



Wetsus 2025 | research program

combining scientific excellence with commercial relevance



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Ministry of Education,
Culture and Science
Ministry of Economic Affairs
Ministry of Infrastructure
and Water Management



WATER &
MARITIME
RIISING CHALLENGES. SMART SOLUTIONS

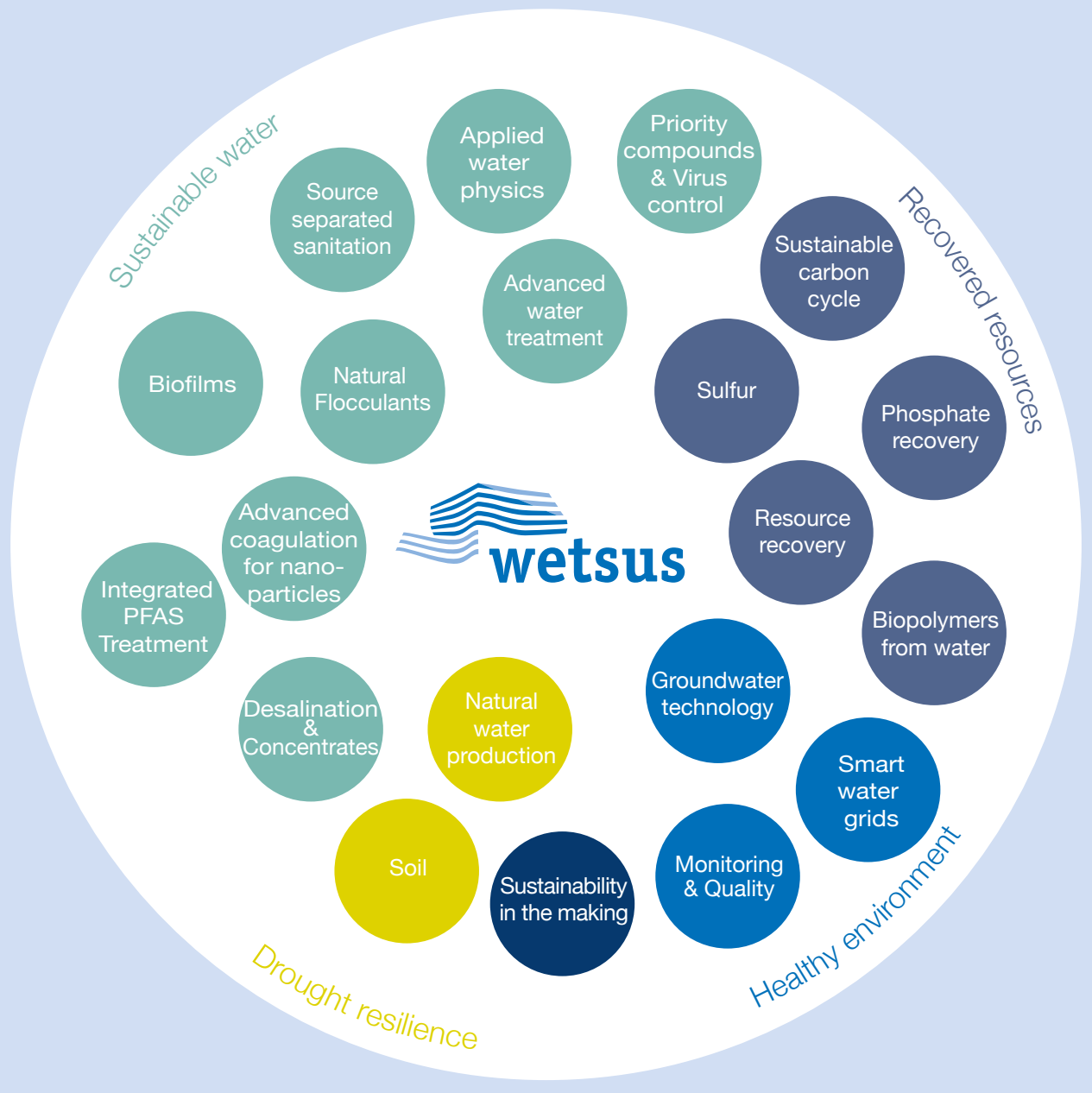


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Wetsus research program

Wetsus' research program is divided into 4 research areas and 20 research themes, which have been assessed in close consultation with the industrial participants. Within these themes, research topics have been defined, which are being addressed in the form of PhD projects. In the following sections, you will find descriptions of the themes and summaries of the current PhD projects.



Advanced water treatment

Advanced water treatment plays a vital role in developing sustainable purification technologies to remove inorganic and organic priority compounds like PFAS, pharmaceuticals, and personal care products, aligning with the Water Framework Directive. This is achieved by investigating new methods based on physical, electrical, and electrochemical principles. Techniques include selective membrane transport for organic micropollutants and salt ions, driven by electricity or pressure,

hydrophobic interactions for adsorption and biological degradation of organic compounds. These processes enhance the efficiency and effectiveness of water purification. Current research focuses on technologies such as multilayer nanofiltration membranes, foam fractionation, and biologically activated carbon-based filtration and conversion, offering innovative solutions for producing cleaner, safer water while promoting environmental sustainability..

Research projects

- **Advait Gangal**, Wageningen University, *Modelling dynamically operated biological activated carbon filters* **NEW**
- **Mario Ilić**, University of Twente, *Integrated greywater treatment using nanofiltration for the production of reusable water* **NEW**
- **Chenxiao Xu**, Wageningen University, *Engineering of biological activated carbon filters for micropollutant removal in wastewater effluent* **NEW**



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Motivation

Biological Activated Carbon (BAC) filters are noted for their ability to remove organic micropollutants (OMPs), compounds that can be harmful to human and environmental health^{1,2}. The augmentation of biological activity to the adsorption process in granular activated carbon (GAC) filters may open new pathways for OMP removal, which remain poorly understood within the BAC filter.

This project aims to assess the validity and impact of interdependent removal processes in the BAC filter, and to construct a model that integrates these processes in a dynamic operation so that the performance of BAC filters may be optimised.

Technological challenge

The several processes hypothesised to be involved in OMP removal in BAC filters² are illustrated in Fig. 1.

Among them, biodegradation refers to the co-metabolism of OMPs with other more abundant energy sources like ammonia or organic carbon. Alongside adsorption, this is expected to be one of the key processes driving OMP removal in BAC filters. It remains unclear, however, to what extent each of these processes affects the removal of OMPs in this integrated system. The contributions of other removal processes, such as chemical oxidation in highly oxygenated water, are also not yet understood. Furthermore, the limited understanding of the transformation products of the OMPs in this context raises concerns about whether their original toxicity is effectively mitigated. These factors impede the development of a robust and adaptable model.

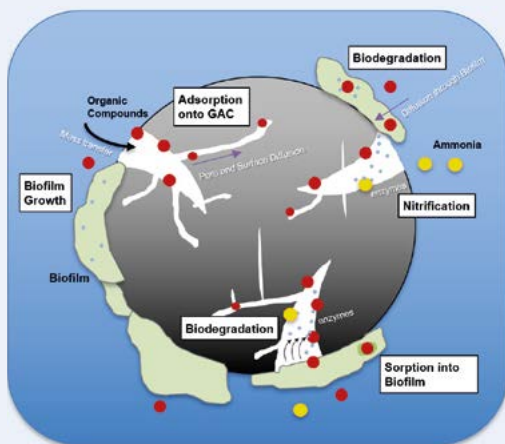


Fig. 1: Illustration depicting the several processes occurring in and around a BAC granule that contribute towards contaminant and OMP removal.

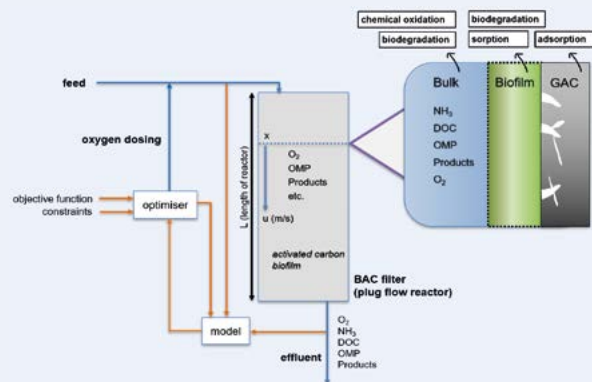


Fig. 2: Schematic of the proposed digital twin of the BAC filter. The control loop incorporates the model into the digital twin. On the right, the various OMP removal processes are labelled according to the various phases in the BAC filter in which they occur, and so integrated into the model.

Research goals

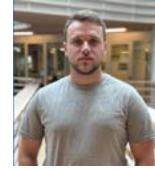
The project seeks to describe each individual process (Fig. 1) within a mathematical framework and assess its impact on effective OMP removal in the context of BAC filter conditions.

The interplay between these processes can then be considered. For instance, biodegradation may partially remediate used sites in the GAC, allowing fresh adsorption again.

The aspirational goal of this project is to integrate relevant processes into one dynamic mechanistic model that can reliably predict OMP removal in BAC filters. In this way, the performance of BAC filters can be optimised both in design and in real-time by controlling system parameters like oxygen dosage and backwash frequency with changes in influent load and hydraulic head among other factors. A digital twin of the BAC filter can thus also be operated alongside the physical filter operation (Fig. 2).

[1] J. P. Gutkoski, E. E. Schneider, C. Michels, Journal of Environmental Management. 349, 119434 (2024).
 [2] O. Bernadet, A. Larasati, H. P. J. Van Veelen, G. J. W. Euverink, M. C. Gagliano, Journal of Hazardous Materials. 458, 131882 (2023).

Integrated greywater treatment using nanofiltration for the production of reusable water



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Motivation

The global demand for sustainable water treatment is driven by water scarcity, increasing urbanization, and the need to reduce environmental pollution^[1]. Greywater, which accounts for the majority of domestic wastewater, is a promising source for subsequent reuse^[2]. However, full-scale adaptation has been limited due to the presence of organic micropollutants (OMPs) and other emerging contaminants present in secondary effluents.

Biological treatment followed by hollow fiber nanofiltration (NF) has shown to be an effective configuration to remove conventional wastewater contaminants and micropollutants^{[3][4]}. However, while NF successfully removed OMPs from the effluent, these substances were not degraded and end up in the concentrate. Therefore, further investigations into combined configurations of biological treatment, nanofiltration and post-treatment for OMPs removal are required to develop sustainable alternative treatment strategies.

Technological challenge

Currently, NF systems for greywater treatment are predominantly used at the pilot scale, where the concentrate streams are not considered as a limiting factor. During large-scale application, implementing concentrate recirculation to the biology could be of interest. However, the impacts of recirculation on the process remain, as of yet, not well understood and require further investigations. The impact of this closed-loop system on the NF unit's operation and its efficiency in OMPs removal on the long term, remains an important area of interest.

Implementing additional treatment steps upstream of the NF could provide additional advantages, such as increased membrane lifetime, but its impacts on the entire process have not been studied in depth yet^[5].

Lastly, the impact of greywater quality on membrane ageing and irreversible changes to the membrane requires more attention.



Fig 1. Nanofiltration unit used during the project

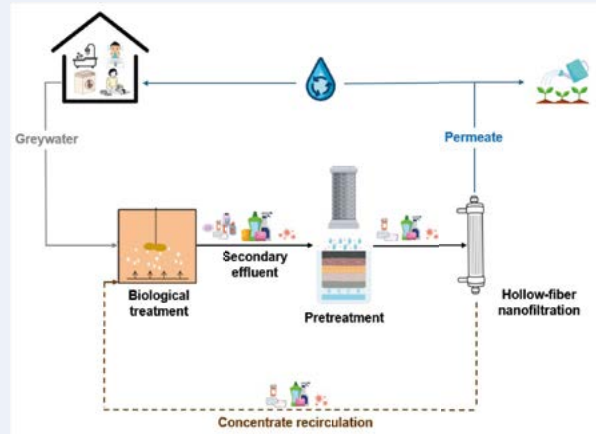


Fig 2. Graphical abstract of the research project

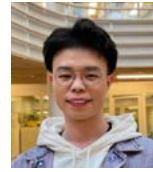
Research goals

- Examine the suitability of the integrated greywater treatment, combined with concentrate recirculation (Fig 2), as an effective approach to remove organic micropollutants and to ensure the production of high-quality water suitable for reuse
- Investigate the effect of secondary effluent treatments to the membrane's key performance indicators
- Explore post-treatment methods, such as advanced oxidation processes, for both the concentrate and permeate to address residual micropollutants
- Assess the environmental and operational impacts of combining biological treatment with NF and other advanced post-treatment technologies to create a sustainable, closed-loop greywater treatment system

[1] M.M. Mekonnen and A.Y. Hoekstra (2016). *Sci. Adv.*, 2, 1-7
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 [3] S. Rutten et al. (2024). Ph.D. thesis, University of Twente
 [4] A. Hall et al. (2024). *Water Pract. Technol.*, 19(3), 900-910
 [5] K. van Gijn et al. (2021). *J. Environ. Chem. Eng.*, 9(5), 106247



Engineering of biological activated carbon filters for micropollutant removal in wastewater effluent



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Motivation

Micropollutants (MPs), including pharmaceuticals, pesticides, and industrial chemicals, are widely detected in surface waters globally at concentrations from pg/L to µg/L^[1]. Wastewater treatment plants (WWTPs) are a primary source of MPs, as inadequate removal during conventional treatment processes leads to their release into surface water through effluents^[2]. Recognizing the environmental risks, the European Union updated the Urban Wastewater Treatment Directive for stricter MP removal from WWTPs^[3]. This highlights the need for sustainable and efficient quaternary treatment technologies. Biological activated carbon (BAC) filters are a promising technology to remove MPs from WWTP effluent before discharge^[4]. Across BAC granules, the MP removal results from a synergy between sorption and biodegradation (Fig. 1). MPs can be temporarily retained through sorption by activated carbon and biofilms, prolonging their biodegradation availability (Fig. 2). The subsequent biodegradation can regenerate partial sorption capacity, extending filters longevity. However, the interdependent effects of sorption and biodegradation to MP removal remain largely unclear.

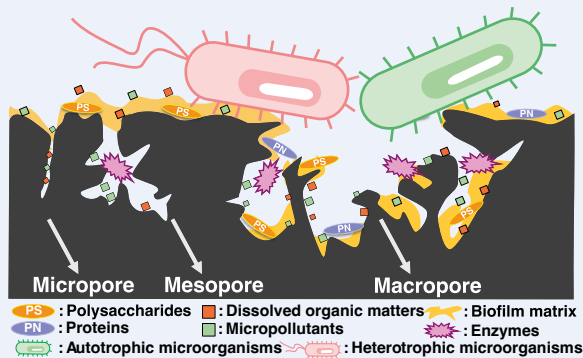


Fig. 1. Illustration of the BAC granules surface.

Technological challenge

For the MP removal, BAC filters combine sorption, desorption, oxidation, biodegradation, and precipitation. Understanding the individual contribution of these mechanisms is still challenging. To maintain functional BAC filters and advance their applications, further investigations and fundamental insights are needed to generate appropriate solutions. For instance, a critical challenge is decoupling the real retention time needed for biodegradation from the empty bed contact time (EBCT), as it directly affects MP removal. Elucidating the biodegradation pathways is also complicated due to the involvement of diverse (extracellular) enzymes. Moreover, varying operational parameters can shape different microbial communities and biofilm characteristics.

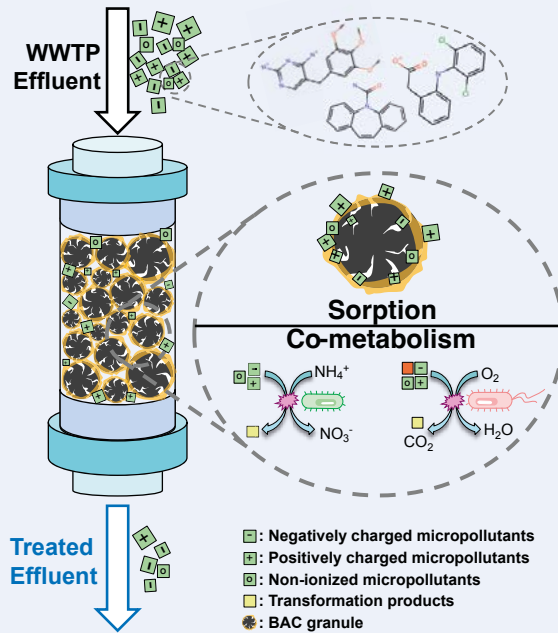


Fig. 2. Schematic of main MP removal pathways in BAC filters.

Research goals

This project aims to enhance our understanding of the mechanisms driving effective MP removal in BAC filters, providing insights to optimize their field applications. Specifically, the project seeks to answer the following questions:

1. How are MPs retained through BAC granules before being biodegraded and/or desorbed? How long does this retention last, and how does it differ from the EBCT?
2. How do the interdependent interactions between activated carbon adsorption, biofilm sorption, and biodegradation influence the removal of MPs with different properties?
3. What (extracellular) enzymes and transformation products are involved in the biodegradation of MPs within BAC filters?
4. How do operational parameters, such as oxygen dosing, affect microbial communities and biofilm characteristics that are relevant to MP removal?

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- [3] European commission, 2024. COM/2022/541.Bernadet, O., et al., J. Hazard. Mater., 2023. 458 p. 131882.



Source separated sanitation

As urban populations grow and centralized water and sewer systems reach capacity, and as rural communities remain disconnected from such infrastructure, Source Separated Sanitation (SSS) systems are becoming essential. SSS is an emerging and scalable concept that addresses these challenges by collecting, transporting, and treating waste streams—such as greywater, urine, and feces—separately at the source. This approach enhances water savings, enables the safe reuse of greywater, and supports the recovery of nutrients and organics from human waste (urine and feces). By preventing the dilution of waste streams, SSS

facilitates more efficient treatment processes, allowing for targeted resource recovery and improved environmental outcomes. The elevated temperatures of these concentrated streams also enable efficient heat recovery and the use of thermophilic processes, contributing to energy savings. Moreover, by isolating waste streams, SSS can help mitigate the spread of antibiotic-resistant bacteria, a growing concern in conventional wastewater systems. These technologies are crucial in providing sustainable sanitation solutions while reducing the strain on existing centralized systems.

Research projects

- **Elfy Ly**, Delft University of Technology
Combined removal of antimicrobial resistance and pharmaceuticals from wastewater
- **Shuoguang Yang**, University Medical Center Groningen, *Untapping the energetic potential of grey water: microbiological safety and downstream re-utilization routes*
- **Melissa Mativo**, Wageningen University, *Optimization of (hyper) thermophilic blackwater treatment for recovery of biofertilizers and energy* **NEW**



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Impact of Advanced Wastewater Treatment on the Spread of Antimicrobial Resistance



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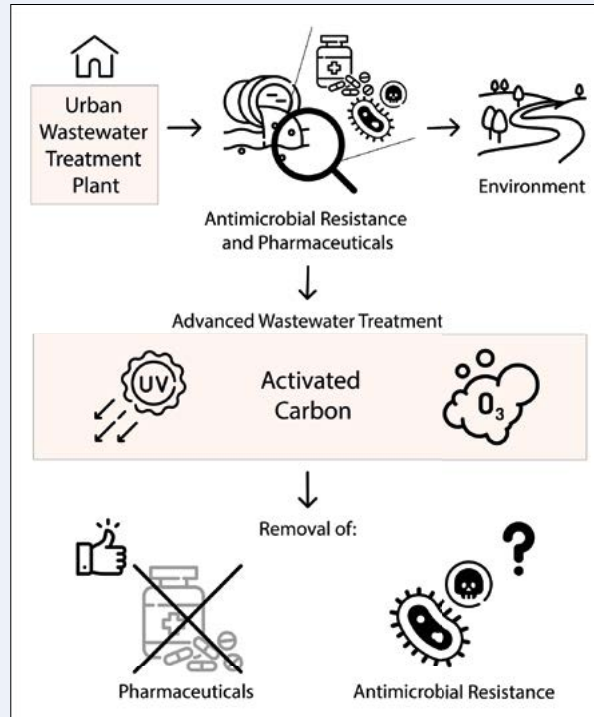
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Motivation

Antimicrobial resistance (AMR) is a global health and development threat and requires urgent multisectoral action according to the World Health Organization^[1]. Wastewater treatment plants (WWTPs) release both antibiotic resistance bacteria (ARB) and antimicrobial resistance genes (ARGs) into the environment^[2]. Advanced wastewater treatment (AWWT), such as activated carbon, UV and ozonation, is currently emerging as an effective treatment to remove pharmaceuticals. The most promising AWWT, ozonation, shows in lab-scale studies that ARB&ARGs are regrowing after application^[3, 4]. With the ability of bacteria to acquire genes from the environment and other bacteria (horizontal gene transfer – HGT), the spread of AMR can be accelerated. The impact of AWTT on the spread of AMR in the environment should therefore be studied.

Technological challenge

The analytical challenge is associated with the detection and quantification of AMR in low concentrations. Moreover, HGT will be monitored with fluorescent microscopy where adequate bacterial and plasmid models must be selected for a robust experimental design. Furthermore, wastewater samples consist of a broad unculturable bacterial community. The computational challenge is to identify the microbial population using metagenomics, where bioinformatics, microbiology and molecular biology knowledge is required to analyze the complex big data.



Research goals





| | | | |
|--|---|--|--|
| <p>1. Removal Efficiency</p>  <p>Determining the removal efficiency of AMR by different advanced WWTP at field scale</p> | <p>2. Regrowth</p>  <p>Identifying AMR surviving and regrowing after ozonation on lab and field scale</p> | <p>3. Horizontal Gene Transfer</p>  <p>Studying if HGT increases AMR in effluents after ozonation</p> | <p>4. Storm Water</p>  <p>Establishing the contribution of storm water overflow to the spread of AMR in untreated wastewater</p> |
|--|---|--|--|

Fig 1. Research goals to study the impact of AWWT on the spread of AMR in the environment.

[1] World Health Organization (2015) Report of the 6th meeting of the WHO advisory group on integrated surveillance of antimicrobial resistance.
 [2] Rizzo et al. (2013) Sci. Total Environ. 447, 345–360.
 [3] Iakovides et al. (2019) Water Res. 159, 333–347.
 [4] Jäger et al. (2018) Environ. Pollut. 232, 571–579

Untapping the energetic potential of grey water: Microbiological safety and downstream re-utilization routes



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Motivation

In the context of global warming, reducing greenhouse gases emission has become one of the most important topics nowadays. European Union recognized wastewater as a renewable energy source in 2018^[1]. Energy harnessing from wastewater formulates a promising strategy to decrease the consumption of fossil fuels and the emission of greenhouse gases.

This research focuses on a district-level greywater reuse and heat recovery system (Fig. 1). In this system, greywater will be first treated through aerobic biological processes combined with a nanofiltration unit. Subsequently, with the help of a heat pump, the heat energy within greywater can be harnessed, stored, and finally reused in households. After the heat extraction, greywater will be directed to the households for different purposes of reuse. However, the microbial quality of the reclaimed greywater, especially after a certain period of storage time, remains unknown. Therefore, the assessment of microbial safety is vital for the development of a sustainable system.

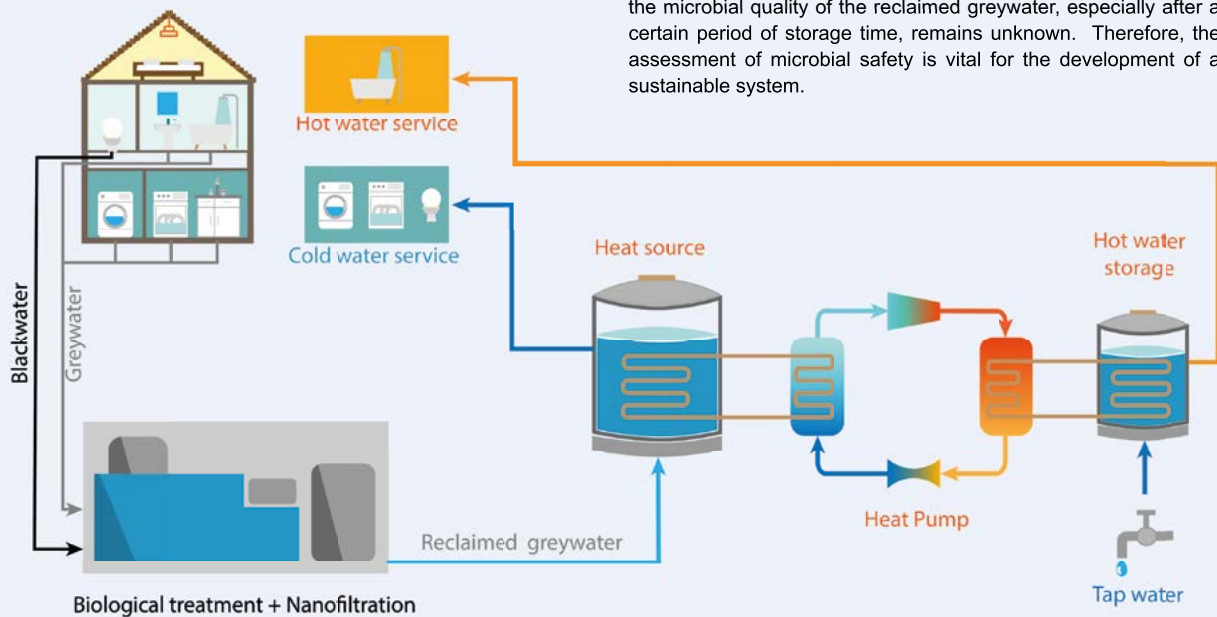


Fig 1. A potential greywater reuse and heat recovery system

Separating wastewater into black water and greywater can facilitate energy recovery. Black water can generate biogas through anaerobic treatment processes, while greywater holds excellent potential for high-quality water and heat recovery. As greywater remains at a high temperature after being discharged into the sewage network, a heat pump can extract large quantities of heat from greywater.

Research goals

- Investigation of the physical, chemical and microbial quality of the greywater after biological treatment and nanofiltration
- Evaluation of the bacterial regrowth within the system
- Optimization of the heat recovery system and assessment of the heat efficiency of the entire system.
- Development of the greywater reuse strategy in households
- Assessment of the necessity and feasibility of different disinfection methods in the system

Technological challenge

The direct heat recovery from greywater has the following limitations: 1. The biofilm formation on the heat exchanger's surface will inhibit the heat pump's availability and performance^[2]. 2. The potential of greywater reuse cannot be exploited entirely due to the lack of microbiological safety. To maximize the energetical and reuse potential of greywater, an advanced system containing greywater treatment, heat recovery, and greywater reuse needs to be developed and investigated.

[1] Directive (EU) (2018). Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources (Recast).
 [2] Zhao, Q., et al. (2005). Chemical Engineering Science, 60(17), 4858–65.



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Motivation

Efforts to address soil deficiencies and improve global food production have resulted in a heavy reliance on mineral fertilizers [1]. Human feces and urine contain essential nutrients such as carbon, nitrogen, phosphorus and potassium which are crucial for plant growth. Fortunately, anaerobic wastewater treatment, which has been traditionally geared toward production of methane, efficiently conserves essential elements in the effluent thereby facilitating nutrient recovery for reuse in agriculture.

Source separated collection of blackwater using (low-flush) vacuum toilets yields a concentrated stream from which nutrients can be more readily extracted. Anaerobic treatment of concentrated blackwater under thermophilic conditions already shows promise for effective COD removal and biogas production [2]. Preliminary experiments have shown that pathogens are also eliminated through the process, enhancing safety of nutrients and biosolids during reuse.

Technological challenge

Thermophilic treatment of blackwater, at 55°C, is a stable process that has been previously pilot tested under the H2020 Run4Life project [3]. Already, COD removal (~70%) and methanization conversions (~60%) comparable to those reported during mesophilic treatment have been achieved while operating at higher organic loading rates (OLRs) and shorter sludge and hydraulic retention times (SRTs and HRTs) [2,4]. Now, along with methane, alternative high-value products, preferably separate CNPK nutrient recovery streams, should be investigated. Furthermore, enhanced hydrolysis should allow for long-term operation at increased loading rates and shorter retention times, without compromising on effluent quality.

Hyper-thermophilic treatment at 70°C, could result in hygienically safe products as well, but at even shorter SRTs. This process however so far, was impeded by unfavorable environmental conditions, i.e., high ammonia levels and volatile fatty acid accumulation [2]. Overall, even though the recovered products may not be risk-free, they need to be risk-mitigated as much as is feasible.

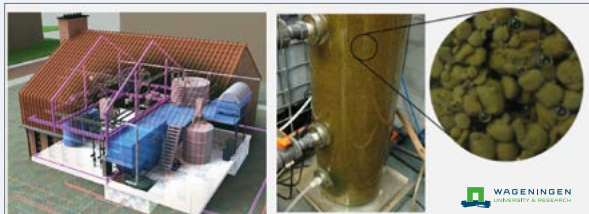


Fig 1. Visualization of the anaerobic blackwater treatment demonstration site at Noorderhoek, Sneek under Run4Life Project (left) and calcium phosphate granulation in lab-scale anaerobic blackwater treatment reactor (right)

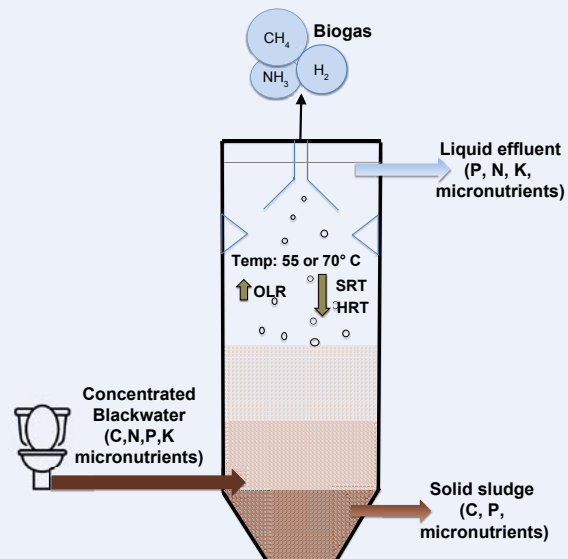


Fig 2. Potential nutrient recovery streams from (hyper)thermophilic anaerobic blackwater treatment

Research goals

Therefore, this project is seeking to optimize the performance of (hyper)thermophilic treatment to maximise the production of reusable recovered products (CNPK, micronutrients, and energy). Specific project objectives are:

- Optimizing (hyper)thermophilic anaerobic reactors for recovery of sludge and nutrients along with energy
- Characterizing (micro)nutrients in concentrated blackwater and their speciation in the reactors
- Developing and testing recovery strategies for CNPK and micronutrients from concentrated blackwater
- Determining the removal efficiency for micropollutants in blackwater through thermophilic anaerobic treatment

References

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- [3] H2020 Run4Life Project, Source: <https://run4life-project.eu/>
- [4] Cunha, J.R. (2018) Anaerobic calcium phosphate bio granulation

Priority compounds & Virus control

The Priority compounds & Virus control theme focuses on the chemical-free degradation and inactivation of human-originated trace contaminants, transforming them into harmless products. We explore two key areas: First, we develop efficient, UV-based advanced oxidation processes (AOPs) to ensure safe drinking water from impaired sources. Second, we aim to create rapid, simple validation methods to measure log removal and inactivation values, crucial for maintaining high safety standards. Without sensitive operational monitoring, valuable log

credits may be lost. Additionally, we address the formation of transformation products (TPs) during AOPs. While AOPs effectively degrade micropollutants like pharmaceuticals and pesticides, some TPs may remain biologically active and go undetected by conventional methods. To tackle this, we combine high-resolution mass spectrometry (HRMS), effect-directed analysis (EDA), and machine learning to identify and assess TPs' potential toxicity, enhancing both treatment safety and effectiveness.

Research projects

- **Yicheng Wang**, ICRA, *Vacuum UV processes for removal of persistent micropollutants*
- **Ingrida Bagdonaite**, Vrije Universiteit Amsterdam, *Effect directed analysis to assess transformation products formed during water treatment*



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Motivation

UV radiation-based technologies (e.g. UV/H₂O₂, UV/O₃) have been developed to remove organic micropollutants (OMPs) from water. Especially, vacuum UV (VUV) radiation at 184.9nm has emerged as an option to eliminate even the most persistent chemicals, such as perfluoroalkyl and polyfluoroalkyl substances (PFAS)¹. Photons of 184.9nm are strongly absorbed by water, generating strong oxidants (e.g. HO·) and reductants (e.g. H· and e_{aq}⁻) for degradation of OMPs (Figure 2). Compared to conventional UV radiation-based technology, the VUV process is capable of *in situ* production of oxidants and reductants without additional chemicals. Current research on the VUV process focuses on interpreting the degradation kinetics and mechanisms of contaminants at a laboratory scale. The reaction kinetics of complex chemistry during the process are less studied. At Wetsus, we will combine kinetic modeling with experimental observation to better understand and utilize the VUV process.

