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Multistage ultrafiltration treatment of brine from fish processing in the aspect of regeneration and reuse in the production cycle

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ABSTRACT

In this paper, the results of the multistage research based on ultrafiltration using ceramic membranes with an active layer of TiO_2/ZrO_2 and 300 – 8.0 kDa cut-off are presented. This work seeks to advance the state of the art in the membrane technology for a protein separation and treatment of waste brine from fish processing. In the first stage, analyses and evaluation of a ceramic membrane performance in model protein-water-NaCl systems were performed and molecular simulation studies on a model protein size and stability in certain pH ranges were carried out. In the second stage, tests on the treatment of industrial waste brines using commercial membrane modules with a filtration area of 0.35 m^2 were conducted. The filtration tests were carried out using a pilot plant with a tubular module under variable process conditions. The ultrafiltration treatment of waste brines was investigated using single and multistage technology schemes. The obtained results were elaborated in the form of a database for a decision support system. In the third stage, the decision support system was developed using MATLAB based on the database of results. The elaborated decision support system enables the selection of an optimal scheme of technology for the treatment of waste brines from fish processing and protein concentration for its further use.

Keywords: Ceramic membranes; Ultrafiltration; Waste brine; Decision support system

1. Introduction

To meet requirements for sustainable development and growing environmental challenges, much attention should be paid to environmental approaches to all areas of human activity. An environmental approach is a concept-oriented term that encompasses green chemistry, cleaner production, waste minimization, and zero waste strategy. In a broad sense, new processes that protect the environment may be called eco-innovations. Such eco-innovations are a way of implementing the "zero waste" strategy [1–4]. It should be pointed out that environmental innovation issues are of much interest not only for researchers, but also for commercial players. Industry can help to overcome global environmental challenges in an economically beneficial way by identifying areas, in which research-derived solutions can substantially reduce impact on the environment. At the same time, environmental innovations are an opportunity for enterprises, especially small and medium ones, to save costs, create new products and work-places, as well as expand into new markets.

When discussing the environmental impact of food processing, it is important to use a holistic approach, which attempts to further related goals: promoting the highest product quality, safety, and production efficiency, while also protecting the environment. A production strategy that employs a holistic approach generally involves closed-loop systems.

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The application of closed-loop systems in wastewater treatment leads to valuable substances recovery and clean water reuse. The ultrafiltration (UF) process, with its application of polymeric and ceramic membranes, is currently the preferred technology for deriving adequate quality water product from used water [5–8].

The fish processing industry characterizes with a high level of water consumption and the production of huge amounts of salted wastewater. Spent brine produced in fish processing is a troublesome by-product, because of its high content of sodium chloride. However, spent brine also contains valuable substances derived from the processed fishes. It contains inorganic and organic particles, which lead to the brine's characteristic deep dark color, high turbidity, and conductivity. A possibility to recycle treated brine and valuable substances in the form of fish proteins and protein hydrolysis products is highly desirable, because of the potentially significant reduction in freshwater demand and waste treatment requirements as well as the conservation of materials.

Advantages of the applying membrane processes and inorganic membranes for utilization of waste brine are that they can be used for both brine treatment as well as proteins recovery. Inorganic membranes have high practical application potential, because of their high-performance and low fouling resistant properties. As has been presented in earlier papers, the concept of regeneration of waste brine with the aim of closing water loops in fish processing consists of a pretreatment step and a multistage UF process using ceramic membranes. Previous studies using UF process have shown that ceramic membrane with a cut-off of 150 kDa may be used as a main step in a hybrid technology for the removal of proteins and protein hydrolysis products from spent brines [9–14].

There are two main factors in the treatment of spent brine by UF process, which relate to its technical feasibility and operational efficiency. The first factor is the selection of membrane cut-off and number of stages in membrane technology. The second factor is the membrane fouling, which limits operation productivity; the feed quality must be addressed through the proper pretreatment of spent brine and operational parameters selection.

Recently, decision support systems (DSSs) have broadly been used in the wastewater management field [16–19]. They are defined as multilevel knowledge-based systems, which not only improve the quality of decisions, but also shorten decision-making time. Most of the researchers in the field have used knowledge-based and rule-based concepts in developing a DSS [20].

