DVGW-Forschungsstelle TUHH

Institut für Wasserressourcen & Wasserversorgung

ANNUAL REPORT

2024

Januar 2025

DVGW-Forschungsstelle
an der Technischen Universität Hamburg

DVGW Forschungsstelle TUHH
Technische Universität Hamburg

Institute for
WATER RESOURCES
AND WATER SUPPLY

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DVGW-Forschungsstelle TUHH

Institut für Wasserressourcen & Wasserversorgung

ANNUAL REPORT

2024

Content

1 At a glance

Dear friends of TUHH and DVGW-TUHH related water research,

this report is once again intended to give you an inspiring overview of the research activities of TUHH institute B-11 and the DVGW Research Centre TUHH. Our research projects NOM-eSorp (DFG) and the joint WAVE-project FITWAS (BMBF) have been completed last year. NOM-eSorp results were incorporated into the ongoing EU project SafeCREW, while FITWAS experiences will be applied into the new BMBF project KeraRes, which with new colleagues started in 2025. As in FITWAS, here we are working with porous ceramic membranes; however, these are modified with the aim of further retaining dissolved water constituents.

KeraRes therefore builds on expertise from the former SULEMAN project (BMWK), where porous polymer membranes were post-treated by layer-by-layer technology in order to increase the retention of dissolved compounds. Here we are also working with hollow fibre membranes - but this time made of ceramics. The aim is to create a single-stage process for industrial and drinking water treatment that can also be used to safely treat water on a decentralised basis. Our partners here include (among others) the SME Inflotec GmbH from Magdeburg (coordinator) and the Bundeswehr Scientific Institute in Munster.

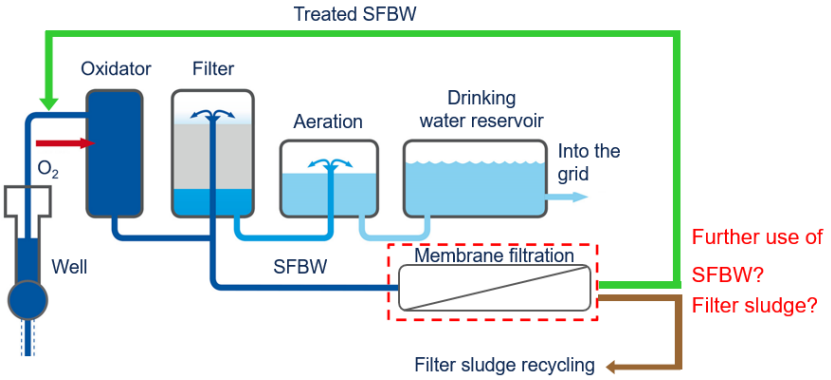
The EU SafeCREW project reached half-time in summer 2025; after a successful project meeting in Tarragona/Barcelona in March, we welcomed a new partner in April 2024. The National University of Water and Environmental Engineering (NUWEE) from Ukraine is contributing more drinking water demonstration sites to the project. With more than 3,000 students, NUWEE is the most important research and educational institution for water related topics in Ukraine. We look forward to entering into a close professional dialogue with NUWEE, which will cover also exchange of EU water policy and technical regulations.

Other new projects in 2024 include the DVGW project "Notverbundleitungen", which we are carrying out in cooperation with Hamburg Wasser and the the coordinator TZW Dresden. Since October 2024, we have Muhammad Ali Inam on board, a dedicated scholarship holder from the Alexander von Humboldt Foundation. During his 2-year research stay, Ali will be working on questions relating to the adsorptive removal of selenium. These are just some of our activities in 2024, we wish you stimulating reading and all the best for 2025.

Mathias Ernst on behalf of
the whole Team of DVGW-TUHH & B-11

2 Research projects

2.1. FITWAS: Reuse of spent filter backwash water from groundwater treatment to secure drinking water supply



Project Duration

01.02.2021 – 30.09.2024

Funding

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

BMBF-Project No.: 02WV1565A

Introduction

Production of drinking water from groundwater sources in Germany usually includes a filtration step for the removal of iron and manganese that consumes a part of the water for filter backwash. The fraction of spent filter backwash water (SFBW) in drinking water production in Germany is between 1% and 4%. This sludge-containing water is usually disposed of and is thus lost to the drinking water supply. At the same time, in many regions the demand for drinking water is continuously increasing as a result of climate, demographic and structural change. In addition, the iron and manganese-containing filter sludge is often not further recovered. Appropriate treatment of SFBW may increase the availability of drinking water. Moreover, the concentrated iron and manganese sludge can be further recycled for different purposes, e.g., to bind sulphur in biogas plants, but also in agriculture or the construction industry.

Research Goals

The aim of the joint research project FITWAS, funded by BMBF, is to provide innovative technologies and practicable operating concepts based on membrane filtration to reuse SFBW from groundwater treatment. Different membrane materials (polymeric/ceramic) and process configurations (pressure/vacuum filtration; inside-out/outside-in) have been examined both in laboratory and at four selected waterworks sites. Particularly, ceramic membrane filtration is considered to be a promising technology for treatment of SFBW due to its high solids loading tolerance, high flux rate and low energy consumption. In this evaluation, legal, energetic, and economic aspects are considered. For the safe return of treated SFBW to the inlet of treatment plant, the filtrate quality has been analysed in detail, covering physical-chemical and microbiological parameters.

Approach

SFBW from the selected waterworks sites has been characterized to determine the variety of water quality parameters and minimum and maximum concentration levels. Thus, experiments with ceramic and polymer membranes at laboratory scale have been conducted to test filtration and cleaning properties of the respective membranes. Different process variants have been investigated in extensive laboratory tests in dead-end filtration. In addition to the membrane material (ceramic and polymer), these differed mainly in the type of module (plate and hollow fibre), the filtration direction (inside-out and outside-in) and the pore size. Very high filtrate fluxes were achieved in particular with ceramic membranes made of silicon carbide (SiC) and aluminum oxide (Al_2O_3). The investigation of upstream sedimentation revealed that this pretreatment increases the irreversible fouling of the membrane. The large particles in SFBW that are removed via sedimentation seem to be necessary for formation of a good filter cake on the membrane. With the results from the laboratory, the optimum membrane material and process, including filtration and cleaning parameters, have been chosen and tested at pilot scale in different waterworks in Northern Germany.

Results of the pilot tests at HAMBURG WASSER are presented in the following. These tests have been carried out with homogenized filter rinsing water at a waterworks site in Hamburg. Besides investigation of operational conditions, the filtrate quality has been monitored to evaluate if recirculation to the raw water in the groundwater treatment process is possible and if a final disinfection step is necessary.

Recent Results

Figure 1: Pilot test with ceramic membrane module submerged in filtration tank (middle), SFBW tank (right) and filtrate tank (left) at waterworks of HAMBURG WASSER

The SFBW (feed) at the waterworks site exhibits turbidity around 700 NTU and iron levels around 110 mg/L (total iron). As a result of the pilot tests with an industrial membrane module with submerged polymeric hollow fibre membranes in out-in negative pressure operation, operation parameters and membrane cleaning procedures for stable filtration have been identified:

- Filtrate flux for basic load 40 L/m²h, for peak load 60 L/m²h
- 30 min backwash interval, 10 h emptying interval
- Chemical cleaning with NaClO and H_2SO_4 as Chemical Enhanced Backwash (CEB) every three days
- Cyclical membrane aeration (only during backwashing and draining)

In the pilot tests with submerged ceramic flat membranes (SiC) in the same waterworks, see Figure 1, hydraulic cleaning has been investigated first. The use of a backpulse, a very short pressurization on the filtrate side with approx. 2 bar for 1-2 seconds, is advantageous compared to conventional backwashing due to the low water input [Kast et al 2023]. A filtrate flux of 150 L/m²h has been identified as suitable for long-term stable operation.

With both membrane types, very good filtrate quality is obtained [Kast et al 2024]. Figure 2 shows the relevant parameters for chemical-physical quality of the filtrate in comparison to the raw water quality of the waterworks. The filtrate can only be recycled as raw water for drinking water production if the filtrate quality is equal or superior to the raw water quality. The filtrate of both membranes exhibits lower concentrations than the raw water for all relevant parameters. The polymeric membrane produces a slightly better filtrate. This is probably due to the smaller pore size of the membrane, though the filtration mechanism is cake filtration.

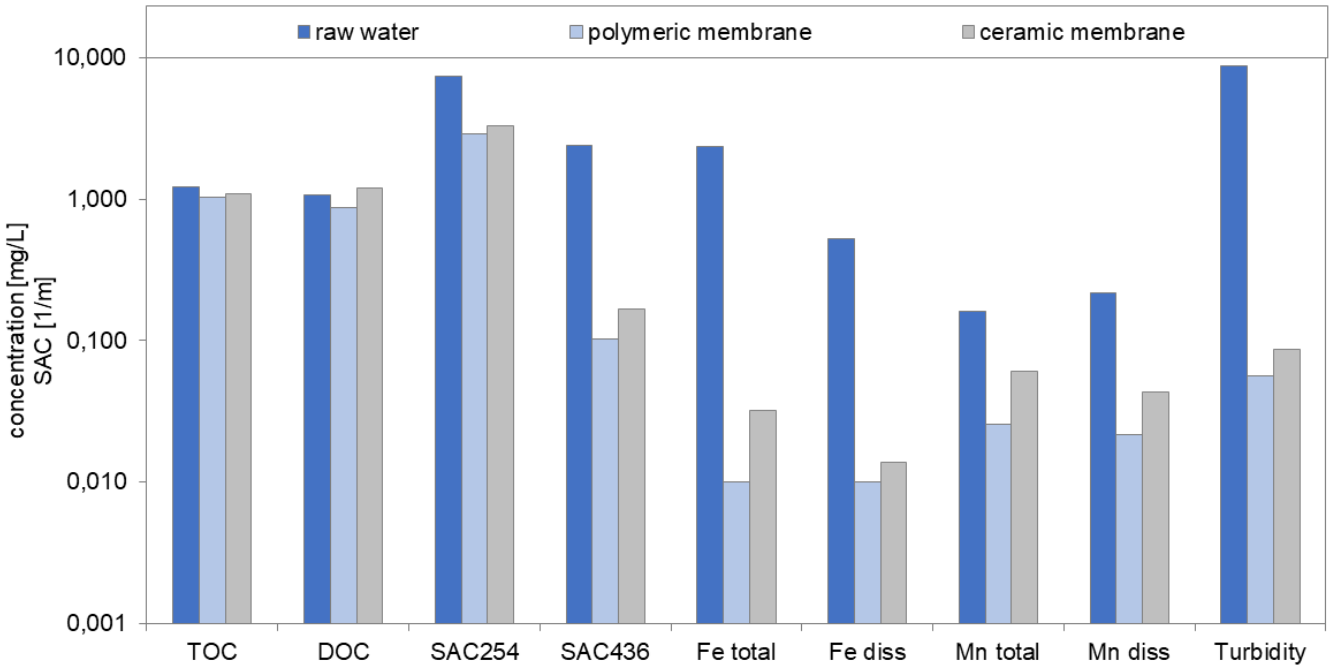


Figure 2: Concentration of physical-chemical parameters, relevant for drinking water, in raw water of waterworks and filtrate of pilot plants with polymeric and ceramic membranes

Conclusion and Outlook

The reuse of filter backwash water for drinking water production using porous membrane processes is technically feasible under the selected framework conditions. The quality of the feed (solids load, particle size distribution, etc.) is decisive for the resulting performance of the membrane process. Piloting at the respective site is recommended for large-scale implementation.

With regard to the process variants of membrane filtration, out-in filtration with submerged membranes is to be favoured for this application based on the practical tests. Very good filtrate quality and high yields are achieved. The ceramic membranes, which have not yet been used for this application, are a good alternative to the established polymeric membranes. They offer comparable filtrate quality, can generally be operated with higher filtrate fluxes and thus lead to comparable treatment costs despite higher membrane costs.