Technological challenges

- Because of the high absorption coefficient of water, most of the 184.9nm photons are absorbed within the 5mm layer³. Generated radicals are consumed within μs scale. It is difficult to understand the complex mechanism and kinetics of direct photolysis and free radical-mediated degradation of OMPs with traditional experimental methods
- Different types of water, such as surface water and WWTP effluent, have various constituents. The effect of the water matrix on OMPs removal is not fully understood to support system scale-up

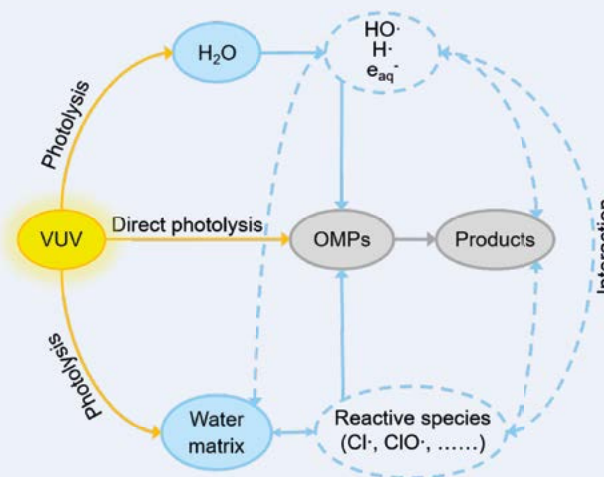


Fig 2. Simplified diagram of vacuum UV process in the water sample².

- In the presence of dissolved organic matter and dissolved inorganic constituents (e.g. halides), undesired by-products would be formed while OMPs degradation would slow down

Research goals

- Evaluate the role of OMPs direct photolysis at 184.9nm on their overall degradation in the VUV process
- Predict the impact of water matrix constituents (primarily dissolved organic matter and chloride) on the VUV process performance
- Elucidate the PFAS degradation with the VUV process, develop a kinetic model and validate it against the experimental data collected from bench-scale tests (Figure 1)
- Examine the VUV process in combination with chemical solutes (e.g. sulfite) as a means of enhancing the PFAS degradation via additional H· and e_{aq}⁻ generation

References

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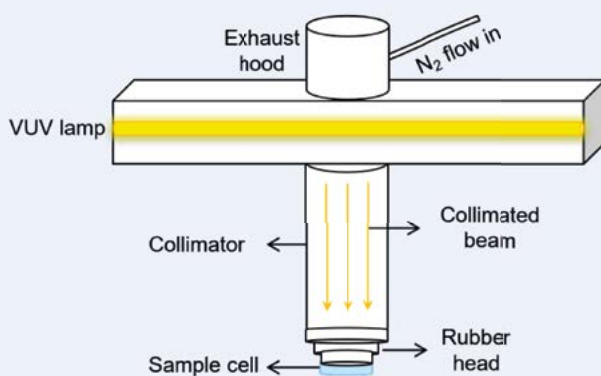


Fig 1. Schematics of the bench-scale (collimated beam) apparatus used in experiment.

Effect Directed Analysis to assess transformation products formed during water treatment



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Motivation

Advanced oxidation processes (AOPs) play an important role in degrading micropollutants like pharmaceuticals and pesticides present in water. However, during treatment, so-called transformation products (TPs) might be formed as micropollutants are not completely mineralized. These TPs can have significantly different characteristics compared to their parent compound and, in some cases, might still be biologically active.

Depending on the micropollutant(s), matrix composition and treatment conditions, a broad range of TPs can be formed. However, many of these chemicals are unknown and are hence not included in conventional analytical techniques. There is a need to develop and implement a (bio)analytical platform capable of detecting and characterizing TPs, assessing their potential toxicity, and linking their formation to AOP conditions and water characteristics.

Technological challenge

We combine advanced (bio)analytical techniques (fig 1), such as high-resolution mass spectrometry (HRMS) and effect-directed analysis (EDA), with computational methods such as in-silico prediction and machine learning models to create a comprehensive platform [1]. Computational approaches will help us prioritize and identify relevant (i.e., potentially toxic) TPs.

The platform will be implemented to assess TPs formation during AOP treatment and to establish operational risk zones based on treatment conditions, matrix, and micropollutant characteristics.

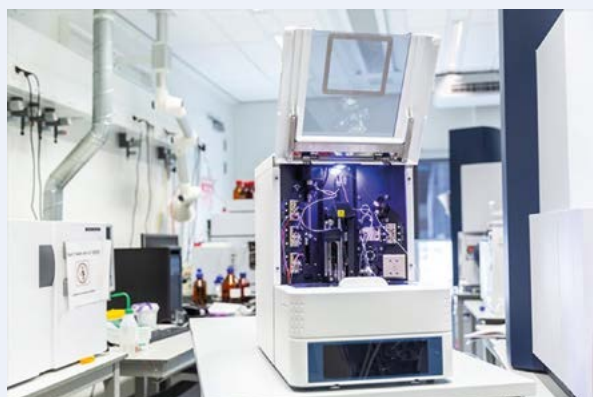


Fig 1. After a liquid chromatography (LC) separation step, the flow is split towards a) the FractioMate™, transporting eluent fractions to a high-resolution bioassay; and b) a high-resolution accurate mass spectrometer (MS) capable of identifying unknown compounds.

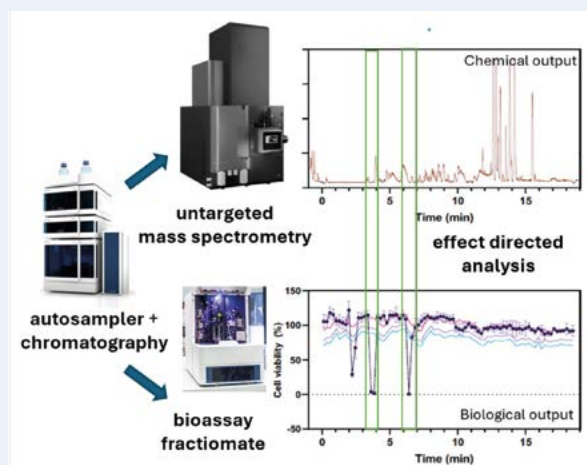


Fig 2 In Effect-Directed Analysis bioassay responses are correlated to mass compound data to identify potentially toxic compounds

Research goals

The goal is to develop an assessment framework to evaluate and identify operational risk zones for selected (waste)water treatment technologies, by:

- Linking the chemical and hazard space of TPs by understanding under which conditions they are formed and what their potential (in-vitro) toxicity is (fig 2);
- Selecting a relevant set of bioassays to be used in Effect-Directed Analysis (EDA) mode;
- Developing an EDA-platform, coupling high-throughput fractionation, effect and LC-HRMS analysis for the detection, identification, and toxicity assessment of TPs formed during AOPs;
- Performing controlled experiments and implementing the EDA-platform to investigate TPs formation during AOP treatment under various conditions;
- Complementing the EDA-platform through the implementation of in-silico approaches (e.g., machine learning algorithms) to (i) detect and prioritise TPs based on molecular structures and (ii) enhance the discovery and identification rate of TPs.

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Desalination & Concentrates

Meeting the growing demand for freshwater and water reuse requires sustainable solutions for desalinating seawater, groundwater, and wastewater. The Desalination & Concentrates theme leads the way in developing innovative, eco-friendly, and cost-effective desalination technologies that either enhance or replace traditional thermal and membrane methods. These cutting-edge approaches can be integrated into closed-loop water treatment systems or used for mineral extraction. The projects focus on reducing energy and chemical use, targeting specific

ions that hinder further processing, recovering valuable materials from brines, and eventually achieving zero liquid discharge. The theme explores diverse, interdisciplinary methods, blending expertise from electrochemistry, crystallization, membrane separation, extraction, and adsorption. Technologies under development include capacitive deionization, electrodialysis metathesis, bipolar membrane electrodialysis, nanofiltration, and crystallization, pushing the boundaries of sustainable water treatment.

Research projects

- **Xiao Zhang**, University of Twente, *Stable polyelectrolyte multilayer based membranes for water treatment under harsh conditions*
- **Kecen Li**, Wageningen University, *High recovery and chemical-free desalination using advanced electrodialysis schemes*
- **Hanieh Geranikolahlooei**, Wageningen University, *Functionalizing nanostructured materials for selective ion recovery* **NEW**
- **Daniel E. Kelly Coto**, Ghent University, *Brine valorization using bipolar membrane electrodialysis* **NEW**
- **Hong Ting (Connie) Au**, Wageningen University, *Development of an on-site electrochemical regeneration method of activated carbon filters for PFAS removal* **NEW**



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Stable Polyelectrolyte multilayer based membranes for produced water treatment under harsh conditions



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Motivation

Enhanced Oil Recovery in the petroleum industry typically involves injecting three or more barrels of water into the reservoir to produce one barrel of oil. The large volume of water that ends up in the production well is so called produced water (PW)^[1]. Due to the complex composition of PW, its processing for discharge is challenging and costly^[2]. Treating PW for re-use offers a more sustainable option. Polyelectrolyte multilayer (PEM) based membranes prepared by layer-by-layer (LbL) assembly have recently shown to be promising for treating PW for re-use (Fig 1)^[3]. However, PW can have very harsh conditions, including high salinity, extreme pH values, the presence of dissolved organics and problematic chemicals. Therefore, it is crucial to further develop these PEM based membranes towards high stability under such conditions.

Technological challenge

Harsh conditions as high salinity can damage the PEM coatings. Some dissolved organics may also reduce the mechanical stability of the membrane support. The conversion of ionic bonds to covalent bonds by chemical crosslinking can improve the stability^[4]. However, this process may also affect the separation performance of the obtained membranes. We propose to develop a unique PEM-based membrane with both high stability and excellent performance in selectivity, permeability, and fouling resistance (Fig 2).

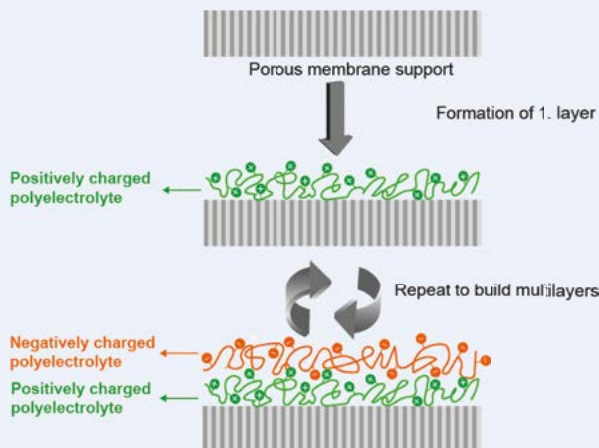


Fig 1. Schematic illustration of a PEM based membrane prepared by layer-by-layer deposition of oppositely charged polyelectrolytes on ultrafiltration membrane support.

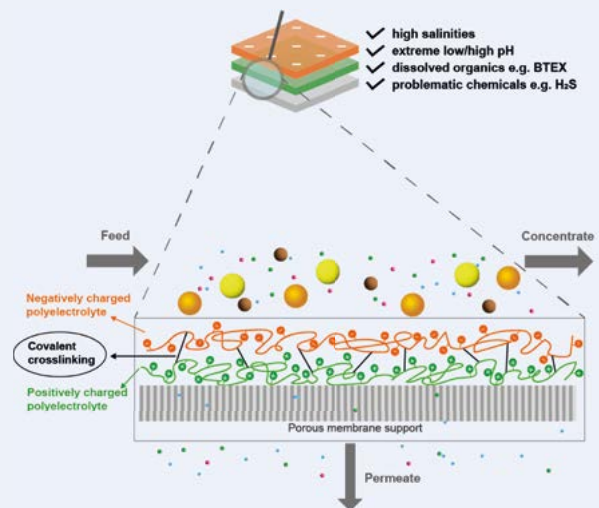


Fig 2. Schematic depiction of produced water treatment with crosslinked stable PEM based membranes. The PEM membranes remain stable under the harsh conditions and allow effective removal of oil droplets, multivalents salt and some dissolved organics.

Research goals

- To study the stability of PEM coatings and their supports under harsh conditions, and to demonstrate the range of harsh conditions under which PEM based membranes can be successfully applied in produced water treatment.
- To develop a crosslinked PEM coating that would allow stability even under harsh conditions.
- To investigate fouling under the described harsh conditions.
- To translate the obtained insights into relevant process designs for the treatment of specific produced water streams for re-use.

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Motivation

Ascending water scarcity permits desalination for additional water supply. Membrane desalination is mature and cost-effective. However, its water recovery is limited due to the oversaturation of 2:2 salts (e.g., CaSO_4 , CaCO_3) in the concentrate, eventually leading to scaling. Antiscalant dosing or ion-exchange processes mitigate this limitation, but these measures have negative operational and environmental impacts. Alternatively, studies have proposed Electrodialysis Metathesis (EDM; Fig 1). The EDM process avoids oversaturation of 2:2 salts; instead, it concentrates highly soluble 1:2 (e.g., NaSO_4) and 2:1 salts (e.g., CaCl_2) separately. However, the process requires the addition of NaCl [1,2].

Our aim is to develop a high-recovery desalination scheme, including EDM, but with electricity and source water as sole inputs (Fig. 2). The process we propose consists of 2 steps. In step 1 monovalent ions migrate from the feed stream to form a 1:1 brine in a monovalent selective ED (mvsED) process. In step 2 divalent ions migrate from the feed to recombine with monovalent counterions from the 1:1 brine from step 1, forming a 1:2 brine (Na-type) and a 2:1 brine (Cl-type).



Fig 1 . Desalination with EDM: divalent ions from feed stream rearrange with monovalent ions from NaCl solution

Technological challenges

Regarding development and real-life applications, the main challenges are as follows:

- Without chemical additions, the source water's ionic composition fully defines the ability to rearrange ions into different brines, hence also the water recovery it can obtain.
- The scheme involves at least four types of ion-selective membranes which interact within the process. Essential are the properties of each of these membranes: e.g., counter-ion over co-ion selectivity, monovalent over divalent selectivity, water permeability.
- The process design is complicated since it includes multiple streams (feed, product, recycle, brines).

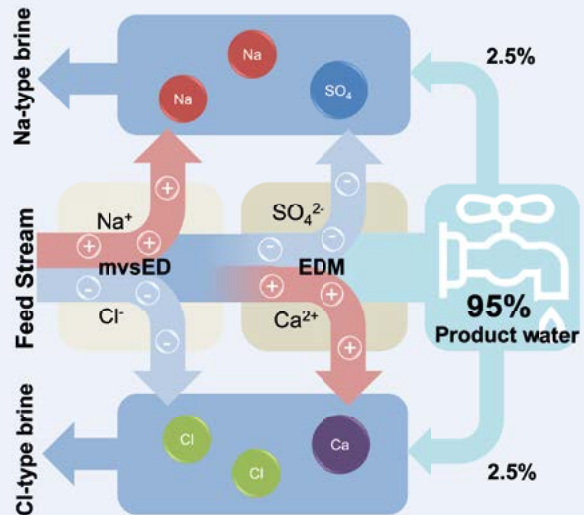


Fig 2. High-recovery (e.g., 95%) and chemical-free desalination: in step 1 Na and Cl are removed from the feed stream by mvsED, in step 2 divalent ions (e.g., Ca and SO_4) are removed from the feed and recombined with Cl and Na, resp.

Research goals

The goal is to give an experimental proof of concept and validate the technology in the lab with real water, and for practical use cases provided by our industrial partners. The following research goals schedule the work plan:

- Conceptualizing and modeling the EDM configurations regarding the characteristics: chemical-free, high-water-recovery, and no too concentrated brine discharge.
- Experimentally validating the concepts and investigating the optimum design and operational conditions, including synthetic and real water tests and accurate modeling for fine tunes.
- Identifying and investigating potential practical use cases of the concepts regarding water recovery or regeneration and brine management in various industries (e.g., drinking water, oil, and membrane companies).

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Functionalized Nanostructured Materials for Selective Ion Recovery Capacitive Deionization



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Motivation

Capacitive deionization (CDI) is a promising technology in the field of desalination and water treatment, which can efficiently separate and recover salts at high purity without using chemicals [1]. It makes use of a pair of porous electrodes and an electrical potential difference to remove charged species from aqueous solutions (Figure 1). The current focus in CDI research is to selectively separate valuable ions, such as precious metals and nutrients. For that, the traditional activated carbon electrodes can be replaced with more selective alternative materials. 3D intercalation materials like Prussian Blue Analogous (PBAs) have been shown to have high salt adsorption capacity and, by adding different transition metals in their lattice structure, also tunable selectivity [2,3].

Technological challenge

The ion selectivity of PBAs can be controlled by using different transition metals, their combinations and composites. However, to successfully address the challenge of improving selectivity, full understanding of PBAs structure-property relationships is needed which is currently still lacking. This needs to focus on various chemical properties such as crystal structure, functionality, redox activity and pore/cavity size.

Furthermore, the new materials must also remain stable and effective during long-term operation. Predicting the stability of a material will require a combination of both theoretical knowledge and experimental testing such as working with certain chemicals or repeated cycles of charging and discharging.

Research goals

The objective of this project is to understand, optimize and tune the ion-selective properties of selected intercalation materials.

The research goals of the project are to:

- Explore different transition metals (Ni, Cr, Mn, Co, Cu, Zn, etc.) for making PBA electrodes, to increase their selectivity and compare them with traditional activated carbon electrodes.
- Understand structure-property relations of the electrodes (PBAs) to obtain different cation selectivity.
- Improve the stability of electrodes by metal combination to get simultaneously high stability and selectivity.

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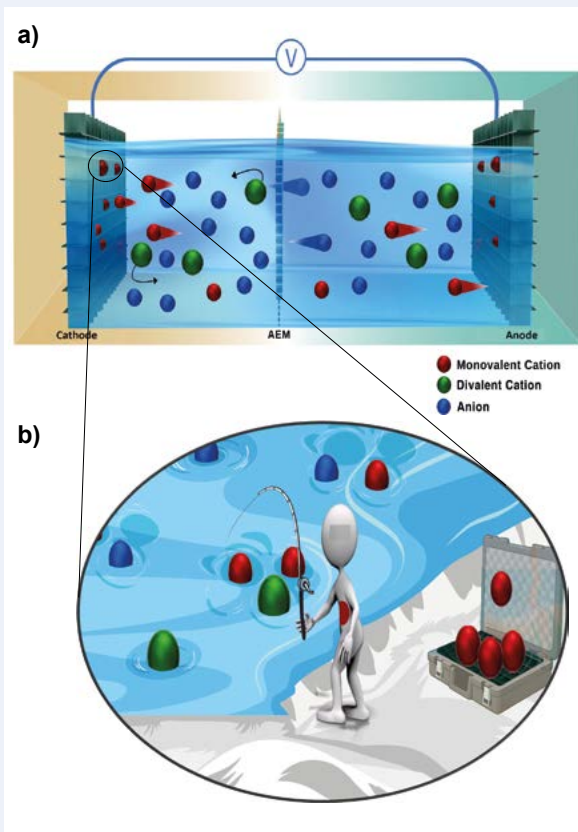


Figure 1. a) CDI setup consists of two PBA electrodes acting as an anode and a cathode, with an anion exchange membrane (AEM) placed between them, within a mixture of monovalent and divalent ions. The PBA electrodes are designed to selectively intercalate monovalent cations from the ion mixture. The membrane allows the passage of anions, enabling them to move across to the de-intercalating compartment. b) PBA electrode selectively removes monovalent cations from the solution.



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Motivation

Membrane-based technologies, such as reverse osmosis, are widely used in industry. While effective at purifying water, they always produce brine that must be managed. One of the limitations preventing further water recovery is the scaling of minerals on the membrane surface. Furthermore, current brine treatment strategies are costly and pose environmental risks^[1], which have driven the interest in resource recovery methods^[2]. Bipolar membrane electrodiagnosis (BMED) is a promising technology for brine valorization^[3], as it enables the production of valuable acids and bases^[4] (Fig. 1). However, BMED requires pretreatment to remove scaling-inducing components (e.g., Ca^{2+} , Mg^{2+}). Conventional methods, such as chemical precipitation or ion exchange, rely on chemical additives. This research proposes a chemical-free brine softening process, coupling crystallization with BMED (Fig. 2) to enhance water recovery, mitigate scaling, and promote resource recovery through acid and base production.

Technological challenge

The main technological challenges include:

- Brine contains a variety of ions and compounds beyond NaCl.
- High hardness and alkalinity increase scaling risk in BMED, while low NaCl concentrations limit acid and base production.
- Real brine often contains antiscalants, humic acids, and other compounds that may affect the process.
- The integrated system must operate without external chemical additives, relying solely on the ions present in the feed water.
- Balancing the crystallization kinetics and BMED process to have a stable operation.

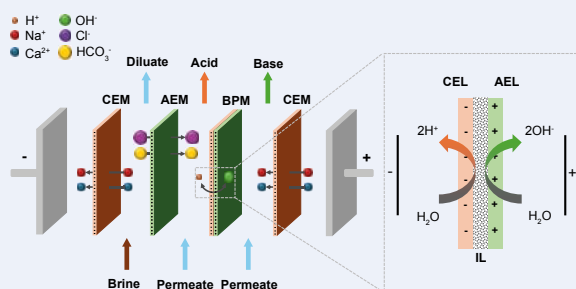


Fig. 1. Conceptual diagram of acid and base production from brine using BMED. CEM: cation exchange membrane. AEM: anion exchange membrane. BPM: bipolar membrane. CEL: cation exchange layer. AEL: anion exchange layer. IL: interfacial layer. Water dissociates in the interfacial layer (IL) into H^+ and OH^- ions, thus producing acid and base.

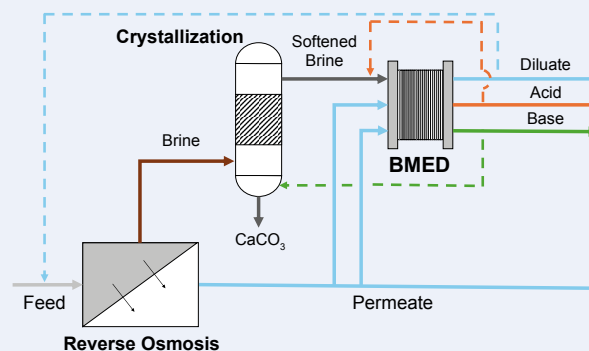


Fig. 2. Process flow diagram illustrating the integration of crystallization with BMED. The RO brine is first treated through crystallization to remove multivalent ions. The softened brine is then processed by BMED to produce acid and base, which are utilized within the system to support the overall process.

Research goals

- 1. Determine and optimize the operational parameters of BMED to maximize acid and base production, while mitigating scaling risk.
- 2. Investigate the ideal conditions for crystallization to effectively remove scaling-inducing components.
- 3. Assess how variations in brine composition influence the performance of crystallization and BMED processes.
- 4. Develop and validate an integrated crystallization-BMED process for brine valorization.
- 5. Evaluate the techno-economic feasibility, scalability, and environmental impact of the integrated crystallization-BMED process.

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Development of an on-site electrochemical regeneration method of activated carbon filters for PFAS removal



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Motivation

Perfluoroalkyl and polyfluoroalkyl substances (PFAS) are persistent and mobile pollutants that present significant challenges in water treatment. Long-chain PFAS have received considerable attention in academic research and health regulation^[1]. The increasing implementation of regulatory limits on the use of long-chain PFAS results in a worldwide shift to short-chain production^[2]. Current solutions, such as granular activated carbon (GAC) filters, demonstrate effective removal for long-chain PFAS but exhibit limited removal efficiency for (ultra) short-chain PFAS, such as trifluoroacetic acid (TFA)^[3]. Furthermore, frequent off-site regeneration of GAC filters at elevated temperatures (>1000 °C) requires high energy and labour input^[4]. Therefore, developing alternative, sustainable, and, preferably, on-site regeneration technologies is required.

Technological challenge

This research explores a novel on-site regeneration technique for GAC filters, referred to as electro-regeneration (Figure 1). By applying an electrical charge to GAC filters, PFAS are desorbed through electrostatic repulsion. This approach aims to eliminate the need for thermal reactivation and significantly reduces the associated environmental impact. First, we use a dual-column system in which the carbon granules are sequentially subjected to adsorption and regeneration steps (Figure 2). Upon saturation of the GAC filters, an electrical current is applied, facilitating the desorption of PFAS. Afterwards, the carbon filters are considered regenerated and prepared for subsequent adsorption cycles. Improved cell configurations and process schemes will be developed. This iterative process offers a sustainable and efficient solution for PFAS removal.

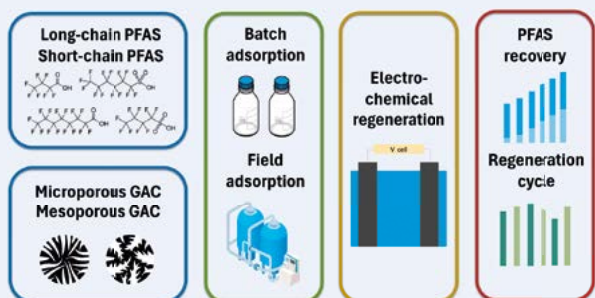


Figure 1. Project overview.

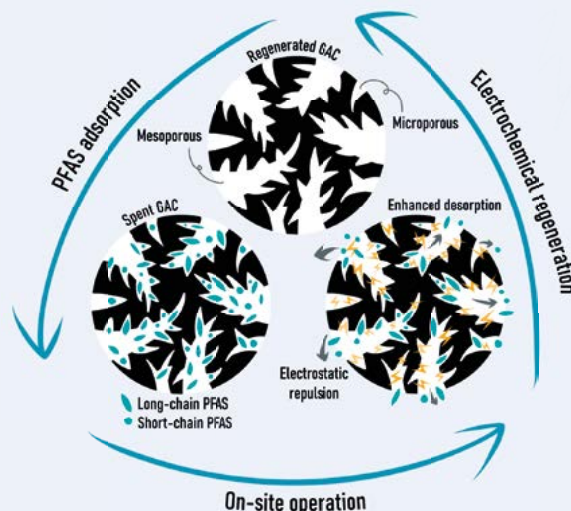


Figure 2. Proposed on-site operation of adsorption and regeneration cycles.

Research goals

The primary focus of this research is to optimize the desorption of a broad spectrum of PFAS, covering various chain lengths and functional head groups. Key areas of investigation include the interactions between PFAS molecules and electrically charged carbon surfaces, and the possibility to remove (ultra) short-chain PFAS. This research will also evaluate diverse operational conditions, water matrices, and reactor configurations. The development of an on-site regeneration technology provides a sustainable approach for PFAS removal.

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Applied water physics

The emphasis of the Applied Water Physics Theme lies in the exploration of these basic properties of water, especially its interactions with electric, magnetic and electromagnetic fields, vortical flow fields, and the effect of such interactions on living organisms like bacteria. Based upon deeper insights into the fundamentals of water, the Theme furthermore

focuses on screening commercially available water treatment concepts based upon such interaction. Thereby, breakthrough discoveries through fundamental research and pioneering screening experiments with physical, chemical and biological model systems are combined to pave the way for the development of seminal, epoch making water treatment technologies.

Research projects

- **Xiaoxia Liu**, *Extended biostability of potable waters through sustainable non-chemical*
- **Roman Klymenko**, Eindhoven University of Technology, *Novel advanced oxidation with plasma discharge in a hyperbolic vortex*
- **Jack Khalil**, University of Natural Resources and Applied Life Science, *Extended Biostability of Potable Water Through Sustainable Non-Chemical Treatment*
- **Adel Bou Alia**, Wageningen University, *Simulating the impact of drinking water microbiomes on the human gut microbiome*
- **Loes Heemskerk**, University of Amsterdam, *Improving ice quality for performance and sustainability* **NEW**



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Academic partners





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Motivation

The accumulation of pharmaceutical residues and micro-pollutants in wastewater in the environment has become a problem of growing concern. Although some compounds are easily biodegradable, many of them are hardly decomposed and pose a health hazard for both aquatic and terrestrial life. The application of gas-phase pulsed electrical discharges [Fig 3.] (plasma technology) is a promising method for the energy efficient oxidative degradation of aqueous organic pollutants. Precursors in oxidative degradation chemistry are reactive oxygen (ROS), and reactive nitrogen species (RNS) [Fig 2.]. These species are generated by plasma operation in humid air. ROS also are produced at the gas/liquid interface by direct water bombardment with energetic electrons creating excited states and ions. Therefore, optimization of the plasma-water interface by combination a plasma with the outstanding mixing capabilities of a hyperbolic vortex is expected to strongly benefit the plasma induced oxidative degradation of aqueous priority materials, since these species are expected to be dissolved effectively by the suction and the highly efficient gas absorption properties of the aqueous hyperbolic vortex^[1].

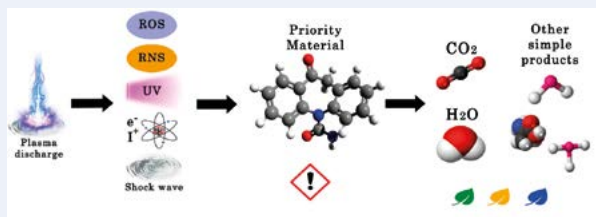


Fig 1. Diagram of the oxidative degradation of micro-pollutant molecules in the water bulk during plasma operation.

Technological challenge

On the one hand, plasma water purification includes various physical and chemical processes, many of which are independent water treatment techniques [Fig 1.] (oxidation, ultraviolet disinfection, ozonation, electrolysis, shockwave water purification etc.). The water vortex also has oxidative degradation-promoting properties by itself, increasing the amount of dissolved oxygen in the water volume as well as other gases. On the other hand, many toxic species can be created in atmospheric discharge plasma such as nitrates, nitrites, etc. Varying the parameters of the discharge, the material of the electrodes and the type of atmosphere changes the amount and type of species created during the interaction of plasma with gas and liquid surface^[3] and, as a consequence their adsorption by water. To remove different micro-pollutants in the water volume, different conditions are required as well as different amounts of energy. Therefore, for each of them, it is necessary to find an optimal hyperbolic vortex plasma discharge mode.

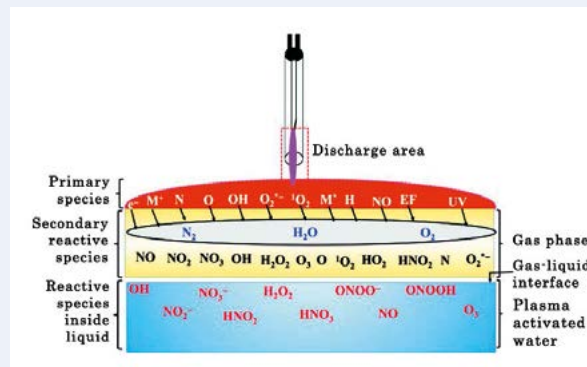


Fig 2. Physicochemical processes of reactive oxygen and nitrogen species formation during plasma-water interaction^[2].

Research goals

- Find the optimal plasma discharge for the water purification in terms of price-quality and plasma-formed substances by testing different discharge parameters (field strength, current density, atmosphere, etc.).
- Design and build the water vortex plasma reactor for purification of the water contaminated by model pharmaceuticals.
- Analyze the resulting plasma exposed water and make sure that the pharmaceutical oxidative degradation products it contains are compatible with aquatic and terrestrial life.
- Optimize and improve the plasma technology for water purification, test it to remove other types of micro-pollutants and scaling it up.

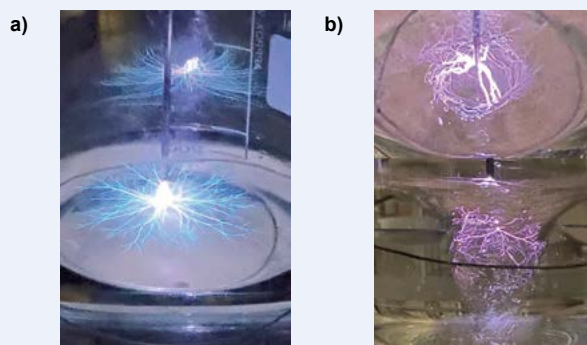


Fig 3. Photo of the plasma discharge: a) above the water surface, b) in the water vortex.

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Extended Biostability of Potable Water Through Sustainable Non-Chemical Treatment



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Motivation

Many types of bacteria belonging to various genera are present in the water ecosystem. Indeed, different sources of water highly influence the composition of the water microbiome.

Moreover, drinking water is characterized by its ratio of high nucleic acid (HNA) content bacteria and low nucleic acid (LNA) content bacteria where generally pathogenic organisms belong to the HNA group and normal flora organisms belong to the LNA group^{[1][2]}.

Bacteria in the LNA cluster are the most dominant in freshwater environments due to their oligotrophic properties^[2]. These two groups of bacteria could be differentiated by flow cytometry where the fluorescence intensity is the indicator of nucleic acid content and the scatter signals as an indicator of cell size^[3].

Microbial calcium carbonate precipitation (MICP) is a natural phenomenon that is hardly done without the creation of bacterial biofilms^[2]. CaCO₃ precipitates in stages: first, the formation of amorphous calcium carbonate (ACC), then the creation of one of the three crystals respectively from least to most stable: vaterite, aragonite, and calcite. Nucleation is a very important step in the precipitation process and genetics play an important role as well in the process of MICP.

Magnetic water treatment (MWT) has always focused on the physico-chemical properties of water instead of its microbiological properties. It has been demonstrated that MWT could help increase the formation of dynamically ordered liquid-like oxyanion polymers (DOLLOPs) that account for > 50% of the calcium found in a given solution^[4].

Since the precipitation of calcium carbonate in drinking water can be performed in various ways including by indigenous water bacteria; it has been a cause of nuisance in water piping systems where biofouling and scaling occur; resulting in the clogging of these pipes^[2].