The main objective of the presented research was to develop and apply a DSS for the selection of a number of stages and membrane cut-offs for purification technology enabling the reuse of spent brine from fish processing and protein recovery. For this purpose, multistep investigations, consisting of UF tests using synthetic solutions and industrial spent brine were carried out together with molecular modeling, physicochemical and high performance liquid chromatogaphy (HPLC) analysis and computer simulations (Fig. 1), including:

- performing one-step UF tests using model protein (bovine serum albumin, BSA and myoglobin, Mb) solutions as a feed to identify, which operating parameters had crucial effect on ceramic membranes permeability and selectivity;
- performing one-step UF tests using industrial waste brine as a feed to determine total protein (TP) rejection and membrane permeability by ceramic membranes with cut-off in the range of 8–300 kDa;
- evaluation of the feasibility of using multistep (two and three) UF system for industrial brine clarification and protein rejection;
- application of experimental and other data necessary to develop an expert system supporting the design of membrane purification technology for brine reuse.

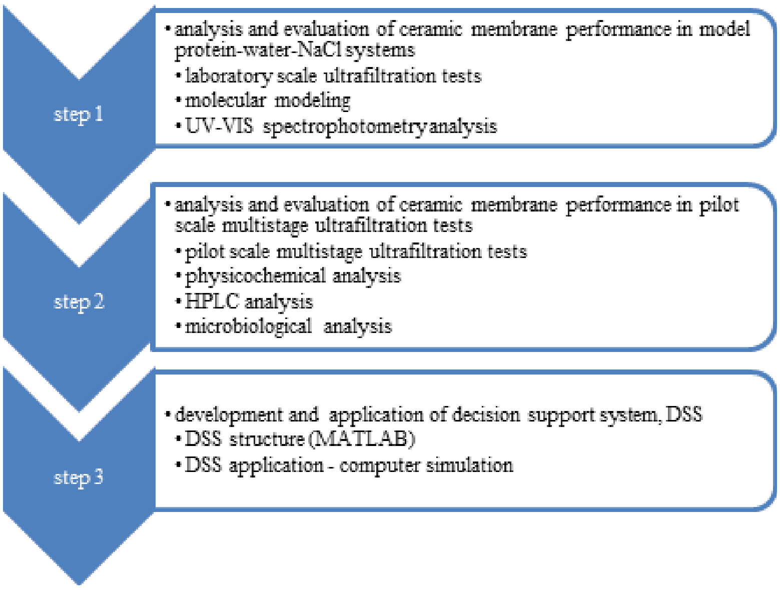

Fig. 1. Main steps in development of membrane technology for protein recovery and treatment of spent brine from fish meal industry.

2. Experimental

2.1. UF tests of model protein solutions

The UF tests were carried out using laboratory and pilot scale membrane installations. The laboratory installation was equipped with the cross-flow module and 150 and 50 kDa flat ceramic TiO_2/ZrO_2 membranes, feed tank of 2 dm^3 volume, heat exchanger, and pressure pump. As a feed, synthetic solutions of Mb and BSA with and without addition of NaCl were used. The pilot plant consisted of the commercial membrane module with noncylindrical 150 kDa ceramic membrane and feed tank of 15 dm^3, in addition to the pump and heat exchanger. The UF operational and measured parameters are summarized in Table 1.

The experiments were conducted in a closed-loop regime with continuous permeate and retentate recycling. After each UF test, the membrane installation was cleaned according to the manufacturer's recommendation. For the determination of the protein concentration in the feed, C_F and the permeate, C_P samples, UV-VIS spectrophotometer with quartz cuvettes was used. During UF tests of synthetic protein solutions, membrane permeability and selectivity, expressed by permeate flux, J_V and protein rejection, r, respectively, was determined depending on operational parameters of the membrane process. As model proteins, BSA with molecular weight, MW = 66.5 kDa and theoretical isoelectric point, pI = 5.8 as well as Mb (MW = 17.1 kDa, pI = 7.0) were used.

2.2. UF tests of waste brine from fish processing in pilot scale

The experiments were carried out using a pilot UF system and commercial ceramic membranes with different cut-off in the range of 8–300 kDa (Table 2). The filtration runs (R1–R4) using waste brine from fish processing were performed as multistage process (Table 4) at constant temperature, $T = 298$ K, constant transmembrane pressure, TMP = 0.2 MPa, and constant cross-flow velocity, CFV = 5 m/s. The operation time for UF runs was in the range of 20–75 min. The scope of filtration runs of waste brine from fish processing is presented in Table 2.

After each UF test, the membrane installation was cleaned according to the manufacturer's recommendation. The tested industrial brines came from two fish processing plants (A and B) and were taken from four different production cycles (1–4). In Table 3, TP content in the industrial brine was summarized with error expressed by standard deviation, SD.