Literature

Kast, C.; Mutis, M.; Wendler, B.; Ernst, M.: Keramische Ultrafiltration zur Wiederverwendung von Filterspülwasser aus der Grundwasseraufbereitung. 15. Aachener Tagung Wassertechnologie, 25. - 26. Oktober 2023, Aachen, ISBN: 978-3-95886-506-8

Kast, C.; Mergel, D.; Wiegand, M.; Mutis, M.; Wendler, B.; Ernst, M. (2024): Aufbereitung von Filterspülwasser - Keramik- und Polymermembran im Vergleich, gwf-Wasser|Abwasser 07-08|2024, S. 77 - 86, doi.org/10.17560/gwfwa.v165i07-08.2743

Project Coordination

DVGW | TUHH Technische Universität Hamburg

Project Partners

HAMBURG WASSER · OOWV · Umwelt Bundesamt · CERAFILTEC CLEAN WATER. EVERYWHERE. · PHL Substratkontor

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2.2 SafeCREW: Climate-resilient management for safe disinfected and non-disinfectedwater supply systems

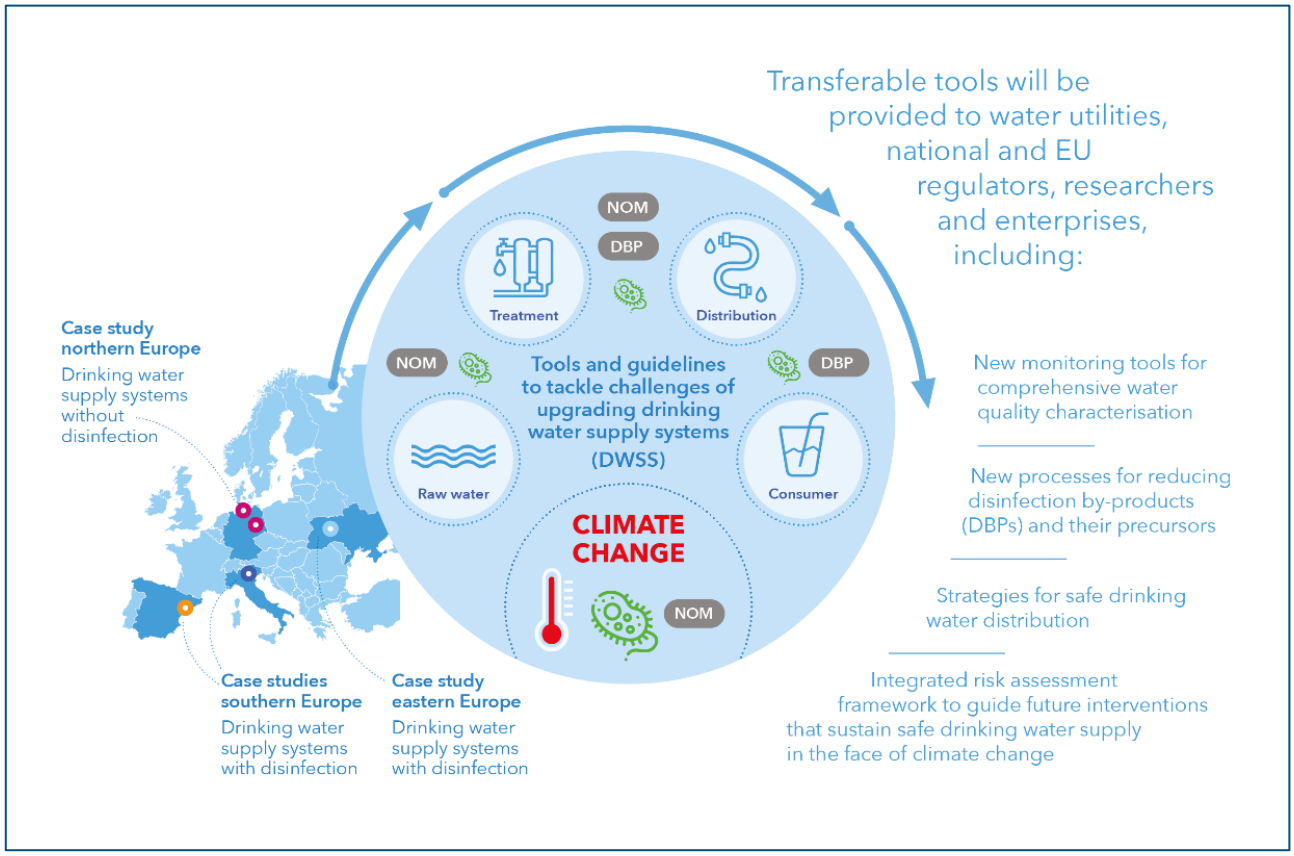
Project Duration

01.11.2022 – 30.04.2026

Funded by the European Union

Funding

Horizon Europe (Project number 101081980)



Introduction

The major aim of SafeCREW is to develop tools and guidelines for water utilities to tackle challenges related to climate change and in particular disinfection. Well-established processes that have so far guaranteed high drinking water quality might have to be changed and adapted. Countries in Southern Europe are currently disinfecting their drinking water and aim to decrease the amount of disinfection by-products. It might be possible that under climate change conditions Northern European water suppliers will need to disinfect in the near future and water utilities would like to be prepared.

Research Goals

The project has recently successfully finished the first reporting period. In this first half of the project, the development of the methodological basis and the generation of data for further analysis have been the focus. While the development of disinfection by-product and natural organic matter detection and characterization have been advanced in the beginning of the project, these methods were now applied within the case studies. Selected results are presented in the following. More details can be found on the website of SafeCREW (www.safecrew.org) as soon as the respective deliverables are accepted and made public.

Recent Results

New partner and additional case study

The SafeCREW consortium already works on case studies in Northern Germany, Italy and Spain that cover non-disinfected and disinfected supply systems with various raw water sources. With the start of the second reporting period, an additional partner has joined the SafeCREW consortium. The National University of Water and Environmental Engineering (NUWEE) from Ukraine complements the existing consortium by adding an Eastern European perspective and they bring in a fourth case study.

Collaboration with other projects

The SafeCREW project is very active in the ZeroPollution4Water cluster, which includes the sister projects from the same call of EU funding. Disinfection by-products are a common thread in this cluster. Several webinars have taken place to inform water experts and interested water utilities about the newest results. New webinars are planned for the second reporting period. The webinars (All about DBPs; DBPs – Monitoring, Treatment, and Regulation; Precursors of DBPs; Drinking Water Systems Modelling and Digitalization) can all be found on the SafeCREW website.

Passive sampler for microbial monitoring

Experimental protocols were developed to analyze interactions between bacteria and passive sampler materials. The idea is to develop an early-warning system that uses long-term sampling to detect sporadic contamination events, which might be missed by traditional grab sampling methods. Up till now, a standardized experimental protocol to test the suitability of materials as passive sampler has been developed. This protocol has been validated to evaluate the performances of some materials for a proof-of-concept.

Test protocol for materials in contact with disinfectants

In Germany and other Northern European countries, drinking water is usually not disinfected. If disinfection becomes necessary, for example due to climate change, it is not known, how the materials will behave that come into contact with disinfectants for the first time. A protocol was developed to analyze the interaction between pipe material and disinfectants. The chlorine consumption as well as the creation of DBPs was analyzed. For maximum release testing, the materials were ground into powder for analysis. This approach allows for a standardized procedure when analyzing leachates from various product types.

Microbial monitoring

Microbial cell numbers were monitored over one year at two case study locations (Berlin and Hamburg). A combination of flow cytometry and ultrafiltration was used to track microbial numbers. Ultrafiltration modules are used for sampling on site to gain a concentrated sample with increased cell number (by about factor 500). In addition organic matter was analyzed by Liquid Chromatography-Organic Carbon Detection (LC-OCD), fluorescence spectroscopy, and UV-VIS absorption measurements. The aim was to detect seasonal fluctuations of microbial loads in raw water influenced by surface water, such as at bank filtration sites. By combining microbiological and organic analyses, a comprehensive monitoring system can be developed that provides extensive information not only on seasonal changes in microbial quality, but also on the underlying causes and influencing factors.

Monitoring of drinking water distribution network

At two case study sites, in Spain and Italy, large datasets have been collected which will now be worked on for the purpose of modelling approaches. The data include information about physicochemical parameters as well as microbiological parameters and both lab analysis and data from online measurements. All data is uploaded to the Zenodo repository in order to make the data available and the results transparent. These large datasets are necessary to understand drinking water distribution network behaviours and model the evolution of water quality through the networks.

Climate change scenarios

A literature review was done to identify climatic drivers and their impact on water availability and quality. To complement this review, historical data from SafeCREW's case study in Spain was analysed to create future projections.

DBP precursor removal by different materials

A guideline has been developed to evaluate conventional and advanced adsorbent materials to enhance water treatment processes in their capability to remove natural organic matter as DBP precursors. This guideline serves as methodological procedure to be followed to rank adsorbent materials.

Conclusion and outlook

While the methodological basis has been set in the first part of the project, currently a lot of data is generated by conventional methods and novel methods. This data is and will further be analyzed to create models and predictions, e.g. for smart management of drinking water treatment and distribution.

Project Partners

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Project Partners

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2.3 SafeCREW: Electro-Regeneration Membrane Adsorbers for the Removal of Precursors of Chlorine-Based Disinfection By-Products in Drinking Water Treatment

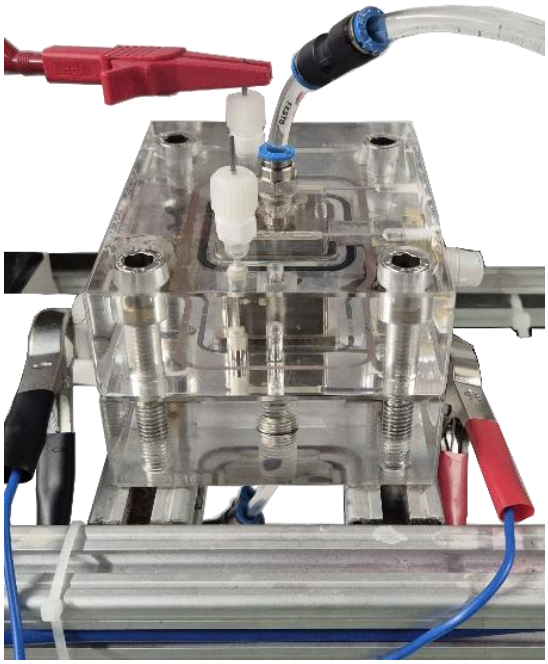

Figure 1: Electrochemically modified membrane cell

Project Duration

01.01.2023 – 01.01.2026

Funding

Horizon Europe (Project number 101081980)

Funded by the European Union

Introduction

Natural Organic Matter (NOM) is recognized as the primary precursor of Disinfection By-Products (DBPs), particularly the regulated Trihalomethanes (THMs). The research conducted within the SafeCREW Project at the DVGW Research Centre TUHH aims to enhance the understanding of the composition of NOM and its complex relationship with DBP formation. Additionally, the project focuses on the removal of NOM using adsorptive membranes and the development of a chemical-free regeneration mechanism. This mechanism involves the use of an electric field to regenerate the spent membrane adsorbers.

Research Goals (DVGW research centre TUHH)

The SafeCREW objectives at the DVGW research centre TUHH can be divided into two sections:

- Improvement of **NOM characterization** methods and linking with DBP formation
- **Chemical-free removal of NOM using membrane adsorbers** to prevent the formation of DBPs

The focus is on further characterizing organics in drinking water using LC-OCD, Absorbance, Fluorescence Spectroscopy and advanced analysis using the PARAFAC method to separate fluorescent organics into individual components and ultimately combine the aforementioned methods to fingerprint waters and link these to the formation of DBPs.

The second focus of the DVGW research centre is on the selective removal of the identified precursors of DBPs. For this purpose, a chemical-free removal method of NOM as the main precursor is to be developed.

Approach

To establish and improve NOM characterization methods, we employed four distinct water matrices representing different water bodies: groundwaters, river, and lake waters. These matrices served as essential benchmarks for lab-scale chlorination experiments, allowing us to investigate the kinetic changes in NOM and subsequent DBP formation. This comprehensive approach enhances our understanding of NOM composition in different water sources and enables us to elucidate the dynamic relationship between NOM transformations and regulated as well as unregulated DBP formation, providing insights for water quality management.

Porous membrane adsorbers are employed to efficiently remove NOM and thus DBP precursors before the disinfection process. Recently, we demonstrated that these adsorbers can be regenerated using a basic solution to create a pH-swing [1]. However, to enhance sustainability, a new method is being developed to regenerate the adsorbers without chemicals: The application of an electrical potential near the membrane surface (Figure 2). This technique may induce local pH changes at the electrodes and near the membrane surface, as well as electrostatic repulsive forces, facilitating the desorption of previously adsorbed NOM and effectively regenerating the membrane.

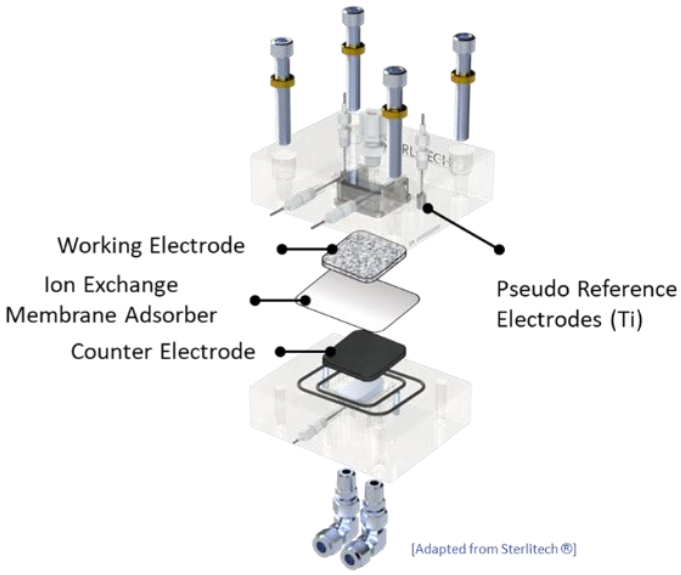

Figure 2: Setup of the membrane cell used for applying an electrical potential

Recent Results

Lab-scale chlorination tests were conducted to examine the complex composition of NOM and its evolution during the disinfection process, focusing on DBP formation. The research investigated four different water sources: a synthetic water sample from Suwannee River NOM extract, and three real-water samples from groundwater in Hamburg (Case Study 1), groundwater in Italy (Case Study 2), and bog water. Using two disinfectants, the study applied absorbance scans, fluorescence matrices analyzed via the PARAFAC algorithm, and LC-OCD analysis to clarify variations in raw water compositions.

Recent findings revealed that regulated DBPs, such as trihalomethanes (THMs), show known correlations with organic matter, particularly the humic fraction. This correlation allows the prediction of THM formation using conventional analysis methods. However, for newly identified DBP classes, such as sulfonated DBPs, these correlations do not hold. The study highlights that advanced analysis using FT-ICR-MS suggests further investigation into water matrices, particularly focusing on sulfonated groups, to predict trends in these "novel" DBPs.

To investigate the chemical-free regeneration of membrane adsorbers, an electrical potential was applied to electrodes in close proximity to the membrane. Dynamic adsorption experiments showed a 50 % breakthrough after approximately 2500 bed volumes for a representative groundwater feed matrix. After reaching the breakthrough, a cell potential of -2.5 V was applied to initiate desorption. As depicted in Figure 3, the process can be conducted cyclically. By applying a voltage, up to 85% of the previously adsorbed TOC can be reversibly regenerated, ultimately extending the adsorber's lifespan. Moving forward, the process will be further optimized and the mechanisms underlying regeneration will be explored in more detail.

