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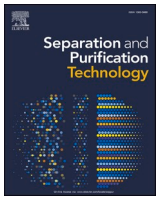

Adsorption-assisted membrane filtration with a cellulose derivative for separation of cationic compounds

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ABSTRACT

This study explores the first-time use of dicarboxymethyl cellulose (DCMC) in an adsorption-assisted membrane filtration (AMF) process for the removal of cationic compounds from aqueous solutions. DCMC and microfiltration commercial membranes were used in an integrated dead-end filtration system, with Cytochrome *C* (Cyt C) as a model protein. The experiments were performed in a stirred cell with powdered DCMC on the retentate side. The work evaluated the effect of stirring, contact time and membrane material on the removal efficiency. Regenerated cellulose, polyamide and polyethersulfone membranes were tested, showing no significant differences in performance. High retention was achieved without compromising permeability, with fluxes up to 700 L m^{-2} h^{-1}. The filtration performance remained consistent after three consecutive regeneration cycles. The adsorption capacity of DCMC was assessed by discontinuous filtration with a PES membrane and 200 mg of DCMC. Following 38 min of filtration, saturation occurred with approximately 1.8 L of a 100 mg L^{-1} Cyt C solution. The results showed that the AMF system was successfully employed, with the adsorbent (DCMC) playing a crucial role in the removal of Cyt C.

1. Introduction

Membrane filtration is a highly efficient process known for its ease of operation and installation, as well as excellent separation efficiency and selectivity [1,2]. However, the deposition of target molecules and the formation of a cake layer can lead to membrane fouling, which impacts the efficiency and lifespan of the membranes [3]. The tuning of the membrane surface charge and hydrophilicity provides anti-fouling properties, which can help reduce one of the drawbacks associated with this technology [3,4]. Currently, petroleum-based polymer membranes are prevalent in the industry, though transitioning towards bio-based materials is necessary to fulfill environmental regulatory goals [5,6].

Adsorption is a widely used separation method for remediation and removal of molecules comprising dyes, proteins and other macromolecules [7,8]. There is a high research interest regarding adsorption on different surfaces, such as silica nanoparticles [9], mesoporous molecular sieves [10], zeolites [11], macroporous cellulose microspheres [12], among others. The adsorption onto polymer surfaces depends on the interaction between polymer and the target molecule, including electrostatic interactions, van der Waals forces, hydrogen bonding, steric effect, charge, and ionic strength of the solution [13]. Overall, challenging adsorbent regeneration and low selectivity can negatively impact the cost and efficiency of the adsorption process, but these limitations can be addressed by functionalizing and tailoring the properties of the adsorbent [14]. Biopolymers, namely polysaccharides like cellulose, chitosan, chitin and carrageenans, can work as natural bio-adsorbents due to the presence of amino and hydroxyl functional groups. Enhancing the inherent properties of these ubiquitous materials or using them as feedstock is both cost-effective and environmentally friendly, providing an affordable alternative to fossil-base adsorbents [15,16].

Described extensively in literature over the past two decades, AMF integrates the processes of adsorption and membrane filtration into a cohesive hybrid separation system [17–19]. This process may be divided in three categories: pre-adsorption, post-adsorption and synergistic integration of adsorption and membrane filtration [20]. AMF offers efficient solute removal, reduced membrane fouling, high flux and low

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cost associated with the regeneration and reusability of the adsorbent (or binding agent) [17,21,22]. By combining adsorption and membrane filtration, this streamlined single-unit process can be applied to the removal of contaminants of emerging concern. This dual-functional approach is widely applied in water treatment, particularly for removing natural organic matter, dyes, pharmaceuticals, metals and other contaminants [17]. Several types of membranes have been used in hybrid systems, including nanofiltration, ultrafiltration and microfiltration membranes. Additionally, powdered activated carbon, zeolites, metal–organic frameworks and polymeric adsorbents have been described for the removal of natural organic matter, heavy metals, dyes and pharmaceuticals [17,19,23]. The target molecules are adsorbed onto the material and then recovered or separated by membrane filtration [24]. This cost-effective approach aims to address the limitations of the conventional single processes and offers an alternative to traditional fixed-bed columns [21,22,24,25]. Adsorptive membranes display the same dual-functionality inherent to the AMF hybrid system in terms of adsorption and membrane separation. Unlike conventional membranes, adsorptive membranes are functionalized with active binding sites that enhance separation, based on chemical affinity towards target compounds [26]. The ability to operate at low pressures results in low energy consumption while maintaining high permeability flux [26,27]. The reversible nature of adsorption enables regeneration and recyclability, which are also key advantages of these processes [27]. Biopolymeric materials, which offer promising alternatives to petroleum-based polymers, further illustrate the importance of bio-based adsorbents in enhancing the sustainability of hybrid systems [6,15]. Among these materials, cellulose is the most abundant. Cellulose content varies significantly depending on its source; wood has approximately 40–50%, while plants like flax, jute and sisal can have up to 70%. Additionally, other components like lignin and hemicelluloses also differ based on the source, impacting cellulose extraction and purification processes [28]. Furthermore, functional groups are added to the cellulose backbone through cellulose derivatization, adding and improving favorable characteristics to the polymer, like the introduction of desired surface charges [22,29].

