MATERIALS INTERFACES
www.advmatinterfaces.de

Regeneration of β-Cyclodextrin Based Membrane by Photodynamic Disulfide Exchange — Steroid Hormone Removal from Water

*Zheqin Dong, Matteo Tagliavini, Jason Darmadi, Vanessa Trouillet, Andrea I. Schäfer, and Pavel A. Levkin**

The occurrence of steroid hormones in water and their serious impact on human and ecosystem demand high performance materials for efficient removal of such micropollutants. Here, an affinity membrane is developed for hormone removal with regenerable binding sites. By using photodynamic disulfides as a linker, UV induced detachment of β-CD ligands from the membrane surface is demonstrated. The macroporous base membrane is first fabricated via a polymerization induced phase separation method using 2-hydroxyethyl methacrylate (HEMA) and ethylene dimethylacrylate (EDMA) monomers. Then the affinity membranes are prepared by immobilizing β-CD ligands to the poly(HEMA-*co*-EDMA) base membrane through the 2-carboxyethyl disulfide linker. The β-CD functionalized affinity membrane shows a 30% increase of E2 hormone uptake compared with the base membrane, attributed to the formation of CD-hormone host–guest inclusion complexes. The photodynamic disulfide linkers enable UV-induced detachment of blocked β-CD ligands from and reattachment of fresh β-CD ligands to the membrane surface after each adsorption cycle, thus conferring the affinity membrane with excellent regenerative properties. It is anticipated that the use of dynamic covalent bonds for binding ligands will be of interest for developing smart affinity membranes with regenerable and readjustable surface properties.

1. Introduction

The increasing release of micropollutants into water resources and their adverse effects on aquatic ecosystem and human health have aroused global concerns.[1] Steroid hormones including natural estrone (E1) and estradiol (E2) and synthetic 17β-ethinyl estradiol (EE2) are one such type of micropollutants widely found in wastewater.[2,3] Despite their trace levels (1–100 ng L^{-1}) in water sources, steroid hormones can disrupt the endocrine system of human and other organisms by interfering the synthesis, secretion, transport, binding of natural hormones.[4] The negative health impacts of steroid hormones on animals are well documented, such as feminization in fish,[5] intersexuality in wild roach,[6] and tachycardia in bullfrog tadpoles.[7] In addition, increasing evidence has shown that exposures to steroid hormones causes negative impacts on human health like obesity, diabetes, intellectual disability, and male infertility.[8] Therefore, it is an urgent task to remove steroid hormones from water source for protecting human health and ecosystem.

Inadequate removal of steroid hormones by conventional wastewater treatment systems has motivated the development of advanced treatment technologies such as activated carbon adsorption, advanced oxidation processes, and membrane technology for treating such micropollutants.[9] Among them, membrane technology is considered to be a promising strategy for water purification because of its high efficiency, ease of operation, and small footprints.[10] For example, nanofiltration (NF) and reverse osmosis (RO) processes have been used to remove hormones via a combination of mechanisms such as size exclusion, charge repulsion, and adsorption.[11–13] However, the low water permeability of NF and RO membranes requires high operation pressure and frequent membrane cleaning,[14,15] which significantly increases the operation and maintenance of such processes. Hence, development of advanced membranes that are able to reject or capture steroid hormones at higher water permeability is highly desired.

Affinity membranes separate molecules based on the specific physical and chemical interactions between ligands and target molecules rather than by sieving mechanisms.[16–19] Combining

Dr. Z. Dong, J. Darmadi, Prof. P. A. Levkin
Institute of Biological and Chemical Systems – Functional Molecular Systems (IBCS-FMS)
Karlsruhe Institute of Technology (KIT)
Eggenstein-Leopoldshafen, Karlsruhe 76344, Germany
E-mail: levkin@kit.edu
M. Tagliavini, Prof. A. I. Schäfer
Institute for Advanced Membrane Technology (IAMT)
Karlsruhe Institute of Technology (KIT)
Eggenstein-Leopoldshafen, Karlsruhe 76344, Germany
V. Trouillet
Institute for Applied Materials and Karlsruhe Nano Micro Facility
Karlsruhe Institute of Technology (KIT)
Eggenstein-Leopoldshafen, Karlsruhe 76344, Germany
Prof. P. A. Levkin
Institute of Organic Chemistry
Karlsruhe Institute of Technology (KIT)
Karlsruhe 76131, Germany
The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/admi.201902100.