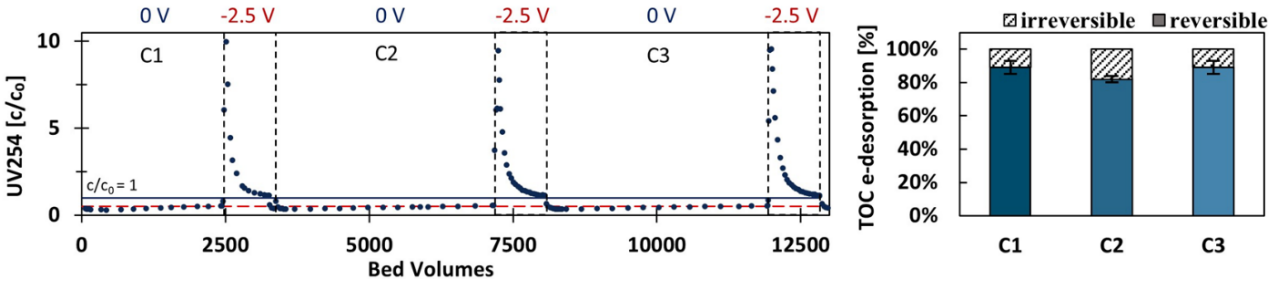

Figure 3: (Left) Cyclic Adsorption (Cell Potential: 0 V) and Desorption (Cell Potential: -2.5 V) of NOM on a weekly basic membrane adsorber. (Right) TOC e-desorption efficiency of the three consecutive cycles.

Outlook

Ongoing research will focus on examining the influence of water chemistry, such as pH value, conductivity, or competing ions, as well as operational parameters like flux and applied potential. Its potential applications at different stages of water treatment will be investigated. Particular attention will be given to the removal of bromide, with further exploration into reducing the formation potential of both regulated and unregulated (brominated) DBPs. Additionally, efforts will be made to optimize the process for longer testing and cycle durations.

[1] Wullenweber, J., Bennert, J., Mantel, T., & Ernst, M. (2024). Characterizing Macroporous Ion Exchange Membrane Adsorbers for Natural Organic Matter (NOM) Removal—Adsorption and Regeneration Behavior. *Membranes*, *14*(6), 124. https://doi.org/10.3390/membranes14060124

Project Partners

Project Coordination

DVGW | TUHH Technische Universität Hamburg

Project Partners

BDS BioDetection Systems

Consorci d'Aigües de Tarragona

eurecat

KWB

MM

Umwelt Bundesamt

multisensor systems sensing measuring protecting

POLITECNICO MILANO 1863

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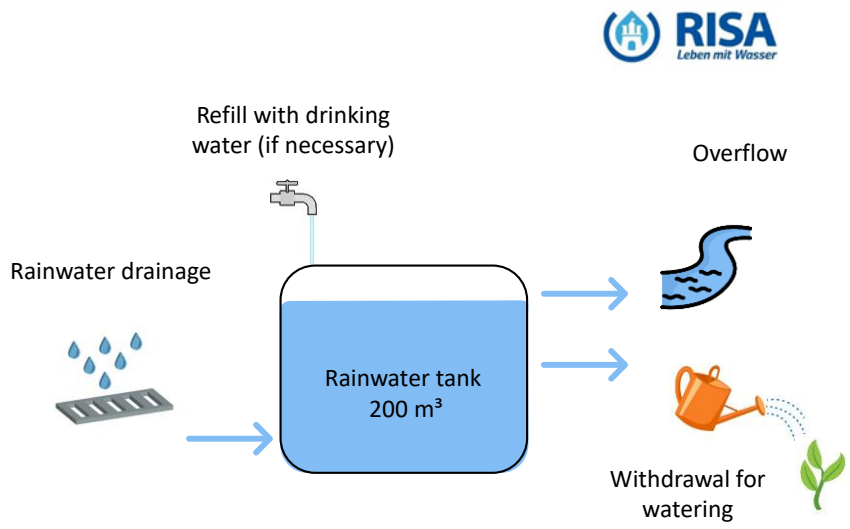
2.4 Rainwater utilization at the Hamburg-Bergedorf cemetery - scientific monitoring of the installation and operation



(© L. Jakubczick)

Project Duration

01.06.2022 – 31.05.2025

Project Funding

BUKEA Behörde für Umwelt, Energie, Klima und Agrarwirtschaft

Hamburg

Gefördert aus Klimaschutzmitteln

Introduction

The project "Rainwater Utilization at Bergedorf Cemetery" explores the use of rainwater for purposes that do not require drinking water quality. The surface drainage from the paved areas on the cemetery in Bergedorf, Hamburg, is collected, filtered and stored in a rainwater tank. From here it is fed into the existing water distribution system and available for irrigation at the cemetery.

This conversion of an existing rainwater drainage system into a management system is part of a RISA (RainInfraStructureAdaption) project, a joint project of BUKEA, Hamburg Wasser and other partners. Only recently the installation has started its performance and the collected rainwater now supplies the local water distribution network and can be taken for irrigation purposes at the tapping points.

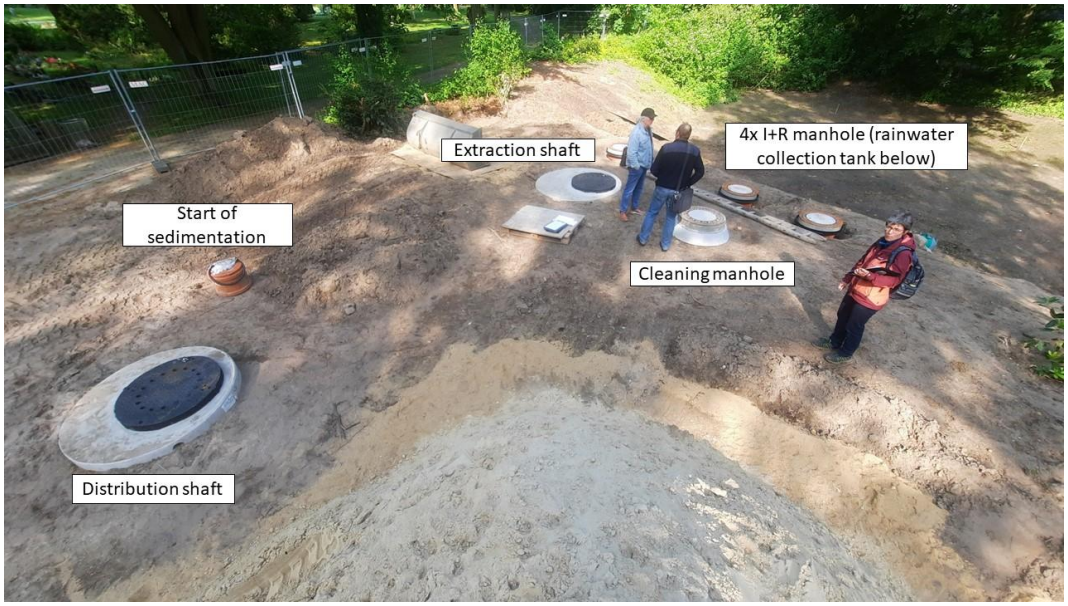


Figure 1: Top view of the rainwater utilization installation. Built underground are collection tanks for 200m³ of rainwater (© T. Dorsch)

Research Goals

The project shall serve as a model project for other rain water utilisation projects. Therefore, the rainwater collection, and withdrawal will be monitored over time and analyzed together with weather data like rainfall and temperature.
On the one hand, the water quality in such a system will be monitored. On the other hand, the water quantity over time will provide information about the usefulness of rainwater collection to save drinking water and face climate change effects such as extended drought periods in summer and increase of heavy rainfalls events.

Figure 2: Sampling from rainwater collection tank (© L. Jakubczick)

Approach

DVGW-TUHH supports the installation with scientific monitoring. This includes the selection and placement of the required sensors and the subsequent monitoring of the management system. Samples are taken for analysis of relevant parameters. These include chemical parameters as well as microbiological parameters.

Figure 3: Sampling and measurements at tap (© L. Jakubczick)

Recent results

The first set of samples have been collected and will be analysed for various parameters. Relevant guidelines have been studied to decide on a set of parameters to analyse water samples from the installation. A first sample has been taken and further will follow to see a seasonal trend of water quality. Samples will be taken at the inlet and storage tank as well as the water taps. The relevant parameters include standard parameters (temperature, pH, conductivity, colouring, turbidity) as well as hygienic parameters. It is also planned to analyse trace substances and ions to exclude relevance and check for influences of for example thawing salt and copper roofs.

Conclusion and Outlook

The selected parameters will be analysed and further samples taken over the course of the project. This will allow an estimation of the water quality and the possible deterioration of water quality in the tank and the pipes. With the data of rain and irrigation waters that will be collected over time, an estimation whether the dimension of the storage tank is sufficient and how much drinking water can be saved, will follow.

These results will help other projects with similar aims. Green areas like parks provide opportunities to save drinking water by rain water collection for irrigation. Another location in Hamburg where this is of interest, is the Planten un Blomen park. The results from this project can also be transferred to other cities where rainwater utilization is planned.

Project Partners

Project Coordination

Behörde für Umwelt, Klima, Energie und Agrarwirtschaft

Project Partners

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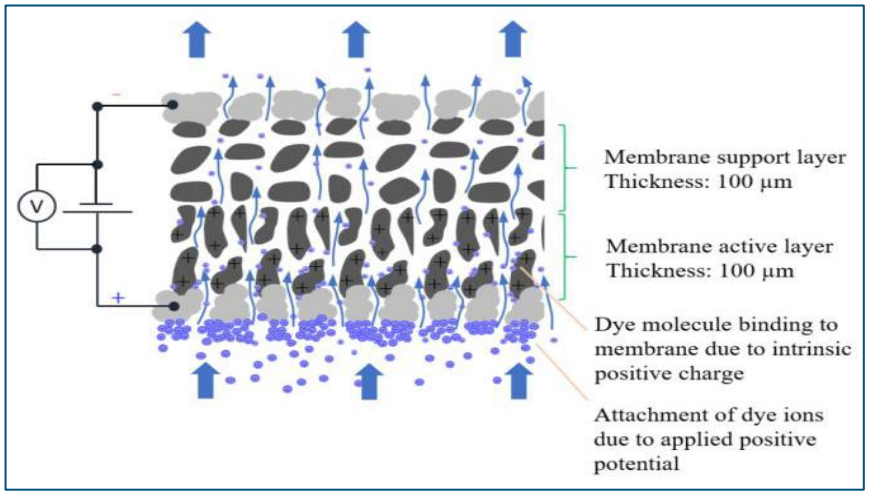
2.5 NOM e-Sorp Membrane: Electro-conductive porous membranes for electro-sorption and –desorption of NOM from water



Project Duration

01.01.2021 – 15.09.2024

Funding

DFG Deutsche Forschungsgemeinschaft
German Research Foundation

DFG-Project No.: ER 683/1-2

Introduction

Surface water, which is the main source of drinking water worldwide, contains NOM, which in general poses significant challenges for their removal in water treatment facilities. The presence of NOM may lead to the formation of harmful DBPs, reduced disinfection efficiency and may cause membrane filtration fouling, thus complicating treatment processes and increasing operational costs. Nanofiltration (NF) membranes, known for their high efficiency in producing high-quality effluent, are often used for NOM removal. However, NF has drawbacks, including low water recovery, complex system designs, membrane fouling, and high energy consumption of up to 4 kWh per cubic meter of treated water as it is operated at higher pressure (3-10 bar). In contrast, ultrafiltration (UF) membranes are less energy-intensive, consuming between 0.3 to 0.5 kWh per cubic meter of treated water. Moreover, most UF plants are operated in dead-end filtration mode, resulting in water recovery rates up to 99%. While UF is effective at removing particles and pathogens, due to its pore diameter (10-50 nm) it is not efficient at removing NOM.

Research Goals

The NOM e-sorp Membrane project aimed to utilise the electrostatic interaction between organic water constituents, mainly NOM which is mostly negatively charged and porous membranes by applying an external electrical potential to an electrically conductive (EC)-UF membrane in dead-end electro-filtration. The primary objective of the project includes understanding how intrinsic material properties impact the electro-sorption/electro-desorption process of organic water constituents on EC membranes. This resulted in an interdisciplinary collaboration between the Institute for Water Resources and Water Supply at the TU Hamburg and the Institute for Membrane Research (IMF) at the Helmholtz Zentrum HEREON (Geesthacht), Dr. Glass, Dr. Filiz). The synthesis and surface modification of PAN with EDA and NaOH are presented in projects publications [1,2].

In addition to membrane materials, the project also focused on elucidating these processes through a theoretical model and evaluate the influence key parameters such as applied electric field strength, feedwater pH, NOM concentration and composition, filtration flux, and ionic strength on the NOM electro-sorption/-desorption processes.

Approach

The ECMs are established by magnetron sputtering of an ethylenediamine (EDA) and NaOH functionalized polyacrylonitrile (PAN) membrane with a porous nanolayer of Pt on both sides of the membrane. The selective side of the membrane serves as the working electrode and the membranes support side is the counter electrode. The project partner HZ Hereon carries the functionalization of the porous PAN membrane with EDA and NaOH. At TUHH, the NEC and EC membranes are characterized as well as applied in dead-end UF applications for the treatment of humic substances-rich waters.

Results & Findings

Membrane characterization

Numerous flat polymer membranes, modified from PAN, were tested for NOM electro-sorption/-desorption. Zeta potential measurements confirmed successful modification with EDA and NaOH. The virgin PAN membrane had a consistently negative zeta potential across pH 3 to 9 and no isoelectric point (IEP). In contrast, the modified PAN membranes showed increased zeta potentials, with PAN-NaOH and PAN-EDA having IEPs of 3.7 and 7.8, respectively.