DCMC is a cellulose derivative obtained via the partial substitution of hydroxyl groups by dicarboxymethyl groups [30]. Several batch adsorption studies involving DCMC, targeting both small and macromolecules, were recently reported [31,32]. Specifically, protein adsorption by DCMC was evaluated and confirmed to be a charge-dependent process. The adsorption of four model proteins, cytochrome *C* (Cyt C), lysozyme (Lys), α-lactalbumin (α-LA) and bovine serum albumin (BSA) showed that adsorption by DCMC relied on electrostatic interactions between polymer and proteins. Hence, at pH = 7 only the positively charged proteins, Cyt C and Lys, were adsorbed by this anionic polymer [32]. The work showed great potential in charge-based protein adsorption by DCMC and influenced further investigation of the application of DCMC in other separation processes. Moreover, the polymer has been reported as a selective adsorbent of other cationic molecules from aqueous media, like white wine proteins [33,34], pharmaceutical compounds [35], methylene blue [31], and other dyes [35].

Primarily, the novelty of this work lies in the use of DCMC in a hybrid AMF process for the first time. This work is based on previous studies on protein adsorption by DCMC, while distinguishing itself by focusing on a combined membrane process opposed to a simple batch adsorption. Thus, DCMC was used as an adsorbent in AMF coupled with commercial microfiltration membranes of regenerated cellulose (RC), polyamide (PA) and polyethersulfone (PES). The hydrophilic properties and pore size of the membranes will contribute to high permeabilities, while effectively trapping the DCMC particles. The effect of stirring and contact time on the adsorption efficiency was studied. Moreover, the reusability of both DCMC and its combined use with membranes was studied. A discontinuous diafiltration operation was implemented to obtain the adsorption capacity and provide the operational parameters related to the breakthrough and exhaust times, as in a fixed-bed column. This study paves the way for future exploration of DCMC-based adsorptive membranes, thereby bridging the current gap between utilizing DCMC solely as an adsorbent and incorporating it into membrane preparation for enhanced separation performance.

2. Materials and Methods

2.1. Materials

Sodium phosphate monobasic (99% purity) and Cyt C were purchased from Sigma Aldrich (Darmstadt, Germany). RC (Cat. No. 18406), PA (Cat. No. 25006) and PES (Cat. No. 15406) membrane filters were obtained from Sartorius (Germany). Sodium phosphate dibasic dodecahydrate was purchased from José M. Vaz Pereira (Lisbon, Portugal). DCMC (DS = 0.03) was synthesized as previously described by the authors [32].

2.2. Characterization of dicarboxymethyl cellulose

Extensive characterization of this polymer, such as Fourier-transform infrared spectroscopy, solid state nuclear magnetic resonance, thermal stability and degree of substitution, has been previously published by the authors [32]. The mean particle size and the particle size distribution (10th percentile, d_{10}; median size, d_{50}; 90th percentile, d_{90}; and span) of DCMC were determined using a laser scattering particle size distribution analyzer Partica LA-960 V2 (Horiba Scientific, Kyoto, Japan). The particle size distribution span, which is derived from the cumulative distribution of the particle size, is calculated using Equation (1). The mean diameter over the volume distribution ($d_{4,3}$, De Brouckere mean diameter) is calculated by the equipment through Equation (2) [36]. Prior to this characterization, a mixture of DCMC and ethanol was homogenized using an ultra-turrax (IKA T-18, Staufen, Germany) for 5 min at 7000 rpm. Then, the suspension was filtered and dried under vacuum pressure. The samples were analyzed by the dry measurement method, with tests performed in triplicate (n = 3) at room temperature. Results are expressed as the mean ± standard deviation.

$$span = \frac{d_{90} - d_{10}}{d_{50}} \quad (1)$$

$$d_{4,3} = \frac{\sum n_i d_i^4}{\sum n_i d_i^3} \quad (2)$$

where n_i is the number of particles with a diameter d_i.