The characteristic feature of the waste brines tested was the content of NaCl above 10% wt., fat content in the range of 22.0–42.0 g/kg and pH in the range of 5.1–6.8. The industrial brine was initially pretreated before UF steps using bag filters (Fig. 2). At the stage of bag filtration, industrial filter bags made of 100 μm polypropylene nonwoven and volume of 3 L were used. During UF tests, membrane installation was operated in the half-open mode with the continuous permeate discharge (cleaned brine) and recycling of the retentate (concentrated fish proteins and products of protein hydrolysis). The scheme and the description of the used multistage membrane system for the treatment of waste brine and tested membrane cut-offs is presented in Fig. 2 and Table 4, respectively.

In order to estimate the molecular weight range of proteins and their hydrolysis products, qualitative analyses of industrial waste brines using HPLC were made. Fig. 3 presents a chromatogram characterizing the molecular weight range of proteins and their hydrolysis products obtained in the UF process of waste brine from plant A using 150 kDa membrane. According to this chromatogram, the tested brines contain fish proteins and their hydrolysis products in the molecular weight range of 100–0.01 kDa (blue curve). The use of the 150 kDa membrane removed the proteins of weight in the range of 100–10 kDa (green curve) and protein substances with a molecular weight in the range of 10–0.01 kDa remained in the permeate (red curve).

In the research on the use of membranes in food processing an important criterion is the microbiological purity of permeate returned to the technological process. Therefore, microbiological tests were performed for permeate samples obtained from the UF process with the use of membranes 300 and 150 kDa. Performed microbiological analyses determined the total number of psychrophilic microorganisms at 20°C as well as number of halophilic microorganisms [14]. The performed microbiological tests showed that the tested microorganisms were absent in both UF permeates from membranes 150 and 300 kDa.

2.3. DSS development

DSS was developed in a form of a program for MATLAB, based on the principles of genetic algorithms and using a dataset containing the experimental data. The program seeks

Table 1
Scope of membrane filtration tests of synthetic protein solutions

Independent variables of the membrane process	Dependent variables of the membrane process
1. Membrane cut-off: 150 kDa (BSA); 50 kDa (Mb)	1. Membrane permeability – permeate flux, J_V, m^3/m^2 s
2. Membrane area: 0.35 m^2 and 0.0056 m^2 (BSA); 0.0056 m^2 (Mb)	2. Membrane selectivity, model protein rejection, r
3. Transmembrane pressure, TMP: 0.05, 0.1, 0.15, and 0.2 MPa	
4. Cross-flow velocity, CFV: 2.4 and 4 m/s (BSA); 2.4 and 3.6 m/s (Mb)	$$r = 1 - \frac{C_P}{C_F} \quad (1)$$
5. pH: 4.8–9.0 (BSA); 3.5–9.0 (Mb)	
6. Protein concentration in the feed: 1 g BSA/dm^3; 0.05 g Mb/dm^3	where C_P and C_F – protein concentration in permeate, P and feed, F, respectively, g/dm^3
7. NaCl concentration in the feed, 0 and 10% wt.	
8. Temperature, $T = 293$ K	

Table 2
Scope of membrane filtration tests of waste brine from fish processing in pilot scale

Independent variables of the membrane process	Dependent variables of the membrane process
1. Membrane cut-off: 300, 150, 50, 15, 8 kDa 2. Membrane area: 0.35 m^2 3. Transmembrane pressure, TMP: 0.2 MPa 4. Cross-flow velocity, CFV: 5 m/s 5. pH 5.0–6.7 6. Total protein content in brine, g/dm^3 7. Fat content in brine, g/kg 8. NaCl content in brine 9. Temperature, $T = 298$ K 10. Filtration time, 20–75 min	1. Membrane performance – permeate flux, J_V, m^3/m^{2}s 2. Membrane selectivity – total protein rejection $r = 1 - \frac{C_P}{C_F}$ (2) where C_P and C_F – total protein, TP content in permeate, P and feed, F, respectively, g/dm^3 3. Transport resistances in membrane module R_M, R_F, – transport resistance caused by membrane and fouling, respectively, m^{-1} $J_V = \frac{\text{TMP}}{\eta\left(R_M + R_F\right)}$ (3) $R_T = R_M + R_F$ (4) η – water/permeate viscosity, Pa. s