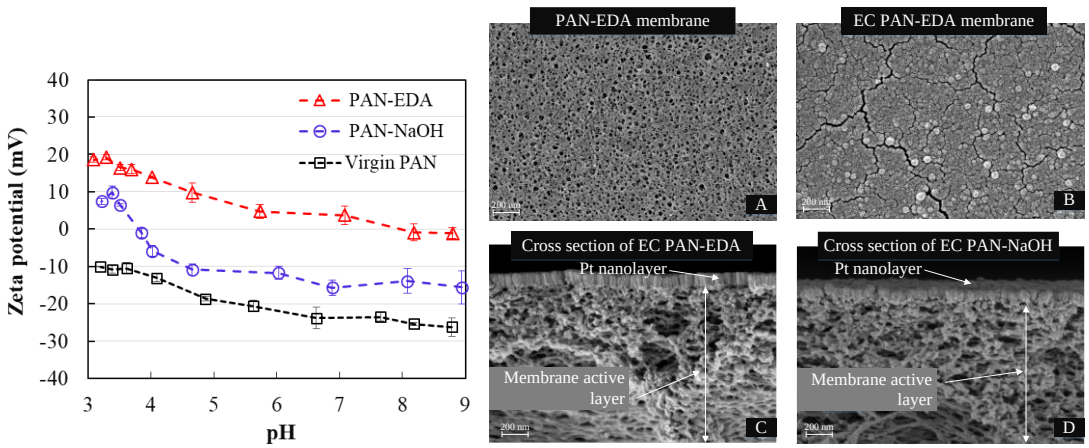


Fig.1: a) left: Zeta potentials of virgin and modified PAN membranes. DOI: 10.1016/j.jwpe.2023.104733, b) right: SEM images of (A) PAN-EDA; (B) EC PAN-EDA membrane; (C) cross-section of EC PAN-EDA and (D) EC PAN-NaOH membranes with 50K magnification [1]. DOI: 10.1016/j.jwpe.2023.104733.

- To address the impact of Pt coating on PWP, 10 nm Pt coating was also tested. The electrical conductivity of 20 nm Pt coating was measured at 2.42 × 106 S/m. In contrast, the conductivity of 10 nm coating was lower, at 1.62 × 105 S/m. The gaps and sparse Pt NPs distribution hindered continuous conductive pathways, reducing conductivity. Additionally, the 10 nm Pt coating showed lower NOM electro-sorption rates compared to the 20 nm coating, indicating that effective electro-sorption requires a minimum conductivity of 2.42 × 105 S/m [1].

- The project also evaluated the intrinsic adsorption properties of virgin and modified PAN membranes. Functional groups in the membranes led to varying charges: PAN-EDA mem-branes had a positive intrinsic charge due to amine groups (-NH_2), while PAN and PAN-NaOH membranes had a negative charge from nitrile, carboxyl, and amide groups. The PAN-EDA membrane showed intrinsic NOM adsorption, whereas PAN and PAN-NaOH did not [1,2].
- Applying a negative potential to the EC membrane (acting as a cathode) caused electro-desorption of NOM and dye due to electrostatic repulsion. A theoretical model based on the modified Poisson–Boltzmann (MPB) equation identified that this repulsion could partially re-generate the membrane (up to 39% at pH 8 equal to IEP of the PAN-EDA membrane), but only within 24 nm of the membrane surface. The model indicated that while the electrostatic repulsive force effectively desorbs NOM and dye near the surface, it is less effective for ions adsorbed deeper within the membrane matrix. [1,2].
- When the EC membrane surface was used as an anode, applying positive potentials resulted in electrostatic attraction, which facilitated the electro-sorption of NOM and dye ions onto the ECM surface without causing severe fouling. The extent of electro-sorption increased with higher applied positive potentials. The MPB model provided a comprehensive explanation for the experimentally observed electro-sorption results, showing that the predicted electrostatic attraction at different positive potentials matched the observed electro-sorption at different positive potentials [1,2].
- The adsorption of organic water constituents on EC PAN-EDA membrane occurs through different mechanisms: intrinsic membrane charge promotes adsorption at charged binding sites within the membrane, while an external positive potential induces electro-sorption by attracting counterions directly to the membrane surface through electrostatic forces [2].
- The contact time between NOM and the membrane, governed be filtration flux had a limited effect on DOC electro-sorption loadings during electro-filtration. This indicates that the kinetics of the electro-sorption are very rapid due to the applied external electrical potential. Higher salt concentrations, such as NaCl, substantially impacts electro-sorption efficiency. At a concentration of 100 mL NaCl, electro-sorption decreased by more than 90%, demonstrating that elevated salt levels interfere with the electrostatic interactions between NOM and the membrane [1].
- Size exclusion chromatography (SEC) analysis identified HSs as the most effective NOM fraction for electro-sorption membranes. In total 75% removal of NOM could be achieved in tested model solutions. Up to 25% of low molecular weight (LMW) NOM was not removed due to the presence of uncharged NOM fractions in the feed water, which are not attracted by the applied electric field. The electro-sorption efficiency decreased with the molecular weight (MW) of the NOM fractions, according to SEC in the following order: building blocks > LMW acids > LMW neutrals. The electro-sorption process was especially effective at removing high MW NOM fractions such as HSs [1].
- SEC further revealed no evidence of NOM oxidation when applied positive potential was below the threshold for oxygen evolution for Pt. Specifically, there were no new or larger peaks for LMW organics in permeate compared to feed sample at +1.5V, +2.0V, and +2.5V. NOM removal occurred through electrostatic interactions with the EC membrane, indicating that electrochemical oxidation was not a contributing factor at the applied potentials [1].
- Reversing the electrical polarity detaches the electrically attracted NOM, demonstrating pro-cess reversibility. Optimal electro-desorption occurs when the pH equals the membrane's IEP, enhancing electrostatic repulsion for efficient counterion detachment. A potential of at least -2.0V is necessary

for effective regeneration and sustained performance, enabling multiple reuse cycles without loss of capacity. This makes the process effective for both NOM removal and concentration of organic water constituents [1,2].

- EC membranes maintained excellent electrical conductivity during electro-sorption and elec-tro-desorption, with only a slight decrease. The SEM images revealed that the membrane morphology remained largely unchanged before and after the process. Additionally, nano-particle tracking analysis (NTA) revealed the absence of Pt NPs in the permeate. These evi-dences suggested that relevant Pt leaching did not occur [2].

Conclusion and Outlook

The performance of EC membranes improved with increasing positive potential and was not significantly affected by the speed of filtration (contact time). The electro-sorption process efficiently removed HSs and the removal of NOM fractions decreased with decreasing molecular weight compounds at applied filtration pressure of <0.2 bar. Moreover, up to 25% of NOM, primarily uncharged fractions, remained in the water. The NOM electro-sorption process on EC membranes was largely reversible. EC membranes showed high NOM separation efficiency (up to 75%) without losing performance, thus allowing for membrane regeneration and consistent performance. An additional advantage of the counter electrode configuration of EC membranes is a significant increase in filtration flux due to the electro-osmotic phenomenon. Additionally, the energy demand for electrofiltration was very low (≈20 Wh/m3).

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Project Partners

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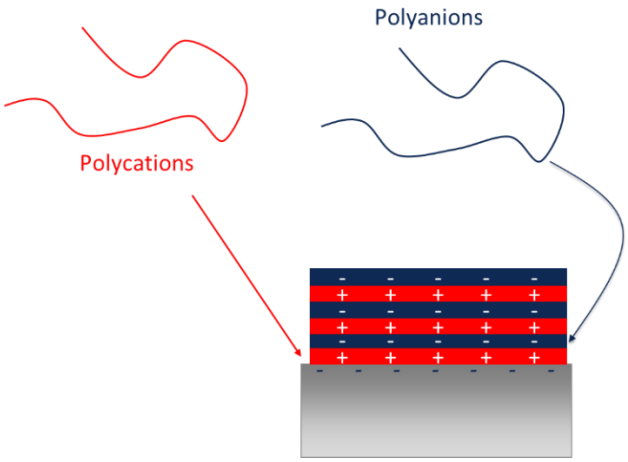
2.6 KeraRes: Layer-by-Layer-coated ceramic membranes for resource efficient production of drinking water and service water



Project Duration

01.07.2024 – 30.06.2027

Funding

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

BMBF-Project No.: 03XP0614B

Introduction

Conventional nanofiltration (NF) membrane systems are generally subject to fouling (particles, organics, precipitates, biofilms), i.e. the membranes are blocked over the operating time due to the formation of a fouling layer of organic and possible inorganic substances. Conventional NF spiral wound membrane modules cannot be backwashed and only part of the covering layer can be removed by membrane cleaning (cleaning-in-place). Upstream microfiltration, i.e. a two-stage process, is a possibility to prevent particle fouling. In KeraRes, backwashable multi-channel modules will be developed to enable a single-stage process. Fouling nevertheless will increase the energy requirement of the NF over the operating time up to the point at which the membrane modules have to be replaced. The KeraRes membrane process aims to solve this problem by regenerating the Layer-by-layer (LbL) coating: the old LbL layer is dissolved by increasing the pH and then the ceramic support will be re-coated.

Research Goals

The KeraRes research project is developing an innovative membrane process for resource-efficient water treatment. The project focusses on modifying a ceramic membrane to obtain a high efficiency in filtering and separating water impurities thanks to a so-called LbL-coating with polyelectrolytes. The system is particularly designed to safely treat water resources such as river water, wastewater, and rainwater, etc., in a single step. The developed membrane will be able to hold back particles such as microplastic and bacteria as well as dissolved components as salts and organic substances and hazardous chemicals such as per- and polyfluoroalkyl substances (PFAS). At the same time, the membrane is designed to be regenerable, backwashable and, compared to conventional ceramic membranes, more durable and less vulnerable to fouling. Regenerability is ensured by removing the LbL-layer by pH adjustment that causes the old LbL-films to dissolve. In this way the membrane performance can be restored by reapplying the polyelectrolyte layer.

Overall, the KeraRes projects goal is to provide a scalable and energy-efficient solution for water treatment that meets the increasing demands for drinking and industrial water supply in various applications. With the possibility of regeneration and modularity, the system offers both ecological and economic advantages that make it attractive for the market in the long term.

Approach

The project is divided into three phases: Membrane development, process development and upscaling. In the first phase the ceramic membrane will be modified. Membrane coating tests and membrane characterization are performed to determine the optimal parameters for the LbL-coating process such as kind of polyelectrolytes, their molecular weights, salinity, temperature and pH value. Following the successful development of membrane coating, new membrane housings (modules) will be developed. Initial tests will be carried out on a laboratory and semi-industrial scale during the process development phase in order to test the durability of the coating and the backwashing behavior and to compare it with established polymeric NF systems. Project work of DVGW-TUHH includes membrane coating and characterization of coated membranes including lab tests. The results are used for comprehensive analyses of the energy and material efficiency of the system to enable a well-founded evaluation as part of a life cycle assessment (LCA), performed by UBA. The final phase of the project is dedicated to upscaling, with the coordinating partner Inflotec that will commercialize the new product.

Outlook

At the moment the laboratory coating tests and laboratory tests of filtration performance of coated membranes are set up. Figure 1 shows a ceramic monotube membrane (top), the membrane module for laboratory tests (bottom) and the laboratory LbL-coating system (right).

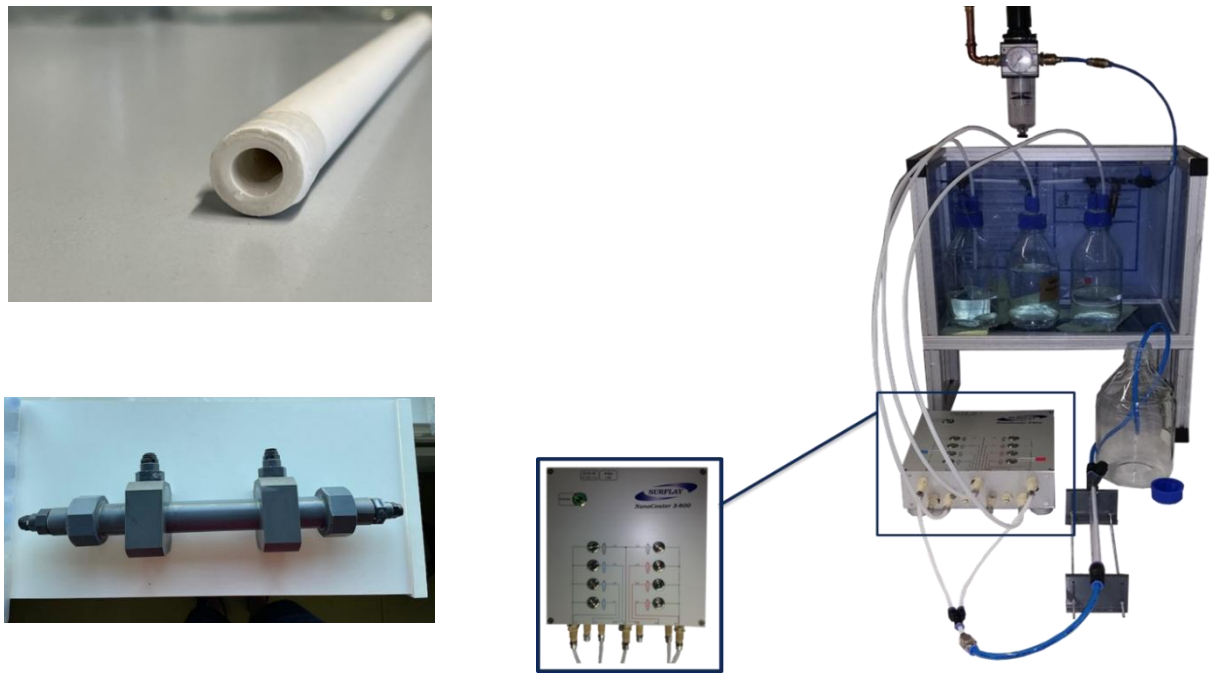


Figure 1: Ceramic monotube membrane for laboratory tests (top), membrane module for laboratory tests (bottom), system with nanocoater for LbL-coating at DVGW-TUHH (right)