2.3. AMF hybrid process

2.3.1. Experimental setup and procedure

Filtration tests were performed in a dead-end stirred-cell device (Amicon Model 8400, Merck Millipore, Darmstad, Germany) with an effective membrane area of 41.8 cm^2. The unit was pressurized with nitrogen gas and pressure was monitored by a manometer connected to the upper housing opening. A flat sheet commercial microfiltration membrane was placed on the appropriate plate, sealed with a silicone gasket, and the solution was stirred with a magnetic impeller. Powdered DCMC (200 mg) was added to the filtration cell. A schematic of the filtration system is presented in Fig. 1. The complete apparatus consists of the dead-end stirred cell, a magnetic stir plate, a nitrogen cylinder, equipped with a two-stage pressure regulator, and a manometer.

A single-component protein solution was prepared for the filtration experiments. Cyt C was selected as the model protein following findings previously reported by the authors [32]. Additionally, this protein was also chosen for its ease of qualitative assessment, as changes in concentration can be easily observed by UV–Vis spectrophotometry. The protein was dissolved in a phosphate buffer solution (1 mM, pH 7), with

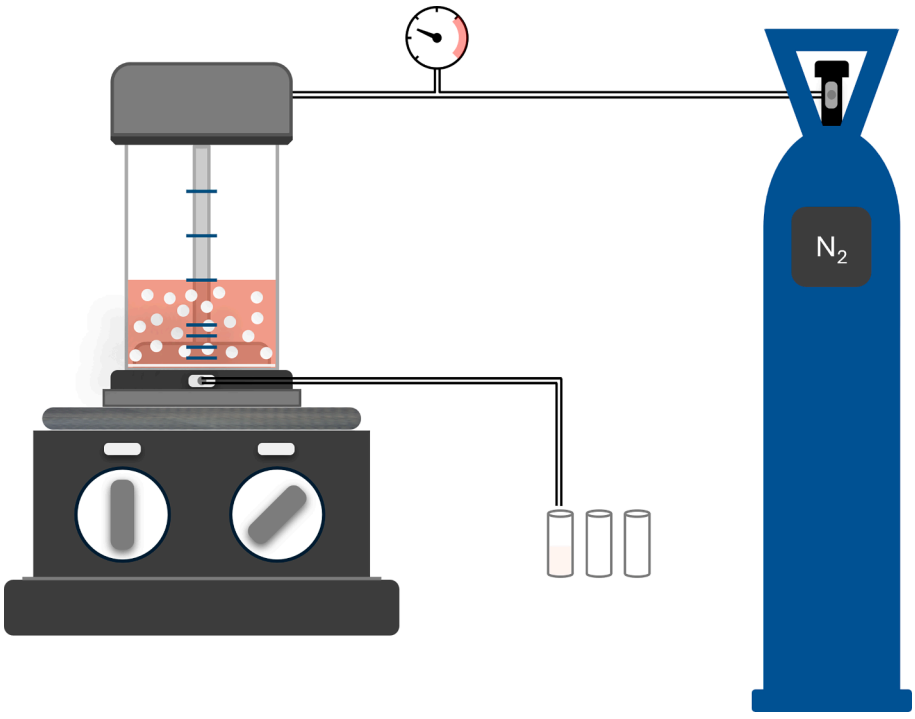

Fig. 1. Scheme of the adsorption-assisted membrane filtration system.

a concentration of 100 mg L^{-1}. Aliquots of the permeate were collected and assayed in a VWR M4 spectrophotometer (Ismaning, Germany) at 410 nm. Cyt C concentrations were calculated with a calibration curve in the range of 0–100 mg L^{-1}. Protein removal was calculated by the following equation:

$$Cytochrome\ C\ removal\ (\%) = \left(\frac{C_f - C_p}{C_f}\right) \times 100 \quad (3)$$

Where C_f and C_p (mg L^{-1}) are the feed and permeate concentrations, respectively.

After each experiment, the permeate flux (J) was calculated using the following equation [37].

$$J = \frac{\Delta V}{A \times \Delta t} \quad (4)$$

where V (L) is the total volume of the permeate, A is the active surface area of the membrane (m^2) and t is the permeation time (h).