Table 3
Total protein content in industrial brine used as a feed in filtration tests (runs R1–R4)

Fish plant/ production cycle	Total protein (g/dm^3)	Average total protein (g/dm^3)	Standard deviation, SD
Brine B1	16.125 16.250	16.188	0.088
Brine A2	12.188 12.063	12.126	0.088
Brine A3	3.600 3.688 3.513	3.600	0.088
Brine A4	4.188 4.144 4.100	4.144	0.044

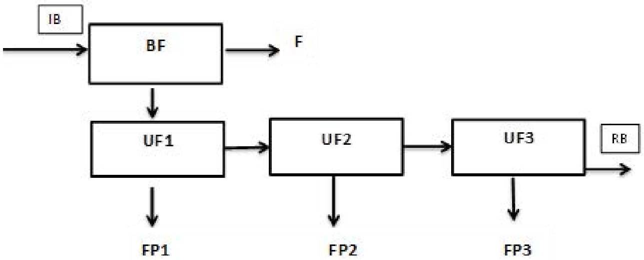

Fig. 2. The scheme of multistage membrane system for treatment of waste brine; IB – industrial waste brine; RB – regenerated brine; BF – bag filtration 100 μm; UF1–UF3 – ultrafiltration steps using ceramic membranes; F – filtration concentrate (mainly fish fat); FP1–FP3 – retentates (concentrated fish protein fractions).

Table 4
Ceramic membrane cut-offs used in the multistage ultrafiltration of waste brine from fish processing

Filtration runs	Membrane cut-off (kDa)		
	UF1	UF2	UF3
R1	300	150	–
R2	150	50	–
R3	300	150	50
R4	50	15	8

to find, among available membrane sets, the configuration that will have the highest rating according to the following criteria: (1) minimum number of membranes in the set, (2) maximum total rejection of the analyzed substance after passing the membrane system, (3) minimum C_P, (4) minimum TMP, and (5) minimum fouling. For each of the criteria, the user assigns a weight from 0 to 1, and the weighted average of the detailed ratings gives the final rating of the analyzed membrane set. It is assumed that one membrane is available for each cut-off.

Each of the membranes was described by the same set of parameters, stored in the form of a genome. The genes described the physical parameters of the membrane and the connections between the membranes in a binary form. As physical process parameters, TMP and CFV, were included and their values were read from the database. The formation of connections between the membranes assumed permeate flow from the higher cut-off membrane to the lower cut-off membrane. Two methods were used as parameters of the genetic mixing mechanism: crossing – with an even probability of choosing ancestors, during which the exchange of a random fragment of genetic material took place, mutation – negation of values at random points of genetic material, with the assumption that the number of these points did not exceed 20% of the total.

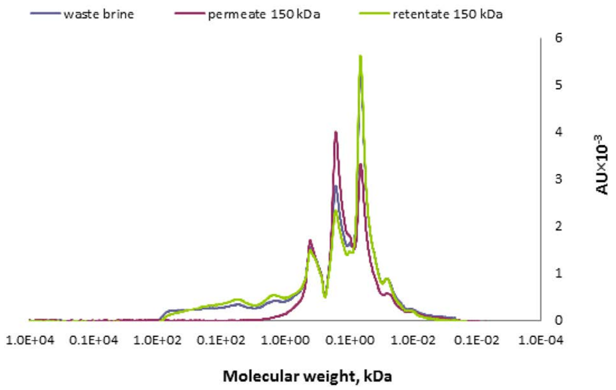

Fig. 3. HPLC chromatogram of industrial brine, permeate, and retentate samples for the UF process using a 150 kDa membrane (run R2).

The initial set of populations was generated randomly. Next, the set was supplemented with a reference case, that is, a cascade arrangement of all membranes. On such prepared set, mixing operations of the genetic algorithm were performed. Based on the evaluation function, the next generation of best adapted (with the highest scores) membrane sets was selected from both datasets (primary and mixed), with the assumption, that duplicated solutions were omitted. The evaluation of membrane sets, in addition to the above criteria, verified the limitation, according to which only the sets having one entry and one exit and deprived of internal loops and branches, were considered for further analysis. All sets, that did not meet these assumptions, were rated 0. For the remaining sets, the purification level was checked, based on the information on the rejection of the analyzed substance on subsequent membranes read from the dataset. For each analyzed set, the final rating, being the weighted average of the detailed assessments, was assigned. The weights of detailed assessments were set by the user in accordance with current needs. The program generated the final result, that is, the genome corresponding to the set of membranes, which was assigned with the highest rating, in the form of a graph representing membranes together with parameters and connections between them. The Graphviz tool [21] used to generate graphs was used for this purpose.