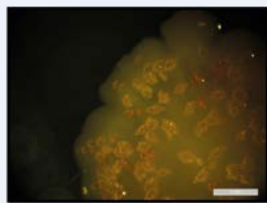
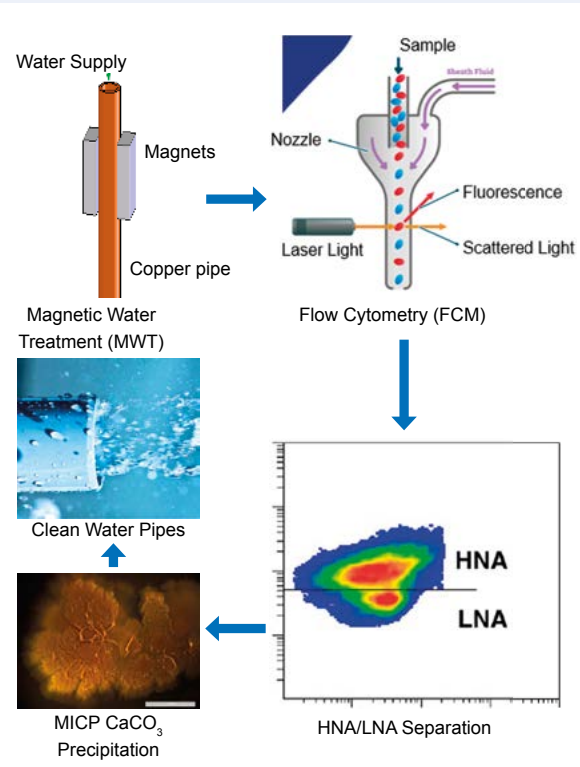


Fig 1. Bacterial culture with CaCO₃ precipitation

Technological challenge

- Accurate detection of the conditions in which HNA and LNA bacteria interchange roles.
- Recording small mutations and other factors involved in the MICP process as well as the outcome of MWT in the genetic changes of the concerned bacteria.
- The successful CaCO₃ precipitation in a manner that does not accumulate on water pipes' surfaces



Research goals

- Detection of the conditions of HNA/LNA shift in drinking water bacteria if any shift happens at all.
- Identification of the genetics behind MICP phenomena and ultimately identifying the effect of MWT on the drinking water itself and the behavior of the water's microbiome.
- Determining whether MWT can eventually increase CaCO₃ precipitation in a manner that does not cause scaling on water pipes' peripheries.

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Motivation

Drinking water is an important source of hydration and a vehicle of microorganisms^[1]. Environmental conditions at the source and water treatment methods^[2] shape the microbial load of the drinking water microbiome (DWM) (Fig.1). Upon consumption, the DWM can interact with the gut microbiome (GM) which is composed of an ensemble of microorganisms and their genomic repertoire (bacteria, archaea, unicellular eukaryotes, viruses) that influence the human host through a range of physiological functions^[3]. While DWM has been suggested to influence the GM via several ways^[4,5] (Fig.1), the mechanistic impact of DWM on the GM remains unexplored. The advent of *in-vitro* fermentation models coupled to high throughput analysis may reveal how the DWM may be modulating the GM and inform on the microbiological quality of water.

Technological challenge

Given the complexity and ethical constraints surrounding *in-vivo* models, an *in-vitro* bioreactor system is a lucrative option to study fecal GM at conditions that recapitulate those of the human gut. However, there are numerous challenges associated with simulating gut-derived microbial metabolic interactions in an *in-vitro* fermentation model such as uncultured species with unknown functions and retaining native functions in the simulator (Fig.2). In parallel, amplicon-sequencing and flow cytometry approaches will be used to trace and monitor bacterial members of the DWM^[6]. Compositional and functional changes in the *in-vitro* bacterial culture will be determined via high throughput techniques and will be compared to a baseline model. Other measurable parameters reflecting a response in the GM culture will be determined and measured such as production of short chain fatty acids^[7].

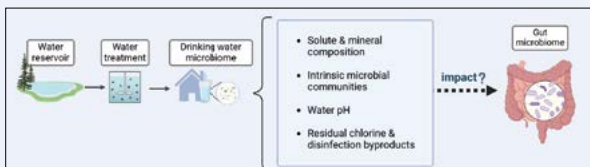


Figure 1. Factors shaping the drinking water microbiome (DWM) and how it may impact the gut microbiome.

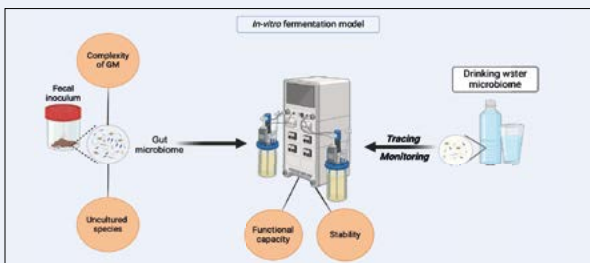


Figure 2. Challenges associated with studying the impact of drinking water microbiomes on the GM in an *in-vitro* fermentation model. GM: gut microbiome

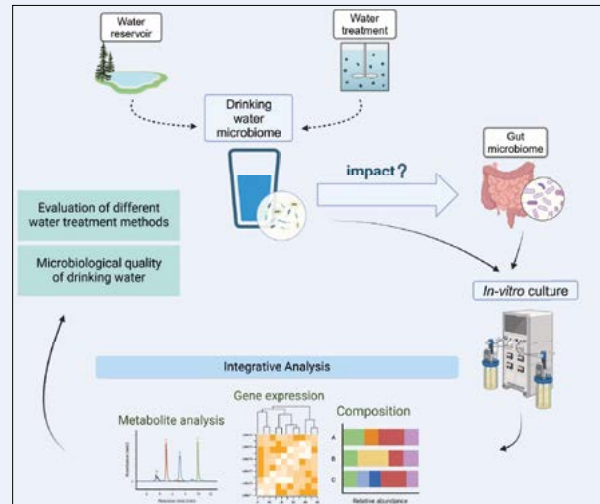


Figure 3. The drinking water microbiome (DWM) may interact with the gut microbiome (GM) which influences host health. By culturing gut-derived bacterial species under conditions that mimic the gut, the impact of DWM on the GM can be simulated. High throughput techniques including next generation sequencing can reveal changes over time to the composition and function of the gut-derived bacterial culture in the presence of the drinking water microbiome.

Research goals

The aim of this project is to evaluate the impact of different drinking water sources and treatment methods on the GM in an *in-vitro* fermentation model. By integrating high throughput analyses on the composition, gene expression, proteins and metabolites produced, a characterization of the synthetic bacterial culture in response to the different drinking water samples can be performed and a conclusion on the microbiological quality of the latter can be made. Understanding how the DWM influences health via the GM will further advise on water treatment methods to improve drinking water quality.

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The physics of ice rinks

Ice skating is an integral part of Dutch culture, from recreational skaters on frozen canals to Olympic athletes pushing the limits of speed and precision. Maintaining high-quality ice, however, is a blend of art and science. The hands-on experience of the “ice masters” at Thialf has ensured a world-class ice rink for both Short Track and Speed Skating disciplines over the last decades. However, this expertise needs to be supported by scientific understanding. Such insights could, in turn, improve ice performance, sustainability, and energy efficiency.

Measurability of Ice Quality

Objectively quantifying the quality of ice rinks is the first challenge. Figure 1 illustrates the relationship between key variables that will be investigated in this study. Subjective terms like grip and glide are commonly used by elite skaters and ice masters to describe ice quality. On the material science side, bulk ice and ice surfaces have been extensively researched under laboratory conditions^{1,2}. However, these findings do not translate well to the practical setting of the ice rink^{3,4,5}. Therefore, robust tools are needed to measure ice quality effectively in real-world conditions.

The second challenge is understanding the variability of ice quality. Ice properties can differ depending on factors such as water composition, environmental conditions in the rink, and the specific needs of each skating discipline. By developing tools to analyze the relationship between the ice’s frictional properties and external variables this understanding can be tested and refined through experiments that simulate realistic rink conditions.

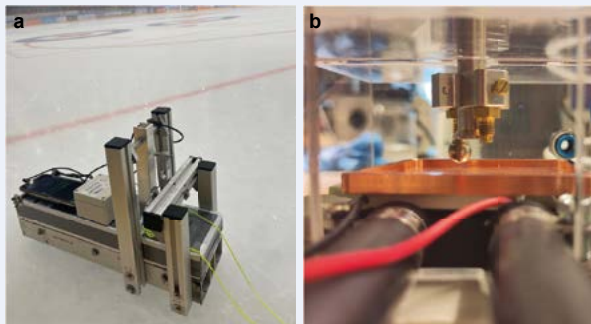


Fig 2. Measuring friction on an ice rink with use of a friction sled (a) and measuring friction in a lab setting with a rheometer (b).

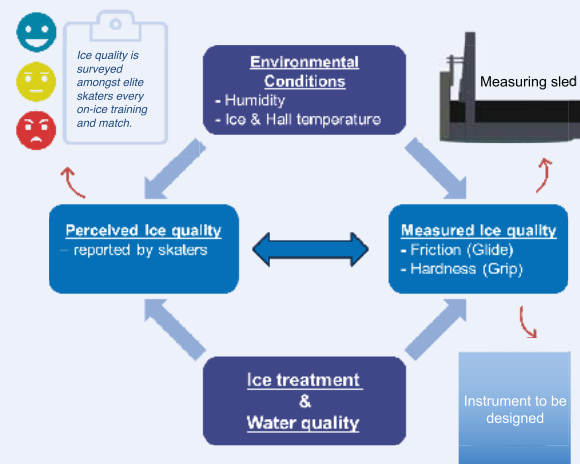


Fig 1. Schematic representation of important relationships between variables that have to be researched and through what means they are studied.

Research goals

The project’s first goal is to develop both objective and subjective measurement techniques for ice quality. This goal will be achieved by combining research tools in the lab, alongside real-world tests at Thialf on the ice rink (see Fig. 2), and combining these with perceived ice quality of the skaters. Over four years, this project aims to establish clear metrics that will allow ice quality to be fine-tuned for different skating disciplines, enhancing both performance and sustainability. The ultimate goal is to create an adaptable system for ice maintenance that improves athletes’ performance while reducing energy consumption.

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Natural flocculants

In this theme, the focus is on developing natural alternatives for synthetic organic polymeric flocculants for the treatment of surface water or wastewater. These alternative flocculants should overcome the disadvantages of synthetic polymers: produced from scarce fossil sources, non-specific, non-biodegradable, and produce large amounts of (toxic) waste that cannot be reused in, e.g., agriculture. Mixed extracellular polymers produced by micro-organisms during biological wastewater treatment are more sustainable than synthetic polymers, and

indications are that they can also give a better flocculation performance. Moreover, possibly in combination with physical separation technology such as membrane treatment, natural flocculants have a potential application to remove particles in drinking water, to produce industrial process water from fresh or saline surface and waste waters, to treat oil-containing wastewaters, to separate algae from their medium in algae cultivation systems, to assist in the retention of valuable biomass in biological wastewater treatment processes, etc. .

Research projects

- **Berke Kisaoglan**, Wageningen University, *Biorecovery and applications of biopolymers from wastewater*
- **Bohan Chen**, Wageningen University, *Engineering natural bioflocculants: production, application, and mechanisms*
NEW



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Motivation

Synthetic flocculants are often applied in coagulation/flocculation process to trigger agglomeration of destabilized particles. A major concern associated with synthetic flocculants is their environmental impact. Promising natural alternatives are extracellular polymeric substances (EPS), due to their ability to bind cations and organics. EPS-derived bioflocculants can be produced whilst treating wastewater by open mixed microbial cultures, thereby offering an environmentally friendly and cost-effective way for synthesis.

Technological challenge

EPS are secreted by microorganisms in their natural environment for several purposes such as adhering to the surfaces, storing nutrients, and retaining water. They contain polysaccharides and proteins as main components. EPS production can be stimulated by environmental stress (Fig 1). It can be achieved with single or mixed carbon sources, pure or mixed microbial cultures and under sterile or non-sterile conditions.¹ Depending on the purity, EPS can be applied in several fields such as food, health, and water treatment.²

In this research, EPS production will be achieved by utilizing wastewater as a nutrient source. Mixed microbial communities will be employed for EPS production under non-sterile conditions (Fig 2, 3). This is accompanied by several challenges including:

- Long-term operation of EPS producing membrane bioreactors
- Extraction and characterization of produced EPS
- Application of EPS as natural flocculant and understanding the flocculation mechanism of EPS
- Investigating the changes in the microbial community during the EPS production process

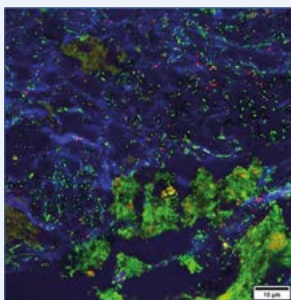


Figure 1. CLSM image of mixed liquor sample taken from EPS-producing bioreactor run under nitrogen limitation. The sample was stained with fluorescent dyes to show individual components of EPS: Sypro Orange (green, proteins), Calcofluor white (blue, polysaccharides), Syto 63 (red, DNA).

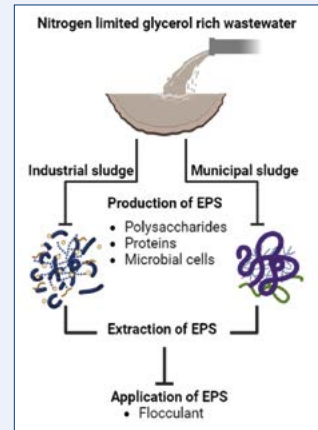


Figure 2. The experimental approach. Two different bioreactors are inoculated with aerobic sludge samples originating from different sources (industrial and municipal sludge). Reactors are fed with nitrogen limited synthetic wastewater containing glycerol as carbon source. Produced EPS are extracted and applied as natural flocculant.

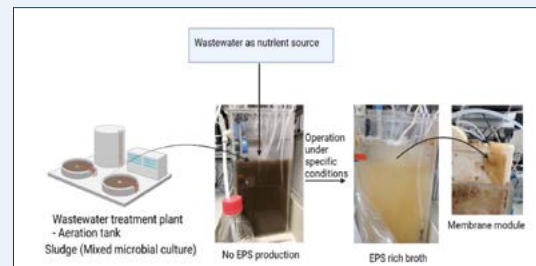


Figure 3. Changes of membrane bioreactor inoculated with aerobic mixed microbial culture during EPS production process. EPS production starts under specific process conditions (nitrogen limitation coupled with short solid retention times). During the production mixed liquor becomes viscous as a sign of presence of EPS.

Research goals

This project aims to:

- Produce EPS from wastewater and understand the effect of wastewater type on yield and characteristics of EPS in long term operation
- Apply EPS produced from various type of wastewater as natural flocculant
- Understand the microbial community dynamics during the EPS production

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Motivation

Synthetic flocculants, such as polyacrylamide, are widely used due to their good flocculation capacity^[1]. However, these synthetic flocculants derived from petrochemicals cause environmental issues such as a high carbon footprint and potential eco-toxicity^[1]. Extracellular polymeric substances (EPS), microbially-secreted polymers, have been studied as a sustainable alternative to petrochemical-derived synthetic flocculants due to their properties like high molecular weight, non-toxicity, and biodegradability^[2]. Recent studies have achieved EPS overproduction in nitrogen-limited open cultures and proven the flocculation potential of EPS^[3].

Technological challenge

EPS properties (e.g., polysaccharide/protein ratio, molecular weight, charge density) affect its flocculation capacity^[3]. Conditions such as nitrogen limitation and short sludge retention time are known to promote the overproduction of polysaccharide-rich EPS with net negative charge^[3]. However, the underlying mechanisms of EPS overproduction are still unclear, and as a result, controlling EPS properties remains a challenge.

Flocculation consists of three processes (Figure 1) that are assumed to be similar for anionic synthetic and microbial flocculants, where adsorption and non-equilibrium bridging amongst colloidal particles promote flocs formation. These processes in EPS flocculation are determined by external factors like hydrodynamic conditions as well as colloid and water characteristics which vary in different types of colloidal suspension. To enhance EPS flocculation performance and promote EPS application, these elemental processes require detailed study.

In short, engineering EPS with strong flocculation capacity for distinct colloidal suspensions is essential to outperform synthetic flocculants.

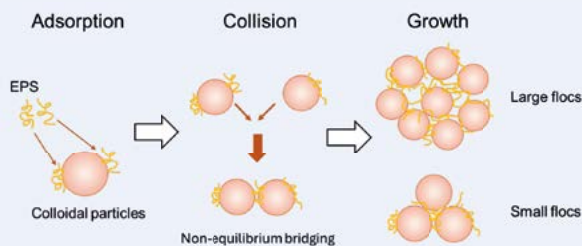


Figure 1. Elemental processes of flocculation with EPS as flocculants

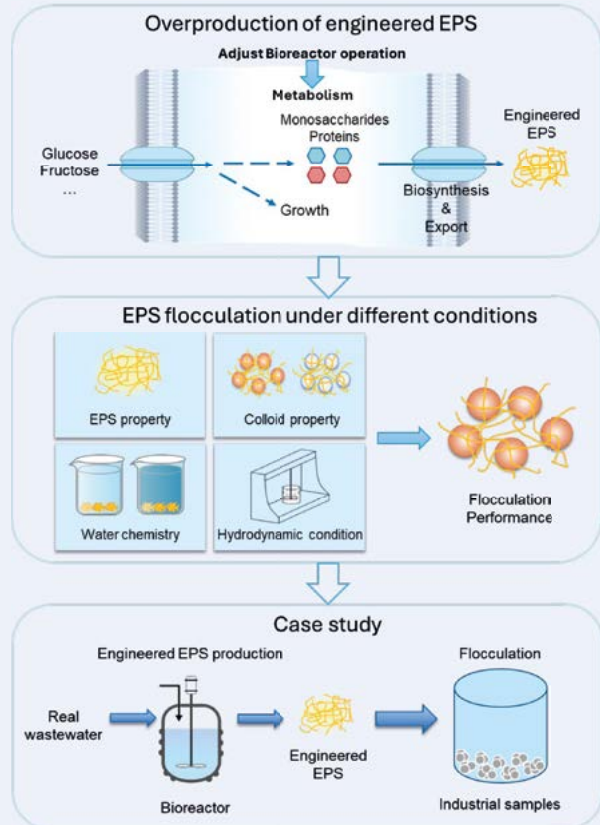


Figure 2. The schematic diagram of the process in this project.

Research goals

A comprehensive approach will be followed as shown in Figure 2. The main research goals of this project are:

- Understand the mechanisms of EPS overproduction and regulate EPS properties by adjusting bioreactor operation conditions.
- Study the processes and kinetics of flocculation in relation to EPS properties, colloid properties, water chemistry and hydrodynamic conditions.
- Develop strategies to enhance EPS flocculation performance in a case study under industrially-relevant conditions.

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Biofilms

Biofilms consist of cells embedded in a polymeric extracellular matrix, produced mainly by the organisms, forming the scaffold for a three-dimensional architecture that protects the microbial community from environmental and shear stresses. Biofilms are found in several environments and play both beneficial and detrimental roles depending on whether their formation is controlled or occurs naturally.

Biofilm formation is a multi-stage process resulting from the balance of several physical, chemical, and biological factors. At Wetsus,

the Biofilms Theme focuses on a multi-level research approach to examine all these factors and the various technologies to characterize, monitor, and control biofilm growth. In this way, we aim to find practical solutions for industries and a better understanding of both beneficial and detrimental forms of biofilms. In particular, elucidation of biofilm structure is a prerequisite to understanding and modeling cell mass transfer and growth within the sheltering extracellular matrix.

Research projects

- **Pamela Moussa**, University of Groningen, *Beyond chlorine: alternative sustainable compounds to remove biofilms in drinking water environments*
- **Rodrigo Nobre**, University of Twente, *Novel coatings for prevention of biofilm formation in drinking water distribution systems*
- **Elisavet Malea**, Wageningen University, *Removing manganese as pre-treatment to limit (bio)fouling in oligotrophic conditions*



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Academic partners



Beyond chlorine: alternative sustainable compounds to remove biofilms in drinking water environments



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Motivation

The drinking water sector depends heavily on drinking water distribution systems (DWDS), and the safety of the water is directly related to people's health. However, the main challenge is to deliver a product that is both aesthetically pleasing and microbially and chemically safe.

One of the main contaminants of DWDS is biofilm growth. In biofilms, microorganisms produce a matrix of extracellular polymeric substances (EPS) rich in proteins and polysaccharides, protecting them from external stresses. Biofilm formation and its detachment into the water stream affects the taste, odor and color of drinking water. Biofilm formation can also affect the drinking water production processes steps, such as ultrafiltration (UF) (Fig. 1). Drinking water utilities all over the world often rely on disinfection with chlorine for eliminating such biofilms, from which harmful disinfection by-products can be produced when interacting with EPS of biofilms [1].

For this reason, research into the application of novel, non harmful, effective anti-biofilm agents is at the core of this project.

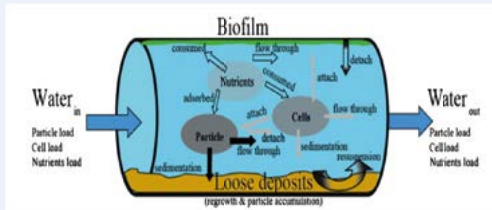


Fig 1. Schematic representation of microbial growth and biofilm formation within drinking water distribution pipes (adapted from [2])

Technological challenge

Once established, biofilms are very difficult to eradicate because the EPS layer protects bacteria from disinfection agents. The focus of this project is the utilization of amino acid derivatives as disinfection/cleaning agent, because their utilization is compatible with human consumption. An example is N-acetyl L-cysteine (NAC), an acetylated derivative of L-cysteine, which can disrupt or degrade EPS, causing the dispersal of existing biofilms (Fig. 2).

The challenges of this project lie in investigating

- Effectivity of NAC and other molecules in inhibiting bacterial growth and surface attachment
- Ability of these molecules to eradicate pre-formed biofilms on polymeric pipe surfaces and UF membrane materials
- Optimal concentration and durability of the effect of such molecules

This will be tested via several experiments and techniques in a laboratory setup mimicking DWDS conditions and utilizing real-grade pipe materials and UF membranes (Fig. 3).

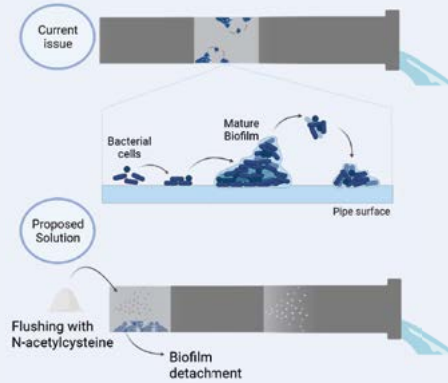


Fig 2. Schematic representation of the current issue and the proposed solution

Research goals

This project aims to:

- Identify non-harmful, sustainable compounds applicable in drinking water environment (from pipe materials to UF membranes)
- Understand their fundamental mechanism of action
- Produce a cost-effective protocol to be used as maintenance strategy or in contingency situations.

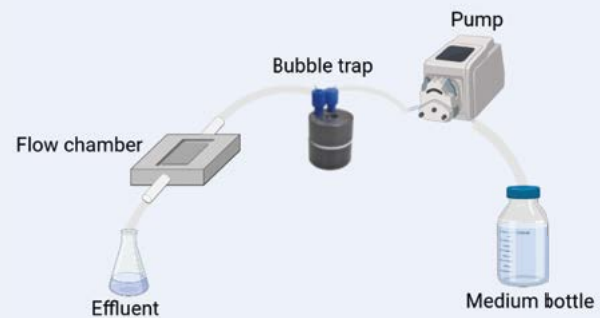


Fig 3. Example of basic flow chamber setup to monitor biofilm growth

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101034321.



Background and motivation

Drinking water can get **contaminated by biofilms** formed in distribution systems^[1]. Bacterial adhesion to surfaces is an energy driven process and is the first event for biofilm formation. The **modification of the surface** of the polymeric pipes, and thus their energy state, could be a possible strategy to avoid bacterial adhesion and prevent biofilm formation^[2]. In our previous work, two hydrogel coatings, synthesized from **poly(sulfobetaine methacrylate)** (P(SBMA)) and **N-isopropylmethacrylamide** on real grade polymeric pipes materials, have been successfully tested against the adhesion of four drinking water bacterial strains. These coatings **increase the surface energy** and thus **repel** bacteria via electrostatic interactions.

In light of a future possible application of the coatings in real-case scenarios (Fig.1), further testing, development and optimization of the synthesis/coating process needs to be performed.

Technological challenges

- The coatings **stability** and **durability** has to be tested in time, and in response of varying turbulence and other influencing factors.
- The synthesis method needs to be adapted and modified for application at a **higher scale** and to keep the **costs low**.
- The formation of a **conditioning film** of organics and inorganics on top of the coatings can **compromise** the coating functioning after a certain period.

To address most of the research questions still open, one of the strategies will be to apply these coatings in a real-case scenario, utilizing an experimental setup in line with the water distribution, which can be monitored in time (Fig. 2).

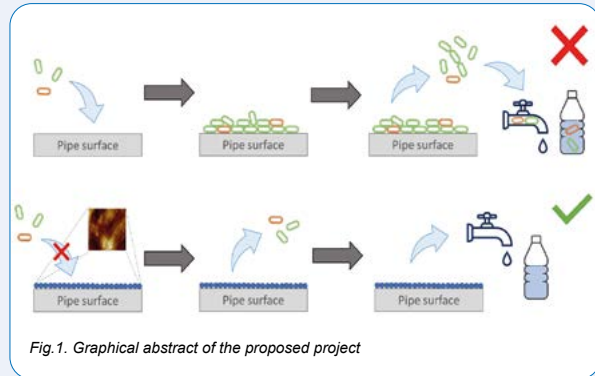


Fig.1. Graphical abstract of the proposed project

Research goals

- Development of new coatings synthesis protocols for future applications.
- Long-term testing of the coating stability and efficiency in bacterial adhesion prevention.
- Studying the possible influence of conditioning film deposition in time on coatings efficiency
- Improve the chemical composition of the coatings even further on the basis of the results collected.
- Investigate possible applications in other water facilities/ technologies

The final objective is to further boost the application of these thin layer coatings as an **easy** and **effective** strategy to extend the life of those materials in contact with drinking water which usually favours biofilm formation.

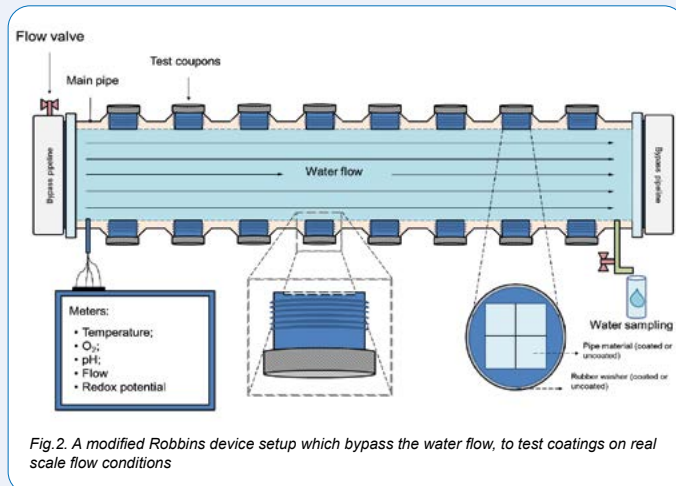


Fig.2. A modified Robbins device setup which bypass the water flow, to test coatings on real scale flow conditions

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 1011034321.

Removing Manganese as Pre-Treatment to Limit (Bio)Fouling in Oligotrophic Conditions



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Motivation

Manganese (Mn) is a common trace metal and a vital micronutrient for many organisms¹. Soluble Mn (Mn^{2+}) is naturally present in various water sources². When exposed to oxidizing agents (biotic or abiotic), Mn is oxidized to its insoluble forms (Mn^{3+} and Mn^{4+}), forming Mn oxides (MnOx). The accumulation of insoluble MnOx during water treatment can result in irreversible membrane fouling, recognizable by the black coloration of the fouling layers⁴. Mn-oxidizing bacteria (MnOB) can remove Mn^{2+} efficiently and selectively in oligotrophic conditions by converting it into Mn oxides. Recent Wetsus research demonstrated that when MnOB grow as a biofilm on biological activated carbon (BAC) granules, they continuously remove Mn^{2+} in oligotrophic conditions (low carbon availability). This resulted in the likely protection of the reverse osmosis (RO) units placed after BAC from significant and irreversible biofouling⁴ (Fig. 1). Therefore, this project aims to assess the effectiveness of using highly selective Mn biological removal as a common practice in various engineered systems to prevent irreversible fouling under oligotrophic conditions.

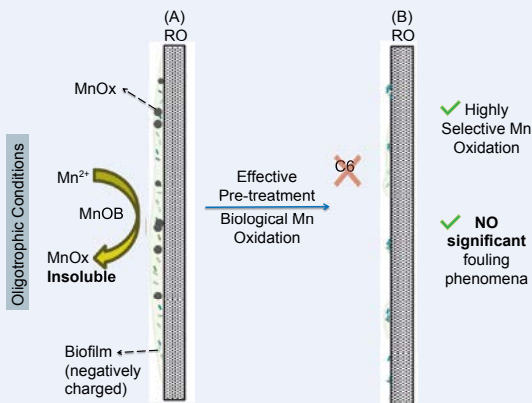


Fig. 1: Illustration of the project hypothesis: fouling may be caused by manganese (A) and removing manganese can limit fouling (B).

Technological challenge

Implementing selective Mn biological removal as pre-treatment before fouling-prone engineered systems (e.g., RO) presents challenges which call for a nuanced understanding of biological functions and system parameters. Optimizing Mn oxidation for efficient removal, considering the diverse water and treatment system characteristics, is crucial in preventing irreversible fouling in oligotrophic conditions. This must ensure cost-effective, longterm operability.

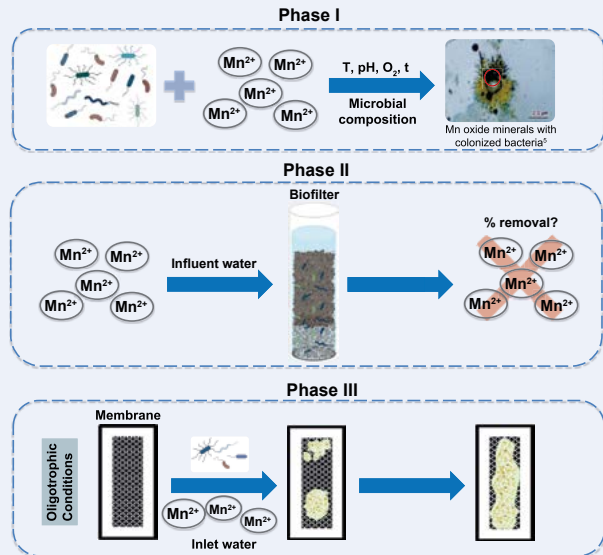


Fig. 2: Schematic representation of the three phases of the project.

Research goals

The project consists of three phases (Fig. 2): (I) exploring the dynamics/kinetics of biogenic Mn oxidation by mixed microbial consortia, (II) studying Mn removal in diverse lab-scale biofilters (e.g., sand and activated carbon-based), and (III) understand the fouling dynamics related to this metal in oligotrophic conditions. This experimental strategy aims to generate missing knowledge in biological Mn removal in engineered systems. The goals are:

- Determine the kinetics of biological Mn removal in various biofilters (in carbon-limited conditions), connecting with operational parameter influence (such as oxygen availability or pH).
- Design the proper biofilter for efficient water pre-treatment
- Generate models for predicting Mn-induced fouling in several engineered systems (RO and ultrafiltration membranes, cooling towers, etc.)

Additionally, we will evaluate the possibility of recovering biogenic MnOx for further use, such as catalyzers for micropollutant removal.

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Advanced coagulation for nanoparticles

Conventional water treatment processes are very well suited to remove particles. However, the smaller particles get (micro- and nanometer-sized), the harder they are to remove. Still, a significant part ends up in effluent and eventually in the environment. The chemical composition (e.g. plastic particles) and size cause these particles to be unwanted in the environment. Their small size allows uptake and accumulation in aquatic life, eventually posing a risk to human health. New technologies are

urgently required to address the problem of nanoparticles and to remove them from water effectively. This theme focuses on a more sustainable approach in conventional water treatment techniques, such as coagulation/flocculation, to remove nanoparticles. We will develop enhanced coagulation approaches to aggregate, especially the fraction of the smallest nanoparticles, allowing their effective removal through standard flocculation and floatation approaches.

Research projects

- **Elorm Obotey Ezugbe**, University of Twente, *Efficient removal of nano-plastics from water through enhanced coagulation*



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UNIVERSITY OF TWENTE.





Motivation

Improvements in water treatment processes are required to tackle the upcoming challenges in water and wastewater due to the influx of emerging contaminants. One such emerging contaminants, nano-plastics, are plastic materials within a size range of 1-1000 nm, formed when larger plastics disintegrate due to mechanical wear, photo-oxidation or fragmentation (see Figure 1). Due to their minute and variable sizes, these nano particles have a high mobility, form stable colloids and can serve as substrates for transporting disease-causing organisms in water [1-2]. Removal of nano-plastics from water poses a significant challenge to current water treatment plants. Conventional physico-chemical processes such as coagulation, flocculation and settling are not able to effectively remove these plastics from water during treatment. This results in the adoption of costly additional treatment steps such as membrane and adsorption technologies.

Technological challenge

Coagulation involves the addition of chemicals to destabilize suspended particles in water. Once destabilized, suspended particles coalesce to form bigger aggregates that can settle. This happens under various conditions of pH, coagulant dosage and mixing rates. Conventional coagulation/flocculation technologies have been optimized towards the removal of larger sized particles from water while smaller sized ones (1-1000 nm), in most cases, escape the coagulation/flocculation stage.