2.3.2. Screening of commercial membranes

Three different commercial membranes (PA, RC and PES), with a pore size of 0.45 μm, were screened for rejection of Cyt C. The entire process was performed at room temperature with the dead-end cell pressurized with nitrogen gas at 0.2 bar. All flat-sheet membranes were pre-conditioned with deionized water for 5 min at room temperature. Immediately after, the phosphate buffer solution was filtered. Afterwards, the Cyt C filtration experiments were carried out. The characteristics of the commercial membranes are listed in Table 1.

Table 1
Characteristics of PA, RC and PES commercial membrane filters used in the AMF system.

	PA	RC	PES
Material	Polyamide	Regenerated cellulose	Polyethersulfone
Pore size	0.45 μm	0.45 μm	0.45 μm
Thickness	115 μm	170 μm	150 μm

2.3.3. Regeneration studies

The adsorption–desorption experiments were carried out as described previously by the authors [32]. DCMC was treated with a 1 M NaCl solution to elute the protein. The adsorbent was washed with deionized water to complete the regeneration and remove the remaining salt ions. DCMC was used in three adsorption cycles to assess its reusability.

2.3.4. Discontinuous diafiltration

The dead-end cell was fed in batch concentration mode, and a total of 2 L of protein solution were added to the filtration cell while the permeate was continuously collected. In this approach, sequential fed-batch adsorption experiments were achieved by addition of a total of ten protein solution volumes (200 mL each). The solution volumes were stirred for 15 min prior to permeation. Then, the next volume was added, and the process was repeated until the 2 L of protein solution were permeated. The results were analyzed as if they were obtained from a fixed-bed column breakthrough curve. The time of breakthrough (t_b) and exhaustion (t_e) were defined as the time when Cyt C concentration was 5% and 95%, respectively, of the initial protein solution concentration [38]. The experimental data was adjusted by a sigmoidal growth function (Logistic5) using Origin Pro 2022 software (OriginLab, Northampton, MA, USA).

3. Results and Discussion

3.1. Particle size analysis of powdered DCMC

The particle size analysis of DCMC is essential for a comprehensive understanding of the morphology of the polymer. The bimodal particle size distribution of DCMC is shown in Fig. 2. The mean particle size of the polymer is 188.68 ± 3.00 μm. For comparison, the commercial cellulose (C6288 Sigma Aldrich) used in the synthesis of this polymer has an average size between 5 and 30 μm [39]. The difference in size between DCMC and its precursor can be attributed to a change in the hydrogen bond structure after the addition of the malonic group. The uneven disruption of the original hydrogen bonding by heterogeneous

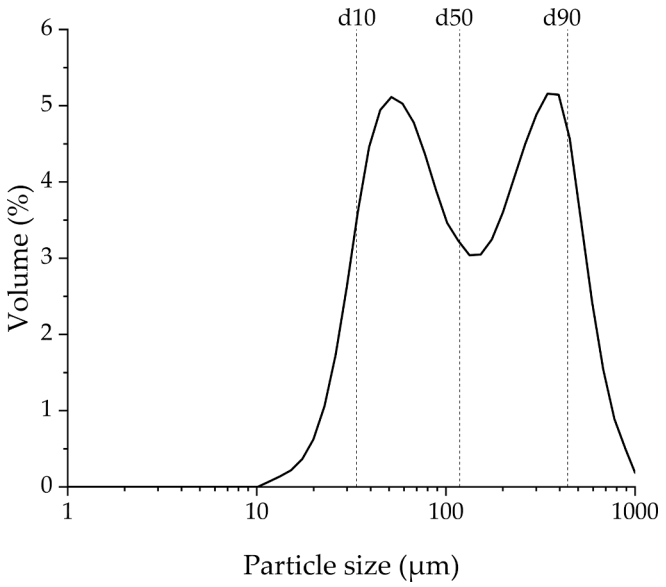

Fig. 2. Particle size distribution curve of DCMC.

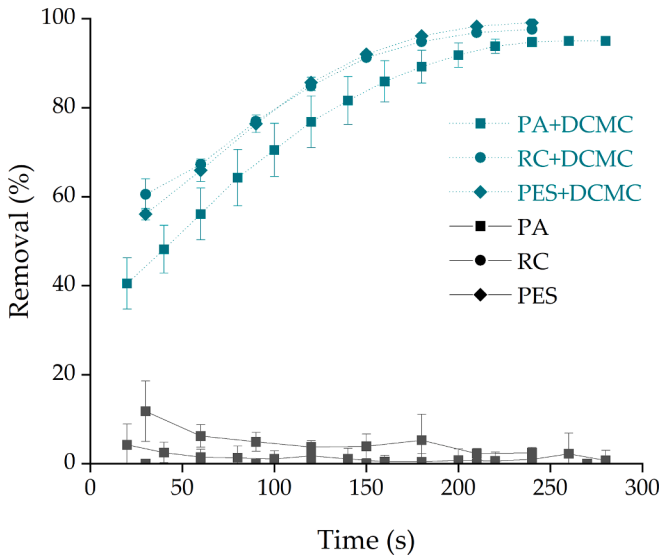

Fig. 3. Removal of Cyt C by PA, RC and PES commercial membranes, both individually and coupled with DCMC.