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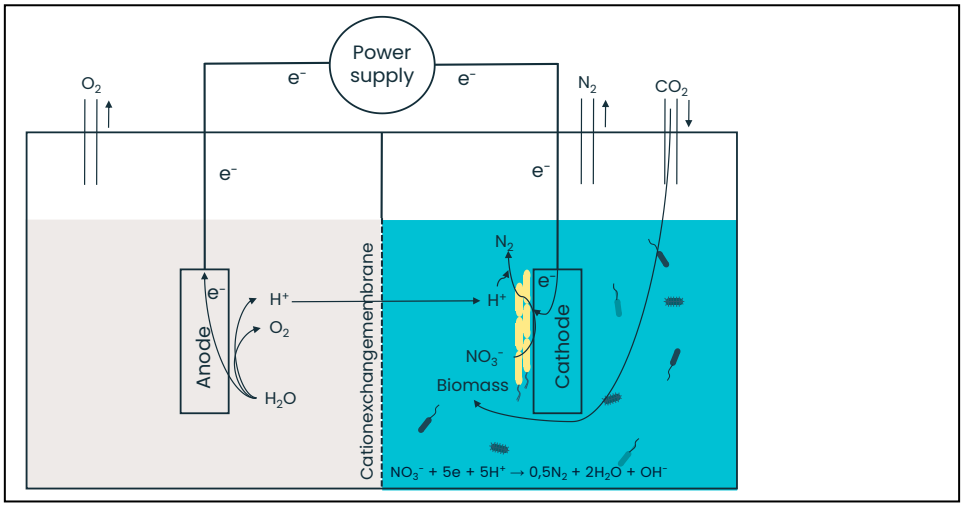
2.7 Autotrophic Denitrification with Bioelectrochemical Systems for Drinking Water Treatment



Project Duration

01.11.2021 – 31.10.2025

Funding

TUHH
Technische Universität Hamburg

Introduction

Elevated nitrate levels in water bodies worldwide, particularly in groundwater, pose a significant challenge to drinking water supplies (Mohseni-Bandpi et al., 2013; World Health Organization, 2011). Biological methods for nitrate removal are particularly promising, as they efficiently convert nitrate into gaseous nitrogen without generating additional concentrated wastewater that requires further treatment (Ortega-Martínez et al., 2024). One such approach is autotrophic denitrification, which does not require added organic carbon. Instead, it utilizes inorganic carbon like carbon dioxide, sulphur, or electrodes as electron donors (Rezvani et al., 2019). However, natural electron donors are often limited in availability. As a result, bioelectrochemical systems (BES) are gaining increasing interest in research on autotrophic denitrification, as these systems can overcome limitations in electron supply (Cecconet et al., 2018; Rezvani et al., 2019). To date, these systems have primarily been tested at laboratory scale.

Research Goals

The aim of this study is to gain fundamental insights into the kinetics of denitrification in bioelectrochemical systems (BES) and, thereby, improve the efficiency and scalability of this technology for future large-scale groundwater treatment. Specifically, the study will examine the effects of key parameters such as electrode materials, poised potential, electrical conductivity, as well as operational conditions like pH level and nitrate concentration on the efficiency of denitrification. The information obtained is intended for developing design criteria for more efficient and better BES systems for autotrophic denitrification.

Approach

At the beginning of this study, a laboratory procedure was established to enable reliable and reproduceable cultivation of microbial organisms that serve as catalysts in the autotrophic

denitrification process. This procedure ensures a stable and consistent reactor operation, which is crucial for conducting further experiments under identical conditions.

The method of bidirectional electron transfer was utilized for cultivating these microorganisms. In bioelectrochemical systems (BES) for autotrophic denitrification, it is essential that electroactive microorganisms effectively transfer electrons from the electrode (in this case, the cathode) to nitrate, converting it into nitrogen gas (N_2). At the beginning, we spiked model waters with small fractions of treated municipal wastewater. To accelerate the growth of these microorganisms, they are initially cultivated under heterotrophic conditions where they break down organic substrates and release electrons. These electrons are then transferred to the anode. Once successful electron transfer is achieved, indicated by an increase in current density, an "electron switch" can be performed, allowing nitrate reduction under cathodic conditions (see Figure 1).

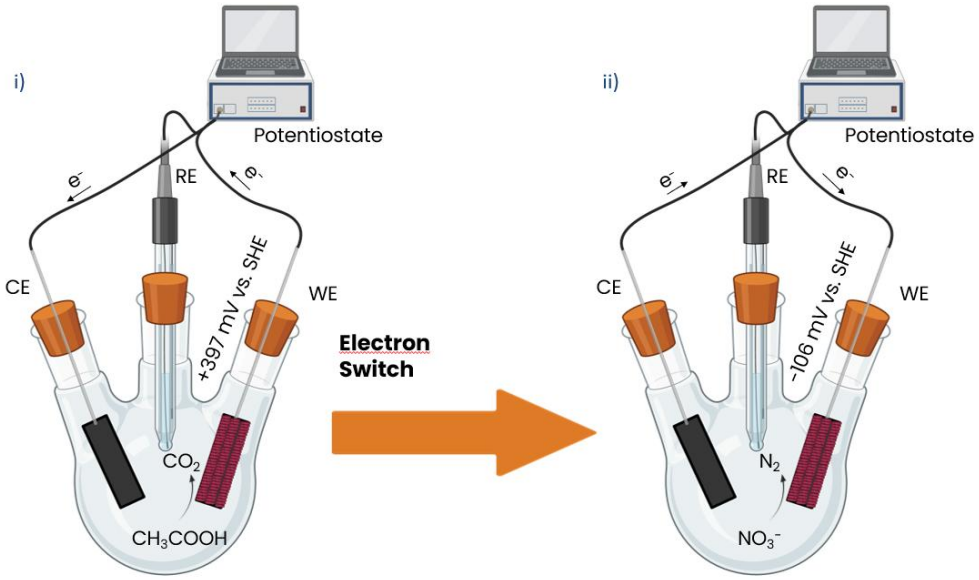


Figure 1: Schematic of the reactor configuration and procedure of electron switch for cultivation of an electroactive biofilm, i) bioanodic conditions, ii) biocathodic conditions

Recent Results

The cultivation of an electroactive biofilm was successfully demonstrated in a four-neck flask, using graphite rods as electrode materials (see Figure 1). After 16 days of inoculation, the electron switch was initiated. The development of current density revealed clear differences between biotic and a parallel operated abiotic reactor (see Figure 2) at a potential of -0.7 V vs. SHE. We changed flags water on days 16, 19, 26, 37, and 42, with measurements of nitrate and nitrite concentrations taken at once after each exchange. In the abiotic reactor, current density remained constant between -0.2 and 0.5 A/m² throughout the experimental period, indicating purely physical electron transfer without biological assistance. In contrast, the biotic reactor exhibited a significantly higher current density, reaching up to -1.7 A/m², which highlights the catalytic activity of the electroactive microorganisms.

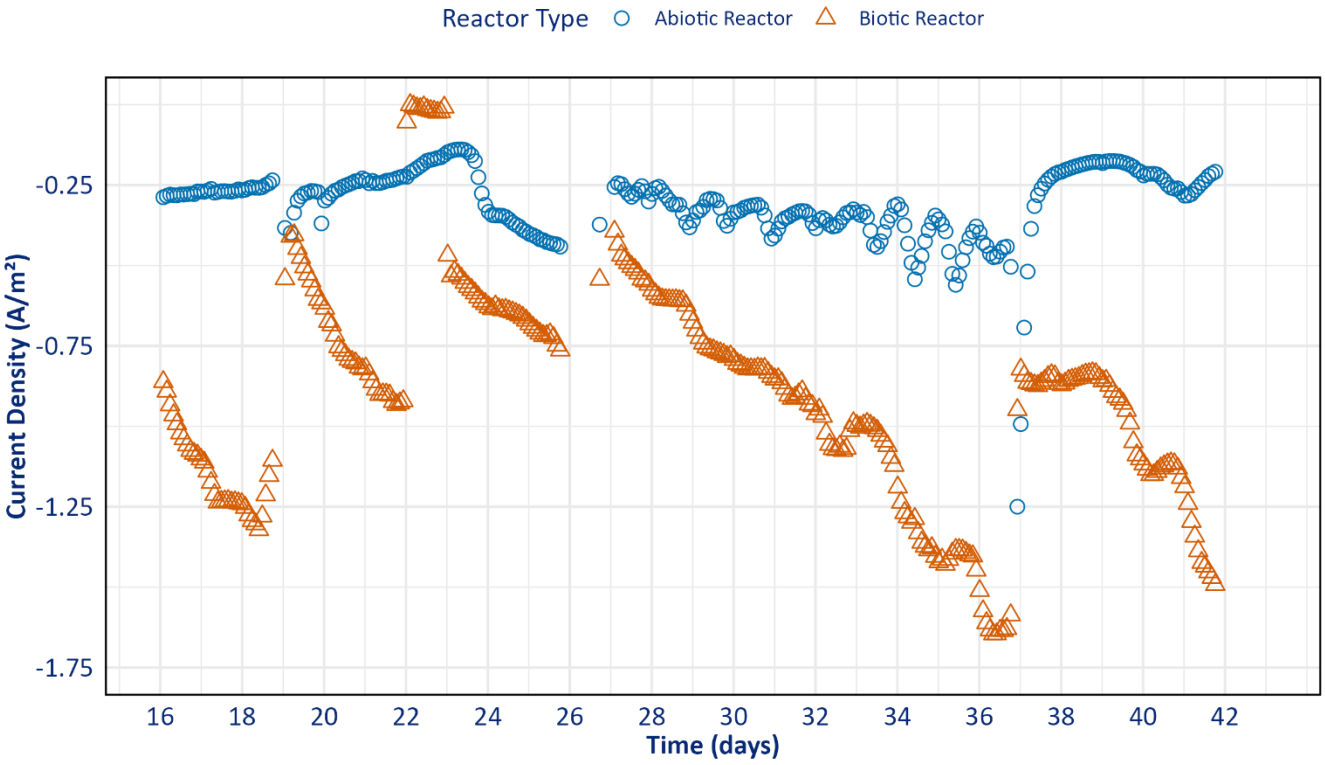


Figure 2: Current density of a biotic and abiotic reactor over time in a four-necked round-flask reactor after 16 days of inoculation. Operation at -0.7 V vs. SHE, exchange of the water at day 16, 19, 26, 37 and 42

The denitrification rates (see Table 1) also showed significant differences between the biotic and abiotic conditions. In the biotic reactor, the denitrification rate reached up to 95 mg/l, while in the abiotic system denitrification rates reached only values up to 10 mg/l. The higher nitrate value observed at day 19 in the abiotic reactor compared to the starting value could potentially be explained by a measurement error or water evaporation, which may have led to a concentration increase in nitrate levels. These data confirm that the biotic reactor, due to the presence of electroactive microorganisms, exhibits a higher denitrification performance.

Table 1: Nitrate and nitrite concentrations in biotic and abiotic reactors compared to the starting concentration

	Initial value		Abiotic reactor		Biotic reactor	
Sampling day	NO_3^- [mg/l]	NO_2^- [mg/l]	NO_3^- [mg/l]	NO_2^- [mg/l]	NO_3^- [mg/l]	NO_2^- [mg/l]
19	83,13	0	106, 30	0	24,84	2,14
26	100,59	0	97,59	0,31	6,19	0,48
37	46,08	0	37,13	18,18	0	0,08
42	79,97	0	69,75	10,45	0,68	0

The increased current density and denitrification rate in the biotic reactor demonstrate that the approach of bidirectional electron transfer enables efficient use of electrons for nitrate reduction. The fact that the experiments remained stable over a period of 24 days indicates the robustness of the process. Overall, the method of bidirectional electron transfer provides a solid foundation for future experiments.

Conclusion and Outlook

The cultivation of electroactive organisms through bidirectional electron transfer allows for the rapid development of organisms for further experiments. This method forms the foundation for all future trials. By the end of 2024, tests will be conducted to investigate the effects of different cathode materials on denitrification performance. Subsequently, using the Reference Surface Method, the influence of parameters such as pH, nitrate content, electrical conductivity, and poised potential on denitrification performance will be analyzed.

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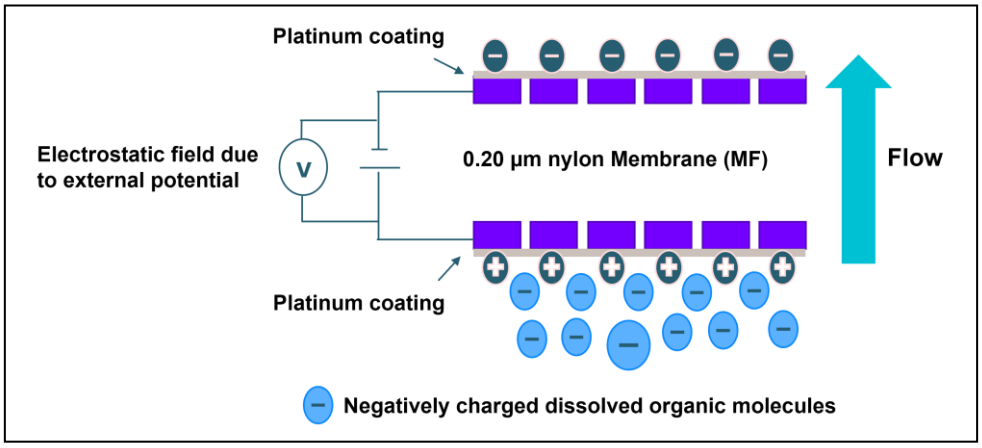
2.8 Modelling of Membrane-Separation Processes for Water Treatment



Project Duration

01.06.2022 – 31.05.2026

Funding

TUHH
Technische Universität Hamburg

Introduction

Due to climate change, raise in population and the increasing amount of pollution in our environment, water scarcity has become a worldwide problem. As an alternative to conventional water treatment plants, membrane-based processes are considered as one of most effective implementations regarding drinking water filtration, wastewater treatment and industrial energy applications (Abdelrasoul et al., 2020). The versatile membrane-separation processes can be effective for the removal of organic pollutants, particles, colour, microbes, and viruses as well as for the desalination of sea water (Ang et al. 2015). However, the challenges in membrane technology concerning fouling behaviour, scaling and energy consumption demand research and development in obtaining more sustainable membrane applications.