DOI: 10.1002/admi.201902100

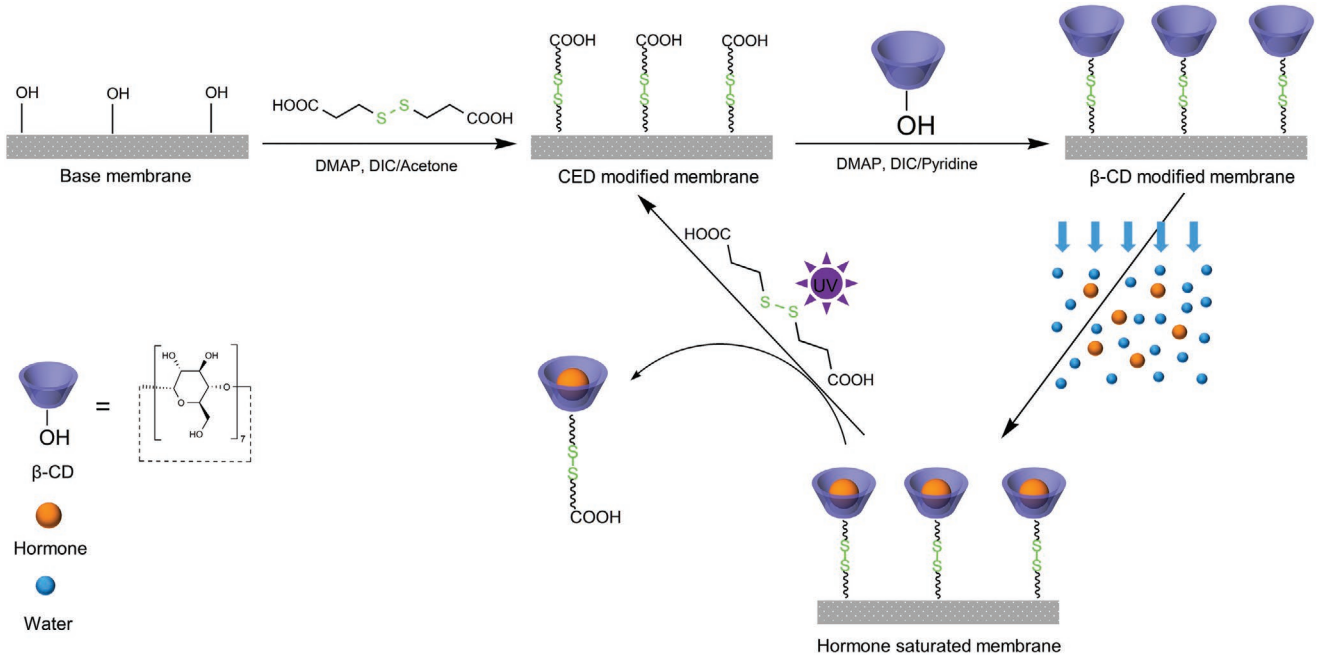

Figure 1. Schematic representation showing the coupling of β-CD to the macroporous base polymer membrane using disulfide linkage (upper panel) and the regeneration of the β-CD modified membrane via photodynamic disulfide exchange reaction (bottom panel).

the advantages of target separation and high permeability, affinity membranes are ideal candidates for treating steroid hormones. Typically, affinity membranes are prepared by attaching affinity ligands to a base membrane, and the base membrane is preferred to have large surface areas in order to achieve good separation efficiency.[17] In this context, we adopted a polymerization induced phase separation approach to fabricating our base polymer membranes. In the polymerization induced phase separation process, monomers and crosslinkers are polymerized in the presence of porogens, and when the growing polymer chain reaches a certain size, the crosslinked polymer phase separates to form a highly porous polymer monolith.[20] Eventually, removal of the porogens results in a macroporous polymer network consisting of interconnected microglobules, affording the macroporous membrane with high surface areas attractive for affinity separation applications.[21–23]

β-Cyclodextrin (β-CD) is an inexpensive macrocyclic compound made up of seven glucopyranose units connected via α-1,4-glycosidic bonds. The toroidal shape of β-CD provides a hydrophobic inner cavity, which can trap thousands of organic molecules via host–guest interactions including van der Waals forces and electrostatic forces, hydrogen bonding and hydrophobic interactions.[24] Because of this unique property, β-CD has been reported for removing a range of micropollutants from water and therefore serves as an ideal ligand for affinity adsorbents.[25–30] Commonly, β-CD is immobilized onto support membranes either by physical adsorption or covalent bonding. However, the stability of physically adsorbed β-CD remains a concern due to its solubility in water. It is reported that nanofibers with physically impregnated β-CD suffered a weight loss of 6.7 wt% after a hormone adsorption process of 96 h.[26] Although membranes loaded with crosslinked β-CD prevented the leaching of β-CD and achieved a high hormone removal efficiency, the regeneration of the membranes is to date not possible.[27] On the other hand, covalently attached β-CD results in a permanent irreversible bonding of β-CD onto the membrane surface. In this case, the binding capacity of β-CD ligands will be lost once they are saturated by steroid hormones or other micropullants in water. In most studies, solvent regeneration is used for desorption of the trapped micropullants and recovery of the blocked β-CD ligands. However the regeneration efficiency of such process relies on the solubility of micropullants in the regeneration solvent, which often results in an incomplete recovery of the binding ligands and therefore a degraded adsorption performance in consecutive adsorption cycles.[28–30]

To address these issues, here we report a novel strategy for dynamic coupling of β-CD ligands to base membrane by using disulfide bonds as linkages. Dynamic covalent chemistry based on reversible covalent bonding provides a versatile and powerful platform for dynamic manipulation and regeneration of surface properties.[31–33] Among them, disulfide bonds are of special interests as they can reversibly form and break under certain external stimuli such as light or pH.[34–36] We show that the photodynamic nature of disulfide bonds enables the UV induced release and reattachment of β-CD ligands on the membrane surface after each adsorption cycle, thus conferring the affinity membrane with excellent regeneration properties (**Figure 1**).

2. Results and Discussion

2.1. Fabrication of Base Membrane

The base membrane was fabricated by a polymerization induced phase separation method as shown in **Figure 2**A.