3. Results and analysis

3.1. Analysis of ceramic membrane selectivity and permeability in regard to UF tests and molecular modeling

The objective of the first step of research (Fig. 1) was to obtain UF data for separation of the investigated model protein as well as to reveal the mechanism of protein rejection by ceramic membrane. For this purpose, both experimental data of BSA and Mb rejection by ceramic membrane and protein molecular modeling data were collected and compared.

The analysis of experimental results showed that Mb rejection was slightly dependent on CFV and TMP in investigated range, 2.4–3.6 m/s and 0.10–0.20 MPa, respectively. In contrast, Mb rejection depended on pH and NaCl concentration in the feed and decreased with the increase of NaCl addition at pH 7.0 and 9.0. The low values of Mb rejection were obtained at pH 7.0 and 9.0 with 10% wt. of NaCl in the feed. Similarly, in the case of UF of water-BSA-NaCl synthetic solutions using 150 kDa ceramic membrane in pilot installation, protein rejection depended on pH and decreased with the increase of pH. The low values of BSA rejection were obtained for pH 6.8 and 9.0 with 10% wt. NaCl in the feed [11]. The influence of pH and NaCl concentration on the rejection of BSA and Mb by ceramic membranes with cut-offs of 150 and 50, respectively, is summarized in Table 5 and graphically presented in Fig. 5.

Investigated model protein rejection by ceramic membrane $Al_2O_3/TiO_2/ZrO_2$ could be explained taking into account membrane-protein-salt interaction with regard to proteins pI as well as membrane IEP. Experimental results presented in Table 5 and Fig. 5 show that BSA rejection was high, $r = 0.998$ and independent of pH for solutions without salt. The lowest BSA rejection was obtained for pH 9.0 in 10% salt solution, meaning that the addition of 10% of

Table 5
The influence of pH and NaCl concentration on rejection of BSA and Mb by ceramic 150 and 50 kDa membranes, respectively; membrane point of zero charge, IEP = 6.9

Model protein in feed	Feed pH	NaCl concentration in feed (% v/v)	Protein rejection, *r*	pH of min. free energy of folding
BSA	4.8	0	0.998	6.1
		10	0.993	
Molecular weight, 66.43 kD	6.8	0	0.998	
		10	0.989	
Isoelectric point, pI = 5.8	9.0	0	0.998	
		10	0.976	
Mb	3.5	0	0.981	6.4
		10	0.975	
Molecular weight, 17.053 kDa	7.0	0	0.915	
		10	0.307	
Isoelectric point, pI = 7.1	9.0	0	0.970	
		10	0.358	

NaCl caused the decrease of BSA rejection with increasing pH, probably due to hindering of protein aggregation and reduction of protein adsorption on membrane surface. The lowest Mb rejection was obtained for pH 7.0 with addition of 10% of salt. On the one hand, it can be explained by electrostatic interaction between Mb and the membrane. The lowest value of Mb rejection should have been obtained at pH around 7 as pI of Mb is 7.1 and ceramic membrane IEP is 6.9. Moreover, this behavior is in accordance with the results of molecular modeling. The pH of Mb structure maximum stability is 6.4 and it is the one at which the free energy takes the minimal value [13]. The molecular weight of tested proteins was smaller than the membrane cut-off, thus the fouling effect probably had to also be considered to explain protein rejection mechanism and membrane permeability behavior versus operational parameters.

The UF data on steady-state permeate flux, J_V and water flux, J_w for 150 and 50 kDa membranes were used for fouling analysis in terms of resistance-in-series model [15]. According to this model, flux decline versus time is caused by total transport resistance R_T, which is a sum of two characteristic resistances, membrane resistance, R_M and fouling resistance, R_F (Table 2, Eq. (4)). Selected membrane fouling data in the form of normalized resistances, R_M/R_T and R_F/R_T for UF of model BSA and Mb solutions by commercial 150 kDa and laboratory 150 and 50 kDa membranes are presented in Fig. 4.