substitution with carboxymethyl groups adds to the complexity of the structure, altering both intra- and intermolecular hydrogen bonding of the polymer [40]. The unsubstituted parts of DCMC caused by the uneven substitution pattern can lead to pseudo-crystalline aggregates [41]. The interaction between hydrophobic moieties results in aggregate formation, which corroborates the results [42]. The particle size distribution parameters, d_{10}, d_{50} and d_{90}, are 33.66 ± 1.50, 118.41 ± 10.67 and 439.34 ± 10.27 μm, respectively. This broad particle size distribution shows that the particle size is not uniform. The span of 3.45 ± 0.36 is consistent with a bimodal distribution, as it indicates a larger particle dispersion [36]. These results show that the pore size of the commercial membranes (0.45 μm) used in this work is significantly smaller than the polymer, thereby preventing its permeation. Although alternative disaggregation processes like high frequency ultrasound or high-pressure homogenization could also be applied for particle size reduction [43,44], the ultra-turrax was used as the standard method in this trial.

3.2. Model protein removal by AMF hybrid process

3.2.1. Screening of commercial membranes

Commercial membranes with the same pore size but fabricated from different materials were tested separately and with powder DCMC for protein adsorption. Fig. 3 shows the results obtained for the removal of Cyt C in a dead-end filtration system. The results demonstrated that none of the membranes screened for these experiments rejected the protein. The removal efficiency was below 10% for any tested membrane. The model protein used, Cyt C, is much smaller (12 kDa, r_H = 1.7 nm [45]) than the pore size of the membranes (0.45 μm), therefore it is permeated through membrane filtration if no non-specific adsorption occurs.

In the AMF approach, DCMC was added to the filtration system, which had a significant impact on the removal of Cyt C. Based on the figure, it is inferred that the polymer is the primary agent responsible for capturing the protein. Previous work showed that the adsorption mechanism of DCMC is predominantly influenced by electrostatic interactions [32]. At pH 7, the anionic group of DCMC is mainly deprotonated while Cyt C is positively charged, promoting electrostatic attraction between the polymer and the model protein. Moreover, the ascending removal rate with time is explained by the adsorption kinetics of DCMC. Despite its fast adsorption kinetics, the polymer requires close to 5 min to achieve complete protein adsorption. In summary, the hybrid system enables the adsorption of cationic molecules by DCMC and effectively retains the polymer in the filtration cell, due to the membrane's pore size being significantly larger than the polymer's particle size.

Fig. 4 illustrates the relationship between permeate flux and the chosen type of system (adsorbent only versus AMF). The results show that the material of the membranes did not severely impact the permeate flux. Additionally, a hybrid approach including the DCMC polymer does not show a direct influence on permeate flux. Overall, permeate flux varies between 640 and 720 L m^{-2} h^{-1}. These fluxes are consistent with those of microfiltration membranes, which typically range from 500 to 10 000 L m^{-2} h^{-1} [46]. It should be noted that the experiments were all performed at a low pressure of 0.2 bar, which justifies the flux values being on the lower end of this range.

3.2.2. Effect of contact time and stirring

The influence of contact time and stirring on the removal of Cyt C is depicted in Fig. 5. The contact time between the polymer and the solution before filtration was examined under three different conditions: 1) immediate pressurization of the stirred cell system after adding the protein solution, 2) after 15 min, and 3) after 1 h of contact. Fig. 5a