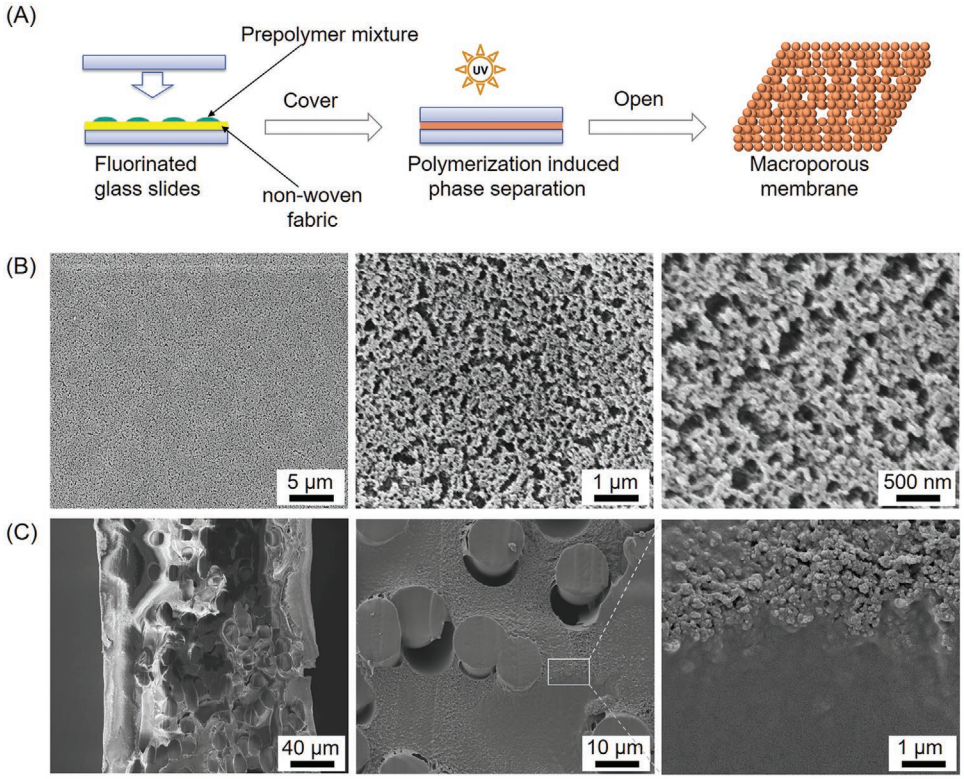

Figure 2. A) Schematic representation of the fabrication of poly(HEMA-*co*-EDMA) macroporous base membrane via polymerization induced phase separation. B) Surface and C) cross-sectional SEM images of the fabricated poly(HEMA-*co*-EDMA) membrane with different magnifications.

Briefly, a prepolymer mixture consisted of 24 wt% 2-hydroxyethyl methacrylate (HEMA) and 16 wt% ethylene dimethylacrylate (EDMA) as monomers, 48 wt% cyclohexanol and 12 wt% 1-decanol as porogens and 0.4 wt% 2,2-dimethoxy-2-phenylacetophenone (DMPAP) as initiator was impregnated into a porous nonwoven polyester fabric. The nonwoven fabric is important for avoiding polymer shrinkage induced cracking of the membrane and for improving mechanical properties of the resultant membranes. The impregnated prepolymer mixture was then covered by two fluorinated borosilicate glass slides and irradiated by UV light (260 nm, 5 mW cm^{-2}) for 15 min, subsequent removal of unreacted porogens by ethanol and air drying resulted in a macroporous polymer membrane of 200 μm in thickness.

As shown by the scanning electron microscopy (SEM) images in Figure 2B, the surface of the poly(HEMA-*co*-EDMA) macroporous membrane is composed of numerous interconnected polymer microglobules of 95 ± 27 nm in diameter. During UV irradiation, the growing polymer chains segregate from the solution forming polymer nuclei, which further grow and coalesce resulting in a macroporous membrane with crosslinked polymer microglobules.[20] This type of membrane surface is very similar to those membranes prepared via non-solvent induced phase separation when crystallization effect is dominant.[37] The cross-sectional images reveal that the fibers of the nonwoven support are wrapped by the HEMA-*co*-EDMA polymers (Figure 2C). However, the integration of the nonwoven support is not ideal, as a dense internal structure is observed and leads to a low membrane porosity (≈25%).

As porogens play a vital role in the phase separation process, the influence of porogen compositions in the prepolymer mixture on the pore size and structure of the poly(HEMA-*co*-EDMA) membrane was investigated. Six prepolymer mixtures with increasing ratio of 1-decanol/cyclohexanol from mix-1, containing pure cyclohexanol as a porogen, to mix-6, containing 1-decanol as a porogen, were prepared according to Table S1 in the Supporting Information. It can be seen from the SEM images that both the microglobule size and pore size of the fabricated membrane gradually increases with increasing 1-decanol content in the mixture of porogens (Figure S1A, Supporting Information). This is mainly attributed to the difference in the solvation of polymer chains in reaction medium by two porogens during early stage of the polymerization.[38] In addition, as revealed by the low magnification SEM images, only the membranes prepared from mix-2 are homogenous and defect-free, while membranes prepared from other mixtures show obvious defects and cracks on their surfaces (Figure S1B, Supporting Information). For membranes prepared from mix-3 to mix-6, the increase of globule size results in decreased mechanical strength and therefore cracks have evolved in the membranes.[39] The membranes prepared from mix-1 show many thin and long cracks on the surface despite its smallest globule and pore size. This might be attributed to the rigidity and brittleness of the highly cross-linked polymer material.[40]

The water permeability of the poly(HEMA-*co*-EDMA) macroporous membranes prepared from different prepolymer mixtures was tested. As shown in Figure S2 (Supporting Information), the mix-2 membrane shows a water permeability of