To solve this problem an enhanced coagulation/flocculation approach will be developed. This process involves the improvement in conditions of coagulation/flocculation and/or the development of novel coagulation aids to improve the settleability of the nano-plastics [3].

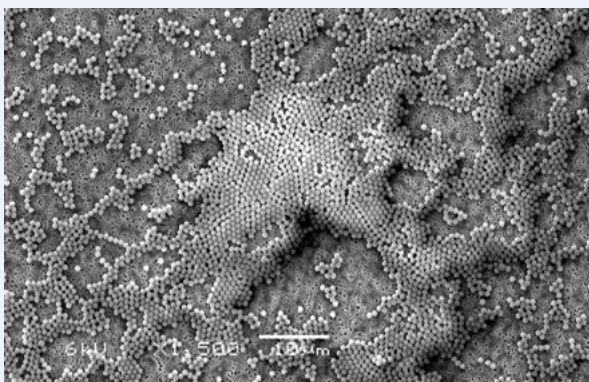


Figure 1. Image of nano-plastics.

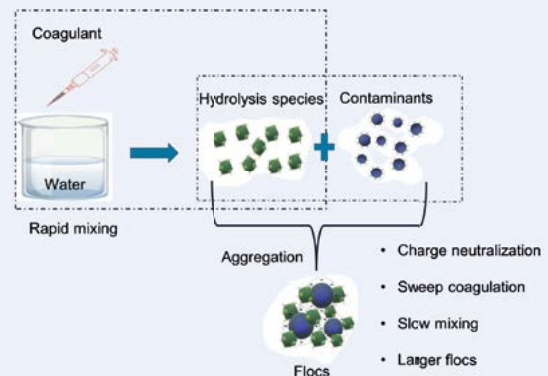


Figure 2. Principle of coagulation: a coagulant added to water undergoes hydrolysis to produce various charged species (hydrolysis species) which destabilize stable particles (such as nano-plastics) within a suspension. Enhanced coagulation approaches involve improvements in coagulation conditions to induce rapid aggregation of stable particles in water.

Research goals

The project objectives are to

- Assess nano-plastic removal from water using conventional coagulation/flocculation processes to understand the gaps in the process (see Figure 2).
- Explore different types of coagulation aids, combining them with commercial coagulants and assessing their efficiency for nano-plastic removal.
- Explore the development of eco-friendly polyelectrolytes as coagulation aids aimed at nano-plastics.
- Larger-scale testing of the developed enhanced coagulation process.

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Integrated PFAS treatment

Perfluoroalkyl and polyfluoroalkyl substances (PFAS) are increasingly showing up in waste streams, sparking serious concerns about their harmful effects on human health and the environment. Known for their extreme stability and resistance to biodegradation, PFAS are notoriously difficult to remove or break down in water treatment processes. This persistence makes them a major challenge, as both

adsorption and degradation methods struggle to keep up. To tackle this, we're developing an innovative treatment system using novel adsorbent materials in high-throughput filters. These filters will be regenerable before PFAS breakthrough, followed by a thermal reductive process to fully mineralize the concentrated waste solution..

Research projects

- **Jesse Goed**, Wageningen University, *Functionalized pillararenes for PFAS absorption from water*
- **Leong Chew Lee**, Eindhoven University *High-throughput membrane adsorbers for selective PFAS removal* **NEW**
- **Rick Nooijen**, Wageningen University, *Pillar[5]arene-based sorbents for efficient, scalable aqueous PFAS removal* **NEW**



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Motivation

Per- and polyfluoroalkyl substances (PFAS) are a class of compounds that is known for their hydrophobicity and oleophobicity. These properties make them useful in many consumer products, such as non-stick coatings, firefighting foams, food packaging, etc. Their extremely high stability, however, causes them to accumulate in biological systems and humans. Despite low environmental concentrations (ng/L), they cause immune disorders, cancers, and birth defects in humans [1]. PFAS adsorption from the environment is key in preventing these toxic effects in the future. Granular activated carbon (GAC) is currently used in water treatment of PFAS-polluted waters, primarily since it is inexpensive. Several other techniques have been investigated, such as anion resins, membranes, and organic/metal frameworks. However, these are either non-specific, non-scalable, or expensive. Non-specificity of GAC and other techniques is detrimental, because it leads to competition with natural organic matter [2]. Thus, new, highly specific PFAS adsorbers are required.

Our group discovered that a type of macrocycle (called pillararenes) functionalized with positively charged groups binds PFOS and PFOA, the two most common PFAS compounds, strongly and specifically. A pillararene-PFAS complex (PiP) was formed with a unique 1:10 stoichiometry, and high breakthrough capacity of 90 mg/g for PFOS and 80 mg/g for PFOA. These findings confirmed their potential as PFAS adsorption technology [3].

Technological challenge

The innovative aspects of this research include:

- Pillararenes as a PFAS-adsorbing technology.
- Computational studies on the contribution of the fluorophilic effect in the mechanism of PiP formation.
- Synthesis of highly charged pillararenes, with the aim to improve stoichiometry and binding constant.
- Pillararene immobilization on different types of surfaces.

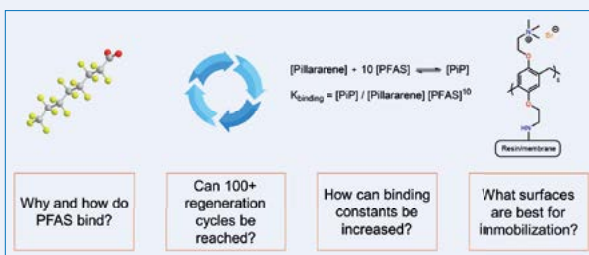


Figure 1. Main areas of focus: understanding the mechanism of PiP formation, improving the regeneration capabilities, increasing binding constants of PiP, and assessing what surfaces are best for immobilization..

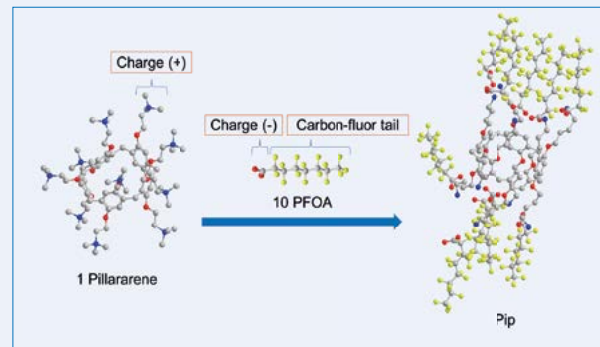


Figure 2. The formation of a PiP complex from 1 positively charged pillararene and 10 negatively charged PFOA.

Research goals

Thus far, the fundamentals of PiP formation are poorly understood. This understanding is paramount for the design of a next generation of PFAS-adsorbing pillararenes. Furthermore, the use of these pillararenes in larger-scale systems must be evaluated. This requires their immobilization on a surface. We have formulated the following objectives for our work:

- Computational study: 1) Study the PiP binding mechanisms. 2) Investigate effects of different pillararene positively charged groups. 3) Review adsorption of different types of PFAS.
- Implement new knowledge on PiP formation in the design of a next generation of PFAS adsorbers.
- Surface modification: 1) Identify the optimal surface for pillararene immobilization. 2) Test pillararene immobilized surfaces on larger scales using real-life water samples.

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Motivation

Per- and polyfluoroalkyl substances (PFAS), often referred to as “forever chemicals” due to their extreme persistence in the environment, pose potential health risks to humans and animals. Recent research reported that 69% of global groundwater samples exceed drinking water safety standards without a known source of contamination^[1]. Providing safe drinking and irrigation water therefore requires effective removal of PFAS. Adsorption (e.g. activated carbon or ion exchange resins) in packed beds is a common PFAS treatment. However, packed beds are often limited by slow diffusive mass transfer, flow channelling and high pressure drops^[2].

This research presents membrane adsorbers designed to overcome existing limitations through direct convective flow, allowing higher throughput operation. Direct mass transfer reduces the time needed for PFAS molecules to reach active sites, thereby increasing adsorptive efficiency. In polymer membrane adsorbers, adsorbent particles are embedded within the membrane or the membrane itself serves as the adsorptive material with specific functional groups^[3]. These membranes are arranged in a column forming hierarchical structures to capture PFAS based components (Figure 1).

Technological challenges

Developing membrane adsorbers presents several challenges:

- Current membrane adsorbers have low surface area-to-volume ratio and large pore size distribution.
- Replacement of commonly used petroleum-derived aprotic toxic solvents for green alternatives.
- Integrating developed membranes into modules to enable scale-up to industrial applications.

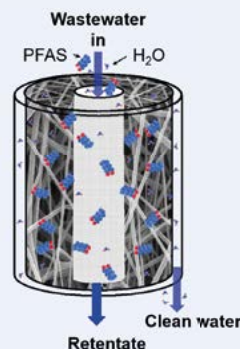


Fig 1. Schematic of radial membrane adsorber module for selective capture of PFAS. The flat-sheet electrospun mat is coiled around a porous tube.

Research goals

The main goal of this research is to develop high-throughput membrane adsorbers to capture PFAS compounds from aqueous streams. The objectives are as follows:

1. Develop membrane adsorbers via electrospinning (Figure 2) under varying process parameters and functionalisation.
2. Explore green and sustainable methods for developing membrane adsorbers.
3. Characterize the morphology and/or functionality of prepared membranes and evaluate their PFAS separation performance.
4. Design and assemble membrane adsorbers into axial or radial modules.

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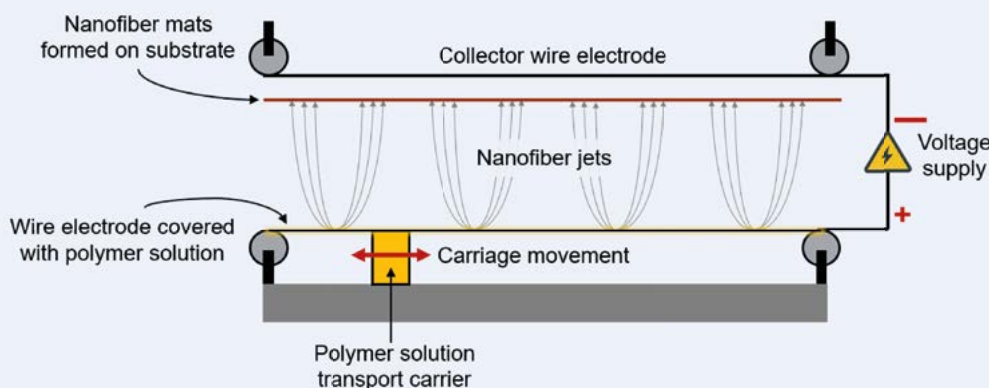


Fig 2. Schematic of wire electrospinning setup for nanofibrous mat development. High voltage overcomes the surface tension of the polymer solution on the wire electrode, forming nanofiber jets. A carrier holding the polymer solution moves to coat the wire through an interchangeable aperture.



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Motivation

PFAS (per- and polyfluoroalkyl substances) are a global problem for water quality and safety, considering the persistent risk PFAS pose to human health. Therefore, authorities are decreasing the acceptable PFAS levels in the environment and drinking water, pushing the need for an effective PFAS-removing technology. Granular activated carbon adsorption is the standard method applied in water treatment to remove organic pollutants, but is inefficient for removing PFAS. Consequently, alternatives like anion-exchange resins and clays are being explored, giving better results. However, small perfluoroalkyl acids, like perfluorobutanoic acid, still cause early failure of the adsorbent¹. Recently, certain cationic pillar[5]arene derivatives (P5) (Figure 1) have proven to be promising adsorbents that offer a new approach for removal. P5 immobilized on resin beads has unique affinity, selectivity and capacity for the capture of perfluoroalkyl acids/sulfonic acids such as PFOA and PFOS in continuous-flow systems². Some interactions between P5 and PFAS that might play a role are shown in Figure 2.

Technological challenge

The promising results of P5-resin encourage the development of P5-based adsorbents or other methods into a real-world applicable system. Broadening P5 application first requires research into appropriate materials to immobilize P5. The functionalized material as a whole must be stable to increase its potential for regeneration. Thereafter, suitable P5-functionalized materials must be tested on a small scale to elucidate the kinetics of the P5-PFAS binding mechanism and robustness against salt and fouling by natural organic matter. Regeneration is important to optimize, because reusability of the material is paramount for cost-efficiency. Lastly, a P5-based method, selected according to performance in small-scale tests, will have to be scaled up. At this step, it is expected that pre-treatment and operational parameters are the major focus. In the case of a packed-bed adsorbent, channeling and pressure drop are important to address³

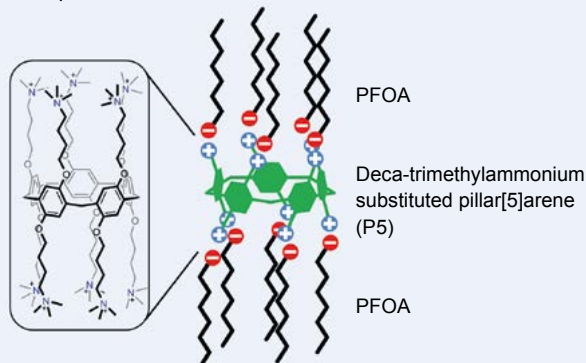


Fig 1. P5 forming a complex with 10 PFOA molecules.

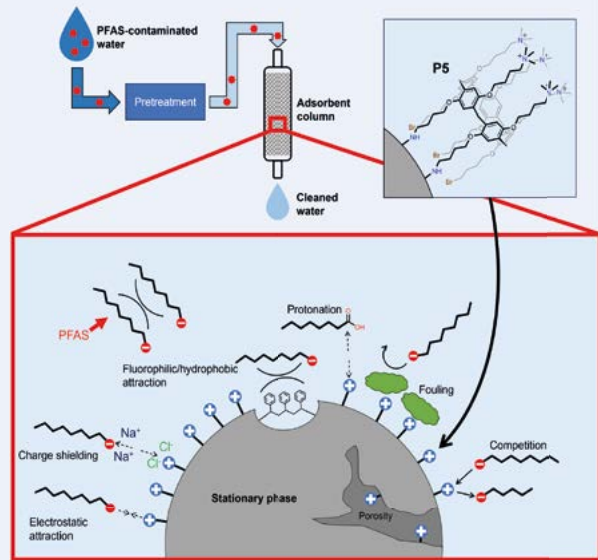


Fig 2. Different kind of interactions and properties that may be at play in a P5-modified resin packed-bed column tested in prior research [2].

Research goals

This project aims to deepen the understanding of P5-based adsorbents in PFAS removal and enhance their performance through investigation of:

1. a range of materials and (adsorption) methods, such as packed-bed resins and other adsorbents, for their compatibility as a base for immobilization of P5 in a flowing system;
2. the efficiency of such regenerable P5-based systems for PFAS capture on a small scale;
3. the requirements for scaling up the best-performing P5-based system to efficiently reduce PFAS levels in water to acceptable levels

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Groundwater technology

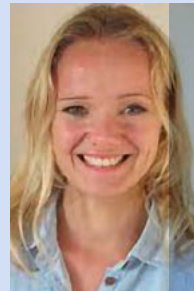
In the Netherlands, approximately two-thirds of the drinking water is produced from groundwater. Due to the filtering capacity of the underground, the quality of groundwater is high compared to surface water. However, the quality and availability of groundwater are threatened by the emission of highly mobile organic micropollutants such as pesticides and pharmaceuticals. Additionally, freshwater aquifers near the coast face pressure from

saltwater intrusion, while increased drainage and prolonged droughts reduce natural aquifer recharge.

The Groundwater technology theme develops tools to address these challenges. These include enhancing natural pollutant attenuation, distributed groundwater flow & quality sensing, and underground infrastructure such as wells and dams.

Research projects

- **Ahmed Mahmoud**, NINFA: *TakiNg actIoN to prevent and mitigate pollution of groundwAter bodies*
- **Dhyana Chalheparambil Bharathan**, University of Twente, *Optics-based distributed sensing for the management of groundwater quality*
- **Han Liu**, Wageningen University, *Engineered nature-based systems to protect drinking water aquifers against organic micropollutants* **NEW**



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Motivation

Aquifers are the major source of freshwater in urban areas as well as for agricultural irrigation. An increase in population and human activities has increased the demands on aquifers. In the coastal areas, excessive pumping from near coastal discharge/pumping wells may cause saltwater intrusion in the nearby aquifers. This is much more than a localized problem because sustainability of resources are at the base of socio-economic development. Hence the saltwater intrusion in aquifers needs to be monitored.

The existing methods of detection involves electrochemical methods that could involve introducing electrical wires, electrodes and/or potentially harmful materials into the aquifer, which would severely complicate the installation, robustness and safety of the sensor. A promising solution is to use Fiber Bragg Gratings (FBGs) (fig.1) as an electrodeless sensing tool which is harmless to the environment and can be used for low loss transmission of signals over kilometers of distance. Multiplexed FBGs in fibers can be used for distributed sensing and can be easily installed vertically into the ground for real time and long-term monitoring of salinity (fig.2).

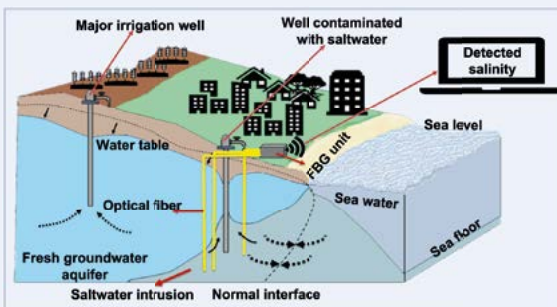


Fig 2: Remote sensing unit of FBG sensors installed for monitoring saltwater intrusion in the coastal aquifers in order to identify quality of drinking water

Approaches

- We will be creating a small tapered section between two identical FBGs (fig.3-A) over which the light in core mode gets coupled to the cladding modes, which are sensitive to the surrounding refractive index. The spectrum of the FBG pair shows any variation of the refractive index as wavelength shift.
- By coating FBG with polymeric materials that swells in the presence of target ions (fig.3-B), the ions cause a change in the FBG periodicity that will be used as a chemically selective sensing tool.
- With FBGs we can limit the excitation to a specific region of the fiber via coupling of light in and out- of the fiber core. Salt sensitive fluorophores indicates the presence of salt (fig: 3-C).

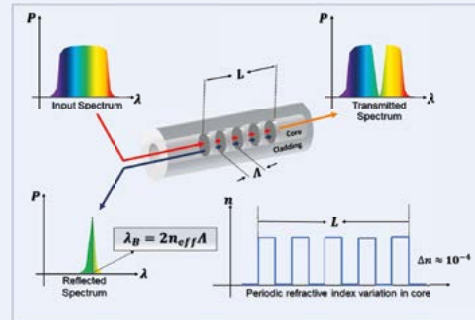


Fig 1: Principle of Fiber Bragg Gratings (FBG). Bragg reflected wavelength depends on the effective refractive index of the fiber and grating period

Research Goals

- Design salinity sensors capable of measuring low salt (NaCl) concentration in water
- Identify and test salt specific fluorophores and polymer coatings; testing durability, sensitivity and specificity
- Build the sensors with robust packaging
- Test the sensors in a laboratory set-up that mimics the changes in physical and chemical conditions in an aquifer
- Comparison studies among various approaches
- Test the FBG-based refractive index sensor in the field and assess long-term survivability

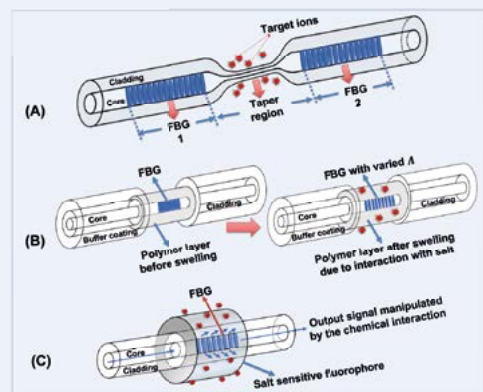


Fig 3: Approaches for target ion sensing: A) Taper seeded FBG-pair, B) Responsive polymer coated FBG, and C) Sensitive fluorophore coated FBG

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Engineered nature-based systems to protect drinking water aquifers against organic micropollutants



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Motivation

The water quality of groundwater is much higher than that of surface water, therefore, in the Netherlands, 60% of the drinking water is produced from groundwater. However, to be able to extract enough groundwater in the future, there is a need to increase aquifer recharge without introducing the organic micropollutants (OMP) present in surface water. Groundwater abstraction sites may be engineered for that purpose.

Nature-based systems, e.g. constructed wetlands, are considered a promising solution for removing OMP from surface water, as they are easy to construct, have a very low energy requirement, are chemical-free, and provide an ecological and recreational value. However, the challenge is to engineer a constructed wetland for optimal OMP removal, i.e. an Advanced Constructive Wetland, which can further utilize biological FeOx & MnOx system and microbially driven ROS to achieve better OMP removal efficiency.

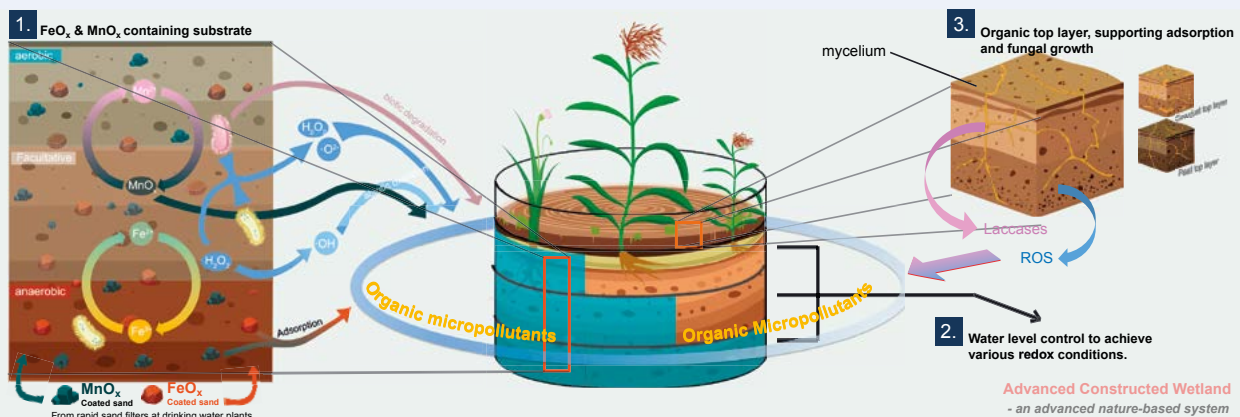


Fig 1. Potential OMP removal mechanisms in a constructed wetland

Technological challenge

A nature-based system should sustain itself and not require active aeration, temperature/pH control or chemical addition. However, the application of different substrate layers, and the control of the water flow and level are parameters to be optimised. These parameters can affect the following **OMP removal mechanisms (Fig 1)**:

1. The **enzymatic** degradation by bacteria/fungi.
2. Oxidation by reactive oxygen species (**ROS**) produced by bacteria/fungi.
3. Oxidation by (biogenic) **MnO_x**. The Mn would be reduced to **Mn²⁺** in the process, but regeneration might be feasible by Mn-oxidizing bacteria in a sufficiently aerobic compartment.
4. Oxidation by **·OH** from Fenton(like) reactions, fuelled by **H₂O₂** from bacteria/fungi. This does require the wetland to comprise an anaerobic compartment to allow the **Fe³⁺** to be converted back to **Fe²⁺** by metal-reducing bacteria.
5. Temporary immobilization (during peak load) by adsorption to Organic matter and **FeO_x & MnO_x** particles.

Research goals

To develop an Advanced Constructed Wetland, that utilizes the synergistic effects of Organic Matter, FeOx & MnOx species, bacteria, fungi, and plants, for optimal OMP removal.

To answer the following research questions:

1. To what extent can ROS/MnOx/Fenton reactions contribute to OMP removal efficiency in a constructed wetland?
2. How to engineer a constructed wetland to generated the environmental conditions (fx. Redox condition) for optimal OMP removal?
3. What is the fate of OMP and their transformation products in an Advanced constructed wetland?

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Smart water grids

The Dutch water supply network ensures high-quality drinking water through an extensive system of water mains, ranging in age from newly installed to over a century old. With a replacement value exceeding €13 billion, managing and maintaining the network is crucial. The condition of the water mains varies significantly, with some sections leaking while others remain in excellent condition, making it difficult to assess their state accurately. Timely replacement of aging parts is essential to maintain water quality, minimize downtime, and optimize resource use. Innovative solutions are needed to improve inspection and prediction methods. The Wetsus

Smart Water Grids research focuses on developing advanced inspection technologies, such as in-line and on-line inspection methods, autonomous inspection robots, and intelligent pipes with integrated sensors. Significant progress has been made in PVC material characterization, leak detection, and data-driven insights. These advancements help predict the condition of water mains and guide maintenance decisions. Collaboration with partners has resulted in scientifically relevant innovations, with companies like Acquaint BV and HULO BV emerging as spinoffs, ensuring practical applications in the water supply industry.

Research projects

- **Mirvahid Mohammadpour Chehrghani**, University of Twente, *Superfluent pipes*
- **Ruixuan Qi**, University of Groningen, *Inline electronic leak detection in water distribution systems*
- **Egge Rouwhorst**, University of Twente, *Applying nonlinear acoustics for detection and assessment of PVC water mains*
- **Jarne van Gemert**, Eindhoven University, *Optimal sensor placement and leakage detection in water distribution networks*
NEW



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Motivation

Drinking water network is very extensive and consists of around 130.000 km of water mains in the Netherlands. The resistance in the water network can be the result of a (relatively) high wall roughness and obstacles in the network; e.g. valves, hydrant, bends, crossings. In addition, the higher the resistance in a pipe, or in the water network in general, the more likely microbial growth will occur. The microbial growth or biofouling decreases the water quality.

Water companies in the Netherlands use pumps to overcome this resistance and to supply drinking water with enough pressure to all customers. By reducing the resistance, pipes with smaller diameters but higher flow velocities could deliver the same volume flow rate demanded by all customers. This is beneficial not only for energy efficiency and impeding the microbial growth, but also manufacturing and maintenance costs of the pipes as well. Therefore, the motivation of this research project is to develop a very low resistance water transport system. The main benefits gained from this would be saving energy by lowering the required pumping power.

Technological challenge

Introducing a solution for lowering flow resistance which is cost effective, nontoxic, and durable is the main technological challenge. One way to overcome this challenge is to fabricate shark skin inspired riblets on the inner wall of the pipes.

Riblets lead to drag reduction by both impeding the translation and lifting the streamwise vortices (Figure 1) [1]. The riblet structures on the skin of fast swimming sharks reduce skin friction drag in the turbulent flow regime allowing them to swim faster (Figure 2).

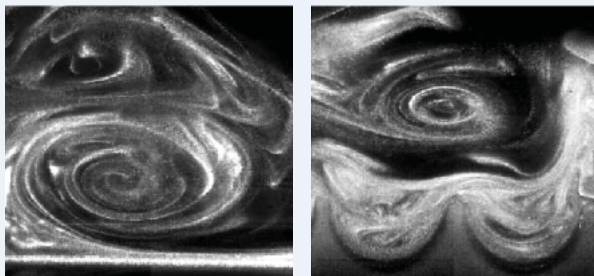


Figure 1. Flow visualization images of streamwise vortices in the vertical cross-section on: (left) flat plate, (right) riblet surface [2].

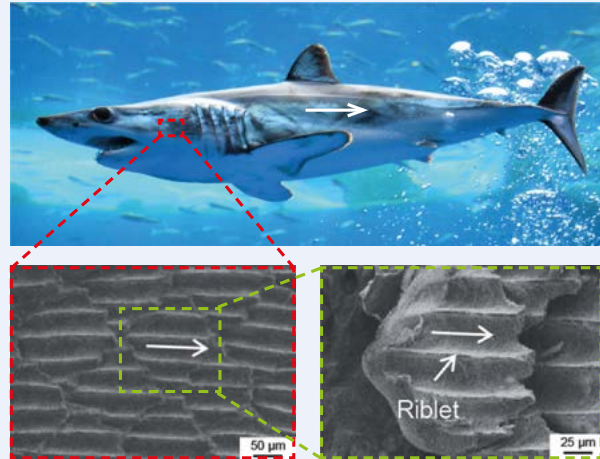


Figure 2. (Top) Digital photo of a Shortfin Mako Shark. Adapted from www.wikipedia.org/Shortfin_mako_shark. (Bottom) scanning electron microscope (SEM) images of shark skin at two magnifications. Adapted and modified with permission [3]. The riblet structures on the skin of fast swimming sharks reduce skin friction drag in the turbulent flow regime allowing them to swim faster.

Research goals

To develop a fundamental understanding of, and engineering design strategy for, the interior surface of a pipeline to enable the reduction of energy losses in water transport systems is the objective of this research.

1. The research goals of the project are to:
2. Understand the relation between flow, pipe resistance, and surface design.
3. Develop an analytical or numerical model, or extend an existing model, to analyze the role of surface topography on drag reduction in pipelines.
4. Fabricate the patterns on surfaces and pipes with suitable texturing procedure or production method.
5. Establish a test setup to quantitatively measure and demonstrate the effect of modified surfaces.
6. Perform a parametric experimental study to uncover the optimum surface topography that drag reduction is maximum.

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Motivation

In urban areas, the majority of the potable water is delivered through a Water Distribution Network (WDN)^[1]. Deteriorating components in the WDN may cause leakage. In some cases, leakage comprises 20 to 30% of the total water production [2]. This is not only a waste of natural resources but also causes financial losses, damage to surrounding structures, potential leakage of contaminants into the water network and increased carbon footprints. Therefore, accurate and cost-effective methods to detect leakage have both financial and environmental benefits.

While many accurate inspection methods already exist, most of them are best suited for metallic pipes^[2] which only comprise a small portion of the total network in the Netherlands. So, new research is required to develop highly accurate methods to inspect non-metallic hydraulic components in the WDN.

Technological challenge

Two methods have been proposed for leakage detection: capacitive imaging and voltage differential. As shown in Fig. 1 a, capacitive imaging utilises the fringing electric fields generated by a pair of coplanar capacitor. The fringing field penetrates non-conductive sample and create an “image” of the interior of the WDN. The required resolution, sensitivity and image processing capabilities to make meaningful detection is unclear and maybe challenging to execute

Unlike CI, the voltage potential method doesn't require a full mapping of the interior. As shown in Fig 1 b, leakages in the pipe creates a “short circuit” and causes a spike in voltage in the detector. However, conductors the WDN will create a similar effect. Elimination of false positive detections will be challenging using this method.

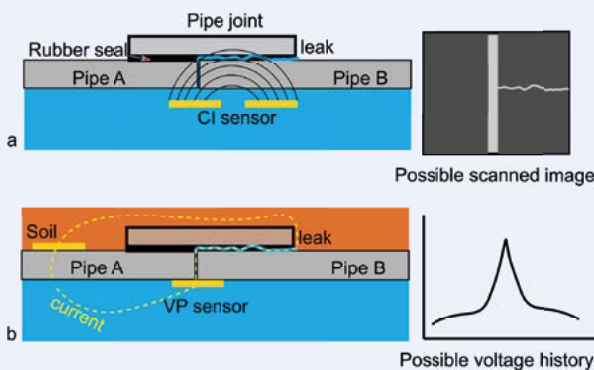


Figure 1: schematic showing the principles behind the: a) capacitive image, b) voltage potential techniques

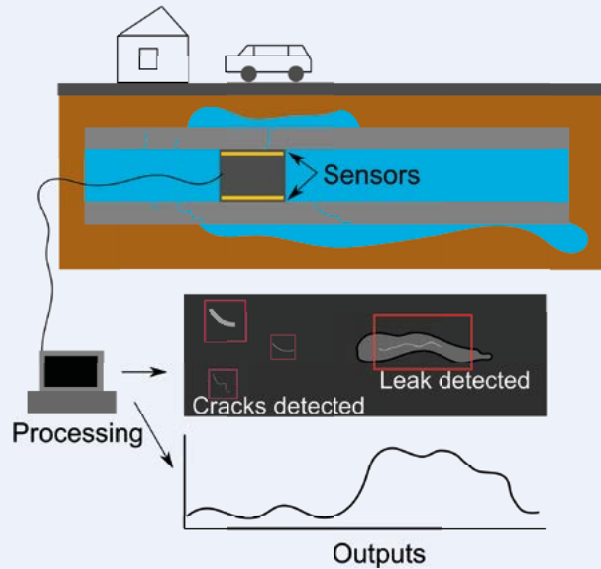


Figure 2: graphical abstract showing the desired outcome of the project

Research goals

This project aims to develop a new inline leak detection method to use in the water distribution network with a particular focus on non-metallic materials. Some of the research questions that need to be answered in this project include:

- Where and how do leakages occur in the non-metallic components of the WDN?
- Can the proposed methods detect leakage in a controlled lab environment?
- Can the proposed methods detect microcracks, is that useful?
- How can the sensors be optimised to deliver the best performance?
- Can the proposed methods work in the field?

A desirable outcome of the project is demonstrated visually in the graphical abstract shown in Figure 2.

[1] A. Ostfeld, "Water Distribution Networks" in Intelligent Monitoring, Control, and Security of Critical Infrastructure Systems, pp.101-124. 2014
 [2] C. Teck Kai, C. S. Chin, en X. Zhong, "Review of Current Technologies and Proposed Intelligent Methodologies for Water Distributed Network Leakage Detection", IEEE Access, vol PP, bll 1–1, 12 2018.