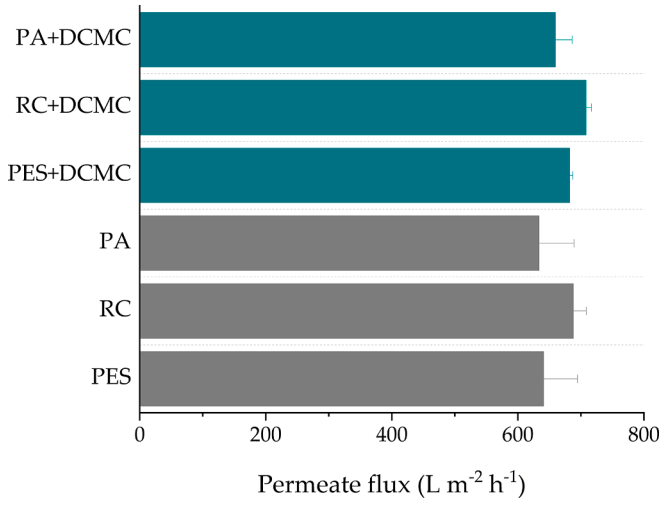

Fig. 4. Permeate flux of PA, RC, and PES membranes, both individually and coupled with DCMC.

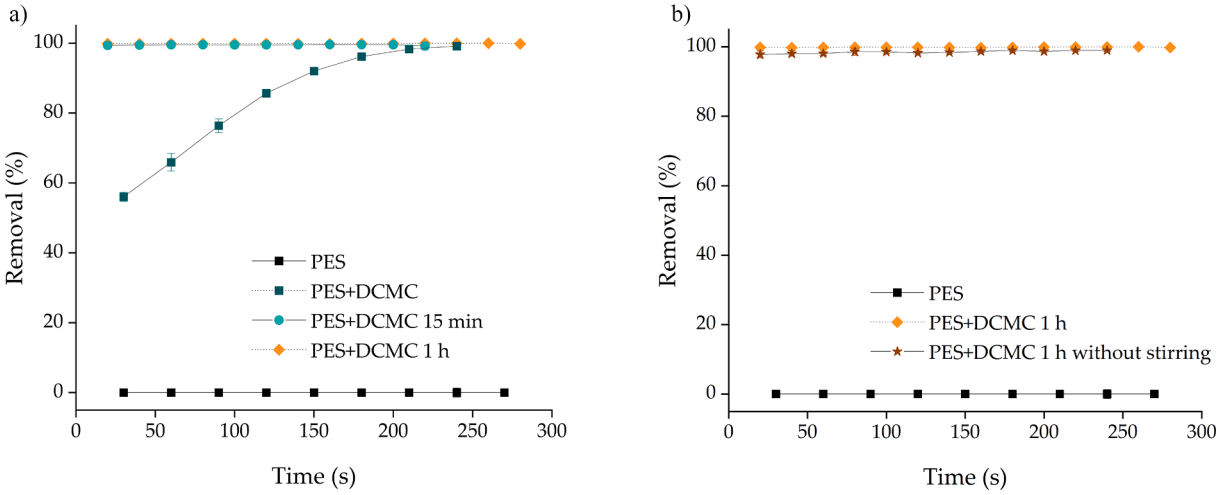

Fig. 5. Effect of a) contact time and b) stirring on the removal of Cyt C by a hybrid system of powder DCMC and PES membrane.

presents the effect of contact time between the polymer and the protein solution before membrane filtration. Once more, it is the contact between the polymer and the protein solution that dictates the results. The adsorption onto DCMC is the mechanism responsible for the removal of the model protein. As demonstrated before, the rejection performed by the commercial membrane is little to none. A 15-minute contact period between DCMC and Cyt C was sufficient to achieve complete protein removal (Fig. 5a). The experiment performed with the protein solution stirred with the polymer for 1 h prior to filtration also results in absence of model protein in the permeate.

Fig. 5b shows the influence of stirring on protein removal. The results throughout this work showed that removal efficiency was not related to the type of commercial membrane, thus PES was selected for this experiment. Although the previous findings showed that complete protein removal was achieved within 15 min under stirring conditions, a contact time of 1 h was chosen to ensure full polymer deposition, which could directly influence the formation of a DCMC cake layer on the commercial membrane. The results obtained for the removal of Cyt C after 1 h contact with DCMC are independent of stirring. This shows that stirring did not play an important role in the adsorption process. The permeate flux was also calculated and did not show significant differences. The deposition of polymer in the absence of stirring could be responsible for cake layer formation that would lead to membrane fouling. However, this phenomenon was not observed, which might be explained by the large polymer particle size, as it can create free space for the aqueous media to flow.

3.2.3. *Regeneration cycles*

The regeneration cycles were performed on the hybrid system, constituted by DCMC and microfiltration commercial membranes. As determined in previous sections, the removal of the model protein was entirely dependent on the interaction with DCMC. Consequently, the assessment of the system's reusability was focused on the regeneration of the adsorbent. The hybrid system was subjected to three consecutive cycles of Cyt C and 1 M NaCl filtration. The salt solution was placed on the dead-end filtration cell and stirred for 15 min prior to filtration. This allowed for the 1 M NaCl to act as a desorbing agent, releasing the cationic protein from the DCMC and successfully regenerating the polymer.