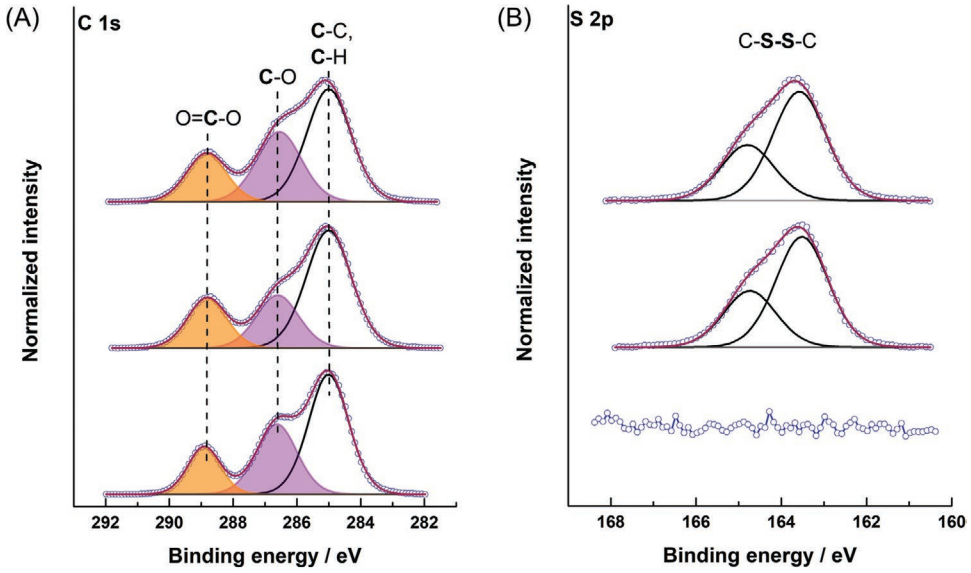

Figure 3. A) C 1s and S 2p XPS spectra of base membrane (bottom), CED modified membrane (middle), and β-CD modified membrane (top).

around 40 Lm^{-2} h^{-1} bar^{-1}, while membranes prepared by other mixtures all possess much higher water permeability of over 200 Lm^{-2} h^{-1} bar^{-1}, consistent with their cracked pore structures observed by SEM. A photograph of the mix-2 membrane illustrating its homogenous and defect-free surface is shown in Figure S3 in the Supporting Information. The reproducibility of the mix-2 membrane is further verified by testing the water permeation of nine different membranes from the same mixture, and an average water permeability of 38.4 ± 9.6 Lm^{-2} h^{-1} bar^{-1} is achieved. Pore size analysis by liquid expulsion reveals that the mix-2 membrane presents a pore size distribution from 0.14 to 0.65 µm, with mean pore size of 0.32 µm (Figure S4, Supporting Information). It is worth noticing that the permeability of mix-2 membrane is much lower than those of commercial microfiltration membranes with similar pore sizes and thickness. This phenomenon might be attributed to the poor integration of the non-woven support and a very dense internal membrane structure (Figure 2C), leading to low membrane porosity (≈25%) and poor pore connectivity. The permeability of mix-2 membrane is still higher than those of nanofiltration membranes used for hormone removal (≈10 Lm^{-2} h^{-1} bar^{-1}).[11,41] In addition, the surface area of mix-2 membrane was measured to be 9 m^2 g^{-1}. Therefore, based on its reproducibility and relatively high surface area, mix-2 membrane was selected as the base membrane for fabricating affinity membranes in the following sections.

2.2. Functionalization of Base Membranes with β-CD

For immobilization of β-CD to the base membrane, 2-carboxyethyl disulfide (CED) was used as a linker to enable the dynamic attachment and detachment of β-CD ligands. The reaction scheme for coupling β-CD to the base membrane is shown in Figure 1. The hydroxyl groups presented on the base membrane enabled the direct attachment of CED on membrane surface via esterification. Then, the attachment of β-CD ligands was realized by a second esterification reaction between β-CD and immobilized CED.

The surface chemical composition of the base membrane, CED modified membrane, and β-CD modified membrane was characterized by X-ray photoelectron spectroscopy (XPS), as shown in **Figure 3**. The C 1s spectra of the base membrane contain three main peaks at 285.0 eV corresponding to C–C, C–H groups, 286.6 eV corresponding to C–O groups and 288.9 eV corresponding to OCO groups (Figure 3A). As the monomers for making the base membranes contain abundant hydroxyl and ester groups, these results are not unexpected. After CED modification, the C–O/OCO ratio decreases from 1.81 to 1.15 due to the formation of ester bonds and the addition of COOH groups. The successful grafting of CED is further confirmed by the S 2p doublet appeared at 163.5 eV (S $2p_{3/2}$), corresponding to the C–S–S–C group in CED (Figure 3B). Finally, the attachment of β-CD on the CED modified membrane leads to an increase of C-O/OCO ratio from to 1.15 to 1.62, which is attributed to the rich hydroxyl and ether groups in β-CD.