With respect to process optimization, modelling of membranes allows to obtain crucial information about the membrane's ability regarding performance and selectivity. Although the mechanisms of permeation and rejection are complex, a mathematical model allows to minimize the number of lab experiments needed in development and therefore resulting in reduced costs and saved time (Ang et al., 2015).

Research Goals

The aim of this project is the development of a mathematical model describing relevant mechanisms in a porous membrane filtration process. The focus is on the electro-sorption process in electrically conducting membrane (ECM) treatment. During operation of ECMs the adsorption of charged dissolved molecules is induced via an application of external electric potential on the membrane surface. The usage of an electric field improves the permeability-selectivity trade-off by combining a high selectivity performance, usually achieved in nanofiltration applications, with high permeabilities such as porous systems like microfiltration. Besides the electrostatic forces initiated by an electric field between the conductive active membranes surface and the conductive support layer (duplex-metal-coating), several other action mechanisms are relevant in the electro-sorption process: Intrinsic adsorption on or in the

inherent membrane material (i), possible direct (ii) and indirect oxidation (iii) at the conductive membrane surface (electrodes) and possible induced local pH-changes (iv) in the vicinity of the membrane surface (Barbhuiya et al., 2021).

Approach

To get a better understanding of the involved processes, the influence on electro-sorption in dead end filtration experiments is investigated. For validation of the model, experimental data is gathered in laboratory experiments e.g. by determining adsorption breakthrough curves. In a parametric study three key parameters are being varied. The applied electric potential (*U*), the *pH*-value and the ionic strength of the solution. In this setup a platinum coated nylon microfiltration membrane (0.2 µm) is used (Figure 1). The feed consists of a negatively charged dissolved organic dye (Eosin Y) and an electrolyte (NaCl). By applying a positive electrical potential to the membrane's active surface and a negative potential on the opposite support layer, the negatively charged dye is adsorbed onto the active side of the membrane.

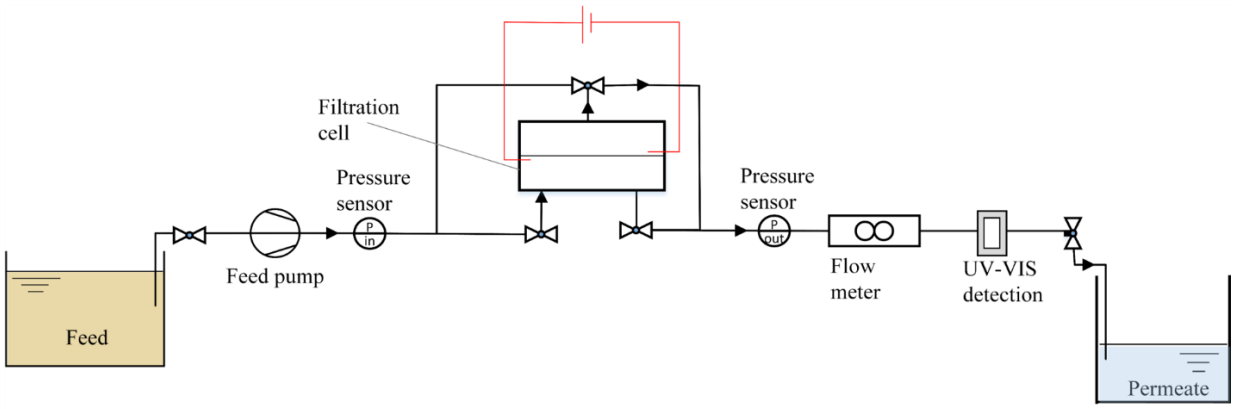


Figure 4: Laboratory setup of electro-sorption with electrically conducting membrane in dead end mode

A 3D-model of the experimental setup is implemented in COMSOL Multiphysics® (Figure 2). The transport of diluted dye as a laminar flow, the electro-sorption at the membrane surface and a Darcy flow through the porous membrane are coupled to model breakthrough curves of the membrane including variation of the key parameters; the main challenges being the implementation of the potential distribution by considering the electric double layer (EDL) at the membrane surface and considering the *pH*-value during filtration.

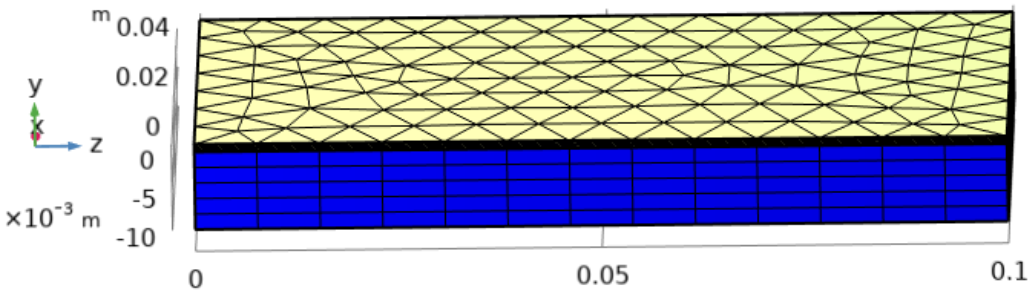


Figure 5: 3D Geometry of membrane including meshing in COMSOL Multiphysics®.

Recent Results

The experimental parametric study has been completed. The variation of key parameters in the filtration experiments showed clear influence on the electro-sorption process. By increasing the potential *U*, higher dye loadings were achieved by adsorption due to the increased electrostatic force. The change of *pH*-value resulted in change of the membrane charge itself and therefore effects of intrinsic adsorption were observed. By increasing the electrolyte concentration in the feed solution, a decreased adsorption performance was obtained due to shielding effects of NaCl compressing the EDL. As for the electro-sorption model, first steps including geometry configuration and a mesh study have been conducted. The configuration of different physics regarding the mass balance and transport equations are being investigated. The collected lab data will be crucial for validation of the model.

Conclusion and Outlook

The model development is continuing in 2025. The focus is the implementation of an adsorption capacity while modelling the potential distribution. In addition, the inclusion of *pH* dependency will be considered.

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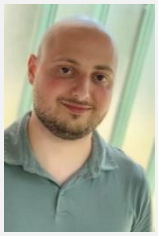

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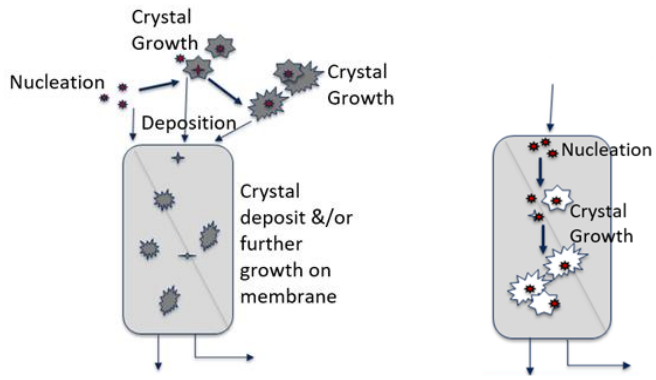
2.9 SafeRO: Safe and legally compliant application of antiscalants in drinking water treatment using reverse osmosis and nanofiltration



Mechanism of homogeneous (left) and heterogeneous (right) crystallisation in membrane processes

Project Duration

01.12.2023 – 30.06.2026

Funding

DVGW-Project No.: W 202324

Introduction

The application of antiscalants (AS) in drinking water treatment through reverse osmosis (RO), low-pressure reverse osmosis (LPRO), or nanofiltration (NF) is standard practice in Germany. Approximately 90 waterworks in Germany utilize a range of technical AS products, primarily phosphonic acid-based (active ingredients include ATMP, DTPMP, PBTC), though there is a growing trend toward phosphorus-free AS formulations based on polyacrylic acids (PAA) and blended products. In recent years, the European market has also seen the introduction of so-called "green AS" products derived from plant extracts (e.g. sodium carboxymethyl inulin, CMI).

The predecessor project KonTriSol, funded by the German Federal Ministry of Education and Research (BMBF) and the German Technical and Scientific Association for Gas and Water (DVGW) and concluded in May 2023, identified acute issues with AS usage in membrane filtration. Residual concentrations of all antiscalants (phosphonates and polyacrylic acids) authorized under the § 20 list of the German Drinking Water Ordinance were detected in permeates or drinking water from associated systems. As a result, downstream processes, such as disinfection or activated carbon filtration, could produce potentially harmful substances from the compounds present in the permeate. Additionally, KonTriSol findings revealed that the PAA-based AS products do not primarily consist of higher molecular weight polymers, as previously assumed, which would be unlikely to pass through the membrane. So, significant proportions of low-molecular-weight PAA components can partially permeate the membrane and end up in the drinking water. Further studies by the DVGW Research Centre at TUHH suggest that this low-molecular-weight content does not inhibit salt precipitation effectively, indicating that it lacks antiscalant properties.

Research Goals

SafeRO aims to close existing knowledge gaps surrounding the application of antiscalants. The project will answer relevant questions on effectiveness of chemical products in preventing scaling, the permeability of antiscalants through membranes relative to membrane cut-off limits, and the bioavailability of the antiscalants used. The research prioritizes phosphorus-free antiscalants, specifically polyacrylic acids (PAAs) with various chain lengths, and the “green” antiscalant CMI. The overall goal of the project is to develop recommendations for adapting DVGW regulations on RO/NF membrane filtration. These updates will be aligned with the Drinking Water Ordinance (§ 20 list) and EU regulations in close collaboration with the UBA.

Approach

Laboratory experiments are conducted to evaluate the effectiveness of antiscalants in preventing the formation of sulphate and carbonate scale. A batch test is performed using a stirred-beaker setup to assess the potential for homogeneous scaling within the aqueous phase. Induction and crystallization times, primarily indicated by increases in turbidity, serve as the main evaluation parameters. This laboratory setup enables an isolated assessment of the antiscalants' effectiveness. To further validate these results, commercially available RO, LPRO and NF membranes are tested in a lab-scale RO pilot system with a similar antiscalant dosage. This approach provides verification under practical filtration conditions and offers insight into the permeability of antiscalants though the membranes.

Recent Results

$CaCO_3$ scaling was investigated along the effect of polyacrylic acids with different chain lengths as antiscalants (average molecular weight (MW) of 1200 Da & 8000 Da). The stirred beaker set-up was used with a supersaturated carbonate solution (33 mM $NaHCO_3$ und $CaCl_2$) as well as a dosage of 0.5 mg/L antiscalant based on the total organic carbon (TOC), stirred continuously with a magnetic stirrer. The turbidity and the pH were continuously monitored. The induction time of the experiments was defined as the time in which the turbidity increased by 1 NTU since the beginning of the experiment and reflects the time needed for the development of first scaling crystal nuclei after supersaturation. The crystallisation time was defined as the time elapsed between the induction time and the achievement of a solution turbidity of 200 NTU and serves as the limit point of the experiment.

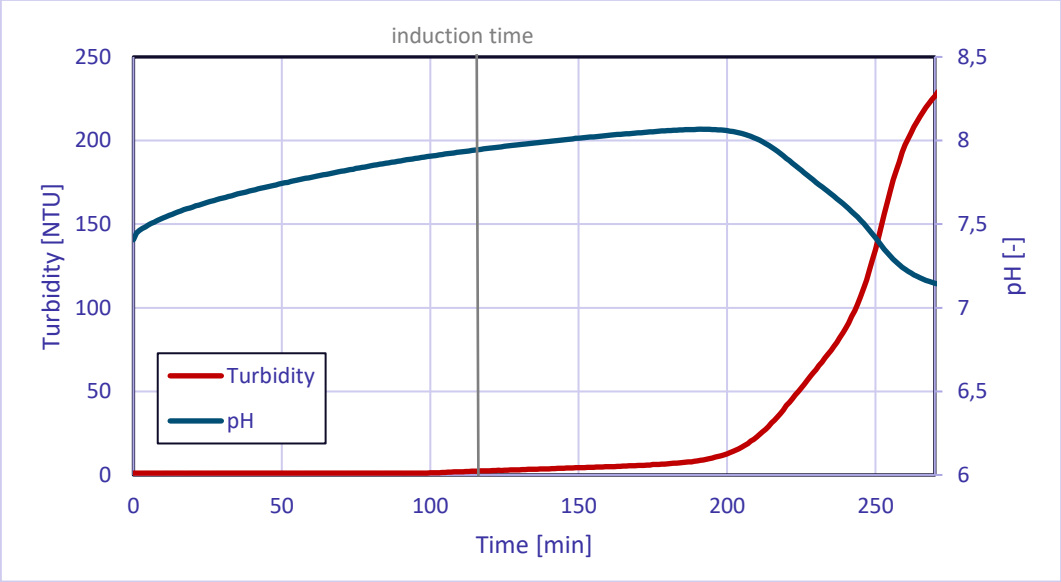


Figure 6: Course of the turbidity and pH for a polyacrylic acid with an avg. MW of 1200 Da, induction time marked at +1 NTU [33 mM $NaHCO_3$ & $CaCL_2$ + 0,5 mg TOC/L AS in stirred beaker setup at T ≈ 11 °C]

Figure 1 illustrates an exemplary experimental profile of turbidity and pH values measured in a stirred beaker experiment. Following an initial, gradual transport of CO_2 from the liquid phase to the surrounding environment, an associated increase in pH is observed. From the indicated induction time, a correlation between turbidity and pH becomes apparent. As calcium carbonate precipitates, the turbidity of the solution rises. Due to the precipitation of carbonate, the calcite equilibrium shifts to lower pH-values. Figure 2 presents the turbidity curves from representative experiments conducted without antiscalant (AS) and with two polyacrylic acids (PAAs) as antiscalants. It can be observed that both PAAs substantially delay the induction and crystallization times compared to the control experiment without AS. Furthermore, a distinction between the two PAAs is evident: the PAA with a higher average molecular weight significantly extends both induction and crystallization times. Theoretically, increased induction and crystallization times correspond to enhanced antiscalant performance, suggesting that a longer polymer chain length improves AS efficacy.