As shown in Fig. 6, there is only a slight variation in the removal of Cyt C when comparing the different combinations between commercial membranes and DCMC. Yet, after three cycles, over 95% removal efficiency was obtained, which is similar to the results presented in previous studies [32]. The desorption of Cyt C from the exhausted adsorbent is achieved by filtration of a desorbing agent. In this specific case, since

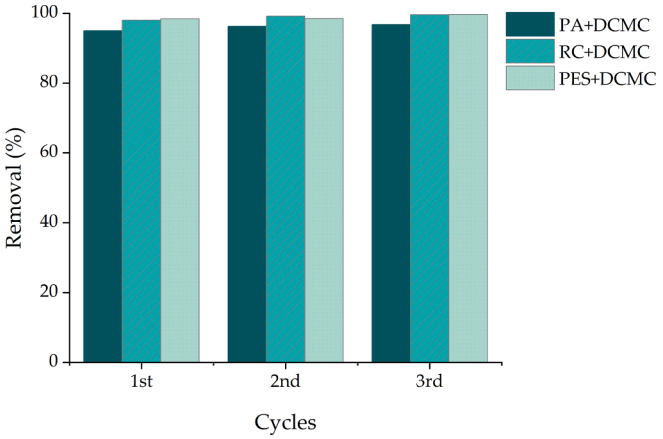

Fig. 6. Removal of Cyt C as a function of the number of regeneration cycles performed on a hybrid system of powdered DCMC and PA, RC and PES commercial membranes using 1 M NaCl.

NaCl solutions are cheap and readily available, that does not compromise operational costs [47]. Furthermore, the ability to perform the regeneration of the adsorbent without changing the system is beneficial in terms of minimizing installation size. From an economic standpoint, this is an attractive system since DCMC can be reused several times. In an ongoing project conducted by this research group, PES membranes incorporating DCMC are currently being prepared. Therefore, the PES commercial membranes were chosen for the remaining experiment of this work.

3.2.4. *Discontinuous filtration*

In this experiment, a discontinuous filtration of protein solution in the AMF system was performed. This dynamic adsorption experiment was used to emulate the behavior of a fixed-bed column and obtain adsorption parameters. Herein, 2 L of Cyt C solution were added to a dead-end filtration cell in a fed-batch mode. A total of ten volumes of 200 mL each were added consecutively to the AMF system, constituted by 200 mg of DCMC and a PES commercial membrane. Each solution was stirred with the polymer for 15 min prior to filtration to maximize the adsorption capacity of the polymer, factoring in its adsorption kinetics. Fig. 7 presents the experimental data obtained from a discontinuous batch filtration of Cyt C solution. The results are expressed as the concentration profile of the model protein as a function of time. As shown Fig. 7, the experiment data followed an S-shaped curve, similar to

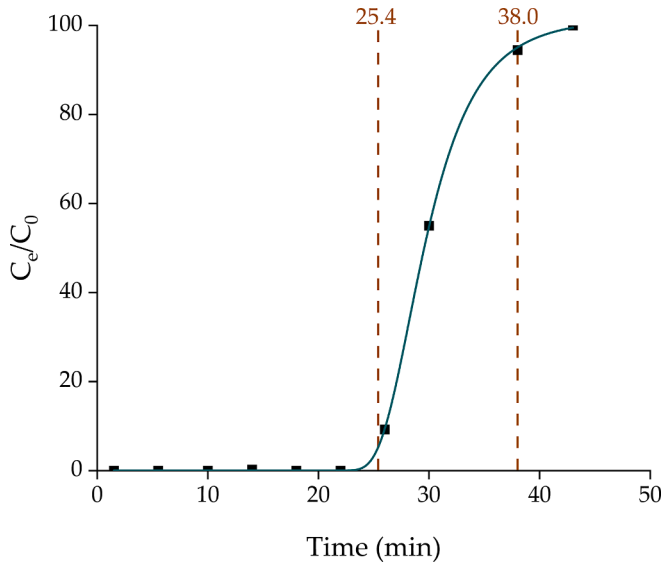

Fig. 7. Discontinuous filtration experimental data of the removal of Cyt C in a hybrid system comprising powdered DCMC and PES membrane.

