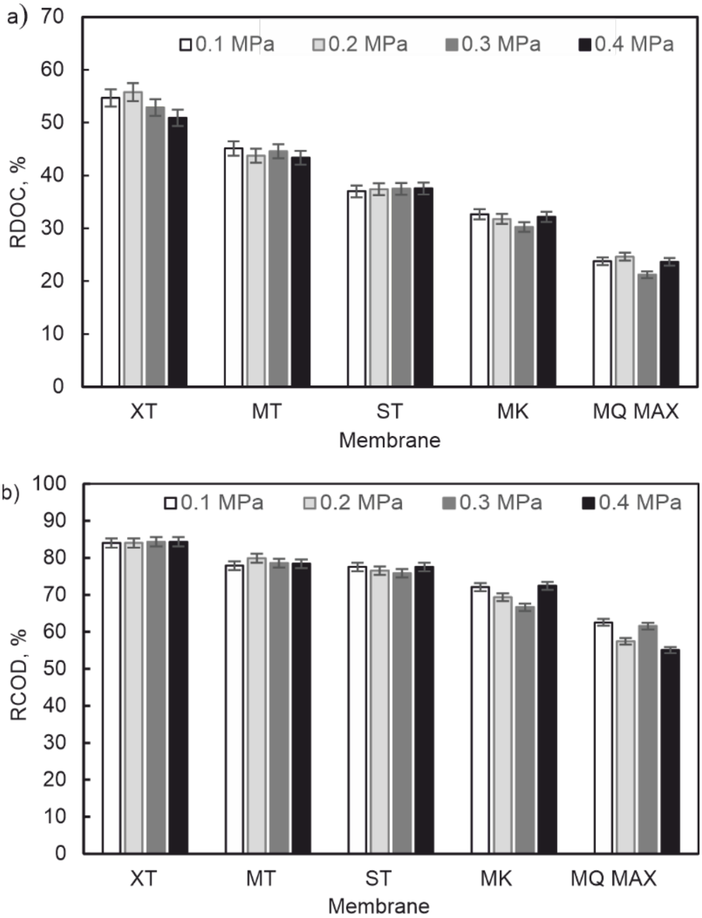

Fig. 2. Effect of TMP on retention rates of DOC (a) and COD (b) of tested UF membranes during brewery wastewater treatment

It was also observed that an increase in pressure between 0.1 and 0.4 MPa did not result in a substantial enhancement in DOC removal efficiency and COD reduction, particularly for membranes with larger pore diameters. The underlying causes of this phenomenon may include the occurrence of concentration polarization, a process in which the accumulation of organic matter near the membrane surface hinders separation efficiency. Alternatively, the deformation of the membrane structure at higher pressures, particularly in more flexible polymeric membranes, could lead to alterations in their separation properties.

The results of the study indicate that the COD reduction is greater than the DOC removal for all membranes. This finding indicates that a subset of the organic compounds responsible for COD is more effectively retained by the membranes, even though their dissolved organic carbon (DOC) continues to pass through the membranes. Additionally, the partial oxidation or degradation of certain pollutants may occur, contributing to a reduction in COD values without a proportional decrease in DOC. The membrane with the largest pore diameter (MK and MQ MAX) exhibited the most significant disparities between DOC removal and COD reduction, suggesting that a greater proportion of organic matter is responsible for COD than for DOC.

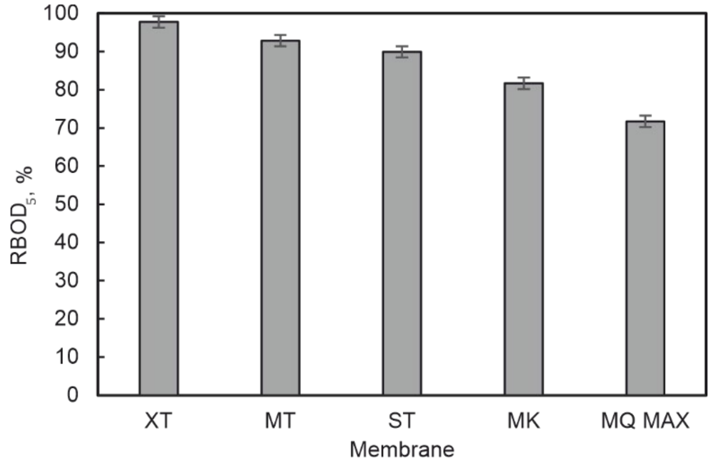

Fig. 3. BOD_5 retention rates of tested UF membranes during the brewery wastewater treatment, TMP = 0.4 MPa