This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101034321.

Applying nonlinear acoustics for detection and assessment of PVC water mains



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Motivation

The Dutch water grid has a vast network of pipes consisting of a variety of materials. Over half of the grid is made of unplasticised polyvinyl chloride (uPVC) [1]. This material was already used in 1950 and was determined to last at least 50 years under most operating conditions [1,2]. Many pipes have reached this age already, but it is unclear what the actual lifetime of these pipes are and when they should be replaced. Since replacement is costly, this is ideally done just before the pipe fails. Currently, the decisions on when and which pipes to replace are mostly based on the number of failures, the risk associated with failure and the pipe's age [3]. To make more adequate decisions, it is beneficial to have a way to monitor and predict the degradation of pipes. Proper predictive maintenance reduces unnecessary material use, and costs and reduces customer hindrance from downtime and contamination.

Presently, no method is yet implemented to non-destructively measure the structural health of a PVC pipe. Wave mixing has been shown to be sensitive towards microcracks and ageing of uPVC [4]. Together with only requiring one sided access as seen in figure 2, this gives it potential for a non-destructive, in-line method of degradation monitoring.

Technological challenge

Because wave mixing requires a precise alignment of the beam, it is very sensitive to the alignment of the transducers and material parameters. A robust method should either control or correct for this. Additionally, which parameters change with age and are responsible for a change of signal are still unknown. Lastly, the measurements currently requires multiple measurements over longer timespans. If the absolute age is to be measured, a (rejuvenated) sample is required for baseline, which is in practice often problematic to obtain.

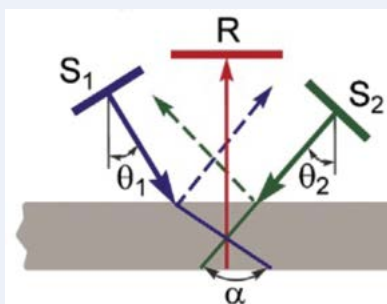


Figure 2. Schematic of noncollinear wave mixing [4]. S_1 and S_2 are sending transducers and R a receiver. The angle α of interaction governs the direction and amplitude of the generated wave.

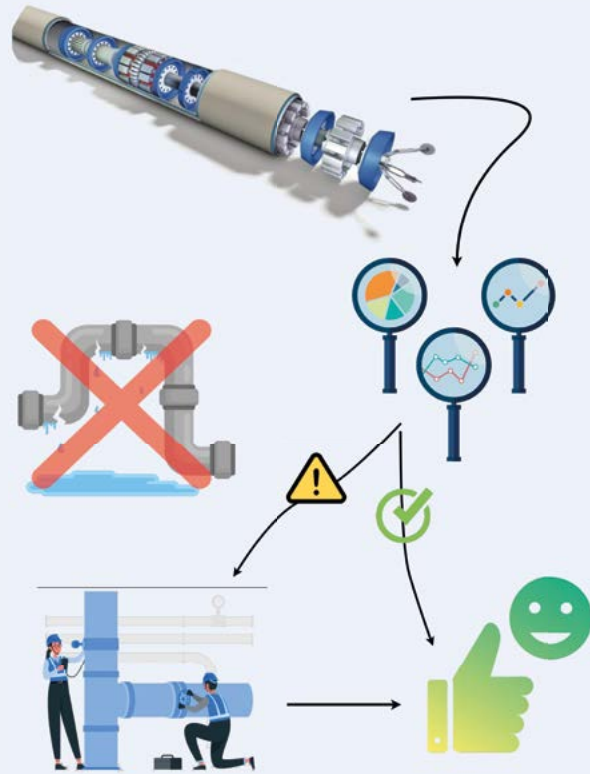


Figure 1. Project vision: using a PIG to gather data on pipes allows for predictive maintenance and leads to happy companies and customers.

Research goals

- Understand the physics of wave mixing & expand the existing model.
- Understand the sensitivity of noncollinear wave mixing to alignment, stress and other parameters.
- Investigate if wave mixing can be made an absolute measurement technique instead of relative.
- Investigate the possibility of the use of measurements relative in space instead of time for detecting material degradation.

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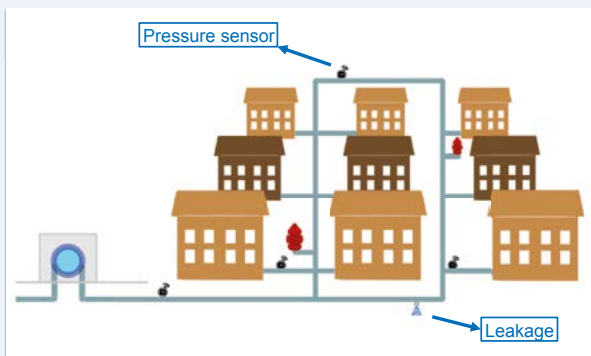
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Motivation

Water distribution networks (WDNs) are essential systems that provide drinking water to various regions, yet water loss due to leakages remains a significant issue. Even in highly developed countries like the Netherlands, approximately 5% of drinking water is lost, while in countries like the UK, this can reach as much as 21% [1]. These figures highlight significant room for improvement. Reducing these losses is not just about conserving water—it also means minimizing financial strain, reducing environmental harm, and ensuring sustainable water management [2].

Innovative methods such as **digital twins** (virtual replicas of physical systems), **observers**, or **data-driven techniques** offer new ways to enhance leakage detection and localization. By advancing these technologies, WDN efficiency can be greatly improved, reducing water losses and supporting long-term sustainability.



Technological challenge

In addressing leakage detection in water distribution networks (WDNs), several challenges need to be overcome:

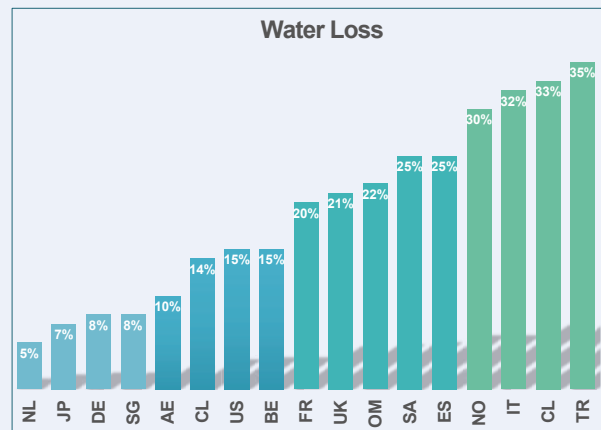
- 1. Leakage Detection:** Sensors and models are essential to detect leaks early before they grow into larger problems. Currently, leaks are often discovered through visible water pooling or user complaints, which are reactive and somewhat inefficient methods.
- 2. Leakage Localization:** Once a leak is detected, its precise location must be identified to minimize excavation costs, water loss, and water contamination. Without accurate sensor data or validated models, localization can be time-consuming, inaccurate and costly.

To improve these two challenges, four technical challenges are formulated as follows:

- 1. High Sensor Costs and Limited Deployment:** Sensors capable of measuring pressure or flow are expensive, which results in a limited number of sensors in WDNs.
- 2. Sensor Placement Optimization:** Determining the optimal number and location of sensors to balance cost and performance is a complex, unresolved problem.

3. Limited Knowledge of Network Parameters: Many parameters in WDNs, such as pipe roughness, valve settings, and pipe lengths, remain unknown or poorly defined. This uncertainty undermines the accuracy of available models.

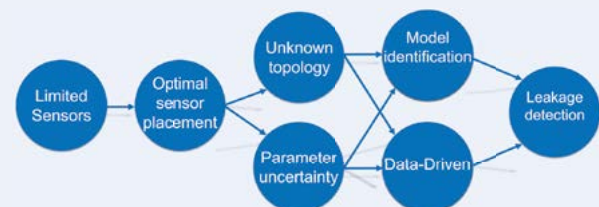
4. Inaccurate Structural Representations: Often, the existing maps and schematics of water networks do not reflect the actual on-ground layout, further complicating model development.



Research goals

- 1. Optimal sensor placement:** Develop strategies for optimal sensor placement that address uncertainties and support model validation, identification, and efficient leakage detection.
- 2. Model validation and network structure identification:** Create innovative methods to validate models of WDNs and accurately identify the network structure.
- 3. Leakage detection and localization:** Develop advanced methods for real-time detection and precise localization of water leakages within the distribution network.

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 [2] A. M. Annaswamy, K. H. Johansson, and G. Pappas, "Control for societal-scale challenges: Road map 2030," IEEE Control Systems Magazine, vol. 44, no. 3, pp. 30-32, 2024.



Monitoring & Quality

Guaranteeing the availability of clean water is crucial for human health. Continuous threats to both water quality and quantity require ongoing monitoring. Since no single method or sensor can assess all aspects of water quality, combining various sensor technologies and data integration from different sources is crucial. A complex interplay of chemistry, biology, and physics influences water quality. While we can individually measure chemical concentration levels or biological activity, we often do not fully understand the sources or how these factors are interrelated. An integrated approach is needed to synergistically use chemical, biological, and physical water properties to comprehend the system's complexity.

Innovations in (bio)sensing technology and data fusion allow future-proof water quality assessment without an unconstrained growth in cost and data complexity. These tools are instrumental in simplifying the system's complexity. This theme builds on previous advancements in sensor development and genomics for water quality monitoring, covering aspects like chemical and microbial composition. It focuses on various water types, including drinking water, wastewater, and surface water, while involving chemical, physical, and biological sensors, as well as data networks to enhance process control and accuracy.

Research projects

- **Alicia Borneman**, University of Groningen, *Monitoring chemical and microbial water quality by transcriptome analysis of single-cells*
- **Asala Mahajna**, University of Groningen, *Machine learning approach for meta-genomic data interpretation in water process control*
- **Chen Lester Wu**, Delft University of Technology, *Remote monitoring of hydrocarbons in groundwater through sensor data fusion*
- **Balaram Guddanti**, University of Twente, *Artificial intelligent sensing to monitor disinfection by-products in drinking water*
- **Ceyda Köksal**, Eindhoven University, *Continuous monitoring of micropollutants and nutrients in surface water with an optical multiparameter sensor platform* **NEW**
- **Fakhira Rifanti Maulana**, Wageningen University, *Real-time monitoring of surface and soil water quality* **NEW**



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Industrial partners



Waterkracht



Academic partners

UNIVERSITY OF TWENTE.





Motivation

Leakage from refined product pipelines and underground storage tanks (Fig. 1) contributes 34,000 m³/year of petroleum hydrocarbon contamination to land and groundwater resources in the USA alone^[1]. The major components of petroleum hydrocarbons are benzene, toluene, ethylbenzene, and xylenes (BTEX) which can be harmful to the environment and pose significant health risks^[2].

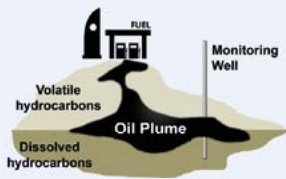


Fig. 1 Oil Plume Conceptual Model

Currently, groundwater is monitored by quarterly or yearly sampling which provides low resolution data. The associated costs and potential health issues comprise a safety and environmental burden to groundwater sampling activities^[3].

Research goals

The goal of this research is to realize the concept of Digital Twin through the development of a reliable and low-cost multi-sensor system together with a computational sensor fusion framework that would enable remote monitoring of BTEX in groundwater under varying conditions (Fig. 2). The Digital Twin concept allows the continuous update of the system in real time through a bidirectional flow of information^[4], usually through sensors (Fig. 3).

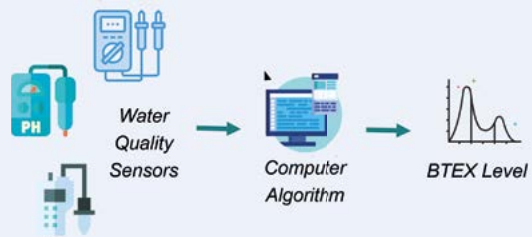
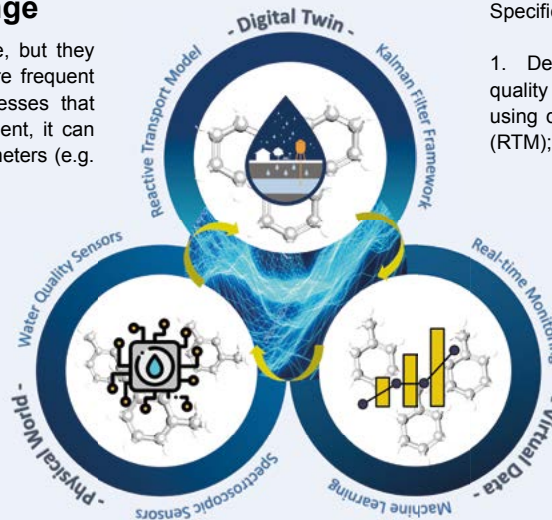


Fig. 3 Sensor Data Fusion Illustration

Technological challenge

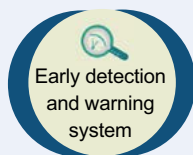
Hydrocarbon sensors are available, but they are relatively expensive and require frequent maintenance. Based on the processes that are triggered following a spill incident, it can be inferred that water quality parameters (e.g. dissolved oxygen, oxidation-reduction potential, pH) can contain indirect information on the level of BTEX. These parameters can be monitored with low-cost sensors. However, the relationship with BTEX levels in groundwater has not been established yet.



Specifically, this research aims to:

1. Determine the correlation between water quality sensor data and BTEX concentration using data from reactive transport modelling (RTM);
2. Develop a Digital Twin based on the RTM using a Kalman filter-based framework with sensor data as input;
3. Validate the Digital Twin concept through laboratory experiments; and
4. Assess the suitability of the developed Digital Twin in real life applications by doing a field test.

Expected benefits



References

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 [2] Pandey, P. et al. (2018). IJPE Vol 4, No. 2, 13-26. 10.18811/ijpen.v4i02.2
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 [4] Jones, D. et al. (2020). CIRP J Manuf Sci Technol Vol 29, Part A, 36-52, ISSN 1755-5817, https://doi.org/10.1016/j.cirpj.2020.02.002



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Motivation

Water is life. Every living being depends on water for their survival. This caters to the need for having fresh drinking water at all times. Unfortunately, the available water can contain hazardous matter causing potentially fatal diseases. To mitigate life-threatening situations, disinfectants like chlorine are added to the potable water^[1]. In certain conditions, this might lead to the production of harmful disinfection by-products (DBPs) like Trihalomethanes (THMs), Haloacetic Acids (HAAs), etc. ^{[2][3]}. Identifying and neutralizing these DBPs has become a necessity for distributing safe drinking water.

Existing solutions include time-consuming water analysis, or the use of DBP sensitive analyzers (Fig 1), which is expensive. To be more cost-effective we envision an intelligent monitoring system and sensing infrastructure to (indirectly) identify DBPs in streaming water.

However, to overcome these issues, envisioning a cost-effective sensing infrastructure and intelligent monitoring system to identify DBPs in streaming water is still lacking.

Technological challenge

The two major technological challenges in this research are:

- Designing a sensing network infrastructure:
The sensing infrastructure includes reliable sensors, low-latent data transmission units, and a micro-controller. Streaming water requires sensors that withstand water flow and can capture data at high frequencies. This ensures mapping DBPs ground truth information to the captured data.
- Developing an intelligent monitoring system:
Building an efficient and intelligent deep learning multi-column regression model that monitors the DBPs with high accuracy in streaming water.

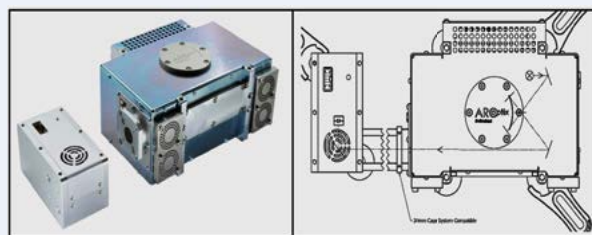


Fig 1. IR-ATR water analyzer (ARCOptix: FTIR OEM 011) - To map the DBPs ground truth information with the sensors data for building AI models.



This work is part of a project that has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101081963.

As there are no cost-effective sensors available to measure DBPs at low concentrations, we therefore aim to build an AI model that uses data from sensors probing the conditions instead of the DBP of interest. Fig 2 shows a possible experimental setup to address the technological challenges.

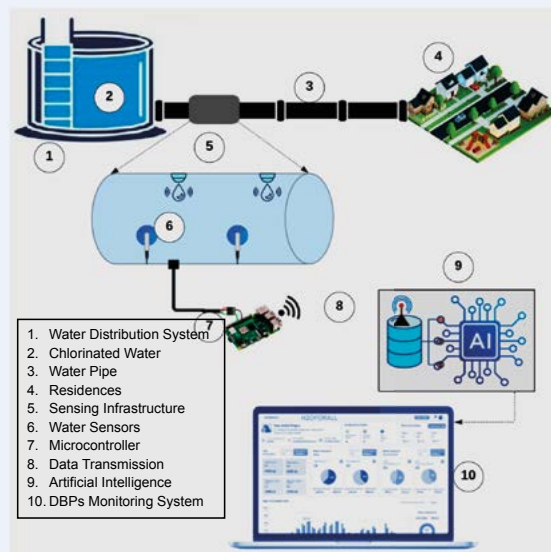


Fig 2. Experimental setup of the sensory infrastructure to monitor the DBPs in streaming water using Artificial Intelligence.

Research goals

The main goals of this research are:

1. Identifying the environmental and chemical parameters that impact the DBPs production.
2. Choosing the right water sensor modules that are reliable, durable, cost-effective, and less power-consuming.
3. Design sensing infrastructure to capture data from streaming water.
4. Building a probabilistic machine learning-based model to monitor the DBPs.

With this, we aim to develop an alternate cost-effective DBPs monitoring system that is highly scalable.

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Motivation

In the Netherlands, we are fortunate to have good drinking water facilities. The drinking water is of high quality and heavily monitored. It is distributed to households via a large and intricate distribution system. The challenge is to keep drinking water quality the same from where it enters the distribution system until the households. One important aspect is to maintain biological stability throughout the system [1]. In this project, we aim at using the indigenous bacteria in the drinking water as indicators of the water quality. Bacteria respond to their environment by switching certain genes on or off, which will lead to changes in mRNA levels [2]. Subsequently, this mRNA profile, or transcriptome, may be correlated to specific environmental stimuli. For example, the transcriptomic response could indicate biological instability or the presence of a certain compound in the distribution system. This may then, require action from the drinking water company (Figure 1). In other words, we propose to use the bacteria in drinking water as microbial sensors by investigating their transcriptomic response. They should potentially also be able to recognize and signal the presence of unknown impurities, which is not possible with the current standard methods.

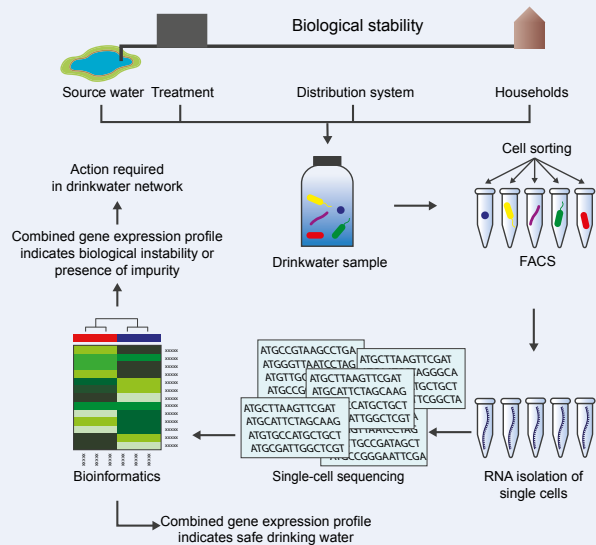


Figure 1: Project overview.

Technological challenge

- Sample preparation. mRNA is very unstable and just present for a short time in the cells. Therefore, sample processing and RNA isolation needs to be performed with care and speed; sample fixation may be necessary [2].
- Distinguishing between microbial subpopulations, such as the active and dormant fraction in drinking water, and sorting those with fluorescence-activated cell sorting (FACS).
- Performing single-cell analysis. We want to perform single-cell analysis to investigate the transcriptomic response in the individual cells instead of the average response of many cells. This is a relatively new and challenging technology, but would greatly improve using the indigenous bacterial cells as biological sensors.
- Data analysis. Analyzing the large amount of data and determining the transcriptomic profiles in relation to specific environmental stimuli will require a lot of bioinformatics and computational power.

Research goals

1. Establish a reliable workflow to distinguish between the microbial subpopulations in drinking water and for single-cell analysis.
2. Investigate what factors influence the biological stability in a full-scale water distribution system, in terms of community composition and bacterial transcriptomes.
3. Determine changes in the transcriptomic profile of microbial subpopulations and single-cells in response to known compounds.
4. Work towards an application that uses the transcriptomic profiles as an indicator for drinking water quality.

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[2] R. Farrel, *RNA methadologies* (2010; 4th edition)



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Motivation

While water treatment processes in the Netherlands are of a very high standard, continuous threats from newly emerging micro-pollutants in (drinking-)water sources are still a challenge. Ensuring bio-stable water, which does not support the growth of microbes during water distribution is important for the prevention of aesthetic, operational and hygienic problems. The emergence of new genetic sequencing techniques that provide detailed information on the composition and response of the microorganisms, has inspired research to gain crucial in-situ information related to the microbial biogeography and occupancy-abundance dynamics in drinking water (illustrated in Figure 1, below). While meta-genomic data has been effectively collected, the analysis has been limited to correlational analysis with the underlying process data. However, an integrated systems biology approach which enables a predictive and adaptive modelling of the microbial dynamics in drinking water is still lacking [1,4,5].

Technological challenge

The technological challenge is to choose and put to use a suitable machine learning approach that will automate the kinetic network reconstruction of carbon degradation and central metabolic pathways in water using metagenomics data. The resulting kinetic model will serve as a digital twin that will provide real-time state estimation of the microbial activities, as a proxy to drinking water quality sensors, and will enable operators to take timely actions to ensure a constant high quality of the treated water[2].

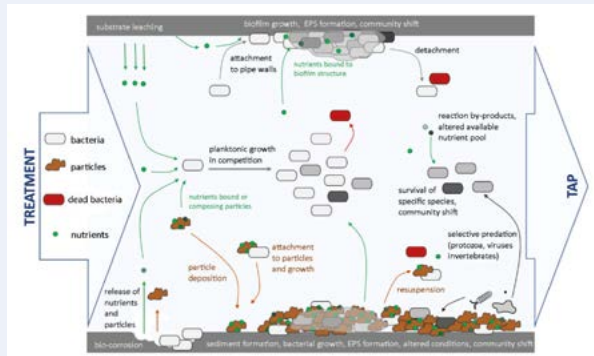


Fig 1. Overview of microbial dynamics in a water distribution pipe. Stimuli include hydraulic conditions, residence time, pipe material, and trophic chain.(modified from [3])

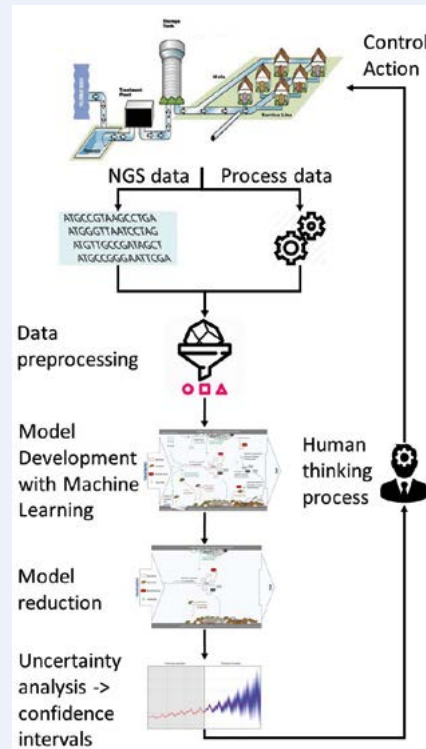


Fig 2. graphical abstract of the project

Research goals

1. Use machine learning tools to analyse meta-genomic and process data for automated kinetic network reconstruction of carbon degradation and central metabolic pathways in the water processing chain.
2. Development of a glass-box model that focuses on these metabolisms as proxies for microbial activities that affect water quality by applying kinetic model reduction techniques.
3. Development of model-based state estimators for the real-time prediction of water quality which includes the estimation of confidence intervals through uncertainty analysis.
4. Translate the model outcome to actions that can be taken to improve the water quality.

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 [2] Prest, E. et al (2016). Biological Stability of Drinking Water: Controlling Factors, Methods, and Challenges. Frontiers in Microbiology.
 [3] Prest E. (2016) Long-Term Bacterial Dynamics in a Full-Scale Drinking Water Distribution System.
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Motivation

Water contamination in surface water is a critical and growing environmental challenge, threatening ecosystems and clean water supplies. Traditional laboratory-based water monitoring techniques face significant limitations, such as time delays between sample collection and analysis, low sensitivity to contaminants at trace concentrations, and interference from other substances in complex samples. These methods are also prohibitively expensive, hindering widespread and continuous monitoring of water quality.

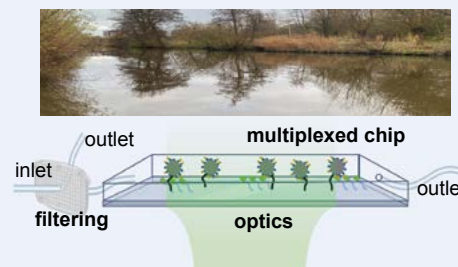


Fig 1. Graphical abstract of the project

Technological challenge

This project seeks to address these challenges by developing a novel, cost-effective sensor capable of real-time, in-field monitoring of water contaminants. The sensor^[1,2] leverages biological interactions to ensure high specificity and minimal cross-talk. Its design includes reversible interactions, enabling continuous monitoring without requiring reagents. The miniature, all-optical system will target two critical contaminants—diclofenac, and phosphate—providing real-time data in diverse environmental settings.

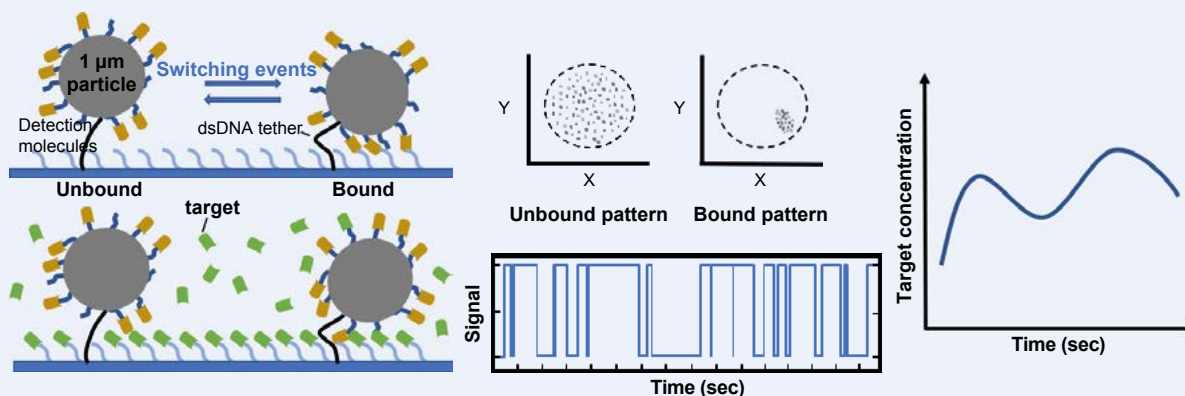


Fig 2. The sensing surface is functionalized with detection molecules and connected to particles via double-stranded DNA tethers. Particle motion alternates between unbound (disk-like motion) and bound (confined motion) states due to reversible interactions with the target analyte. Switching events are optically detected and tracked over time, generating a digital signal that reflects analyte concentration. The sensor's output parameter, is calculated from the number of switching events, enabling real-time monitoring.

Research goals

Specifically, this research aims to:

- Develop a miniaturized interferometric microscope (iSCAT)^[3] capable of imaging across a large field-of-view, optimizing its optical design for multiplexing and integration into a portable sensor system.
- Design and integrate fluidic systems with actively cleaned membranes, ensuring long-term operational stability and antifouling performance in diverse environmental conditions.
- Conduct field testing to validate the sensor's functionality, benchmarking its performance in real-world scenarios such as sewage treatment facilities and agricultural sites.

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 [3] Priest, Lee, and Philipp Kukura, Chemical reviews 121.19 (2021) 119374-11970



This project has received funding from the Netherlands Organization for Scientific Research (NWO) in the framework of the collaboration programme of NWO with Wetsus on Sustainable Water Technology (grant number 19517).

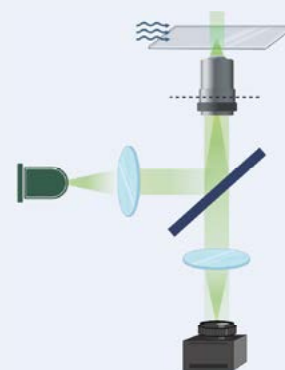


Fig 3. Illustration of the optical setup.



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Improving Water Quality by Monitoring

Heavy pollutant loads from intensive agricultural practices have deteriorated the soil and surface water quality, threatening human health and the ecosystem. The Water Framework Directive (WFD) has set a deadline to improve overall water quality status in the EU by 2027 [1]. In this case, continuous water quality monitoring in agricultural areas becomes a critical tool for the predicting the water quality status, understanding the pollutant dynamics, and assessing the impact of farming practices. However, real-time water quality monitoring in agricultural fields is often bypassed, hindered by the lack of affordable nutrient sensors [2]. Therefore, advancing this technology is crucial for improving water quality.

- **Building a suitable dynamic model** for SDF that is accurate, compatible with data availability, and has low complexity. We will construct a straightforward soil water quality model enforced with physics, machine learning, and spatial analysis to simulate nutrient pollutants (Total Nitrogen, Total Phosphorus, and Total Organic Carbon) and related water quality variables.
- **Assimilating the sensor data and model predictions** using SDF to estimate the physicochemical variables of water quality and evaluate their relation to fertilization and irrigation practices.

Challenges in Sensor Data Fusion

Sensor data fusion (SDF) is a promising approach for real-time estimation and prediction [3]. The key challenges include:

- **Generating a high-quality time series dataset** that reflects water quality in agricultural areas. Our approach uses a cost-effective multisensor dataset deployed in local agricultural fields and ditches to indirectly measure the water quality variables [4].

Research goals

1. Develop a dynamic model of soil water quality to predict the water quality in real time.
2. Develop a dynamic model of surface water quality to estimate the water quality in real time.
3. Build an integrated soil and surface water quality model to estimate the water quality in real time.
4. Evaluate the relationship between water quality and farming practices.

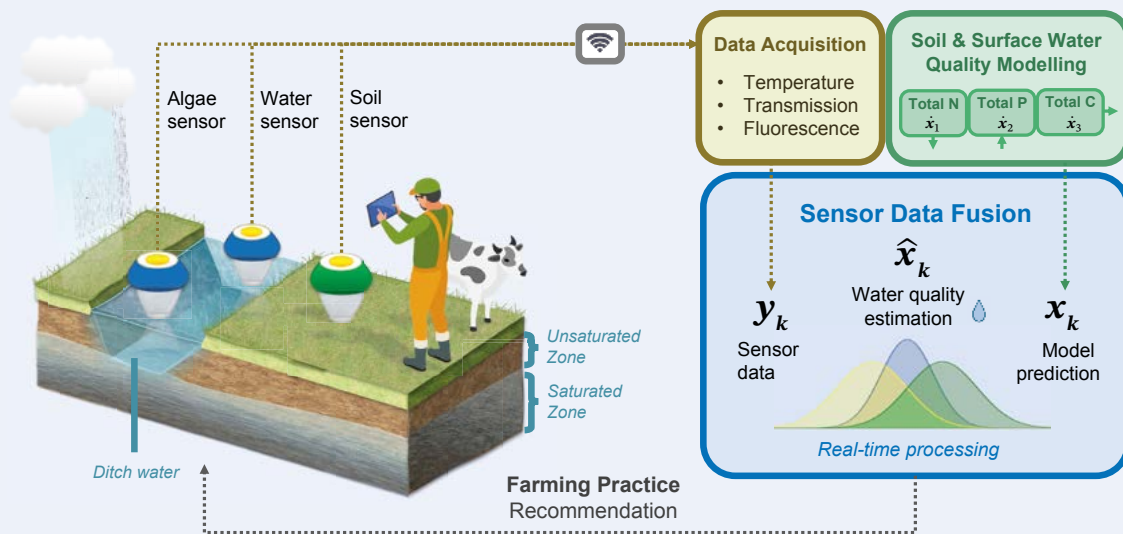


Fig 1. A schematic framework of real-time water quality monitoring approach in agricultural areas with a time index k

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Sulfur

This theme focuses on integrated processes for removing and converting volatile sulfur compounds from aqueous solutions. These solutions are used to scrub volatile sulfur compounds from oil and gas and have a high pH and salt concentration. The process scheme consists of scrubbers and bioreactors and aims to remove all volatile sulfur compounds

like sulfide and thiols (e.g., methanethiol). The water consumption of this process can become zero by treating the bleed stream, enabling the recycling of all water. The scientific disciplines needed to develop such an integrated process are chemistry, microbiology, biotechnology, and modeling.