a typical breakthrough curve obtained from a fixed-bed column adsorption process, or an enrichment curve from a polymer-enhanced ultrafiltration experiment. The data was fitted to a sigmoidal growth function and adsorption parameters were obtained. The breakthrough (t_b) and exhaust times (t_e) were determined as 25.4 and 38.0 min, respectively. Correspondingly, breakthrough and exhaust volumes are 1.2 and 1.8 L. These results provide information on operating parameters. The efficiency of the polymer declines after breakthrough time and reaches its saturation after 38 min of operation. Ideally, DCMC should be regenerated after reaching the breakthrough point to ensure a continuous and efficient operation. Based on these results, at breakthrough time, 200 mg of DCMC adsorbed 1.2 L of a 100 mg L^{-1} protein solution, presenting an adsorption capacity of approximately 600 mg g^{-1}. After the polymer was completely saturated (t_e), the adsorption capacity increased to 900 mg g^{-1}. These results are consistent with our previous work with batch adsorption, where the maximum adsorption capacity was found to be 851 mg g^{-1} [32].

In the end, 2 L of protein solution were filtrated in the AMF system in 43 min, which resulted in a permeate flux of 668 L m^{-2} h^{-1}. Overall, fouling was not observed in the conditions of this study. The work focused on the filtration of a model aqueous solution, where only salts and the model protein were present in the media. It is assumed that blockage of the membrane pores did not occur since the performance of this system was not affected after filtration of a larger protein solution volume.

The scale-up design of this system could be achieved by establishing criteria and operational conditions that should be kept constant. For demonstration purposes, the following parameters will be fixed: system geometry, polymer dose (200 mg per batch volume), and protein solution concentration (100 mg L^{-1}). Moreover, this scale-up design aimed to maintain a consistent permeate flux (668 L m^{-2} h^{-1}) and stable breakthrough time of operation (25.4 min). From the permeate flux calculations (Equation (4)), the following volume-to-area (V/A) ratio was obtained:

$$668 = \frac{\Delta V}{A \times \frac{25.4}{60}} \Leftrightarrow \frac{V}{A} = 283\ L\ m^{-2} \quad (5)$$

Table 2 shows examples of calculated parameters for different scale-up factors. Next, a step-by-step explanation of the calculations is provided. For a scale-up factor of 50, the new solution volume would be 59.1 L. By fixing the V/A ratio, the new membrane area should be approximately 0.209 m^2. Accordingly, for this scaled-up process, 10 g of DCMC would be required for successful adsorption of 59.1 L of protein solution. Additionally, DCMC can be regenerated at least three times, meaning it could be used in three consecutive adsorption processes if there is a regeneration cycle in between. Therefore, the total volume processed could be, at a minimum, 177 L. By maintaining the V/A ratio and the aforementioned parameters, the new scaled-up process could achieve the same efficiency as the original experiment.

Table 2
Calculated scale-up parameters for the AMF hybrid system comprising DCMC and PES membrane.

Scale-up factor	V (L)	A (m^2)	Polymer mass (g)	Volume with three regeneration cycles (L)
1	1.18	0.00418	0.2	3.54
10	11.8	0.0418	2	35.4
50	59.1	0.209	10	177
100	118	0.418	20	354

4. Conclusions

In this study, a combined AMF approach was utilized for the removal of Cyt C from a buffer solution. The results indicate that the integration of microfiltration with adsorption onto DCMC is an effective method for removing cationic species from aqueous solutions. The hybrid system can offset the limitations of the separation processes by employing a highly quick and efficient adsorbent such as DCMC. Protein removal efficiency was independent of stirring, but a minimum of 15 min of contact between the solution and DCMC was required for complete adsorption of the model protein. A study on the effect of stirring showed that the absence of stirring did not lead to membrane fouling. After three consecutive adsorption/desorption cycles, DCMC maintained its removal efficiency. A dynamic adsorption experiment provided valuable insight on operation process parameters. The maximum breakthrough adsorption capacity was determined to be between 600 and 900 mg g^{-1}, based on breakthrough and exhaust times, respectively. These results are a great step towards large-scale operations using this cellulose derivative as an adsorbent.

This study lays the groundwork for future research in the preparation of DCMC-functionalized membranes within the membrane engineering field. Future studies will focus on the preparation, characterization and application of DCMC membranes. Specific examples of upcoming work include the incorporation of DCMC as a filler in mixed matrix membranes and evaluation of their performance in the filtration of aqueous solutions with cationic compounds.

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Declaration of competing interest

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

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Data availability

Data will be made available on request.

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