The findings concerning BOD_5 retention rates for the UF membranes evaluated in the context of brewery wastewater treatment at a constant TMP 0.4 MPa are consistent with the earlier results on DOC removal and COD reduction (Fig. 3). The highest BOD_5 retention values were achieved for the XT membrane (97.8%, reduction from 59.853 to 1.340 g O_2/m^3), and the separation efficiency decreased with increasing pore diameter. The enhanced efficiency of the XT membrane can be attributed to its capacity to retain small-molecule organic substances with high biodegradability, which exert an influence on the BOD_5 value. The MT membrane exhibited marginally diminished BOD_5 retention, a phenomenon that may be associated with the partial permeation of smaller fractions of pollutants through the membrane pores. Membranes with larger pore diameters (ST, MK, and MQ MAX) exhibited significantly lower BOD_5 retention rates, confirming their limited effectiveness in retaining lower molecular weight organic compounds. The findings indicate that the reduction of BOD_5 exhibits a comparable trend to that of DOC and COD, suggesting that decreasing the membrane pore diameter enhances separation efficiency. This finding lends further credence to the notion that the predominant contribution to BOD_5 value is derived from low-molecular-weight organics, which can be most efficiently removed by membranes with exceedingly small pores, such as XT and MT. Consequently, while MK and MQ MAX membranes can be effective in removing suspended solids and larger organic particles, they are insufficient in reducing compounds affecting BOD_5, thereby limiting their application in the final stage of brewery wastewater treatment.

The study also examined the impact of the timing of the UF process on the effectiveness of eliminating organic pollutants from the test solution. The results of the changes in the retention values of DOC, COD, and BOD_5, obtained after using each of the tested membranes, are shown in Fig. 4.

The experimental findings demonstrated that the efficiency of contaminant separation remained relatively constant throughout the UF process. This constant UF efficiency implies that membrane filtration can be conducted over a brief period (up to four hours) without necessitating additional membrane regeneration procedures, such as rinsing or chemical cleaning. This is of paramount importance from an operational perspective, as it eliminates the need for process interruptions and reduces the consumption of chemicals and water for membrane flushing.

The minor fluctuations observed in the obtained results indicate that the membranes maintain their separation stability under the studied conditions, suggesting a limited fouling phenomenon during the analyzed filtration period. Such small fluctuations in the values of the retention coefficients may be due to dynamic changes in the filtration process, such as the deposition of organic particles on the membrane surface, leading to a temporary reduction in the pore permeability, followed by their partial removal by the filtrate flow, natural changes in the composition of the wastewater, and simultaneous mechanisms of adsorption and desorption of pollutants. The behavior of these mechanisms can be attributed to the temporary settling of certain organic substances on the membrane surface, followed by their partial desorption, which may result in slight changes in separation efficiency.

In the event of intensive fouling of the membranes, a gradual decrease in DOC removal efficiency and a decrease in COD and BOD_5 would be expected. However, these phenomena were not observed during the time interval studied. The underlying reasons for this phenomenon encompass the effective membrane structure, which curbs the swift accumulation of contaminants on the surface and within the pores, the presence of optimal filtration conditions, including sufficient TMP (0.4 MPa) to impede excessive organic deposition, and the nature of the brewery wastewater, which may contain a reduced quantity of hard-to-remove substances, resulting in intensive fouling.

An analysis of the stability of the process in the context of different membranes reveals that the smallest changes over time are observed in membranes with the smallest pores (XT, MT), suggesting that they are less susceptible to dynamic changes in the composition of the wastewater and possible deposition of contaminants.