Using mix-2 membrane as the base, the static adsorption of estradiol (E2) on membranes before and after surface functionalization with β-CD were measured. **Figure 4**A shows the time dependent uptake of E2 hormone by the base membrane, the CED functionalized membrane and the β-CD functionalized membrane. The E2 uptake of all membranes increases rapidly in the first several hours and then reaches equilibrium after 20 h. The CED functionalized membrane uptakes 48.9 ng g^{-1} of E2 after 30 h of incubation, almost the same level compared to the base membrane (51.4 ng g^{-1}). In contrast, the β-CD functionalized membrane demonstrates an E2 uptake of 67.6 ng g^{-1} after 30 h incubation, about 30% higher than that of the base membrane. This shows the necessity of immobilization of β-CD to the membrane to achieve efficient E2 removal. The hormone uptake of β-CD functionalized membrane towards other kinds of hormones including estrone (E1), progesterone (P), and

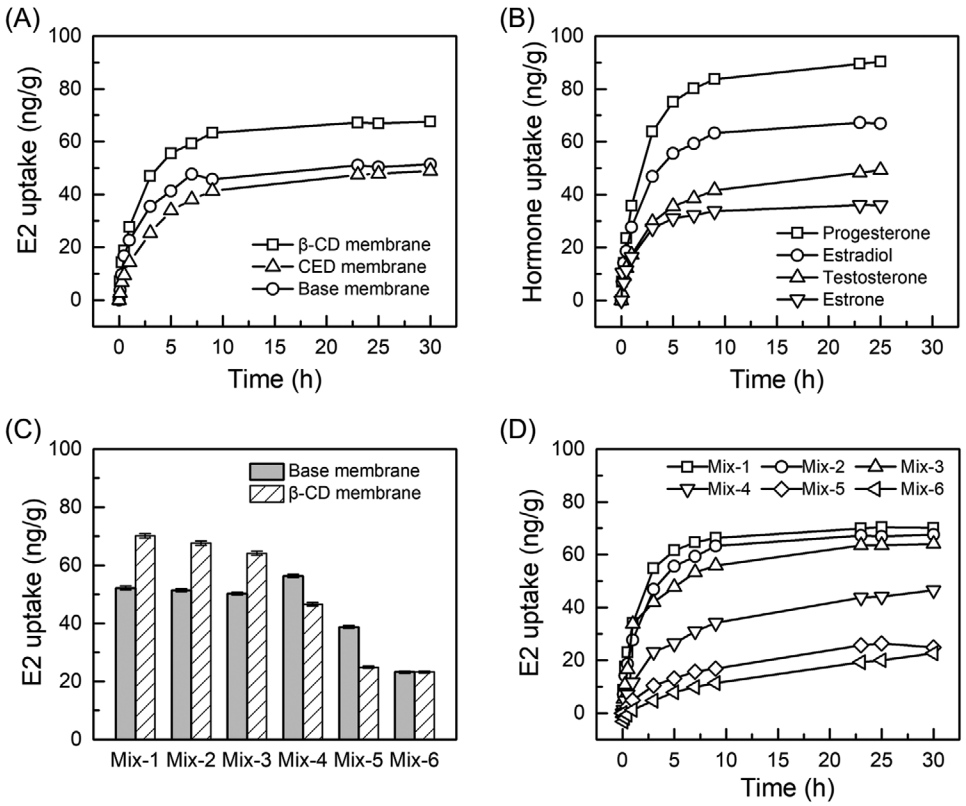

Figure 4. A) Static adsorption kinetics of estradiol (E2) on the base membrane, the CED functionalized membrane and the β-CD functionalized membrane prepared using prepolymer mix-2. B) Static adsorption kinetics of estrone, estradiol, testosterone, and progesterone on the β-CD functionalized membrane prepared using prepolymer mix-2. C) E2 uptake after 30 h on the β-CD functionalized membranes and base membranes prepared by different prepolymer mixtures. D) Static adsorption kinetics of E2 on β-CD functionalized membranes prepared by different prepolymer mixtures.

testosterone (T) were investigated and the results are shown in Figure 4B. The β-CD functionalized membrane demonstrates the highest uptake of 90.3 ng g^{-1} for progesterone and the lowest uptake of 36.0 ng g^{-1} for estrone after 25 h. Such difference is attributed to the varied association strengths of the four hormones to β-CD, and the trend is consistent with previous studies on cyclodextrin-hormone complexes.[42,43] Kinetic modeling results show that second-order kinetic model fit best for all test hormones (Figure S6 and Table S2, Supporting Information), suggesting that chemisorption is dominant and controls the adsorption.

The adsorption capacity of E2 for base membrane and β-CD functionalized membranes prepared using other prepolymer mixtures were also measured. As shown in Figure 4C,D, the E2 uptake of β-CD-functionalized membranes gradually decreases from mix-1 to mix-6. This decrease might be attributed to the increase of the polymer globule size of the membranes prepared from mix-1 to mix-6 (Figure S1, Supporting Information), which, in turn, may lead to a decrease in surface area, reducing both the loading of β-CD and unspecific adsorption.

2.3. Regeneration of Affinity Membrane

A key challenge in the practical applications of affinity membranes for micropollutant removal is efficient regeneration of the membrane's activity after prolonged adsorption process, as the binding sites would be blocked by the micropollutants or other organic substance in real water. For β-CD functionalized adsorbents, solvent regeneration process is typically used to regenerate the adsorbent's activity. However, it has been observed in several studies that the adsorbents gradually lose their adsorption capacity after each cycle due to the incomplete recovery of binding cites after solvent regeneration.[29,31] The dynamic disulfide linkers used in this study enable the β-CD ligands to be dynamically detached and reattached from the base membrane after each adsorption cycle, and therefore provide a promising way for membrane regeneration (Figure 1).