Research projects

- **Joris Bergman**, Wageningen University, *Understanding the kinetics, transfers and reactions in the biological gas desulfurization process*
- **Ding Fang**, Wageningen University, *High rate biological production of hydrogen sulfide from elemental sulfur for industrial application* **NEW**



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PAQUES

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Understanding the kinetics, transfers and reactions in the biological gas desulfurization process



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Motivation

H_2S is a toxic and environmentally harmful gas that can be found in (bio-) gas streams. Therefore, it must be removed, which is traditionally done through physio-chemical methods such as the Claus process, an energy-intensive process that uses harmful chemicals. The biological gas desulfurization process is an environmentally friendly process that converts H_2S into elemental sulfur (S^0) using sulfur-oxidizing bacteria (SOB) under haloalkaline conditions (pH 8-9.5 and ionic strength 1-1.5 M)^[1]. Within the process, biological, chemical and mass-transfer reactions take place simultaneously. The process consists of three steps: 1) absorption of H_2S into a (bi)carbonate solution to form dissolved HS^- , 2) anaerobic uptake of HS^- by SOB and 3) aerobic conversion of stored HS^- into S^0 .

Aside from S^0 , SO_4^{2-} (sulfate) and $S_2O_3^{2-}$ (thiosulfate) can also be formed through biological or chemical oxidation. Theoretically, 98% of incoming S atoms can end up in S^0 , but in practice lower percentages are achieved^[2]. Modelling can help understand the interplay between the different processes in order to improve the process design and control. Understanding can be generated at multiple scale levels, starting at single (bio)chemical reactions and cross-film mass transfer all the way up to a full-scale integrated process.

The aim of this research is to model the biological gas desulfurization process at each of these scale levels, starting at the smallest scale. Past experimental data will be supplemented with new small-scale experiments and used for model validation.

Technological challenge

Three challenges must be overcome in the modelling of the biological gas desulfurization process:

- Aspects of the SOB biology, e.g. their ability to take up and store HS^- under anaerobic conditions. This most likely requires the development of models that go beyond Monod kinetics.
- Both sulfur crystals and bacteria are known to enhance mass transfer in the absorber column^[3,4]. To date no quantitative information exists on the relative contributions of both forms of enhancement and no model exists in literature that combines both biological and chemical mass transfer enhancement.
- Investigating the hypothesis that most of the chemical conversions in the micro-aerophilic reactor take place within a gradient around the reactor O_2 and HS^- injection points. This necessitates the use of computational fluid dynamics (CFD).

Interesting system properties to investigate after model development are observability and controllability, properties relevant to process monitoring and control. Observability is a measure of how well external outputs (i.e. sensor measurements) can be used to estimate state values (e.g. HS^- concentrations in the process units). Controllability is the degree to which it is possible to move state values to any value within their solution space, using only achievable control inputs.

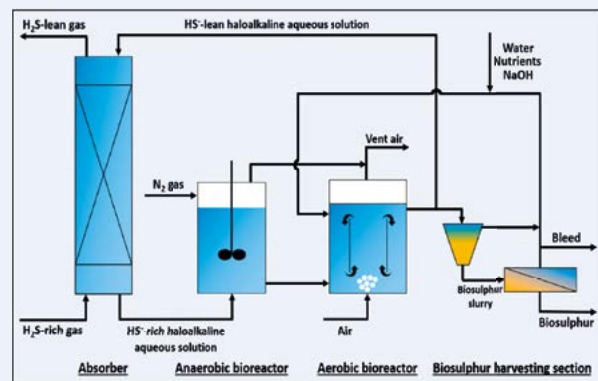


Fig 1: process scheme for the biological gas desulfurization process

Research goals

1. Determine the dominant physical, chemical and biological processes and quantify their kinetics;
2. Develop a novel model for the SOB biological rates;
3. Model simultaneous chemical and biological mass transfer enhancement in the absorber column;
4. Model the processes that take place around the HS^- and O_2 injection points and determine how the mixing pattern around these points affects the process performance;
5. Determine to what degree the biological gas desulfurization process is observable and/or controllable;

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Phosphate recovery

Phosphate is an important fertilizer needed for food production. The sources are finite, and mining and processing the ore is energy intensive and polluting. An appreciable part of the phosphate in food ends up in wastewater and manure. Currently, chemicals and energy are used to remove the phosphate from the wastewater as emissions from phosphate to the

surface water is unwanted. This theme focuses on technologies to remove phosphate from wastewater in such a manner that the phosphate becomes available as fertilizer and the water will be clean. The theme will focus on expanding and improving current technology to produce more phosphate at lower costs while producing high-value products.

Research projects

- **Wokke Wijdeveld**, Pilot projects for reversible phosphate adsorption to ultra low concentrations (BioPhree) and vivianite crystallisation to recover phosphate (ViviCryst) as part of the H2020 project Water Mining
- **Ha Nguyen**, Delft University of Technology, Magnetic vivianite recovery from sewage sludge
- **Sophie Banke**, Delft University of Technology, Transformation of P precipitates in manure to vivianite and subsequent magnetic recovery
- **Milan Adriaenssens**, Wageningen University, Iron recovery and arsenic isolation from drinking water treatment sludge
- **Jéssica Papera de Oliveira**, Delft University of Technology, Prevention of freshwater eutrophication through P recovery via manipulation of Fe and P interaction
- **Yuwei Huang**, Delft University of Technology, Developing iron oxide adsorbents and regeneration strategies for phosphate recovery from surface water
- **Leon Korving**, Wageningen University, The road to truly circular & sustainable sewage treatment



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Motivation

Phosphorus is one of the most important elements constituting life and acts as the limiting major component for plant growth. Currently, Europe is highly dependent on the import of phosphorus. Meanwhile, the mining process of phosphate rock is polluting and its linear use can lead to eutrophication problems. Phosphate recovery ensures resource preservation, food security and political independence in the future. Sewage sludge is an attractive secondary source for phosphate recovery, with the ability to cover 20 – 30% of Europe's fertilizer demand^[1].

Recently, it was discovered that in wastewater treatment plants dosing iron to remove phosphate, up to 90% of phosphorus in sludge is present as vivianite ($\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$)^[2]. This mineral is thermodynamically and kinetically favored in reduced environments like excess sludge and anaerobic digester. Since vivianite is paramagnetic, its recovery from sludge is possible with magnetic technology originating from the mining industry. This research aims to understand the characteristics of vivianite in relation to its separation, optimize the recovery efficiency and explore the best valorizations for the recovered vivianite.

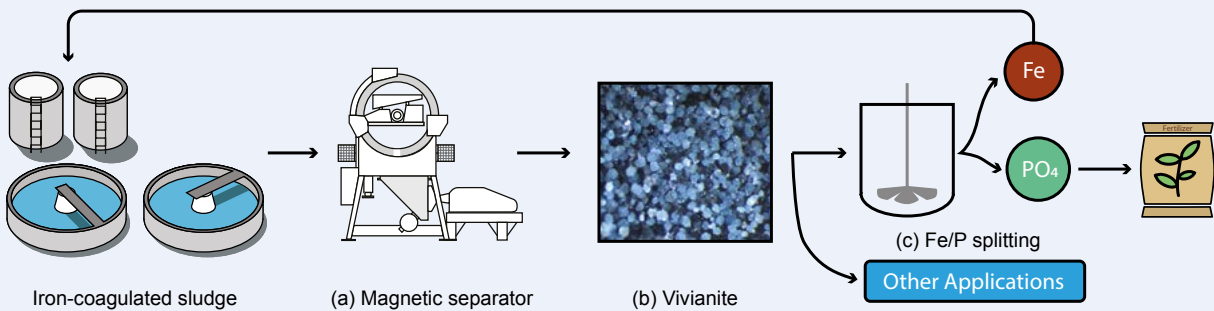


Fig 1. Schematic overview of the phosphate recovery via vivianite process. The project focuses on: (a) the optimization of the magnetic separator, (b) vivianite properties (color changes from transparent to dark blue as oxidation occurs), (c) splitting Fe/P and circular use of Fe and other applications.

Technological challenge

The recovery of vivianite is strongly tied to its quantification and identification. The fact that vivianite is prone to oxidation makes it more difficult for accurate quantification, even for the best technique available like Mössbauer spectroscopy. Moreover, oxidation could also affect its magnetic recoverability.

Magnetic separation was proven to successfully recover vivianite from sewage sludge [3]. However, there are discrepancies in recovery efficiencies that require deeper understanding.

Lastly, the valorization of vivianite is necessary to close the resource recovery loop. Splitting iron and phosphate is an option that would enable the reutilization of Fe in a circular way. However, the process still needs optimization. Additionally, creative ways to use vivianite can make the technology economically viable.

Research goals

- Improve vivianite quantification (e.g., with Mössbauer spectroscopy).
- Investigate the influence of vivianite properties (e.g., oxidation, particle size) in relation to its extraction from sludge.
- Understand the influence of sludge characteristics (e.g., viscosity) and operational parameters on magnetic separation efficiency.
- Optimize Fe/P separation for circular use of Fe, for example, by alkaline leaching or via electrochemical processes.
- Explore alternative applications of vivianite.

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Transformation of phosphorus precipitates in manure to vivianite for recovery



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Motivation

Phosphorus (P) is crucial for the cellular processes of all living organisms. Therefore, the modern global food production system is dependent on supply of P fertilizer usually produced from mined rock. However, phosphate rock sources are dwindling, giving rise to geopolitical constraints and endangering food security. Moreover, P is used in excess on agricultural soils leading to its run off into water bodies. This leads to increased algae bloom, hypoxia and acceleration of eutrophication, endangering aquatic ecosystems [1].



Fig. 1: Three matrices containing phosphorus for recovery (left to right): manure, sewage sludge and lake sediment.

Sources of P that are of interest (Fig. 1) include:

1. Livestock production: Manure accounts for 1.75 million t P a year in the EU [2]. High phosphate concentrations in European soil coincide with areas of intense agricultural activity such as the Netherlands, Belgium, Denmark and Northern Germany. Manure spreading is considered to provide a significant amount of P input [3].
2. Human waste: P in wastewater treatment in the EU is about 450,000 t P a year. Wastewater treatment plants there have to remove P and accumulate the P in sewage sludge. A significant amount of the P in the sludge can not be used effectively and is lost [2].
3. Lake sediments: In the EU, 200,000 t P per year are lost to the hydrosphere [2]. Due to high P influent into lakes, P is loaded into the sediment. Even when external P sources are restricted, P from sediment is released back into the lake leading to a slow recovery from eutrophication [4].

Technological Challenge

Manure spreading restrictions in countries like the Netherlands lead to its export implicating extra cost and loss of valuable organic matter. In manure, P is mostly bound to magnesium (struvite) and calcium phosphates. To allow better local use of organic matter in manure, P could be recovered, but it is rarely done so far. A possible approach to recover P proceeds via acidification and precipitation using alkaline magnesium or calcium salts. This implicates a high use of chemicals and a challenging extraction of the precipitated phosphate minerals making this approach not ideal. Overall, there is a need to further study chemical interactions between iron (Fe), P, sulfur (S) and organics in manure to develop P recovery procedures [5].



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One possibility to remove P during wastewater treatment is precipitation with Fe. Under anaerobic conditions in sludge digesters, an iron phosphate mineral, vivianite ($\text{Fe(II)}_3(\text{PO}_4)_2 \cdot 8 \text{H}_2\text{O}$), is formed. The magnetic recovery of vivianite due to its paramagnetic characteristic has been demonstrated at pilot scale [5]. A similar approach may hold potential for manure treatment. Yet, about three times more Fe in comparison to sewage sludge had to be added to manure to convert all P into vivianite [6]. Based on knowledge from soil sciences, Fe-binding to organics could explain the high dose of iron required for vivianite formation. In addition, Fe is known to bind S more preferentially than P. A way of restricting Fe-organic as well as Fe-S interactions should be found in order to favour Fe-P binding. Knowledge of chemical interactions in lake sediment and sewage sludge could serve as reference and inspiration (Fig. 2).

Research Goals

- Investigate and compare the interactions between Fe, P, S and organics in manure, sewage sludge and lake sediment
- Find possibilities of minimizing Fe binding to organics and S using previously elucidated relationships and hence favour Fe-P binding

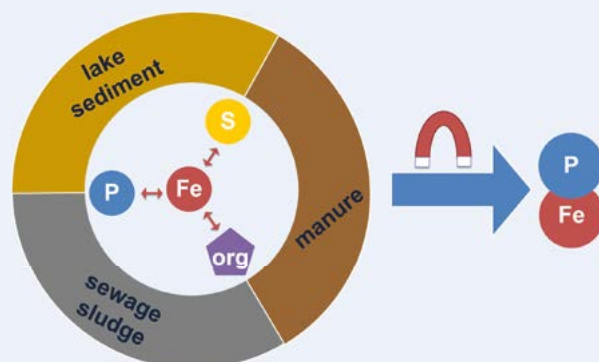


Fig. 2: Fe-P, Fe-S and Fe-org (organic) interactions in three different matrices (left), the goal of improving Fe-P interaction using that knowledge and magnetically recovering vivianite (right).

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Motivation

Phosphorus (P) is a key nutrient for freshwater eutrophication (Fig. 2) as it usually limits primary production. Therefore, its excess allows the growth of primary producers populations, commonly in the form of algae blooms. Current methods that aim to control P release from the sediment and reduce P concentrations in the water work by adding binding agents which make P unavailable for biological uptake. These methods can have drawbacks such as being vulnerable to environmental conditions, costly, and they do not recover P, only immobilize it. Meanwhile, P is an important macronutrient for life. Unfortunately, it is expected that, over the next few decades, demand for P will surpass its supply^[1]. Therefore, it is necessary to find ways to recycle P.

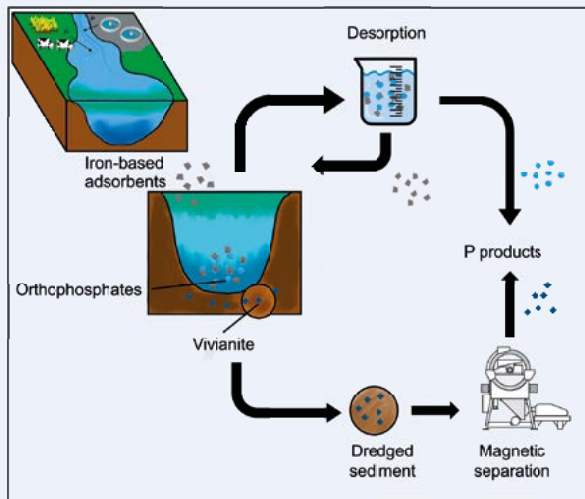


Fig. 1: Schematic representation of a proposed approach for lake restoration through phosphorus recovery.

Project approach

The strong affinity between iron and P makes iron a great candidate to aid P removal and recovery. Thus, this study will use iron-based adsorbents as lake restoration tools (Fig. 1).

It is believed that vivianite ($\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$) authigenesis in lakes is an important phosphorus sink in the right conditions, i.e., reducing environment, high orthophosphate, and ferrous iron concentrations, and low presence of sulphides^[2]. Thanks to vivianite's paramagnetic properties, the share of P present as this mineral may be removed from sediments using magnetic separation (Fig. 1), as has been shown to work for wastewater sludge^[3].



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Technological challenge

Lakes differ from each other in the way they receive nutrient loading, mixing regime, and other variables which may influence P speciation and internal loading. The success of a restoration using iron-based adsorbents is heavily dependent on the P speciation as the material will only adsorb orthophosphate. Therefore, the presence of P in other fractions such as particulate organic P will pose a challenge. In addition, we aim to immobilize P as vivianite (Fig. 3) to an extent that will allow its separation from the sediment, potentially in situ. This may be difficult to achieve as concentrations of P in the sediment are not as high as in wastewater sludge. It can also be a challenge to perform magnetic separation within the lakes due to factors such as depth of vivianite formation, potential harm to benthic animals, and interference of macrophytes in the sediment.

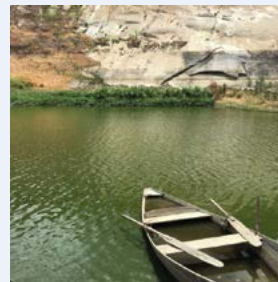


Fig. 2: Eutrophic lake.

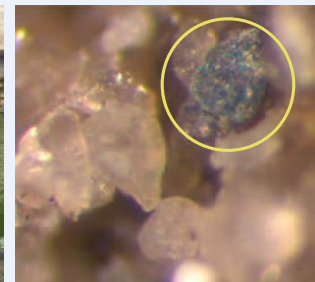


Fig. 3: Vivianite in lake sediments. Bouvigne, The Netherlands.

Research goals

- Investigate the influence of lake characteristics on P speciation, thus its impact on the success of interventions using iron-based adsorbents.
- Develop methods to use iron-based adsorbents to remove P from water bodies that consider site-specific characteristics.
- Further understand the conditions for vivianite formation in lake sediments.
- Investigate the feasibility of P removal from sediments in the form of vivianite through magnetic separation potentially in situ.

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Motivation

During the production of drinking water, carcinogenic arsenic is removed from the raw water into an iron sludge. While the iron in the sludge still has value, a high concentration of arsenic in the sludge challenges its reuse. Consequently, drinking water sludge is regularly landfilled, risking arsenic leaching into soil and groundwater and inhibiting circularity in drinking water production. With the development of an iron-sludge treatment technology, both iron recovery and stable arsenic storage are aimed for, eliminating iron landfilling.

Technological challenge

Clean drinking water can be obtained, due to the high affinity of arsenic to iron adsorbents. However, this results in a challenge to separate/mobilize arsenic from the iron compounds, an essential first step in the isolation of arsenic and recovery of iron. By altering reaction conditions, affecting both chemical and biological processes, a separation between iron and arsenic is hypothesized^[1,2] (Fig 2). Secondly, the obtained arsenic should be immobilized into a stable mineral to avoid environmental contaminations when disposed of. For example as scorodite, which has a low Fe/As molar ratio^[3] (Fig 1).

Finally, the recovered iron needs to be obtained in a quality/purity suitable for other applications. Potential end-users could be WWTPs for phosphate removal or bio fermenters for sulfide elimination. If reuse in drinking production is possible, lower operational costs can be obtained, making safe drinking water more available.

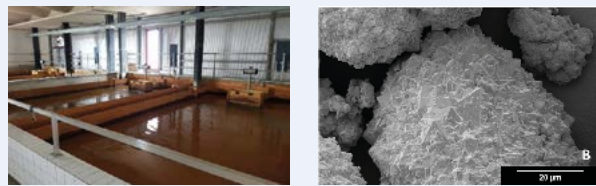


Fig 1. Left; a drinking water production plant, right; SEM picture of bioscorodite [3].

Research goals

- Understand the mobility of iron and arsenic under different reaction conditions.
- Identify reactions to form a stable As-mineral at low arsenic concentrations.
- Comprehend how different conditions affect the value of the obtained iron product.

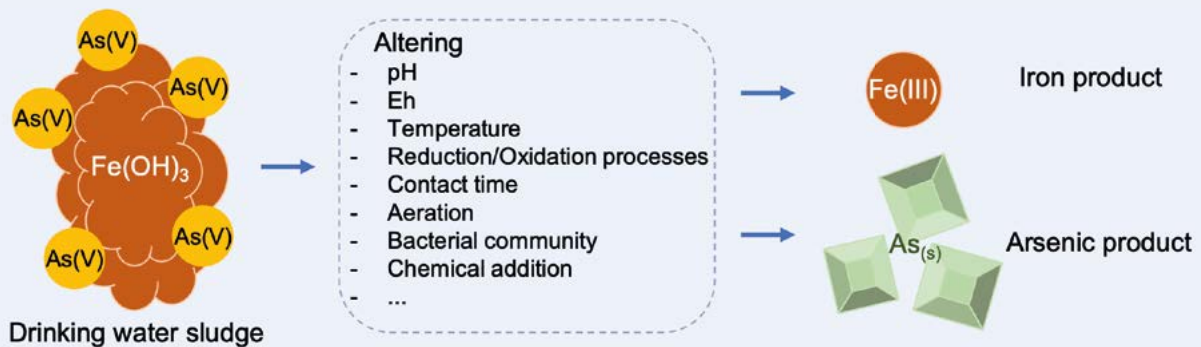


Fig 2. Proposed scheme for iron recovery and arsenic isolation.

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This study is partly funded by the TKI Water Technology project entitled "Verwijdering van arseen uit drinkwaterslib". Involved companies are Pidpa, Evides, Brabant Water, and Aquaminerals.



Motivation

Phosphorus management is key issue in wastewater treatment. While phosphorus is a vital plant nutrient crucial for agriculture, its excessive presence has well-documented detrimental effects on the natural environment, including eutrophication, algal blooms, and aesthetic and recreational impacts^[1]. The Water Framework Directive required EU Member States to achieve good status in all surface water bodies by 2027^[2]. Given the eutrophication threshold of 10-15 ug/L^[3], it becomes important to efficiently remove phosphate during wastewater effluent polishing to mitigate eutrophication. Among the potential solutions, adsorption presents itself as a valuable approach for waters contaminated with low levels of phosphate. Given the abundance, affordability, and ease of synthesis of iron oxides, there is growing interest in employing iron minerals for phosphate recovery^[4]. However, while much research focus on developing adsorbents from the adsorption perspective, the regeneration and reusability aspects still lack a comprehensive understanding. Addressing this gap in knowledge is a vital next step in advancing the field and enhancing economic viability^[5]. By gaining insights into the regeneration of adsorbents, we can refine and optimize the entire process, moving closer to sustainable and efficient phosphate removal in wastewater treatment.



Fig 1. Eutrophic reservoir with algal bloom.

Technological challenge

Research on using iron oxide adsorbents for phosphate recovery presents several challenges. An important aspect is gaining a comprehensive understanding of the Fe-O-P binding mechanism, both bond formation and breakage, which essential for both improving the adsorption performance and optimizing the regeneration strategies. As for exploring adsorbent regeneration, the challenges including regeneration efficiency, adsorbent deterioration, dilution or loss of regenerant, and phosphate recovery. Additionally, low phosphorus levels in discharged wastewater also pose a challenge for phosphorus adsorption^[5]. These challenges add to the complexity of achieving an effective and sustainable adsorption-regeneration cycle.

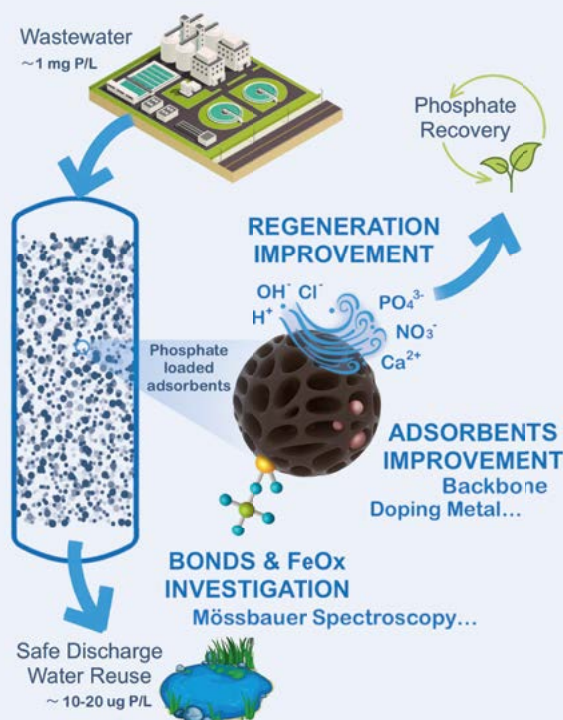


Fig 2. Graphical abstract of the research.

Research goals

Embarking on a comprehensive exploration of phosphate recovery through iron oxide adsorbents involves several research goals:

- Understanding the Fe-O-P binding mechanism by Mössbauer Spectroscopy.
- Optimizing the regeneration process for enhanced efficiency.
- Improving the adsorbent for increased reusability.
- Exploring innovative regeneration methods and adsorbent designs.

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Resource recovery

In the Resource Recovery theme new technology is developed to harvest nitrogen from waste streams like urine and industrial wastewater in the form of ammonia that is converted to e.g., ammonium sulphate. Another focus is the electrochemical harvesting of phosphate from a phosphate rich waste stream from the dairy

industry in the form of hydroxyapatite. As a continuation of studies on microbial fuel cells and microbial electrolysis cells, the bio-anode is studied in case of intermittent control to improve store of energy in the biofilm. Bio-anodes can also be used for a biological cell for harvesting of ammonia.

Research projects

- **Simona Pruiti**, Wageningen University
Optimising electrochemical phosphate recovery
- **Widya Prihesti Iswarani**, Wageningen University, *Electrochemical nutrient recovery improvement and scaling prevention*



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Academic partners





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Motivation

Phosphorous (P) is a crucial and unreplacable nutrient for human life. Nowadays, it is mainly extracted from phosphate rocks. Unfortunately, this source is a finite and non-renewable resource. Moreover, there are no substantial P reservoirs in the European Union (EU). For these reasons, the EU declared this element a critical raw material in 2014. In addition, P is also a major pollutant, and its abundance in wastewater is relatively high^[1,2]. A solution that would solve both aspects is the circular use of phosphorus. However, newer and cheaper solutions are needed for P removal and recovery from industrial wastewater. Electrochemically induced calcium phosphate precipitation is a suitable way to achieve that. This technology is particularly appealing for wastewater where P is close to saturation and the salinity is high (i.e., cheese wastewater) (Figure 1).^[3]

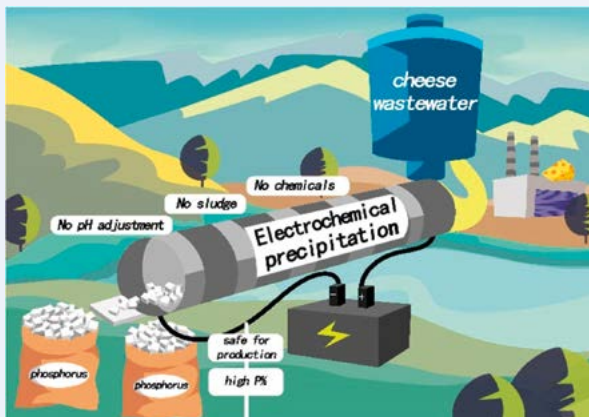


Figure 1. Phosphorous recovery from cheese wastewater. Adapted from Lei et al [4].

Technological challenge

This novel technology can induce calcium phosphate precipitation thanks to the higher local pH created at the cathode by the hydrogen evolution reaction without dosing any chemicals (Figure 2, up)^[3]. The feasibility of electrochemical phosphate recovery has already been proven on a laboratory scale using real cheese wastewater and non-precious metal cathodes (Figure 2, down). However, the following issues need to be addressed to scale up the technology:

1. Avoid chlorine evolution
2. Reduce the energy consumption of the cell
3. Reduce the cost of the cell
4. Find a suitable way to collect the product in continuum.



This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101034321.

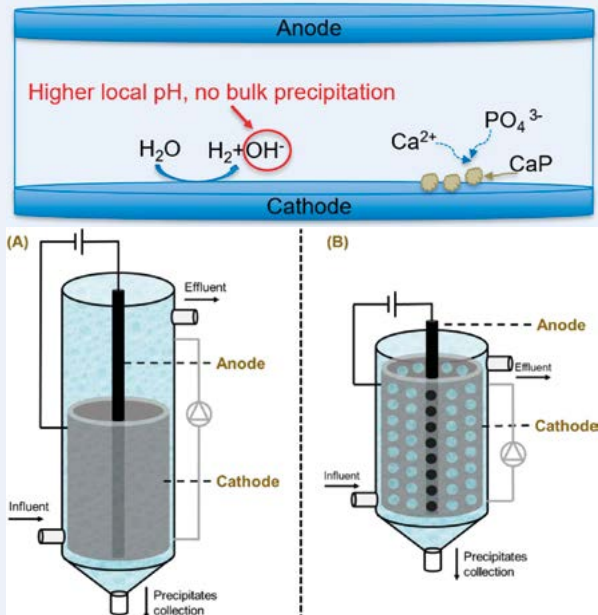


Figure 2. (Up) Schematic of the electrochemical cell for calcium phosphate precipitation. Adapted from Lei et al^[3]. (Down) Design of prototype reactors. (A) The column-shaped electrochemical reactor consists of a non-open tubular stainless-steel cathode. (B) The column-shaped electrochemical reactor consists of a tubular stainless-steel cathode (35.4% open area). Adapted from^[3].

Research goals

To develop a pilot to treat cheese wastewater with our industrial partners and finally extend its usage to other wastewater streams, the following research questions are proposed:

1. Are there ways to limit/avoid chlorine evolution and toxic product formation?
2. What are the suitable electrode materials that reduce both capital and operation costs?
3. What kind of cell design would allow for an effective and safe operation at the largest scale?
4. Can this technology be expanded to other suitable industrial wastewater cases?

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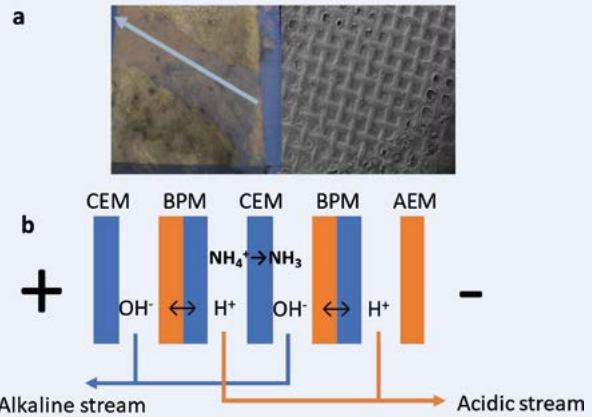


Motivation

Agricultural productivity depends on the use of nitrogen (N), phosphorus (P) and potassium (K) fertilisers. However, the conventional production of these fertilisers is energy and resource-intensive and these fertilisers end up in waste streams [1]. The production of fertiliser from (source-separated) wastewater, particularly through electrochemical systems (ES), offers significant benefits. ES can use renewable electricity and minimise the use of chemicals. Therefore, ES facilitate the recycling of nutrients to agriculture while minimising resource depletion and preventing environmental damage [2, 3].

Technological challenge

The concept is proven, however inorganic scaling on the membrane still limits the application of ES on a larger scale (Figure 1, Graphical abstract) [4]. This project aims to mitigate unwanted inorganic scaling within the ES by investigating integrated chemical-free solutions. Improvements in cell design and operation are required to enhance circularity. Therefore, the use of fresh acids such as sulfuric acid or nitric acid in ES to separate ammonia from the concentrate stream will be limited in this project (Graphical abstract). In addition, the possibilities of ES for producing innovative sodium (Na⁺) and chloride (Cl⁻)-free pure fertilisers for agricultural use, such as NH₄NO₃ and K-rich streams, will be investigated.



Graphical abstract. a. Inorganic scaling in CEM and spacers of ES. The arrow shows the direction of the flow. Adapted from [3] b. ES with possible production of acidic and alkaline streams. The possible use of these streams still needs investigation. AEM: anion exchange membrane, BPM: bipolar membrane. Adapted from [5].

Research goals

In order to further improve electrochemical nutrient recovery to allow its integration into (source-separated) wastewater treatment, and at the same time, enhance its application in agriculture, the following research goals are proposed:

1. Apply chemical-free solutions to prevent inorganic scaling in ES.
2. Develop a model to predict scaling formation and optimise inorganic scaling prevention inside ES.
3. Reduce the chemicals (acid/base) required during ES ammonium recovery.
4. Design ES to effectively produce ammonium and potassium fertilisers (free of Na⁺ and Cl⁻).

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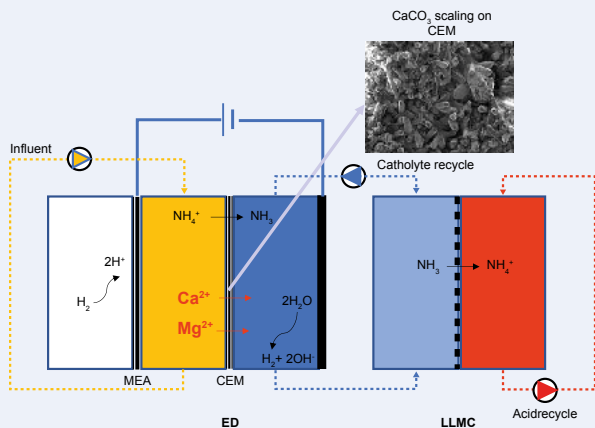


Figure 1. Inorganic scaling of CEM in ES ammonia recovery. MEA: membrane electrode assembly, CEM: cation exchange membrane, ED: electrodialysis, LLMC: liquid-liquid membrane contactor. Adapted from [4].

Biopolymers from water

Wastewater treatment most often involves the use of biological processes to reach effluent water quality objectives. The by-product of biological treatment is a surplus biomass that is rich in microbial activity. Research has shown that it is possible to engineer biological treatment processes for both municipal and industrial wastewater to be naturally enriched with bacteria that can store an excess of biopolymers. The biopolymers are from the family of polyhydroxyalkanoates (PHAs). PHAs are biodegradable thermoplastic materials that are attractive ingredients for bioplastics. The status of current know-how provides for an

interesting opportunity of synergy to combine water quality management services with resource recovery and the realization of new biopolymer value chains in regional circular economies. Research in this theme is to build on and bridge fundamental bioprocess engineering and materials science with downstream commercial opportunities for platform chemicals and bioplastics. The theme is an incubator to reach optimal insights and strategies to produce value added biopolymers for industry in combination with the ongoing demands for increasingly more effective wastewater treatment methods.