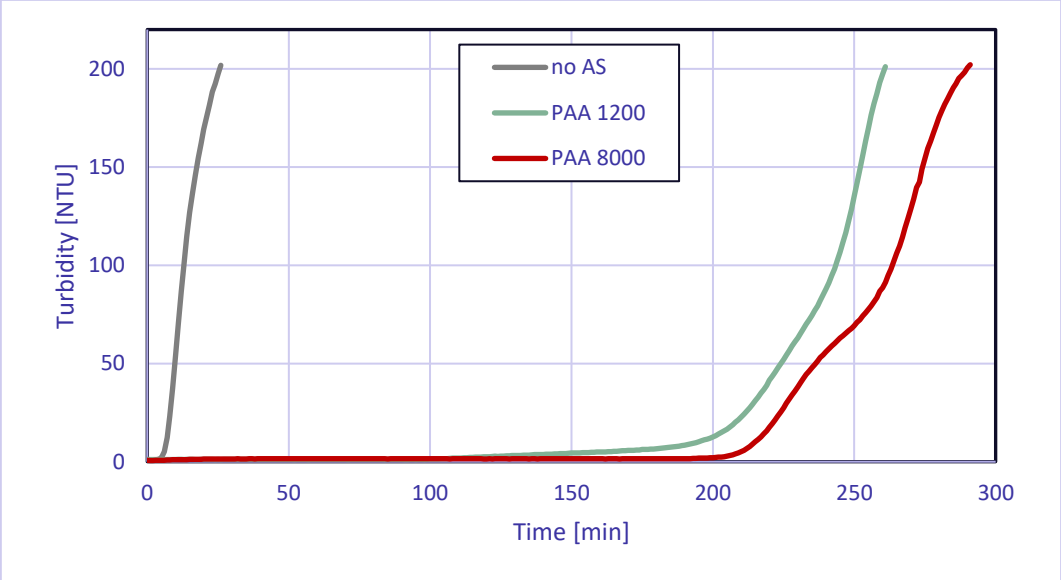


Figure 7: **Comparison of the turbidity trend with no antiscalant and polyacrylic acids with an avg. MW of 1200 Da & 8000 Da [33 mM $NaHCO_3$ & $CaCL_2$ + 0,5 mg TOC/L AS in stirred beaker setup at T ≈ 11 °C]**

Conclusion and Outlook

The present study is part of the SafeRO project aiming at investigating phosphorus-free antiscalants and providing recommendations for regulatory guidelines concerning RO/NF filtration. Although it does not serve as a comprehensive representation of real-world operating conditions, the stirred beaker setup functions as a crucial tool for the isolated investigation of antiscalant effectiveness. However, the results from the stirred beaker tests are sometimes associated with high standard deviations, as they are highly sensitive to changes in hydrodynamic conditions. Therefore, careful execution of the experiments is essential. On comparing the different polyacrylic acids, an increasing chain length appears to correlate with a stronger antiscalant effect. Further investigations on this matter are being conducted with additional chain lengths and also will be performed in a more realistic setting in an RO pilot plant.

Project Partners

Project Coordination

Project Partners

Associated Partners

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2.10 (Emergency) interconnecting lines

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Project Duration
01.10.2024 – 30.09.2027

Project Funding
DVGW-Project No.: W 202404

Introduction

The resilience of water supply systems in Europe is becoming increasingly important due to climatic changes, demographic shifts, and industrial considerations that align with European strategies. One of the critical measures to ensure a resilient supply of drinking water is the usage and maintenance of interconnected and emergency supply lines. The connections of infrastructures are addressed explicitly in the national water strategy. However, discussions with various water suppliers revealed that practical insights and comprehensive guidelines in the operation of such interconnecting lines are lacking.

Approach

The primary goal of the research project is to develop practical guidelines and recommendations concerning interconnected and emergency lines, which can also contribute to the advancement of existing regulations. The following aspects are part of this research project: Consolidation of practical knowledge, legal and contractual aspects, hydraulic aspects, commissioning and operation, and water quality aspects.

One part of the project, dealt with at the DVGW research centre TUHH, is the effect of mixing different waters. When introducing water of a different quality into a supply system (as per DVGW W 216), there can be processes such as redissolution potentially leading to colored water (e.g., brown water), changes in corrosion behaviour, regrowth of microorganisms, etc.. These are critical considerations when commissioning emergency supply lines. The project will evaluate different water qualities among utility partners and find cases where waters of varying qualities mix and what are the consequences. The aim is to derive recommendations to prevent adverse mixing effects.

The project will also investigate the “aging” of water during stagnation. Stagnation can alter the physical and chemical constitution of water, with the material of the pipeline potentially playing a significant

role. Initial investigations will be conducted on parameters such as pH, conductivity, temperature, oxygen, total organic carbon (TOC), anions, cations, and buffering capacities. Alongside physical and chemical changes, the microbiological evolution of water during stagnation is also a central research focus. The study will involve methods such as microscopy, flow cytometry, qPCR, and ATP assays to assess microbial abundance and viability. The presence of nutrients facilitating microbial growth will be measured using AOC (assimilable organic carbon), TOC, and key nutrients like phosphorus, nitrogen, and iron.

Outlook

The outcomes of this research are expected to offer valuable insights for enhancing the resilience of Europe's water supply system. By addressing the gaps in existing knowledge and regulatory frameworks, the project aims to provide evidence-based recommendations for the operation of interconnected and emergency supply lines. Findings related to water quality, particularly in terms of mixing compatibility and the effects of stagnation, could lead to significant improvements in water supply infrastructure and management.

Project Partners

Project Coordination

TZW Technologiezentrum Wasser

Project Partner

DVGW | TUHH Technische Universität Hamburg

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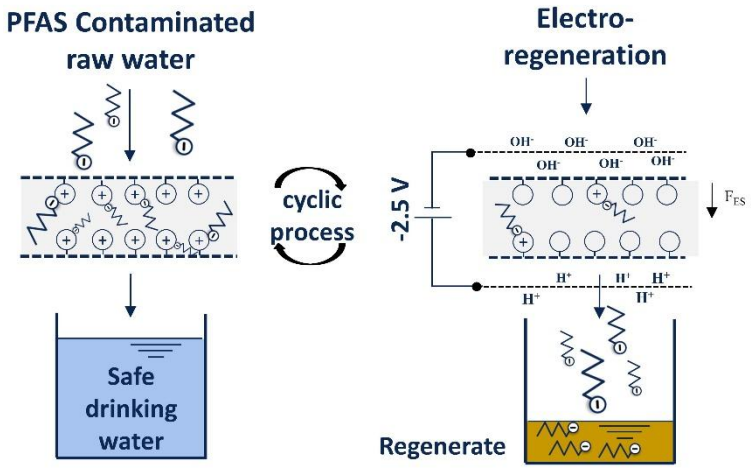
2.11 PFASecure: Water Security through Circular PFAS Removal with Advanced Membrane Adsorbers in the Face of Climate Change



Project Duration

01.04.2024 – 30.06.2025

Funding

I3 Junior Projects 2024 (TUHH)

TUHH I3 Programm
Interdisziplinarität und Innovation in den Ingenieurwissenschaften

TUHH Institute for Water Resources and Water Supply

Introduction

Per- and polyfluoroalkyl substances (PFAS) are known and widely used for their durability but also present significant environmental and health challenges due to their extensive use and tendency to accumulate in ecosystems and human bodies. New EU and German regulations, like the upcoming limit of 0.1 µg/L for 20 PFAS compounds in drinking water starting January 2026, underscore the need to find efficient ways to remove them. Conventional methods such as activated carbon and reverse osmosis are prevalent; however, there are concerns about their environmental impact and carbon emissions. Given the added pressure on water resources from climate change, adopting sustainable water management practices is essential to provide safe drinking water, particularly as PFAS regulations become stricter. There is a need to investigate new, effective, and environmentally sustainable technologies for PFAS removal. Ion-Exchangers show promising results in removing PFAS. However, once exhausted these need to be disposed or regenerated using chemicals. Electro regeneration offers a promising alternative to overcome this limitation.

Research Goals

The PFASecure I3 Junior Projects 2024 objectives can be divided into two sections:

- Investigation of the removal performance of PFAS using Ion-Exchange Membrane Adsorbers
- **Chemical-free regeneration** of exhausted Adsorbers

Approach

An existing setup and approach used to remove anionic humic substances has been further adapted and modified to target PFAS, since many PFAS carry a negative charge at neutral pH conditions. All relevant components and tubing of the setup have been revised and replaced to enable PFAS-free operation. Literature has shown that ion exchangers can remove short- and long-chain PFAS to distinct degrees.

Additionally, in competing conditions within real water matrices limitations of PFAS removal have been observed. Therefore, as part of the project, real groundwater samples with minor PFAS contamination as well as real drinking water samples spiked with PFAS are examined. Commercial anionic porous anion exchange membrane adsorbers were employed for this purpose. To evaluate the application in a cyclic process, two regeneration methods were investigated: a conventional pH-swing method using sodium hydroxide and an electrochemical approach utilizing an electrical potential. The potential-assisted regeneration process was initiated after successful adsorption by applying a potential to external electrodes placed in close proximity to the membrane.

Recent Results

Adsorptive removal was conducted using a weak basic diethylamine-functionalized membrane adsorber, exhibiting distinct removal rates. Short-chain carboxylate PFAS, such as PFBA, PFPeA, and PFHxA with chain lengths of C4, C5, and C6, respectively, showed limited removal rates of 7-12 %. In contrast, the long-chain carboxylate PFDA (C10) achieved removal rates of up to 74 %. Interestingly, even the short-chain sulfonated PFAS C5 L-PFPeS exhibited a 29 % removal rate, while C6 sulfonated L-PFHeS and PFPHxS showed 51-56 % removal. The sulfonated PFOS (C8) demonstrated removal rates of up to 66 %. These findings indicate enhanced removal efficiency for long-chain PFAS, particularly sulfonates, due to their stronger hydrophobic and electrostatic interactions. Removal efficiency is limited for short-chain carboxylates because of their higher water solubility and weaker electrostatic interactions. Chemical regeneration using sodium hydroxide achieved efficiencies comparable to those of the initial adsorptive removal process. Although carboxylate PFAS were regenerated only to a minor extent, sulfonated PFAS experienced significant regeneration.

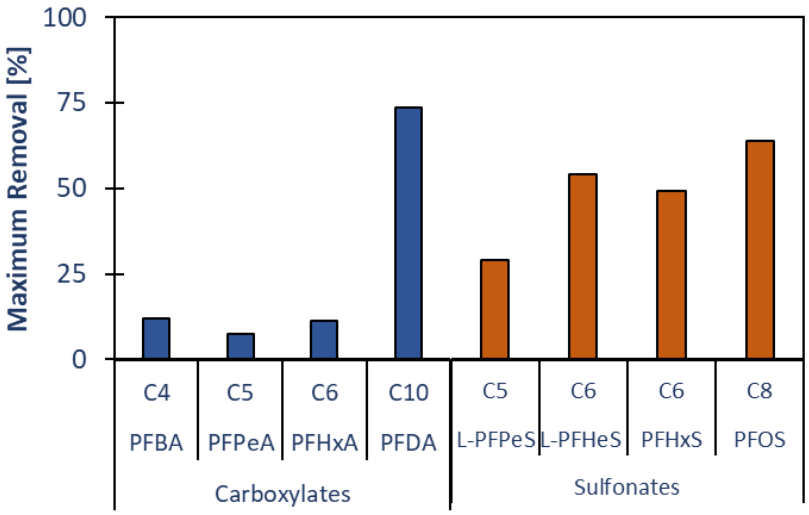


Figure 8: Removal rates of carboxylated and sulfonated PFAS, depending on their chain length (C4-C10)

Outlook

Electrochemical potential-driven regeneration was successfully established in a PFAS-free experimental set-up. Ongoing investigations and analyses of the results are being used in current experiments to examine the influence of the water matrix, competing humic substances, and the choice of process parameters, such as the applied potential and electrodes.