The regeneration of the β-CD functionalized membrane was achieved by the photodynamic disulfide exchange reaction (Figure 1).[34] The hormone saturated membrane was first wetted by a CED solution in dimethylformaldehyde and irradiated by UV light (260 nm, 5 mW cm^{-2}) for 2 min, which replaced the attached β-CD ligands by CED molecules. Then, the CED modified membrane was reacted with new β-CD via esterification reaction (7 h) to regenerate fresh β-CD on membrane surface. XPS analysis of those membranes shows that the C–O/(C–C, C–H) ratio on membrane surface decreases after hormone adsorption since the hormone is essentially made of aliphatic and aromatic bonds and contains very few C–O (Figure S7, Supporting Information). After UV-induced disulfide exchange reaction, the C–O/(C–C, C–H) and C–O/OCO ratios decreases

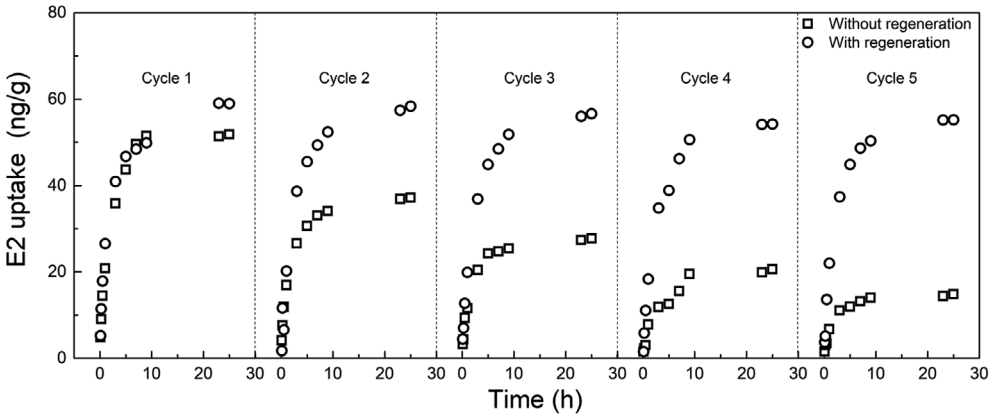

Figure 5. Static adsorption of estradiol (E2) on two β-CD functionalized membranes as a function of time in five consecutive adsorption cycles: with photodynamic regeneration of β-CD between each cycle (circle) and without photodynamic regeneration between each cycle (square).

and reaches values slightly higher than CED modified membrane, indicating a high efficacy of the photodynamic disulfide exchange reaction. The efficiency of the membrane functionalization and regeneration steps was further confirmed by Raman analysis of the membranes prepared at different stages (Figures S8 and S9, Supporting Information).

To evaluate the regeneration efficiency via photodynamic disulfide exchange reaction, the E2 uptake of β-CD functionalized membranes with or without the regeneration process was first tested in static conditions. As shown in **Figure 5**, after five consecutive adsorption cycles, the E2 uptake of β-CD functionalized membranes without photodynamic regeneration decreases gradually from 51.9 to 14.9 ng g^{-1} after five cycles, indicating the loss of the binding sites after each cycle. In contrast, the membrane regenerated via the photodynamic disulfide exchange reaction between each adsorption cycle demonstrates a nearly complete restoration of the adsorption capacity during each of the five cycles. The E2 uptake only decreases from 58.9 to 55.2 ng g^{-1} after five adsorption cycles, confirming the very efficient regeneration of the membrane´s adsorption capacity via the photodynamic disulfide exchange reaction. However, we note that the detached hormones will end up as a complex with β-CD in the reaction solvent, which will require further treatment. Further work on the use of green solvents and in situ degradation of pollutants is required.

In membrane filtration, removal of micropollutans is mostly done in dynamic filtration conditions. Therefore, the hormone binding capacity of β-CD functionalized membrane and the efficiency of the photodynamic regeneration were also tested in flow-through conditions. E2 solution (100 ng L^{-1}) was filtered through the membrane at an operating pressure of 3 bar and a flux of 144 ± 12 Lm^{-2} h^{-1}, corresponding to a residence time of 1.25 s. The breakthrough curves and the E2 uptake of the β-CD functionalized membrane in three regeneration cycles as well as the base membrane are reported in **Figure 6**. Immediate breakthrough is observed for all membranes, which might be attributed to the short residence time (1.25 s) encountered during the adsorption process. Compare to the base membrane, the β-CD functionalized membrane shows about 38% increase of E2 uptake after 300 mL feed solution is permeated (Figure 6B), consistent with their adsorption performance in static conditions (Figure 4A). Furthermore, the hormone uptake profile of the β-CD functionalized membrane remains almost the same level after two cycles of photodynamic regeneration. Such results promise the use of photodynamic regeneration strategy for dynamic filtration applications.

3. Conclusions

In summary, we have developed a novel affinity membrane for effective removal of steroid hormones from water. The base membrane was fabricated via a polymerization induced phase separation approach where HEMA and EDMA monomers were polymerized in the presence of inert porogens. The compositions of polymerization mixtures were optimized to obtain a reproducible and homogenous poly(HEMA-*co*-EDMA) macroporous membranes with satisfied permeability. Then the affinity membrane was prepared by coupling β-CD ligand to the poly(HEMA-*co*-EDMA) base membrane using the photodynamic disulfide linkages. The β-CD functionalized affinity membrane showed a 30% increase of E2 uptake compared with the base membrane, attributed to the formation of inclusion host–guest complexes. Last but not least, the photodynamic nature of the disulfide bonds enabled the photodynamic regeneration of the membrane´s original affinity properties by UV-induced regeneration of the β-CD ligands on the membrane surface after each adsorption cycle. We envision that the new concept of using dynamic covalent bonds for the binding of affinity ligands to membranes in order to achieve the ability to restore the adsorption capacities of membranes by the photodynamic exchange or removal of such ligands will lead to the development of smart affinity membranes with regenerable, exchangeable and rewritable surface properties for various separation applications.