Research projects

- **Raquel Barbosa**, EU Agro2Circ Project, *Recovery of PHA from halophilic biomass, Scale up of recovery methods and process water management in collaboration with CEW plus other project partners*
- **Yizhou Xing**, Delft University of Technology, *Production of PHA from municipal primary sludge VFAs in support of upscaling of PHA production from municipal surplus activated sludge*
- **Liang-Shin Wang**, Eindhoven University of Technology, *Integrated PHA recovery from biomass with formulation and production of functional films, membranes, and/or coatings*
- **Zarja Medved**, Maastricht University, *Fabrication of PHA-based release systems for agrochemicals* **NEW**



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Motivation

The increasing world population causes the production of large quantities of urban and industrial waste. Every person can generate up to 30 kg dry sludge solids per year due to wastewater treatment for environment protection. During recent years, a plethora of research has shed much light on the techno-economic feasibility of energy and resource recovery from the wastewater treatment by-products. Production of polyhydroxyalkanoate (PHA) using waste activated sludge (WAS) and fermented organic waste is one valorization route for residual organic material. It is estimated that the PHA accumulation potential of WAS from wastewater treatment plants (WWTPs) can result in more than 60 % (w/w) of the organic matter in the product biomass being PHA^[1]. This potential suggests that full-scale WWTPs can serve as process units to supply organic and biomass resources for commercial scale PHA production (Fig 1). Integrating production of PHA with municipal wastewater treatment also opens up an opportunity for reducing the carbon emissions and lowering the combined cost of waste treatment and biopolymer production.

Technological challenge

Production of PHA as a recovered product coupled to wastewater treatment requires viable process methods that can maximize quantity of product, with quality control (Fig 2).

With the presence of nutrients in the fermentation feedstocks there is a risk for growth of non-PHA storing bacteria and that reduces the PHA process productivity^[2]. Methods to promote the selective growth of the PHA-storing biomass while mitigating flanking population growth directly in a PHA accumulation process is a key to the reliable commercial PHA production. Bioprocess methods need to be optimized with help of a deepened understanding of influencing competition strategies for different kinds of bacteria that comprise the WAS biomass.



Fig 1. Municipal wastewater treatment plant BATH. This WWTP treats wastewater for 500,000 person equivalents and has the potential to supply biomass to produce 2000-2500 ton PHA/year^[1].

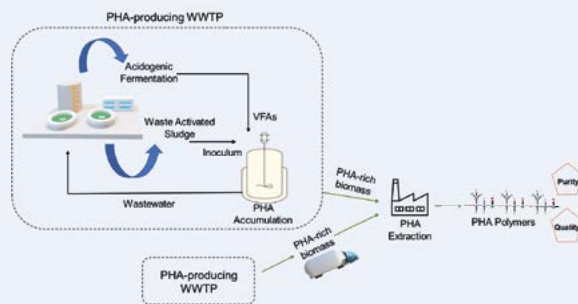


Fig 2. Schematic of PHA production from wastewater treatment by-products.

Moreover, VFA rich feedstocks coming from acidogenic fermentation of primary sludge may often be in the moderate to low VFA concentration (<10 gCOD/L). An industrial facility for PHA production would need to accommodate variability of feedstock VFA composition and concentration, while still guaranteeing predictable quality of the produced polymer.

Lastly, polymer molecular weight is a critical parameter that influences what the polymers can be used for. Quality control of molecular weight has been lacking in the developments to date that have been published in the research literature.

Research goals

The project objectives are to:

- Unravel and exploit the underlying mechanisms that favour selective growth of the PHA-producing microorganisms over non-PHA accumulating microorganisms in the PHA accumulation process.
- Establish robust bioprocess methods to accommodate variability of feedstock VFA composition and concentration.
- Maximize the polymer quality with molecular weight in the accumulation process and define boundary conditions of environment(s) to conserve molecular weight in the production of the primary product as a renewable resource from the WWTP – a dried PHA-rich biomass.

[1] Bengtsson et al (2017) PHARIO report, STOWA, 11.

[2] Estévez-Alonso et al (2021) Bioresource Technology, 327: 124790



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Motivation

Membranes and films are well-established and known for ease of use and low energy consumption in applications. 95% of the market consists of polymeric materials, most of which are petrol-based^[1]. Though membrane technologies provide tremendous benefits, improvements for more sustainable and environmentally friendly materials and production methods are of ongoing interest.

Polyhydroxyalkanoates (PHAs) are an alternative polymer family for petrol-based materials. Specifically, poly(3-hydroxybutyrate) (PHB) and poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) can be produced from wastewater and offer a wide range of possible blend compositions for versatility in applications (Figure 1). They are biobased, biodegradable, and can contribute to enhancing membrane and film environmental sustainability.

Technological challenge

PHAs have been investigated for membrane, film, and coating applications^[2]. However, developments are at an early stage. Systematic modulations of the properties coupled with polymer recovery and quality process control, with potential for impact on membrane properties and performance, are unexplored.

Traditionally, the recovery process of PHA from biomass and the application conversion process has been considered separately from one and the other. The polymer was to be recovered to its maximum possible purity. However, the properties of the polymer, such as molecular weight and purity, should be inextricably linked to the specific requirements for the intended application areas. Much effort has been spent on cost reduction and speculatively discussed rather than linking challenges to finding viable commercial outcomes coupled to the overall production process. Thus, synergy of the PHA production with recovery for membrane processes is a way to deliver desired quality for its utilization.

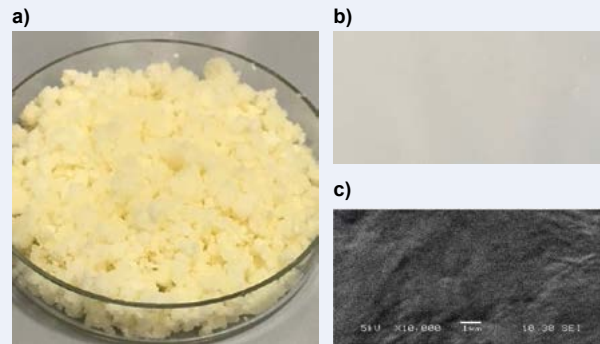


Fig 1. a) Solvent extracted PHA. b) PHA film casting with dimethyl carbonate (DMC). c) SEM image of the film.

Research goals

This project aims to develop biobased PHA membranes. It not only investigates the membrane formation process and methods to tune membrane properties, but it also intends to merge the steps of polymer recovery and the membrane formation process (Figure 2). This investigation includes:

Development of principles to modulate and control PHA qualities during polymer processing towards specifications required for membrane formation for selected applications.

Generation and characterization of PHA membranes, films, and coatings using relevant technologies, e.g., electrospinning and phase separation, and exploring the operational windows.

Advancing the concept to integrate PHA recovery and subsequent membrane formation processes together.

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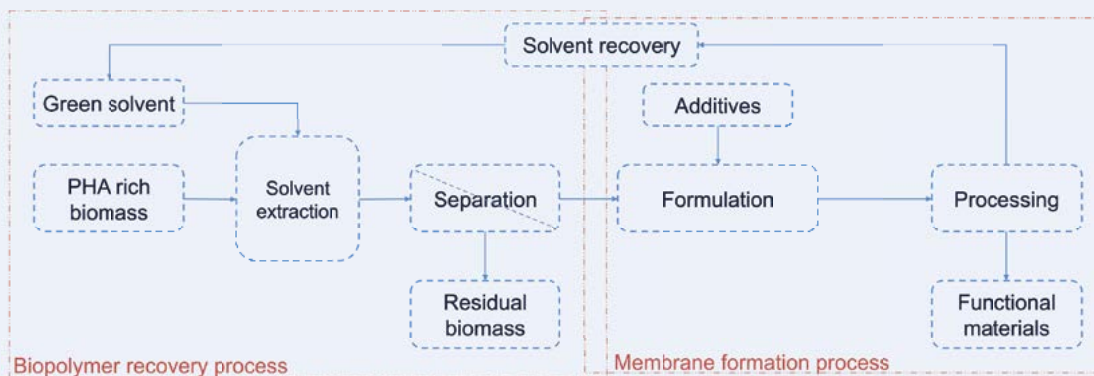


Fig 2. Schematics of the proposed synergy between the processes for PHA recovery and membrane formation.



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Motivation

Agricultural sustainability is critical as global food demands rise alongside evolving global environmental challenges. Agrochemicals, such as fertilizers, herbicides and pesticides, are central to modern agriculture practices. However, their (over)use leads to runoff and leaching – risking groundwater contamination and ecosystem disruption. Innovative release systems are needed to ensure that benefits from applied agrochemicals are possible without any environmental risks.

Polyhydroxyalkanoates (PHAs) are a family of biobased polyesters produced naturally by many species of microorganisms. They occur as intracellular storage granules for carbon and energy. The inherent biodegradability and thermoplastic properties of PHAs make them ideal engineering materials for the fabrication of agrochemical delivery systems. Furthermore, emerging EU legislation on fertilizing products (Regulation (EU) 2019/1009) motivates their use in these developments. The regulation is intended to ensure strict compliance with biodegradability criteria, with an effort to prevent microplastic pollution [1].

Technological challenges

PHA can be produced through fermentation, using (waste-derived) carbon-rich substrates. Engineered bioprocesses enable large-scale production, yielding batches of PHA-rich biomass. A step of recovery and purification is required to prepare the PHA for use in applications. PHA recovery has traditionally employed halogenated “PHA-good” solvents that are effective in solubilizing PHA from the biomass. However, the use of halogenated solvents poses environmental and health risks. Alternatively, nonhalogenated solvents are considered “greener” and offer a more sustainable approach to the recovery process, requiring elevated temperatures to effectively dissolve the PHAs, thus being referred to as “PHA-poor” solvents [2].

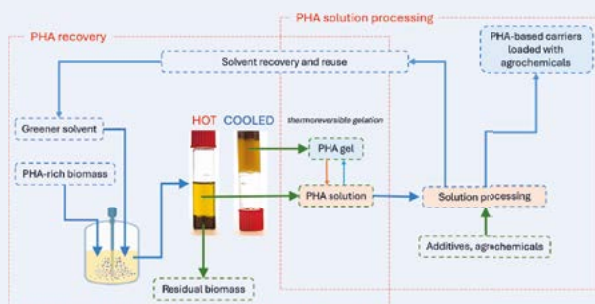


Fig. 1 Integration of “greener” solvent PHA recovery process steps with solution processing for preparation of PHA-based delivery systems.

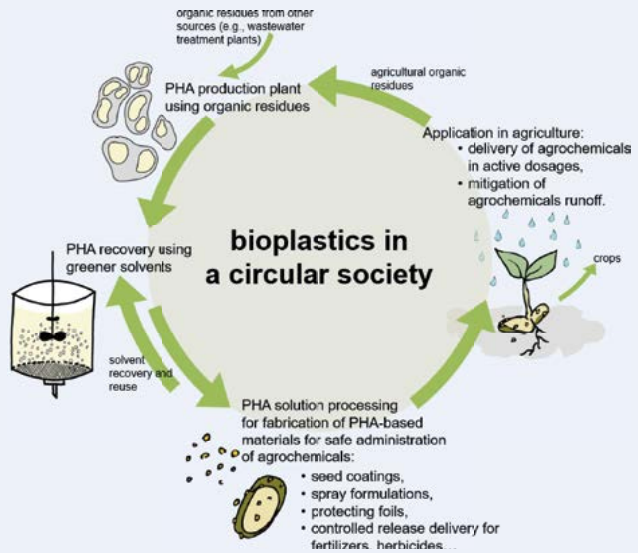


Fig. 2: Illustration of PHA circularity in agriculture.

During recovery with “PHA-poor” solvents, a viscous polymer solution is formed. Upon cooling, the solution undergoes gelation where PHA forms a stable semi-crystalline 3D polymer network with trapped solvent (Fig.1). Gelation is (thermo)reversible and presents the basis of an opportunity to develop innovative methods for making biodegradable PHA-based controlled-release agrochemical systems. Fabrication methods will depend on the interplay between PHA properties (molecular weight, crystallinity, co-polymer composition, polydispersity) and “PHA-poor” solvent characteristics, which influence gelation behaviour. There is value in the dual use of the extraction solvent by integrating PHA recovery and fabrication of applications.

Research goals

This project aims to advance a fundamental understanding of PHA gelation. That understanding will be applied to integrate PHA extraction with innovative fabrication methods using “PHA-poor” solvents to fabricate PHA-based agrochemical release systems. This research will advance on ongoing efforts to scale up PHA production using regional municipal wastewater and organic waste residuals as renewable resources [3]. Thus, the project impact is directed to resource management and supporting regional circular economies with products and services for sustainable agriculture and water quality protection (Fig. 2).

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Sustainable carbon cycle

Interest in Carbon Capture and Utilization (CCU) has been growing recently, i.e. the development of technologies to remove CO₂ from flue gas and the atmosphere, and use the captured CO₂ as a working fluid or source of carbon. At Wetsus, the Sustainable carbon cycle theme aims to develop energy-efficient technologies to capture CO₂ from the atmosphere and from renewable sources, and convert the captured

CO₂ into valuable chemicals. Our research focuses on electrochemical methods based on new electrode materials, ion exchange membranes, and new reactor designs. The SCC theme builds on the long research experience at Wetsus in the field of applied electrochemistry for salinity gradients, capacitive deionization (CDI), and energy recovery from flue gas (CO₂ energy).

Research projects

- **Sara Vallejo Castano**, *ConsenCUS project*
- **Ragne Pärnamäe**, Wageningen University
Novel nickel-based electrodes for hydrogen production
- **Mu Lin**, Wageningen University,
Electrochemical carbon capture: novel electrochemically-assisted processes for electricity-driven CO₂ capture and carbon-neutral production of minerals
- **Shih-Hsuan Lin**, Wageningen University,
Integration of direct air capture and biological processes for sustainable production of chemicals
- **Ana Camila Zenteno Illanes**, University of Groningen,
Enhanced phototrophic biomass production through the addition of hydrogen



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Motivation

Hydrogen is considered the most promising fuel for its high energy density, abundance, and no emissions during combustion. Today, however, it is almost entirely produced via steam methane reforming, a process which uses natural gas to produce syngas – H₂ mixed with CO₂. To avoid the use of natural gas, a non-renewable hydrocarbon, and the production of a greenhouse gas CO₂, hydrogen can instead be sustainably produced by water electrolysis using renewable electricity. Water electrolysis is a process where electric current between two electrodes is used to decompose water into hydrogen and oxygen on their surface. The performance of electrolysis depends heavily on the electrodes, which need to be highly catalytic to facilitate the gas' formation. Platinum group metals have outstanding catalytic performance but are expensive. Therefore, new cost effective alternatives are necessary.

Technological challenge

Since the development of electrolyzers, nickel-based materials have remained state of the art non-noble hydrogen evolution reaction (HER) catalysts for alkaline water electrolysis. While nickel is the most active non-noble metal^[1], it does not outperform platinum group metals. Thus, much effort has been put into optimizing nickel based catalysts' chemical structure and morphology. Modifying the chemical structure of pure nickel materials by doping them with other highly catalytic materials can significantly improve their catalytic activity^[2]. Optimizing the morphology of such electrodes enhances the detachment of the formed hydrogen and oxygen bubbles from the electrode surface^[3-4].

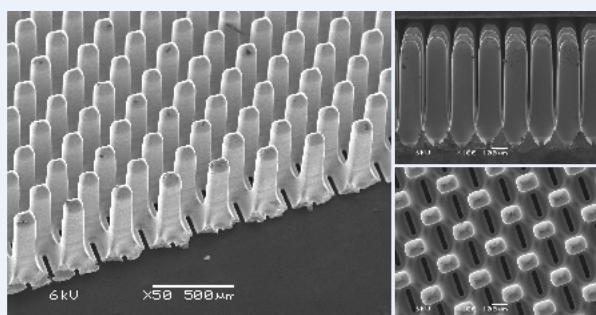


Fig 1. SEM images of the electrodes as provided by the manufacturer (Veco Precision BV).

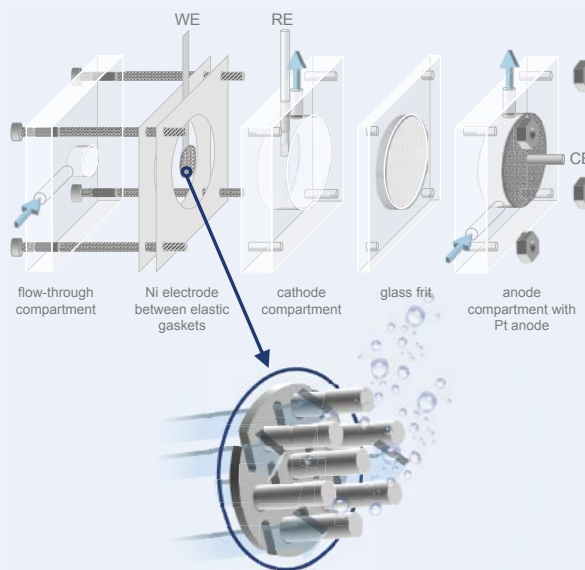


Fig 2. Experimental cell with a flow through configuration for improved bubble detachment.

Research goals

This project investigates pillared nickel electrodes and optimizes their design for hydrogen production via alkaline water electrolysis.

Focus is put on three research objectives:

1. Testing the electrodes against state of the art alkaline HER catalyst (Raney nickel) and optimizing the electrode design (pillar spacing and length, electrode porosity) for improved performance.
2. Improving the electrodes' catalytic activity with noble and non-noble dopants.
3. Identifying and demonstrating novel applications for such electrodes.

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Motivation

Capturing CO₂ from industrial emissions to prevent further increase in atmospheric CO₂ concentration is essential to mitigate climate change and shift towards a climate neutral industry by 2050. Conventionally, CO₂ is absorbed in amine solvents which then are thermally regenerated. However, high energy cost and solvent degradation associated to thermal regeneration raised the interest in developing alternative processes. Here, electrochemical systems offer the clear advantage to conveniently use green (renewable) electricity as energy input for a pH-swing based regeneration. The scope of the study is to demonstrate a novel CO₂ capture process based on pH-swing regeneration (Fig.1) in an electrochemical system (Fig. 2).

Technological Challenge

Previous studies on electrochemical CO₂ capture and regeneration system proves the feasibility of the idea of establishing an acidic trap for the depletion of CO₂ in the basic solvent [1-2]. However, both energy and CO₂ removal efficiency are still below the benchmark of the state-of-the-art CO₂ capture via amine scrubbing [3]. Additionally, a full understanding of such a process from a thermodynamic perspective is still lacking in literature, and it would be fundamental to guide the design and further scale-up of the electrochemical technology. The technological challenge remains to understand and reduce the electrical overpotentials while maintaining a high current density and energy efficiency. This novel process will be also investigated on pilot-scale, and addressing potential challenges in the scale-up process will be crucial to provide input for follow-up studies towards full-scale implementation.

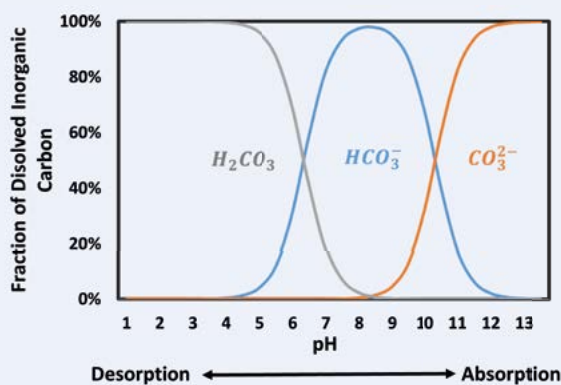


Fig. 1. Fraction of chemical species as function of the solution pH for the H₂O-CO₂ system at 25 °C.

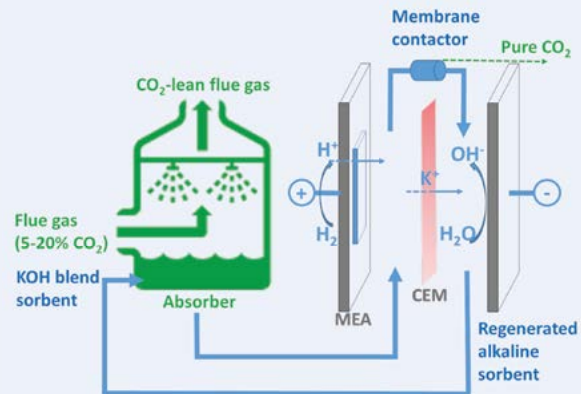


Fig. 2. Schematic illustration of the CO₂ capture process based on absorption in alkaline (KOH) blend and electrochemical regeneration.

Research goals

- Understand the thermodynamics behind the pH swing-based electrochemical regeneration;
- Optimize the electrochemical system for CO₂ capture based on a membrane electrolysis cell with pH swing;
- Reduce energy consumption of the system to compete with the conventional CO₂ capture technologies;
- Study the feasibility of the system and design optimization for further scale-up (100 kg/h CO₂).

References

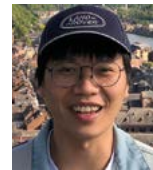
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- [2] Shu et al., Environmental Science & Technology (2020), 54(14), 8990-8998
- [3] Bui et al., Energy Environ. Sci. (2018), 11 (5), 1062–1176



Acknowledgments

This work is performed in the framework of the Consensus project ("Carbon Neutral clusters by Electricity-based innovation in Capture, Utilization and Storage"). The Consensus project has received funding from the European Union's Horizon 2020 Research and Innovation program under Grant Agreement no. 101022484 (www.consensus.eu).

Integration of direct air capture and biological processes for sustainable production of Methane



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Motivation

Carbon capture and utilization (CCU) is one of the strategies proposed for mitigating dependency on fossil resources. Direct air capture (DAC) technologies are able to capture CO₂ directly from ambient air [1]. The captured CO₂ can be used as commodity for multiple purposes or as a carbon feedstock for chemical production. A particularly interesting product is methane. With CO₂ and H₂ as feedstock, biomethanation reactors are able to produce grid-quality (>95%) methane [2].

Biological CO₂ methanation take place in anaerobic, mild conditions [3], with pH range between 6.2-8.5 and temperature between 35-40°C (mesophilic) or 55-65°C (thermophilic), according to the following reaction,

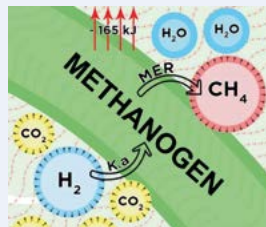
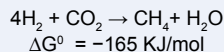


Fig.1 Biological CO₂ methanation [2]

This research seeks to develop an energy-efficient process to produce renewable and biomass-independent methane with CO₂ from atmosphere, by integrating an previously described electrochemically-assisted DAC (Fig. 2) [4] and biological CO₂ methanation step (Fig. 3).

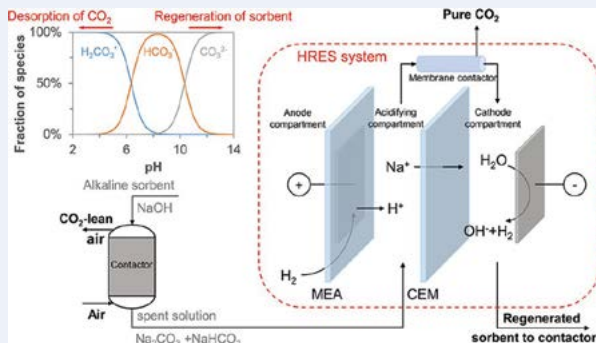


Fig.2 Principle of DAC process using a Hydrogen recycling electrochemical system (HRES) for CO₂ desorption.[4]

Technological challenge

Typically the electrochemical system can be characterized as fast-responding with extreme conditions, whereas the bioreactor operates best at mild and stable conditions. To integrate the electrochemical unit with the bioreactor unit, the balance between these two systems is crucial.

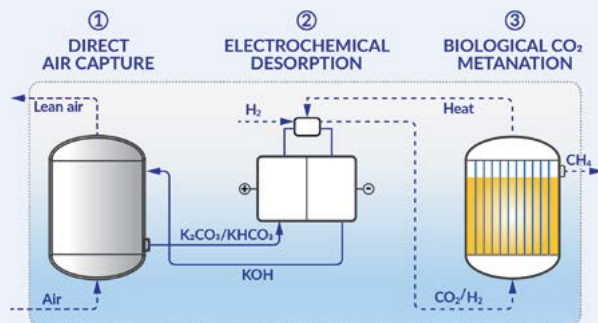


Fig.3 Schematic drawing of the integrated DAC-Biomethanation system.

Mass flows need to be explicitly tuned to sustain a stable substrate/product balance for biomethanation. Heat and pH need to be managed to keep methanogens at optimal metabolic activity. Finally, in order to reach an efficient methane production, individual mass and energy flow need to be optimised in terms of energy requirements (kJ/mol CO₂), and product yield (mol CH₄/m³ air).

Research goals

The research will be organized into three main objectives:

- Reach stable and tunable performance for integrated DAC with electrochemical desorption
- Optimize operating conditions and gas feeding strategy for biological CO₂ methanation
- System integration and overall process optimization. Concerning CO₂ and H₂ conversion efficiency, heat integration, electrical energy input, water production and losses in the system.

[1] Sanz-Pérez, E.S., et al., *Direct Capture of CO₂ from Ambient Air*. Chemical Reviews, 2016. **116**(19): p. 11840-11876.
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 [3] Lecker, B., et al., *Biological hydrogen methanation – A review*. Bioresource Technology, 2017. **245**: p. 1220-1228.
 [4] Shu, Q., et al., *Electrochemical Regeneration of Spent Alkaline Absorbent from Direct Air Capture*. Environmental Science & Technology, 2020. **54**(14): p. 8990-8998.



This research received funding from Dutch Research Council (NWO) in the framework of NWO Wetsus Partnership Programme on Sustainable Water Technology, under project number ENWWS.2020.004.



Motivation

Microalgae production has gained a lot of attention in recent years. As stated by the European Commission, there is a general interest to unlock algae potential increasing sustainable production, safe consumption, and innovative use of biomass¹. Eukaryotic algae and cyanobacteria can transform CO₂ into organic carbon, using light as the sole energy source. Up to 10% of this energy can be captured but in general microalgal outdoor production systems rarely exceed 6%². Therefore, the productivity and economics of microalgae production depend heavily on the capacity of the photobioreactor to achieve an ideal volume to surface ratio that will increase the capture of light and in consequence the areal productivity.

As an alternative to light-dependent systems, it has been suggested that hydrogen could act as an additional reductive power that would add up to photosynthesis. *Synechocystis sp.* has been reported to be capable of using hydrogen as a supplementary energy source next to light. (Figure 1). This was correlated with the activity of bidirectional hydrogenases that can oxidize hydrogen and use the spare electrons to enhance productivity under low light intensity³. However, it is still unknown to what extent hydrogen addition can add up to photosynthesis, under which conditions, and if it is a common feature among other microalgal species.

The motivation of this research is to investigate what are the effects of using hydrogen as a supplementary source of energy to enhance the phototrophic growth of biomass.

Research goals

To fully explore the effect of hydrogen supplementation on biomass production of phototrophic organisms, the research goals of the project are to:

1. Determine the biochemical changes and productivity of *Synechocystis sp.* after supplementing hydrogen in a batch system.
2. Understand the mechanism of hydrogen uptake and the role of light requirements.
3. Evaluate the effect of hydrogen supplementation on different algal species.
4. Scale-up the production system into a continuous reactor and posteriorly into an industrial setup.
5. Perform a techno-economic analysis of the production process.

Effect of hydrogen supplementation on phototrophic microorganisms

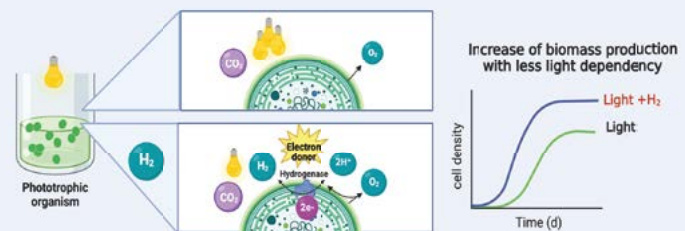


Figure 1. Effects of hydrogen supplementation on *Synechocystis sp.* (Created with Biorender).

Technological challenge

To increase the biomass production using hydrogen as a supplementary energy source, an axenic culture of *Synechocystis sp.* will be firstly grown on batch systems at laboratory scale. This will allow monitoring factors such as growth rate, biomass composition, and transcriptomic changes that could reveal potential benefits and difficulties of the process. Other experimental conditions, such as gas and medium composition, light intensity, and temperature could be optimized.

Finally, scaling-up the process will allow determining the feasibility of this approach on continuous and large-scale production systems (Figure 2). The influence of hydrogen supplementation on the production's costs and benefits will also be assessed.

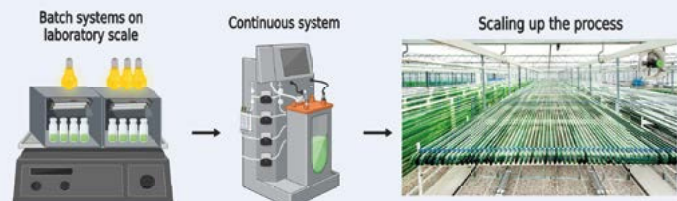


Figure 2. Schematic representation of different stages of a scale-up process with phototrophic microalgae. Going from left to right: batch system, continuous system, and large-scale production system. (Created with Biorender)

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Soil

Soil fertility is a central parameter in the global ecosystem, linking water, food, and nutrient flows. Soil erosion and declining soil fertility pose a significant threat to food production, freshwater availability, and carbon storage. Soil organic matter plays a vital role in the buildup of healthy soil in terms of soil structure and biological activity. To strengthen the circular economy approach, organic streams such as sewage sludge, animal manures and agricultural

plant residues can recycle organic matter and nutrients back to the soil. Organic matter treatment is required to reach appropriate biochemical conditions for soil application. The scope of this theme is to define the most suitable form of organic matter addition, the treatment necessary and the interactions between the organic matter and soil components concerning micro-organisms, organic carbon, and nutrients/minerals.

Research projects

- **Chris Schott**, *Closing nutrient and carbon cycles and contact for Agriculture*
- **Ángel Velasco Sánchez**, *EU SUS-SOIL & SOILCRATES project coordinator*
- **Mithat Can Kuşcu**, Wageningen University, *EPS-based solutions to increase soil structure and resilience to drought*
- **Lourens van Langeveld**, Wageningen University, *Optimization of manure processing: Towards more sustainable manure-based fertilizers*
- **Marija Gadzimuradova**, Wageningen University, *Using organic amendments to prevent pesticide leaching in soils*
- **Brenda Speek**, Wageningen University, *The effect of different organic fertilizers on the soil microbiome*
- **Feride Ece Kutlar**, Wageningen University, *From Waste to Resource: Optimizing Phosphorus and Methane Recovery from Cattle Manure* **NEW**
- **Lilian Quispe Livisi**, Wageningen University, *Unraveling phosphorous crystallization in animal manure: "defining mechanisms to innovate phosphorous recovery* **NEW**
- **Rok Pekusek**, Wageningen University, *Pioneering the link between livestock farming and resource recovery: Correlating production chain effects with the treatment of animal manure* **NEW**



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Motivation

Although several studies demonstrated the potential of different substrates applications such as organic amendments (OA) (Figure 1), to improve microbial diversity, as well as soil structure and aggregate stability^{[1], [6]}, it has been estimated that almost 40% of the total agricultural land in Europe is prone to soil degradation at a moderate or higher level of severity^[4]. Increasing temperatures due to climate change, with more scarce and intense rainfall, accentuates these processes further lowering the capability of soils to store and release water and nutrients and support plant growth. Microorganisms and their metabolic products affect soil structure by binding loose soil particles into water-stable aggregates^[3]. In particular, extracellular polymeric substances (EPS), produced by soil microorganisms, are known to have numerous, positive effects on soils, including improved water retention and aggregate stability^[2]. Gaining insight into the mechanisms regulating EPS formation in soil and their role in determining soil properties can enable solutions to prevent soil degradation. Therefore, this research project aims to develop engineering strategies to enhance EPS production and increase soil structure and resilience to drought.

Technological challenges

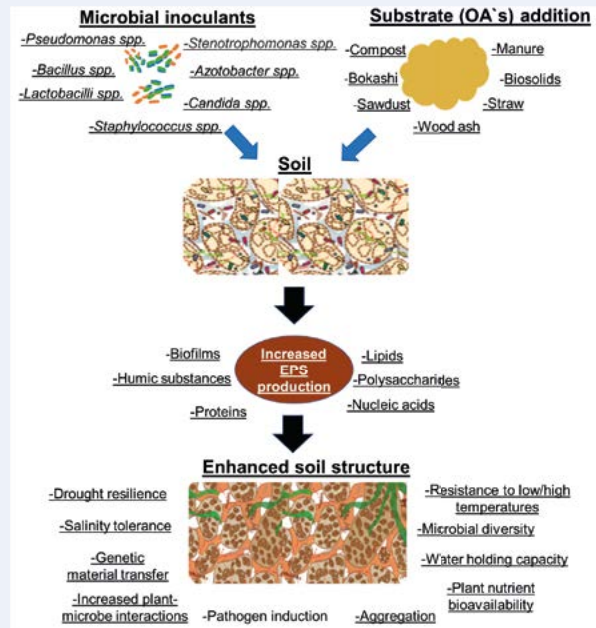
Despite decades of research on the industrial potential of EPS (e.g., bio-lubricants, thickeners, and preservatives)^[5]:

- The use of EPS in agriculture is still very limited
- Our knowledge of EPS composition, structures, and functions is far from complete.
- Our understanding of the mechanisms involved in the biosynthesis and degradation of EPS in soil and their role in determining soil properties is still unclear (Figure 1).