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2.12 Removal of selenium oxyanions from drinking water by batch and continuous mode adsorption on granular ferric hydroxide

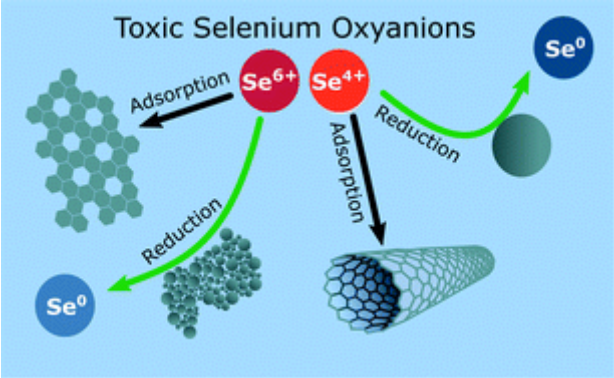

Figure 9: Selenium oxyanions removal and recovery pathways via adsorption [1]

Project Duration

01.12.2024 – 30.11.2026

Funding

Alexander Von Humboldt Stiftung

Introduction

The presence of high concentrations of ionic contaminants in groundwater reservoirs pose a serious threat to humans and environment. Selenium (Se) oxyanions have been recorded in groundwater because of mining, petroleum refining, fossil fuel combustion, and irrigation [2]. In accordance, high Se concentration i.e., 2103 µg/L, 800 µg/L, 2700 µg/L and 4475 µg/L have been found in Soan Sakesar Valley, Pakistan; Atacama Desert, Chile; Martin Creek Reservoir, Texas, USA; and Sirmaur district of Himachal Pradesh, India; respectively [3]. Nevertheless, Se is an essential mineral required by human body however it becomes noxious when found in greater concentrations in drinking water supplies. The oral intake of higher Se concentration (>400 µg/day) may cause serious health problems including reproductive anomalies and developmental abnormalities in foetus, hair loss, body pain, muscle damage, liver and kidney failure, cancer, and even death may occur. Therefore, German drinking water ordinance, World Health Organization (WHO) and U.S. Environmental Protection Agency has set Drinking Water Regulation Limit (DWRL) for Se as 10 µg/L, 40 µg/L and 50 µg/L, respectively [4,5]. To meet stringent Se guidelines and ensure public health safety, an efficient and technoeconomic feasible treatment approach is needed.

Adsorption technology utilizing commercial iron-based adsorbents has shown promising performance for removing contaminants including metal oxyanions from a wide range of water matrices. However, eliminating Se from drinking water is challenging owing to its toxicity, solubility and varying oxidation states. It is commonly found in environment as selenate (Se(VI): $HSeO_4^-$, SeO_4^{2-}), selenite (Se(IV): H_2SeO_3, $HSeO_3^-$, SeO_3^{2-}), selenium (Se(0)) and selenide (Se(-II): H_2Se, HSe^-) depending on pH and redox conditions [2]. Previous research [6–8] has shown wide applicability of commercially available iron-based adsorbent i.e., granular ferric hydroxide (GFH) for removal of other oxyanions including arsenic, phosphate, vanadium etc. from water. Therefore, it may be hypothesized that GFH may contain potential in eliminating toxic Se oxyanions from drinking water supplies. In addition, release of iron from poorly crystalline GFH structure into the solution particularly at low redox potential, leading to its higher residual content, has been rarely investigated. Therefore, it will be critical to examine the stability of

GFH at long term operations along with its effectiveness in remediating targeted contaminants. In accordance, little is known on how Se oxyanions will behave and react with GFH in aqueous environment. It will therefore be worth exploring the mechanistic insights into the fate, mobility, transformation, and removal behavior of Se species under environmentally relevant conditions. In addition to commercial adsorbents, prior research has focused on utilization of iron-based sorbents for Se remediation from drinking water, however, all these studies only discussed in-depth understanding of batch mode operation [9]. Moreover, there always remains a research gap in utilizing adsorbent material in GEH® adsorbent unit for continuous mode Se treatment from drinking water supplies. Therefore, the planned project aims to address these research gaps and provide practical and sustainable solution to drinking water industries when dealing with toxic Se oxyanions.

Research Goals

The currently planned research project comprises of following three innovative and important objectives: (i) Unravelling Se(IV) and Se(VI) removal behavior in aqueous matrices using commercial iron-based adsorptive material i.e., GFH in systemically designed batch-mode sorption experiments; (ii) Investigating the optimum boundary conditions for removal of selenium in small-scale adsorption filters relevant for practical applications in drinking water treatment; (iii) Conducting a techno-economic feasibility analysis of developed water filtration technology for selenium removal from real source waters of drinking water supply. It is also planned to present the project and the results to wider professional public at an Alexander Von Humboldt Network meeting and through a publication.

Approach

The goal of this research is to initially investigate the adsorption performance and iron leaching aspects of GFH upon its contact with toxic selenium (Se) oxyanions under a series of batch mode laboratory experiments in various solution chemistries (e.g., GFH dosage, solution pH, contact time, suspension temperature, initial Se(IV, VI) concentration, coexisting ions etc.). Mathematical models on experimental results and characterization techniques on virgin and spent GFH will be later employed to explore mechanistic insights into adsorption and transformation behavior of Se oxyanions in water. The research work will then be expanded to small-scale continuous mode GEH® adsorbent unit for Se removal from drinking water, where GFH loading rates and initial Se oxyanions level will be tested in synthetic test solutions as well as real raw waters at long term operations. To achieve the Se permitted value of 10 µg/L in drinking water and to optimize the Se removal process using GFH, a response surface approach will be employed. The spent GFH media will be examined for various physiochemical variations at different bed depths using analytical techniques. In conjunction with technical aspect, economic feasibility of GEH® adsorbent unit will also be evaluated.

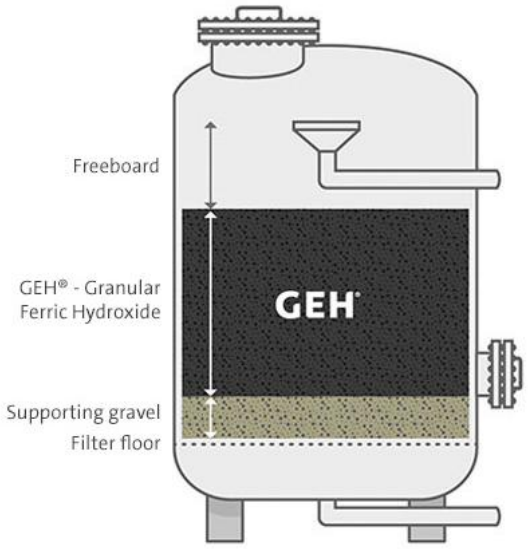

Figure 2: Basic Design of GEH® adsorbent unit. [10]

Outlook

The initial experimental investigations on detection of Se oxyanions to very low concentration i.e. 10 µg/L using ion chromatography coupled with conductivity detector are currently in progress. After developing methods for Se(IV) and Se(VI) analysis, batch mode experiments are planned using GFH for eliminating Se oxyanions from synthetic test samples. These experimental investigations will lay the foundation for small-scale GFH based GEH® adsorbent unit for Se oxyanions removal from real raw samples under continuous mode operation. In this regard, the expected outcomes of these research activities will contribute to the development of economical, and efficient water filtration technology on a large scale. Importantly, these research endeavors align with the United Nations Sustainable Development Goals (SDGs), specifically addressing SDG no. 3 on 'Good health and well-being', SDG no. 6 on 'Clean water and sanitation', and SDG no. 14 on 'Life below water'.

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Project Partners

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2.13 Development and performance of Layer-by-Layer modified hollow fiber membranes as capillary nanofiltration

Dr.-Ing. Jakob Stumme; 03.09.2025, Congratulations for the Doctorate

Summary

Within this study the potential of Layer-by-Layer (LbL) modified hollow fiber ultrafiltration (UF) membranes was examined as one option in terms of ion rejection, rejection of dissolved organics, molecular weight cut-off (MWCO), fouling, and mechanical and process stability. Furthermore, a model was derived to differentiate between predominant polyelectrolyte (PE) build up during modification in terms of pore vs layer dominating PE multilayer formation.

Filtration in lab scale as well as pilot scale results in water works achieved high rejection rates for divalent ions (> 90 % for sulfate and magnesium, and > 80 % for calcium). However, some external parameters were investigated which influenced the resulting ion rejection. As shown in lab scale, high ionic strength in the feed solutions led to swelling of the PE structure, resulting in a change of separation characteristics. Nevertheless, swelling was highly dependent on the present type of ions and respective concentration. Model supported results clearly identified concentration polarization (CP) through the laminar boundary layer as dominating factor for the removal efficiency for sulphate as a model substance for divalent ions. Besides crossflow velocity and resulting laminar boundary layer thickness, model results showed a severe influence of CP dependent on membrane length. Further investigations in lab scale showed that the modification of the membranes resulted in an MWCO in the lower range of NF membranes, providing high removal rates of dissolved organic substances. SAC254 removal rates of > 90% and TOC removal of > 80 % could be achieved even in Dead End operation for solutions containing natural organic matter (NOM).

Membranes could successfully withstand the stress of hydraulic backwash (hydr. BW), though it was limited to a maximum hydr. BW flux of 50 L/(m² h). Combined with the good chemical stability, it would allow the implementation of a regular CEB, which was highly efficient for the removal of NOM foulants off the membrane surface. Overall, the LbL modification of hollow fiber UF membranes was successful on lab scale and on industrial scale membranes and could be operated successfully for several months. The modified membranes combined exceptionally high NOM removal rates with the possibility for high divalent ion rejection and the stability of regular mechanical and chemical cleaning.

3 Annex

3.1 Publications

Kast, C.; Mergel, D.; Wiegand, M.; Mutis, M.; Wendler, B.; Ernst, M. (2024): Aufbereitung von Filterspülwasser - Keramik- und Polymermembran im Vergleich, gwf-Wasser|Abwasser 07-08|2024, S. 77 - 86, doi.org/10.17560/gwfwa.v165i07-08.2743

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Kaushik, S.A., Armbruster, D., Dittmer, J., Bruniecka-Sulewski, D., Wendler, B., Ernst, M.: Investigation of scaling inhibition and biofouling potential of different molecular weight fractions of a PAA antiscalant. npj Clean Water 7, 36 (2024). https://doi.org/10.1038/s41545-024-00332-7

Wullenweber, J.; Bennert, J.; Mantel, T.; Ernst, M. Characterizing Macroporous Ion Exchange Membrane Adsorbers for Natural Organic Matter (NOM) Removal—Adsorption and Regeneration Behavior. *Membranes* **2024**, *14*, 124. https://doi.org/10.3390/membranes14060124

Usman M, Vahedi S, Glass S, Filiz V, Ernst M. Elucidating the Mechanism of Electro-Adsorption on Electrically Conductive Ultrafiltration Membranes via Modified Poisson-Boltzmann Equation. *Membranes*. 2024; 14(8):175. https://doi.org/10.3390/membranes14080175

Usman, M.; Sharma, D. D.; Ernst, M.: In: Powerfuels : Status and Prospects / edited by Bullerdiek N.; Neuling U.; Kaltschmitt, M.; Seawater and Brackish Water Desalination - Book part, 1st ed. 2025. - Cham : Springer Nature Switzerland ; Cham : Imprint: Springer, 2025 Publisher DOI 10.1007/978-3-031-62411-7_8

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Wang, Q.; Lechtenfeld, O. J.; Rietveld, L. C.; Schuster, J.; Ernst, M.; Hofman-Caris, R.; Käsler, J.; Wang, C.; Yang, M.; Yu, J.; Zietzschmann, F.: How aromatic dissolved organic matter differs in competitiveness against organic micropollutant adsorption - Journal Article, Environmental Science and Ecotechnology 21: 100392 (2024), Open Access | Publisher DOI 10.1016/j.ese.2024.100392

Usman, M.; Belkasmi, A.I.; Ernst, M.: Dynamic membrane pre-coated with micro-sized iron oxyhydroxide for arsenic removal: Application study and mathematical modelling - Conference Paper 8th International Congress and Exhibition on Arsenic in the Environment (As2021) Publisher DOI 10.1201/9781003317395-126

Benne, P.: Untersuchung des CARIX™-Verfahrens zur Entfernung anthropogener Sulfat-Emissionen aus einem Trinkwasser mit erhöhter NOM-Konzentration - Doctoral Thesis, Technische Universität Hamburg 20 DOI 10.15480/882.1361324

Grieb, A.: Climate resilient and safe management for disinfectant and non-disinfectant water supply systems - Journal Article, GWF, Wasser - Abwasser 165 (1): 54-55 (2024)

3.2 Project/Bachelor/Master Theses

Meyer, Maximilian (Master): Investigation of the electrosorption process on a platinum-coated nylon membrane for the removal of organic dyes, 23.10.2024

Rezai, Baktasch (Bachelor): Impact of climate change on German water supply - focus North Germany, 12.06.2024

Nandila, Swathi Naik (Master): Development of a standardized approach for the detection of nitrate-reducing bacteria in an autotrophic bio-electrochemical system, 15.04.2024

Schönettin, Hannah Marie (Master extern): Substitution of drinking water in the Planten un Blomen park, Hamburg, 25.07.2024

Kröger, Henriette Elif (Bachelor): Investigation of the adsorption behaviour of natural organic matter (NOM) on membrane adsorbers in drinking water treatment, 05.06.2024

Weselmann, Lars (Bachelor): Investigation of backpulsiing parameters to minimize membrane fouling in spent filter backwash water treatment, 19.06.2024

Malich, Malina (Master): Influence of the characteristics of spent filter bachwash water from groundwater treatment on the membrane perfomance of a submerged ceramic membrane, 11.09.2024

Westarp, Ursula (Project): Evaluation of cyclic voltammetry for the assessment of extracellular electron transfer, 05.12.2024

Bennert, Julia Helena (Master): Enhancing Membrane Adsorber Performance for Anionic NOM and PFAS removal with Potential-Driven Regeneration, 11.12.2024

Jag, Mirjam (Master): Evaluation of different graphite-based cathode materials for autotrophic denitrification in bioelectrochemical systems (BES), 19.12.2024

Hachmöller, Theresia (Project): Investigation of the removal of organic substances in drinking water treatment from groundwater an surface water at two locations, 09.10.2024

Wöst, Berrit (Project): Sponge city as flexible rain infrastructure - concepts for urban design of near-natural water management and an overview of practical implementation using the example of the city of Hamburg, 30.10.2024

Harms, Giulia (Project): Determination of Molecular Weight Cut-Off of Ceramic and Polymer Membranes using fluorescent Nanoparticles, 29.10.20024

3.4 PhD Theses

Stumme, Jakob (Doctor): Development and performance of Layer-by-Layer modified hollow fiber membranes as capillary nanofiltration 03.09.2024

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Technische Universität Hamburg

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WATER RESOURCES
AND WATER SUPPLY