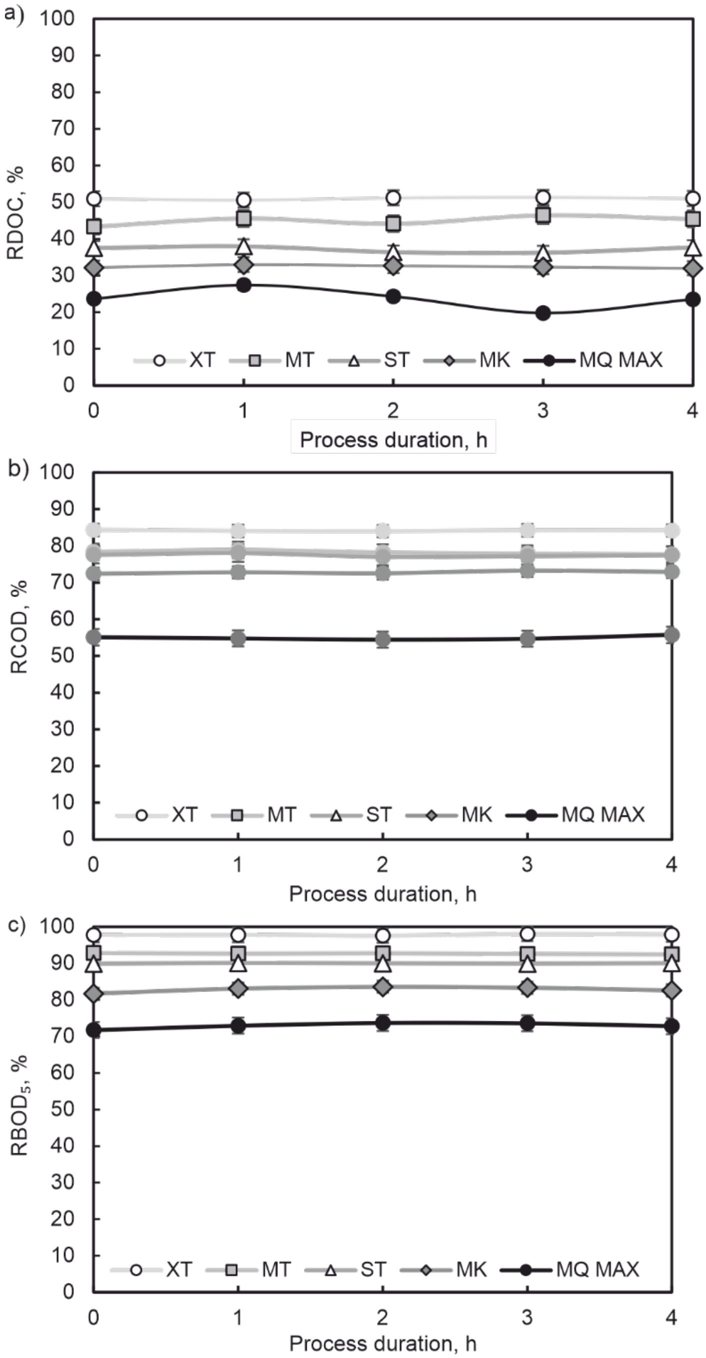

Fig. 4. Effect of membrane filtration time on DOC removal efficiency (a), COD reduction (b) and BOD_5 (c) during the brewery wastewater treatment, TMP 0.4 MPa

Membranes with larger pores (MK, MQ MAX) also demonstrate relatively stable performance; however, their separation efficiency is notably lower. This phenomenon can be attributed to the higher permeability of the larger pores, which results in a relatively stable efficiency level throughout the filtration process. However, this efficiency level does not reach the same heights as that observed in membranes with finer pores.

3.2. MEMBRANE TRANSPORT PROPERTIES

The effectiveness of membranes in the treatment of several types of solutions, including brewery wastewater, is determined not only by their separation properties but also by their transport parameters. Filtration efficiency is contingent on two factors: the membrane's capacity to eliminate contaminants and its permeability, which exerts a direct influence on operational efficiency. Consequently, the present study aims to ascertain the key transport properties of membranes, including volume flux and susceptibility to fouling. Fouling can reduce filtration efficiency, and thus to the need for frequent membrane cleaning or replacement. The permeate flux for the tested membranes, contingent on the applied pressure, is illustrated in Fig. 5.