4. Experimental Section

Materials and Methods are provided in the Supporting Information.

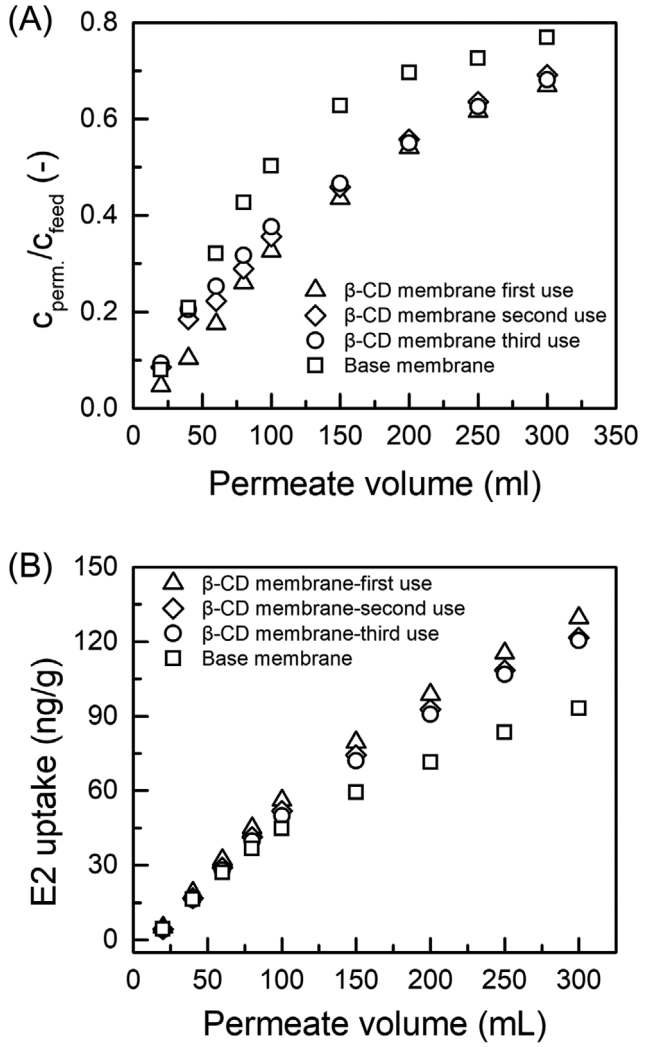

Figure 6. A) Ratio of permeate to feed concentration and B) hormone uptake as a function of permeate volume on β-CD functionalized membranes in dynamic filtration conditions (pressure of 3 bar, feed of 100 ng L^{-1} and flow rate of 144 ± 12 Lm^{-2} h^{-1}). The β-CD functionalized membrane was regenerated using photodynamic exchange reaction after each cycle of usage. The poly(HEMA-*co*-EDMA) base membrane was also tested for comparison.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

The research was supported by the Helmholtz Association's Initiative and Networking Fund (grant VH-NG-621), the European Research Council starting grant (ERC-2013-StG337077-DropCellArray). The authors thank the strategic initiative by the Science & Technology of Nanosystems (STN) research programme and the recruitment initiative for ITG-MT. The authors also thank Maryam Faghih for helping with the stirred cell system set-up. The K-Alpha+ instrument was financially supported by the German Federal Ministry of Economics and Technology on the basis of a decision by the German Bundestag. The authors thank Dr. Jiarong He for his help with the Raman measurements.

Open access funding enabled and organized by Projekt DEAL.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

affinity membranes, disulfide exchange, photodynamic chemistry, steroid hormone removal, surface functionalization

Received: December 12, 2019
Revised: June 6, 2020
Published online:

[1] R. P. Schwarzenbach, B. I. Escher, K. Fenner, T. B. Hofstetter, C. A. Johnson, U. von Gunten, B. Wehrli, *Science* **2006**, *313*, 1072.
[2] C. Baronti, R. Curini, G. D'Ascenzo, A. Di Corcia, A. Gentili, R. Samperi, *Environ. Sci. Technol.* **2000**, *34*, 5059.
[3] Y. Luo, W. Guo, H. H. Ngo, L. D. Nghiem, F. I. Hai, J. Zhang, S. Liang, X. C. Wang, *Sci. Total Environ.* **2014**, *473–474*, 619.
[4] E. R. Kabir, M. S. Rahman, I. Rahman, *Environ. Toxicol. Pharmacol.* **2015**, *40*, 241.
[5] J. P. Sumpter, *Toxicol. Lett.* **1995**, *82–83*, 737.
[6] T. P. Rodgers-Gray, S. Jobling, C. Kelly, S. Morris, G. Brighty, M. J. Waldock, J. P. Sumpter, C. R. Tyler, *Environ. Sci. Technol.* **2001**, *35*, 462.
[7] R. F. Salla, F. U. Gamero, R. Z. Rissoli, S. E. Dal-Medico, L. M. Castanho, C. d. S. Carvalho, E. C. M. Silva-Zacarin, A. L. Kalinin, F. C. Abdalla, M. J. Costa, *Chemosphere* **2016**, *144*, 1862.
[8] L. Trasande, R. T. Zoeller, U. Hass, A. Kortenkamp, P. Grandjean, J. P. Myers, J. DiGangi, M. Bellanger, R. Hauser, J. Legler, N. E. Skakkebaek, J. J. Heindel, *J. Clin. Endocrinol. Metab.* **2015**, *100*, 1245.
[9] C. P. Silva, M. Otero, V. Esteves, *Environ. Pollut.* **2012**, *165*, 38.
[10] M. A. Shannon, P. W. Bohn, M. Elimelech, J. G. Georgiadis, B. J. Mariñas, A. M. Mayes, *Nature* **2008**, *452*, 301.
[11] A. I. Schäfer, L. D. Nghiem, T. D. Waite, *Environ. Sci. Technol.* **2003**, *37*, 182.
[12] L. D. Nghiem, A. I. Schäfer, M. Elimelech, *Environ. Sci. Technol.* **2004**, *38*, 1888.
[13] A. I. Schäfer, I. Akanyeti, A. J. C. Semião, *Adv. Colloid Interface Sci.* **2011**, *164*, 100.
[14] E.-m. Gwon, M.-j. Yu, H.-k. Oh, Y.-h. Ylee, *Water Res.* **2003**, *37*, 2989.
[15] K. O. Agenson, T. Urase, *Sep. Purif. Technol.* **2007**, *55*, 147.
[16] E. Klein, *J. Membr. Sci.* **2000**, *179*, 1.
[17] A. M. Urmenyi, A. A. Poot, M. Wessling, M. H. V. Mulder, *J. Membr. Sci.* **2005**, *259*, 91.
[18] T. Barroso, M. Temtem, A. Hussain, A. Aguiar-Ricardo, A. C. A. Roque, *J. Membr. Sci.* **2010**, *348*, 224.
[19] Q. Zhang, Y. Cao, N. Liu, W. Zhang, Y. Chen, X. Lin, L. Tao, Y. Wei, L. Feng, *Adv. Mater. Interfaces* **2016**, *3*, 1600291.
[20] F. Svec, J. M. J. Frechet, *Chem. Mater.* **1995**, *7*, 707.
[21] F. Svec, J. M. J. Fréchet, *Science* **1996**, *273*, 205.
[22] F. Svec, *J. Chromatogr. A* **2010**, *1217*, 902.
[23] H. Wang, H. Zhang, Y. Lv, F. Svec, T. Tan, *J. Chromatogr. A* **2014**, *1343*, 128.
[24] A. Harada, Y. Takashima, M. Nakahata, *Acc. Chem. Res.* **2014**, *47*, 2128.
[25] A. Alsbaiee, B. J. Smith, L. Xiao, Y. Ling, D. E. Helbling, W. R. Dichtel, *Nature* **2016**, *529*, 190.
[26] A. I. Schäfer, K. Stelzl, M. Faghih, S. Sen Gupta, K. R. Krishnadas, S. Heißler, T. Pradeep, *ACS Sustainable Chem. Eng.* **2018**, *6*, 2942.
[27] A. M. Khalil, A. I. Schäfer, *J. Membr. Sci.* **2020**, 118228.

[28] X. Liu, L. Yan, W. Yin, L. Zhou, G. Tian, J. Shi, Z. Yang, D. Xiao, Z. Gu, Y. Zhao, *J. Mater. Chem. A* **2014**, *2*, 12296.
[29] L. Jiang, Y. Liu, S. Liu, X. Hu, G. Zeng, X. Hu, S. Liu, S. Liu, B. Huang, M. Li, *Chem. Eng. J.* **2017**, *308*, 597.
[30] J. H. Lee, S.-Y. Kwak, *Appl. Surf. Sci.* **2019**, *467–468*, 178.
[31] J. Xia, P. Zhao, K. Zheng, C. Lu, S. Yin, H. Xu, *Angew. Chem., Int. Ed.* **2019**, *58*, 542.
[32] J. Deng, L. Ma, X. Liu, C. Cheng, C. Nie, C. Zhao, *Adv. Mater. Interfaces* **2016**, *3*, 1500473.
[33] N. Sowan, L. M. Cox, P. K. Shah, H. B. Song, J. W. Stansbury, C. N. Bowman, *Adv. Mater. Interfaces* **2018**, *5*, 1800511.
[34] X. Du, J. Li, A. Welle, L. Li, W. Feng, P. A. Levkin, *Adv. Mater.* **2015**, *27*, 4997.
[35] L. Li, W. Feng, A. Welle, P. A. Levkin, *Angew. Chem., Int. Ed.* **2016**, *55*, 13765.
[36] X. Du, M. Wang, A. Welle, F. Behboodi-Sadabad, Y. Wang, P. A. Levkin, Z. Gu, *Adv. Funct. Mater.* **2018**, *28*, 1803765.
[37] T.-H. Young, L.-P. Cheng, D.-J. Lin, L. Fane, W.-Y. Chuang, *Polymer* **1999**, *40*, 5315.
[38] C. Viklund, F. Svec, J. M. J. Fréchet, K. Irgum, *Chem. Mater.* **1996**, *8*, 744.
[39] F. P. Knudsen, *J. Am. Ceram. Soc.* **1959**, *42*, 376.
[40] K. B. Singh, M. S. Tirumkudulu, *Phys. Rev. Lett.* **2007**, *98*, 218302.
[41] M. Tagliavini, A. I. Schäfer, *J. Hazard. Mater.* **2018**, *353*, 514.
[42] K. Uekama, T. Fujinaga, F. Hirayama, M. Otagiri, M. Yamasaki, *Int. J. Pharm.* **1982**, *10*, 1.
[43] N. Sadlej-Sosnowska, *Eur. J. Pharm. Sci.* **1995**, *3*, 1.