The analysis of results presented in Fig. 4 indicates that in the examined UF systems fouling resistance, R_F had a greater effect on the flux than the resistance of the active membrane layer, R_M. It was also observed that membrane permeability and fouling of both 150 kDa and 50 kDa membranes in UF of model BSA and Mb solutions were depended on pH, TMP, and presence of NaCl in the feed solutions. The highest membrane fouling and lowest permeability was observed at pH value below membrane IEP (6.9) and BSA and Mb isoelectric points, pI 5.8 and 7.1, respectively. At pH values above 7.0 membrane fouling by both proteins was smaller, but increased with the addition of salt. Thus, both membrane-protein charge interactions and fouling effects were responsible for the protein rejection mechanism.

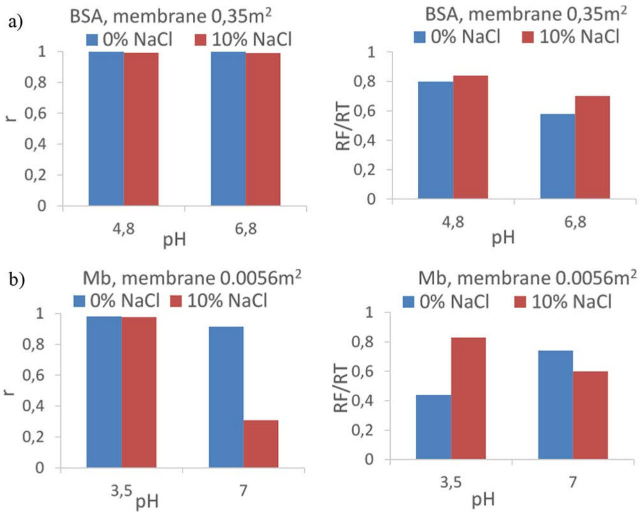

Fig. 4. Graphical presentation of the influence of pH and NaCl concentration on protein rejection, *r* and normalized transport resistance, R_F/R_T for ultrafiltration of model BSA (a) and Mb (b) solutions by ceramic 150 and 50 kDa membranes, respectively.

Fig. 5 presents a comparison of the analysis of the influence of pH and salt concentration on normalized resistance, R_F/R_T for UF results obtained using a model BSA protein solutions and two membrane installations, laboratory and pilot ones. The conclusions from the analysis, using the normalized fouling resistance, R_F referred to the total transport resistance, R_T are convergent. In the case of a practical application, the recommended pH is in the range of 6.8–7.1, close to protein pI and ceramic membrane IEP.

3.2. UF of industrial waste brine in pilot scale

The experimental results characterizing membrane selectivity obtained for tested multistage UF runs, R1–R4 (Table 4) using ceramic membrane with cut-off 300, 150, 50, 15, and 8 kDa are presented in Table 6 and Figs. 6 and 7.

The results of TP content in industrial brines and permeates listed in Table 6 are the mean values of two (R1, R2) and three (R3, R4) measurements with an error determined by the SD.

The curves R1–R4 presented in Fig. 6 show the decrease in TP content in purified streams leaving subsequent stages of multistage industrial brine UF.

According to the results summarized in Table 6, the highest TP rejection, above 50%, was obtained using three technological schemes: UF150→UF50 (R2), UF300→UF150→UF50 (R3), and UF50→UF15→UF8 (R4). Moreover, the results presented in Figs. 6 and 7 show that TP rejection as well as TP content in final permeates depended on the TP content in the treated industrial brine.

The analysis of the data presented in Table 6 and Figs. 6 and 7 leads to the conclusion that membranes with cut-off 300, 150, 50, and 8 kDa could be taken into account as the best solution for multistage UF treatment of waste brine. The permeates obtained after multistage UF process were transparent with good smell. Considering the microbiological and organoleptic analysis of permeates after UF of waste brine, it can be concluded that they can be recycled to the production cycle in fish processing [14].

3.3. Application of DSS

A developed DSS was used for the evaluation of the rejection and TP content in the final permeate for multistage UF process (Fig. 2) and membranes with different cut-offs

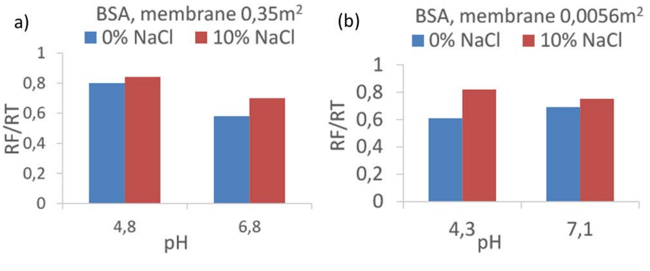

Fig. 5. The comparison of the influence of pH and salt concentration on normalized resistance, R_F/R_T for UF process of model BSA protein and two membrane installations with commercial (a) and laboratory (b) scale ceramic 150 kDa membrane.