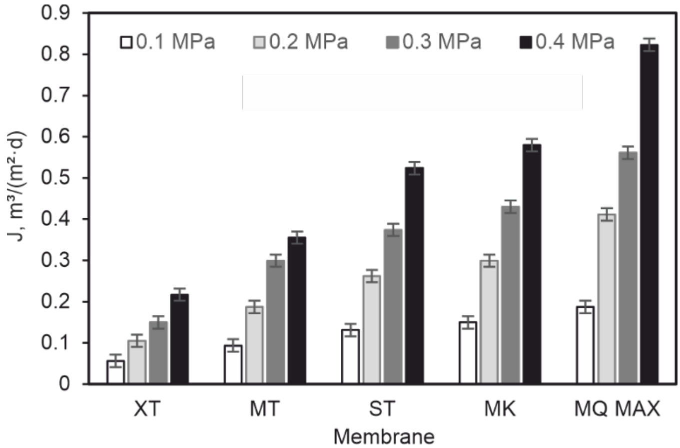

Fig. 5. Permeate flux for the Sterlitech polymer membranes as a function of TMP obtained during UF of brewery wastewater

The variability in permeability among the membranes is attributed to the variation in cut-off values. The water flux ranged from 0.05 to 0.22 $m^3/m^2 \cdot d$ for XT membranes with the lowest permeability and from 0.19 to 0.83 $m^3/(m^2 \cdot d)$ for MQ MAX membranes characterized by the highest permeability. The observed values were found to be consistent with the characteristics of the membranes, as detailed in Table 3. Conversely, the permeability of all membranes exhibited an increase in proportion to the increase in

TMP. This phenomenon can be attributed to the operation of multiple pivotal physicochemical mechanisms. Primarily, elevated pressure engenders an amplified driving force for solvent transport across the membrane, culminating in an augmentation of permeate flux in accordance with the Darcy equation. Secondly, at sufficiently elevated pressures, the pores of the membrane can undergo expansion, a phenomenon particularly evident in polymeric structures, thereby facilitating fluid flow. However, it is imperative to note that excessive pressure can lead to membrane compression, which, in the long term, can result in a decline in membrane performance.

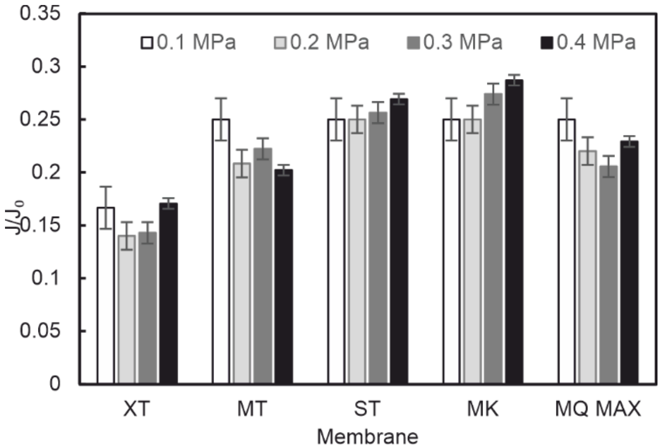

Fig. 6. Relative membrane permeability during UF (at different TMP) of the brewery wastewater using Sterlitech polymeric membranes