Table 6
The effectiveness of multistage membrane systems in relation to total protein (TP) rejection; R1–R4 experimental runs

Filtration runs	TP concentration in IB (g/dm^3)	TP concentration in P (g/dm^3)	TP rejection for one step	TP rejection for BF + UF system	TP rejection for UF system
R1 (brine B1)	16.19 ± 0.09				
BF		12.90 ± 0.08	0.20		
UF300		8.80 ± 0.09	0.32		
UF150		9.40 ± 0.13	–	0.42	0.27
R2 (brine A2)	12.13 ± 0.09				
BF		8.90 ± 0.07	0.27		
UF150		6.51 ± 0.03	0.27		
UF50		5.19 ± 0.06	0.20	0.57	0.42
R3 (brine A3)	3.60 ± 0.09				
BF		2.98 ± 0.09	0.17		
UF300		2.74 ± 0.01	0.08		
UF150		1.60 ± 0.07	0.42		
UF50		1.60 ± 0.02	–	0.56	0.46
R4 (brine A4)	4.14 ± 0.04				
BF		3.47 ± 0.04	0.16		
UF50		2.48 ± 0.02	0.29		
UF15		2.29 ± 0.02	0.08		
UF8		1.98 ± 0.03	0.14	0.52	0.43

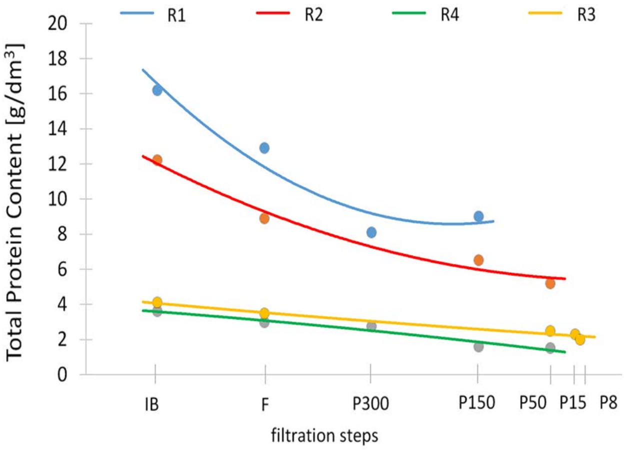

Fig. 6. Total protein content in industrial waste brines (IB), filtrates (F), and permeates (P) for filtration runs with different membrane cut-offs (R1–R4, Table 4).

(Table 4) used in experimental study. DSS allows for the selection of the best treatment scheme taking into account the following criteria: (1) the minimum number of connections between the individual membrane modules, (2) the maximum TP retention, (3) the minimum concentration of the removed component in the final permeate, (4) possibly low TMP, and (5) minimum fouling (depending on the permeate volume flux, J_V). The selected solutions obtained using DSS are summarized in Table 7 and Fig. 8. Simulations, S1–S6 were performed with selected weights assigned to criteria 1–5 in the range of 0–1.

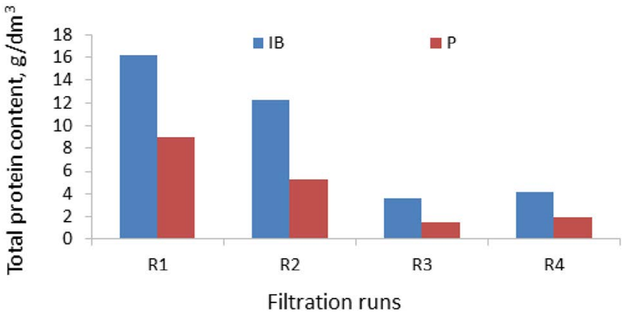

Fig. 7. Total protein content in industrial waste brine (IB) and final permeates (P) (Table 6) for filtration runs R1–R4 (Table 4).

According to the data presented in Table 7, the problem solution, that is, number of stages in the UF system and membrane cut-offs depends on the weight of the criteria 1–5. The solutions characterized with the highest degree of the protein retention (0.78) were obtained for two- and three-stage UF systems (S5, S6). If the priority were two basic properties of the membrane process, that is, low protein concentration in the permeate (criterion 3) and fouling (criterion 5) with the same weights (0.5), the optimal choice was two-stage UF using 150 and 50 cut-off membranes. However, if the requirements for the permeate purity were higher (criterion 3 with a weight of 0.9), it would be necessary to supplement the technological scheme with another UF module and membrane with cut-off of 8 kDa.

Using the developed DSS, it is possible to generate graphs (Fig. 8), which enable to determine protein retention for individual stages of the UF system. The graph shown in Fig. 8

Table 7
Results of selected simulations using DSS for two and three-stage UF systems

Simulation runs	TP concentration in feed to UF system (g/dm^3)	TP concentration in final P (g/dm^3)	TP rejection for UF system	Criterion number	Criterion weight	Solution with the highest rating	Rating
S1	12.9	9.0	0.3	1	1	150	0.96
UF300				2	0		
UF150				3	0.5		
				4	0		
				5	0.5		
S2	8.9	5.2	0.42	1	0	150	0.99
UF150				2	0	50	
UF50				3	0.5		
				4	0		
				5	0.5		
S3	3.00	1.5	0.50	1	1	150	0.92
UF300				2	0		
UF150				3	0.5		
UF50				4	0		
				5	0.5		
S4	3.5	1.98	0.43	1	1	50	0.96
UF50				2	0		
UF15				3	0.5		
UF8				4	0		
				5	0.5		
S5	8.9	1.98	0.78	1	0	150	0.99
UF150				2	0	50	
UF50				3	0.5		
UF8				4	0		
				5	0.5		
S6	8.9	1.98	0.78	1	0	150	0,96
UF150				2	0	50	
UF50				3	0.9	8	
UF8				4	0.2		
				5	0.6		

presents the output of DSS program. In the graph, information on initial and final content of treated substance as well as membrane rejection and concentration in permeate in each step is included.

4. Conclusions

Currently, eco-innovations that implement a "zero waste" strategy are an important factor in making industrial plants competitive in the international market. In the case of spent brine from fish processing plants, the implementation of a "zero waste" strategy can be achieved by solutions, which enable both the recycling of treatment brine and the separation of valuable substances in the technological cycle in the plant.

When considering environmental and cost savings technology for spent brines, utilization of the concept of a multistage membrane system, with the aim of closing water loops as well as reusing recovered byproducts, is a most promising technique. Due to the large range of various contaminants in fish brines, several steps in the developed treatment technology have to be considered, when applicable, that is, pretreatment by filtration, protein fractionation by multistage UF with different cut-offs, and nanofiltration to clean water thoroughly.

In the three-step research, the technical feasibility of a membrane UF system for protein separation and treatment of waste brine from fish processing was determined. Results from laboratory and short-term pilot scale tests were encouraging with regard to practical applications. The main conclusions of the study include the following:

- analysis of experimental results obtained using model proteins in regard to molecular modeling data enables understanding the dependence of protein rejection and membrane fouling on two crucial feed parameters, NaCl concentration and pH.
- the UF results of industrial brines in one-, two-, and three-stage systems determine membrane rejection and permeability characteristics and allow for the selection of suitable membrane cut-off for each step of the treatment

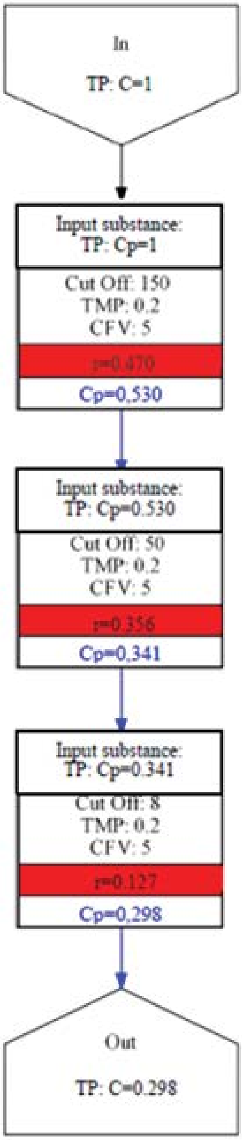

Fig. 8. An exemplary graph of solution obtained using the developed decision support system for simulation run S6.

technology as well as for choosing the appropriate operational parameters; the highest value of TP rejection for one stage in multistage systems investigated were obtained for ceramic membrane with cut-off 150, 50, and 8 kDa.

- the developed DSS allows for the selection of the best treatment scheme and membrane cut-off taking into account five membrane criteria with weights in the range of 0–1.
- the selection of the number of stages and cut-off membranes for brine regeneration using DSS is consistent with the results of experimental tests.

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