Membrane fouling needs to be considered when using these membranes for UF treatment of beer wastewater. An examination of the J/J_0 values obtained (Fig. 6) reveals a general increase in the relative permeability of the membranes with increasing pressure (from 0.1 to 0.4 MPa). This suggests that at this stage of the experiment, the separation efficiency has not yet been significantly reduced by blocking phenomena. It was also observed that some membranes, e.g., XT and MQ MAX, exhibited a comparatively lower increase in permeability compared to others (e.g., ST and MK), which may indicate their heightened susceptibility to blocking, particularly at higher pressures. The accumulation of sediment or the adsorption of substances on the membrane surface may impede the growth of permeability, even under conditions of increasing pressure. It is plausible that membranes demonstrating higher permeability increases (e.g., ST, MK) exhibit enhanced resistance to membrane blockage resulting from particle deposition on the surface (i.e., surface blockage) or penetration into the pores (i.e., internal blockage). This enhanced resistance may be attributed to increased hydrophilicity or a more homogeneous pore structure. While an increase in pressure generally enhances transport through the membrane, it can also promote intensification of fouling, particularly when particles are more firmly pressed against the membrane surface. Consequently, it can be deduced that if permeability does not increase or begins to decrease at even higher pressures (above 0.4 MPa), this may suggest the predominance of fouling processes. Consequently, while the graph suggests a positive correlation between pressure and membrane permeability, the observed differences in growth dynamics among diverse membranes imply that certain membranes may be more vulnerable to fouling, potentially resulting in a decline in membrane efficiency downstream.

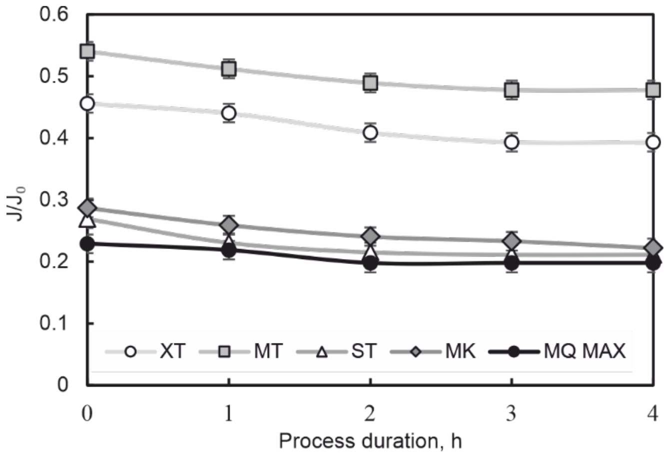

Fig. 7. Effect of UF process duration
on relative membrane permeability (TMP = 0.4 MPa)

An evaluation of the effect of membrane operating time on the change in the value of relative membrane permeability (Fig. 7) revealed a systematic decrease in relative membrane permeability with increasing process time. This finding is indicative of a progressive obstruction of the pores and subsequent deposition of impurities on their surface. It was further observed that XT and MT membranes exhibited the highest initial permeability, yet their decrease over time was more pronounced compared to the other membranes. This observation may be indicative of their heightened susceptibility to fouling, likely attributable to surface characteristics or pore structure. In contrast, the MK and MQ MAX membranes exhibited lower initial permeability, yet their performance decline was less pronounced over time. This observation suggests a higher degree of resistance to blockage in these membranes. Consequently, further research is recommended to investigate the mechanisms of membrane fouling, encompassing the nature of the sludge and its impact on permeate flow restriction. Optimization of process parameters and the potential use of cleaning methods could improve the long-term performance of membranes and increase their utility.

4. CONCLUSIONS

A series of deductions can be formulated in light of the findings:

- The selection of an appropriate membrane is imperative for the efficacy of brewery wastewater treatment.
- Separation properties are contingent on the limiting resolution of the membranes – a decline in permeate quality was observed as this parameter increased.
- The XT membrane (1000 Da) exhibited the highest DOC removal efficiency and reduction of COD and BOD_5 due to the smallest pores, which effectively restrict the permeation of organic molecules.
- An increase in TMP did not result in a substantial enhancement in separation efficiency, particularly for membranes with larger pores.
- Over the analyzed time interval, the UF efficiency remained stable, indicating good resistance of the membranes to their blockage and no need for frequent regeneration in short-term filtration cycles.
- The transport properties of UF membranes significantly depend on TMP, cut-off, and membrane lifetime.
- An increase in the TMP and cut-off of the membranes increased the permeate flux value, while the hydraulic capacity of the membranes successively decreased with the time of operation.

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