This knowledge gap hampers the possibility of developing effective agricultural strategies able to enhance EPS formation in soil.



Figure 1. Practical sources of soil organic amendments.

Figure 2. Modified conceptual framework of the research approach^[3].

Research goals

The project's ultimate goals are to develop nature-based management strategies to increase soil structure and resilience to drought via EPS stimulation (Figure 2). To develop a fundamental understanding of the EPS production mechanisms in soil, the research will be targeting the following research questions:

- 1: What is the role of OAs and C/N ratio in soil EPS production?
- 2: What is the role of EPS in soil aggregation?
- 3: What is the relationship between EPS and drought resistance of the soil?
- 4: What are the effects of OA-induced EPS on different types of soils?

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Optimization of manure processing: Towards more sustainable manure-based fertilizers



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Motivation

Organic matter supports many ecosystem functions vital for crop production and plays a central regulatory role in GHG-emission control and soil C sequestration^[1]. Globally, soil organic matter, and thus C stores are increasingly depleted as a result of intensive farming practices, affecting both soil functionality and productivity. As a result, many ecosystem services are negatively impacted, such as water holding capacity, greenhouse gas (GHG) sequestration, and crop growth. Reintroduction of C into the soil system is often achieved by amendment with (treated) manure. However, current methods can lead to increased GHG-emissions and eutrophication, as treatment methods and application strategies are far from optimized^[2,3]. In addition, the effect of the treated manures on the microbial, physical, and chemical characteristics of the soil are poorly understood. Steps are made to move from intensive agricultural practices to more regenerative agricultural practices, with the intention to maintain crop output whilst ameliorating soil health, also improving drought resilience.

Through optimization of manure (post and pre-)treatment technologies, nutrient mass balances can be tailored to the needs of the local soil. In essence this poses as a means of nutrient stewardship, which can improve ecosystem services^[4]. As a result, fewer synthetic fertilizers may be necessary for agricultural practices. This can reduce costs, eutrophication and N emissions, whilst improving the soil status in terms of organic matter, aggregation properties, microbial diversity, and water holding capacity. Ultimately, this will make the soil more resilient against exogenous forcings and drought.

This research project aims to improve current manure treatment technologies by combining knowledge and integrating the frontier between bioprocess technology and soil science.

Technological challenge

Manure digestion, and other (post- or pre-)treatments, can improve the sustainability of agricultural practices by allowing increased reintroduction of C and nutrients into the food chain^[2,5]. However, the impact of such treatments in soil needs to be elucidated to achieve more effective amendment use. This calls for challenging data collection and analysis techniques, to determine among others^[4,6]:

1. C uptake
2. GHG emissions
3. Nutrient leaching
4. C and N use efficiency (CUE/NUE)
5. Contribution of microbial C to SOM
6. Effect of organic input (and associated microorganisms) on soil microorganisms

Research goals

1. Determine the differences in effects of various (post and pre-) treatments on physico-chemical and microbial properties of manure, as well as C and nutrient mass balance.
2. Assess the effect of treated manure and its stoichiometry on soil microbial communities looking at changes in the fate of C in soil, specifically OM stabilization and GHG-emissions.
3. Optimization of (post and pre-)treatments to reach tailored CNP balances with the right C quantity and quality.
4. Determine preliminary treatment strategies in relation to soil conditions.

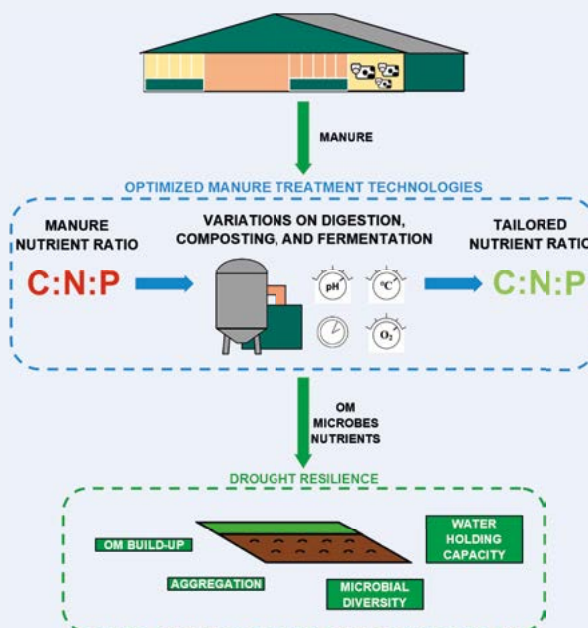


Figure 1. Chain of events

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Motivation

More than 2.4 million active pesticide ingredients are applied worldwide annually to control the occurrence of weeds, insects, and other unwanted organisms [1]. European Union Directive 2020/2184 sets a limit of 0.1 µg/L for pesticides in the water intended for human consumption. Despite the regulations, one or more pesticides in concentrations above 0.1 µg/L are detected in 30 % of all EU water monitoring sites, posing hazard to humans and ecosystems [2]. Alternative methods for pesticide removal from drinking water are imperative to protect human health [1].

Organic amendment (OA) application is an agricultural practice that increases soil nutrient and organic matter content. Additionally, organic residue application modifies the sorption behavior of pesticides. This effect has potential to enhance future pesticide transformation and reduce their transport through the soil profile [3]. Thus, OA application for direct pesticide remediation in the soil is a promising approach to preventing water pollution.

This research aims to develop a fundamental understanding of factors responsible for the fate of pesticides in soil, as well as interactions between pesticides and organic amendments. Obtained knowledge will be used to propose soil management and organic amendment application guidelines for pesticide leaching prevention.

The main benefits are:

- Obtaining nature-based solution for pesticide removal in soil.
- Preventing surface and groundwater pollution.

Technological challenges

- Complexity and abundance of the physical, chemical, and biological interactions in the soil-water matrix [3].
- Variable nature of the organic amendments, and pesticide intrinsic properties [2].
- Establishing the influence of soil management practices on pesticide environmental fate [3].
- Combining the obtained knowledge to propose soil management and OA application guidelines.

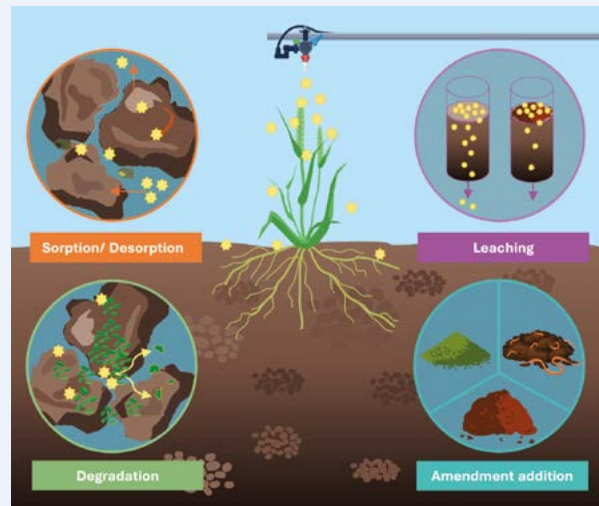


Figure 1. Pesticide fate steering processes and management strategies investigated in this project.

Research goals

1. Determine the mechanisms and kinetics of selected pesticide sorption in different soils.
2. Establish the mechanisms and kinetics of pesticide degradation in different soils.
3. Elucidate the influence of organic amendments with different organic matter content and composition on sorption and degradation of pesticides.
4. Determine the mobility potential of pesticides in soils with and without organic amendment addition under different flow and pesticide aging conditions.

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This project has received funding from the Raak Pro project "Schoon water door duurzaam bodembeheer"



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Motivation

Grasslands cover approximately 70% of agricultural soils worldwide and account for 53% of agricultural grounds in the Netherlands [1, 2]. Fertilization is an essential component of grassland management, used for increasing forage production and yield.

In the Netherlands, grasslands are often fertilized with animal manure [2], which serves as a vital source of nutrients crucial for plant growth and development. Manure is rich in nitrogen; excessive application contributes to emission of greenhouse gases, loss of nutrient through leaching and soil acidification [4]. To make agricultural practice more sustainable, nitrogen emission needs to be reduced.

Technological challenge

Microorganisms play important roles in soil nitrogen cycling [5], yet the impact of organic fertilization on grassland microbiomes remains understudied. Especially in Northern-Europe, research on this topic is still lacking. Therefore, insight is needed to unravel the influence of manure application on soil microbiomes, particularly the effect on microorganisms involved in the nitrogen cycle and their influence on plant nitrogen uptake and unwanted emissions to the environment.

By elucidating the effect of manure fertilization on the soil microbiome, this study aims to contribute to the establishment of efficient fertilization strategies and reducing nitrogen emission.

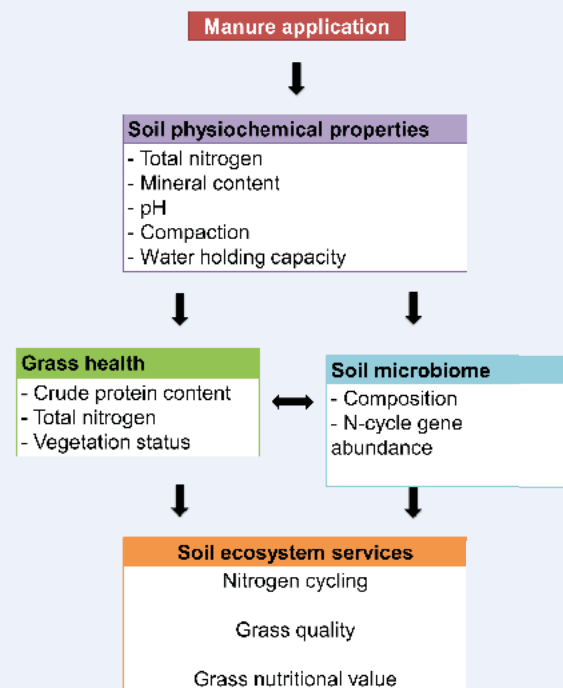
Research goals

The goals of this research is to investigate the effect of different forms of manure fertilization (slurry, digestate and composted) and two different application methods (injection and above ground spreading) on the grassland soil microbiome, with a particular focus on the nitrogen cycle.

This research aims to answer the following questions:

1. What is the impact of different organic fertilizers on composition and diversity of the soil microbial community in grasslands?

2. How does fertilizer injection influence the soil microbial composition and diversity compared to above ground application?
3. Can soil and grass nitrogen content be linked to nitrogen-cycle related gene abundance?



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From Waste to Resource: Optimizing Phosphorus and Methane Recovery from Cattle Manure



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Motivation

Phosphorus (P) is typically sourced from non-renewable phosphate rock, and its uncontrolled release causes environmental issues like eutrophication. Animal manure is the largest secondary source of P which can be recovered and reused^[1]. The Netherlands produces 74 million tons of animal manure annually, of which 61.2 million tons come from cattle as represented in Fig. 1^[2].

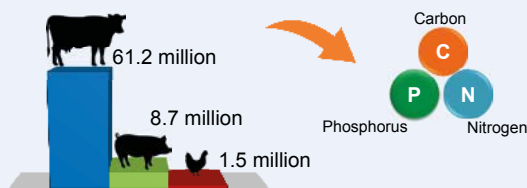


Fig. 1. Manure production in the Netherlands (tons per year) [2]

Therefore, it is crucial to focus on the recovery of P from sources such as cattle manure to prevent the depletion of natural reserves. This project aims to develop a technology that simultaneously recovers calcium phosphate (CaP) and methane (CH₄) within the same reactor. The recovered CaP can be used as fertilizer, while the CH₄ can be an energy source on the farm. The goal is to design a sustainable system that reuses the resources in the manure for on-farm use by using natural principles and the microorganisms already present in cattle manure (Fig. 2).

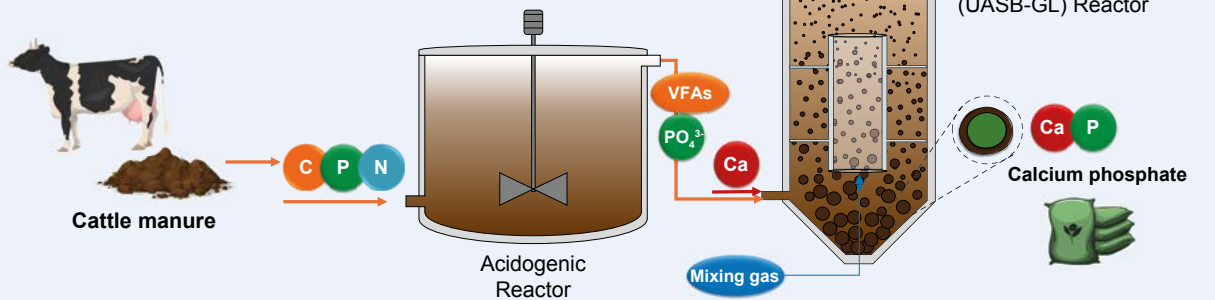


Fig. 2. Proposed phosphorus and methane recovery system

Research goals

- Enhancing technology for efficient P and CH₄ recovery from cattle manure by using natural principles and the microorganisms already present in cattle manure.
- Developing strategies to tackle limited P availability and high inorganic carbon simultaneously.
- Boosting the efficiency and sustainability of manure management through advanced recovery technologies, contributing to better nutrient recycling and waste treatment practices.

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Unraveling phosphorus crystallization in animal manure: Defining mechanisms to innovate phosphorus recovery



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Motivation

Europe has the priority of deriving phosphorus (P) from secondary sources to mitigate dependency on phosphate rock. Animal manure (AM) is the largest secondary source of P and contains significant amounts of nitrogen (N) and P⁽¹⁾. A primary challenge in utilizing AM as a nutrient source is its N:P concentration ratio, where the P content often exceeds crop requirements, leading to runoff and adverse effects on aquatic ecosystems⁽²⁾. An understanding of the mechanism that drives calcium phosphate (CaP) precipitation allows for the separation of P from other nutrients, thereby facilitating its targeted application on land and improving the sustainability of agricultural practices.

Research goals

The possible challenges lead to the following research goals:

1. Investigate the effect of calcium addition on struvite dissolution to enhance CaP formation and P recovery.
2. Elucidate the abiotic and biotic conditions that promote or inhibit CaP precipitation and aggregation in AM.
3. Identify and evaluate potential biochemical mechanisms that could induce CaP precipitation and aggregation in AM.
4. Optimize reactor conditions (molar ratio Ca:P, hydrodynamics, temperature, etc) in an anaerobic reactor to maximize P recovery by CaP precipitation.

Each research goal is illustrated schematically in Figure 1.

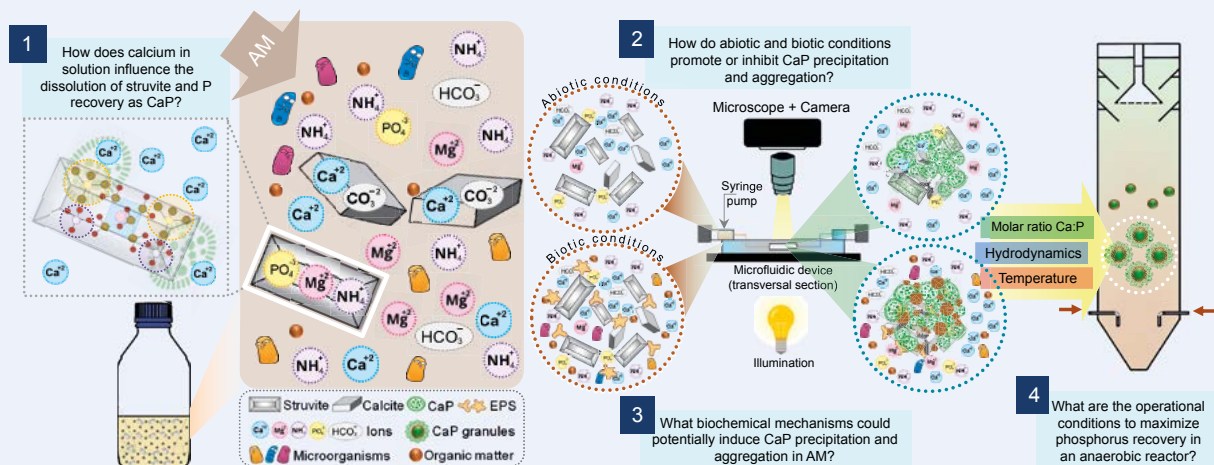


Figure 1. Project overview and schematic approach to achieve the research goals.

Technological challenge

At Wetsus, blackwater (BW) and AM have been investigated for CaP recovery in an Upflow Anaerobic Sludge Bed (UASB) reactor. In BW, microorganisms locally increased the pH within the granules, biologically inducing CaP precipitation in the reactor⁽³⁾. In AM, however, P recovery as CaP was more chemically driven. High ammonia levels in pig manure inhibit microbial growth, leading to a more chemical mechanism in which CaP precipitates with calcite⁽⁴⁾. In cow manure, an acidification step before the UASB reactor was required to release ions and enable CaP precipitation⁽⁵⁾. The challenges of recovering CaP from AM arise from the fact that P is mainly in struvite, intense ion competition and varying precipitation kinetics among supersaturated minerals (struvite, CaP, calcite). Additionally, lack of granulation and the production of biopolymers or EPS during substrate degradation, which may promote CaP aggregation and precipitation. These factors have not been thoroughly explored to understand their impact on CaP precipitation in AM.

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Deutschland – Nederland

ReFarM

Natural water production

The theme natural water production aims to enhance precipitation and make more freshwater available. The key to enhancing precipitation is to increase evaporation and water recycling in a

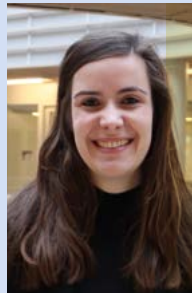
watershed. To make this vision a reality, a strong interdisciplinary approach is taken, including disciplines like meteorology, hydrology, forestry, and water technology.

Research projects

- **Jolanda Theeuwen**, University of Utrecht
Stimulating the natural water cycle over the Mediterranean for more water
- **Sarah Warnau**, Wageningen University,
Identifying meteorological pathways for more rain in dry areas through Enhanced Atmospheric Moistening
- **Gholamabbas Sadeghi**, Wageningen University, *Enhancing the local water cycle via evaporation for a sustainable water supply*



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Motivation

Unsustainable land use is an important driver for desertification and land degradation in dryland areas. Because of this, extreme weather patterns (e.g. droughts) will become more recurrent and intense, intensifying land degradation. Additionally, climate change enhances intensity and frequency of these patterns. Especially in the Mediterranean areas there is a high risk for droughts. There are indications that vegetation reduces the risk of droughts (Figure 1). However, the exact impact of vegetation restoration on weather patterns is difficult to assess. This project aims at **better understanding the influence of vegetation restoration in the Mediterranean area on land-atmosphere interactions**. In this regard, this project aims to assess the feasibility to increase fresh water availability through vegetation restoration in Mediterranean areas.

Technological and Scientific challenge

Land-atmosphere interactions are not fully understood due to the uncertainty in multiple relations (see Figure 2). These relations need to be better understood to improve land surface models and experiments. **To increase this understanding more data sets of evapotranspiration and soil moisture are required and new methods to analyze these and existing datasets need to be acquired.** We will investigate how this knowledge can contribute to improve the assessment of the impact of vegetation restoration on land-atmospheric processes. For this, it is important to first, determine the location dependency of land-atmospheric processes to get a better understanding where greening should be applied, and second, understand the influence of the construction of wetlands on the energy balance and thereby on moisture transport.

Research goal

The goal of this research is **to investigate whether vegetation restoration in Mediterranean areas can increase fresh water availability**. For this research, four objectives are formulated:

- Determine where in the Mediterranean an increase in evaporation could enhance precipitation.
- Determine the effects of vegetation restoration on the local hydrological balance.
- Determine the effects of vegetation restoration on the hydrological balance of a remote area.
- Determine the effects of vegetation restoration on large scale weather and its impact on the hydrological balance.

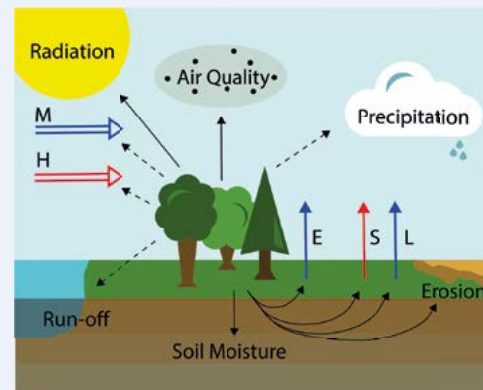


Figure 2. Schematic overview of land-atmospheric relationships. Black arrows indicate direct (continuous) or indirect (dashed) relation. M: transport of moisture, H: transport of heat, E: evaporation, S: sensible heat flux, L: latent heat flux.

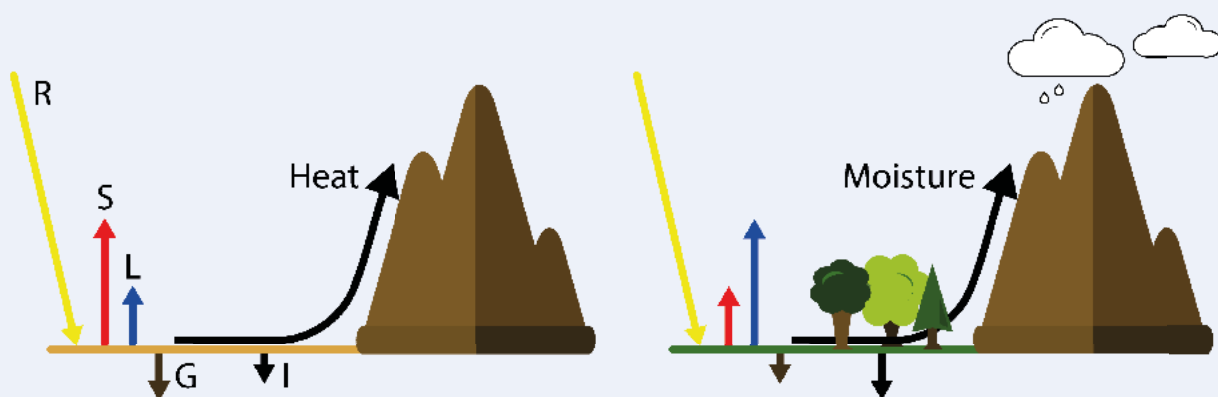


Figure 1. Graphical abstract: Vegetation restoration changes the energy balance the latent heat flux (L) is enhanced and the sensible heat flux (S) is reduced which minimizes the advection of heat and improves the advection of moisture, possibly resulting in fresh water. Also, vegetation enhances Infiltration (I) of water into the soil which allows for an increase in evaporation. R: incoming radiation, G: ground flux. (Icon made by Freepik from www.flaticon.com)

Identifying meteorological pathways for more rain in dry areas through Enhanced Atmospheric Moistening



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Motivation

Freshwater scarcity is a pressing global issue, driven by several processes, including land use change, global warming and regional climate change, and the increase in demand due to population growth. Water conservation strategies play an important role in alleviating the stress on the freshwater resources. However, there is a point where these measures alone may be insufficient. In certain regions, there is a fundamental scarcity of freshwater. In these situations, an input of freshwater is needed. With the Natural Water Production theme at Wetsus, we are looking into **Enhanced Atmospheric Moistening (EAM) by efficiently evaporating sea water with the goal of enhancing rain regionally as a new way of increasing freshwater availability.**

Technological challenge

The state of the atmosphere is driven by large scale systems (synoptic) and diurnal and seasonal changes in incoming solar radiation, affecting the regional energy and water balances, and thus the evaporation rate of the technology. This affects the growth and the composition of the Atmospheric Boundary Layer (ABL), the lowest layer in the atmosphere that is directly affected by the surface of the earth. For clouds to form and develop two levels need to be reached:

- First, moist air parcels from the surface need to be lifted to reach their lifting condensation level, where droplets can form.
- Second, the level of free convection needs to be reached for clouds to deepen and become rain clouds (Fig. 1).

There are two important mechanisms to lift a moist parcel (Fig. 2):

- Convection and growth of the ABL, and
- Lifting of the ABL, e.g. by passing over a mountain range.

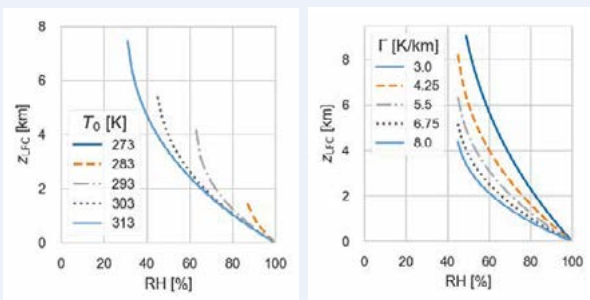


Fig 1. The height of the Level of Free Convection (z_{LFC} [km]) as a function of relative humidity (RH [%]) at the surface, for different linear profiles of temperature for the Free Atmosphere (FA) without a boundary layer: $T_{FA}(z) = T_0 - \Gamma z$. On the left: LFC for different surface temperatures (T_0 [K], $\Gamma = 6$ K/km). On the right: LFC for different lapse rates (Γ [K/km], $T_0 = 303$ K). Not all conditions result in an LFC, e.g. the temperature must be high enough. Furthermore, a more stable atmosphere (lower Γ) will cause the LFC to be higher and thus more difficult for moist air from the surface to reach. With EAM we aim to increase the RH to lower the LFC.

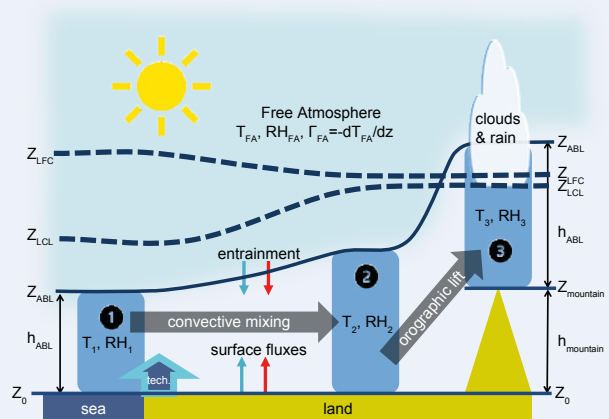


Fig 2. Schematic of the passing and development of an Atmospheric Boundary Layer (ABL) through a watershed bordered by the sea on the left and a mountain range on the right. The temperature (T) and relative humidity (RH) of the ABL change over time because of heat and moisture fluxes from the surface and entrainment of relatively warm and dry free atmospheric air (situation 1 to 2). T and RH change further because of adiabatic expansion through lifting, in this case orographic lifting (situation 2 to 3). Because of the changes in the ABL properties, the Lifting Condensation Level (LCL) and the Level of Free Convection (LFC) can go up or down. Using an evaporation technology (blue arrow, tech.) to moisten the ABL at the right time under the right atmospheric conditions can enable the ABL to reach the LCL and LFC and deep convective rain clouds to form.

Using an evaporation technology can not only affect the moisture content of the ABL, but also the temperature and stability (Fig. 1). This interaction between the meteorological conditions and the evaporative flux of the technology make the design and implementation of EAM for more rain a challenge. On top of that, the atmospheric response to EAM in the form of rainfall (more rain, less rain, or no response) depends on the location, the daily conditions, and the type of technology that is used for evaporation.

Research goals

The goal of this project is to understand the atmospheric conditions and processes that determine how EAM with a technology for regional rainfall enhancement can be successful. With this knowledge we can

- improve the design of the technology for specific conditions,
- determine suitable locations where the probability of success is large, and
- design a control strategy for the technology. Since not all days are suitable for EAM to enhance rainfall, we need to be able to timely determine if the technology should be “switched on” and how much water vapor is needed for the best results.



Gholamabbas Sadeghi

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Motivation

Solar radiation is absorbed by the Earth's surface. Part of it is lost as sensible heat (warming the atmosphere), and another part as latent heat (evaporation) [1]. Fig. 1(a) shows a schematic of the natural water cycle, in which the water evaporates by sunlight, moves upwards, forming condensation clouds, and finally precipitates to complete the cycle. Higher atmospheric temperatures lead to drought. Even though evaporation increases due to the increased water-carrying capacity of air, condensation/precipitation no longer occurs because the point of saturation is not reached anymore. This is often the problem in semi-arid areas of high(er) temperature. The water cycle can be enhanced by promoting evaporation and inhibiting the warming of the atmosphere. Here we explore technology to maximize the sun's radiant energy transformation, using a so-called solar simulator into water evaporation while reducing sensible heat production. In order to improve the evaporation performance and lower the sensible heat transferred to the environment, a solar absorber can be customized [2] as indicated in Fig. 1 (b).

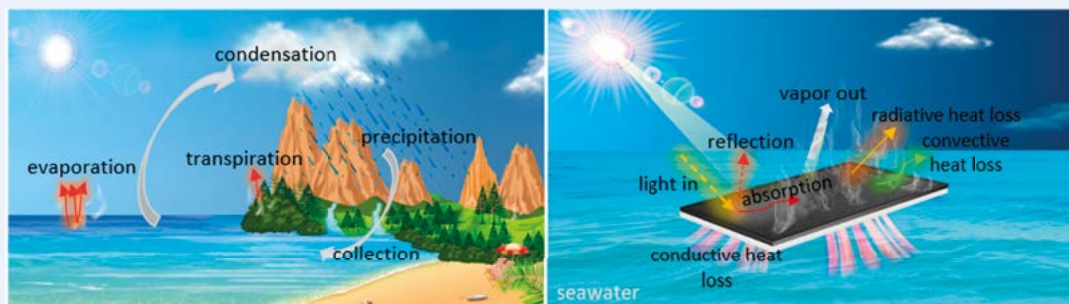


Fig. 1. (a) Schematic of the natural water cycle including evaporation from seawater, transpiration from plants, forming clouds as condensation, and precipitation to enrich watersheds. (b) energy balance of a direct solar steam generator (DSSG) throughout the input light to the vapor generation processes indicating the involved energy interactions.

Technological challenge

In terms of solar evaporation efficiency, the latent heat production in Fig. 1(a) is far from optimal. One reason is that part of the incident light on the sea surface is used to warm up the bulk water underneath by means of conduction. This energy is later released as radiative heat loss (infrared bypass radiation) warming the atmosphere. To remedy this energy loss, localized heating will be exploited. The primary challenge is to ensure minimal radiative heat loss (infrared bypass radiation) from the solar evaporator despite a highly efficient light absorption property. The experimental setup is further composed of a concealed light simulator, a light absorber immersed in water, thermocouples to monitor the temperature along the entire system, and a balance to record the evaporation rate. Challenges ahead include mimicking solar radiation regarding light quality and light intensity, effective water transport from bulk to the surface of the light absorber, and mitigation of salt deposition. Research lines of the ongoing project include different desalination-evaporation geometries as well as investigation of the effect of different environmental conditions like wind speed.

Research goal

This project aims to regreen deserts in semi-arid areas by providing sufficient water for agriculture. It is foreseen that in the final stage, the vegetation itself restores the local water cycle. In general, the major goals of this research can be summarized as:

- The design and building of an efficient solar simulator to mimic sunlight.
- Optimizing a direct solar steam generation (DSSG) material that absorbs low-wavelength light but has a low emissivity of high-wavelength radiation.
- Designing an integrated desalination device.
- The evaluation of the (large-scale) device in terms of impact applying atmospheric boundary layer (ABL) modeling.

References:

- [1] NASA (2022). "earthobservatory.nasa.gov/features/Energy Balance/page5"
- [2] Liu, X., et al. (2020). "Towards highly efficient solar-driven interfacial evaporation for desalination." *Journal of Materials Chemistry A* 8(35): 17907-17937

Sustainability in the making

Wetsus aims at responsible water technology innovations that strengthen a fair, sustainable and productive society. To get ahead, it is necessary to have both a good technological innovation base and a clear insight into the road towards these responsible innovations.

This theme focuses on studying such responsible innovation roads using state-of-the-art social sciences theories, concepts and

models. Projects will focus on specific Wetsus innovations and will be tightly embedded within the Wetsus network. In this way social sciences together with public companies, end users, technology providers, and natural sciences will cooperate to provide a framework for analyzing and strengthening the responsible innovation process of Wetsus and its partners.

Research projects

- **Irina Pozhidaeva**, University of Groningen, *In search of the foundations of successful collaboration in research-innovation networks*
- **Bernardo Coutes Soares**, Wageningen University, *Sustainability in the making: the case of new sanitation in the Netherlands*
NEW



THEME COORDINATOR
Xiaoxia Liu
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Industrial partners



Phenotypo Studio



开 明 咨 询



WETTERSKIP
FRYSLÂN



Academic partners



university of
 groningen



WAGENINGEN
UNIVERSITY & RESEARCH



Irina Pozhidaeva

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Motivation

University-industry collaboration (UIC) is often seen as an economic driver because knowledge transfer between academia and industry can stimulate innovation. However, the diverse background of partners can have negative consequences that may outweigh the benefits of such cooperation. Intermediary organizations are established to overcome the cognitive distance between participants and facilitate UIC [1].

This study aims to pick out the key social factors that contribute to successful cooperation in UIC knowledge-intensive projects and identify the place of intermediary organizations in this process. For this purpose, we explore Wetsus, a unique Q/Q helix network consisting of academia, industry, government, environment, and civil society [2].

Research challenge

The interaction between universities and industry is attracting increased attention from scholars who are looking for factors that determine success. However, there is a dearth of understanding regarding the patterns and configurations leading to satisfactory results. In this research project, we apply a multidimensional approach based on the social system concept [3] to uncover several possible paths to UIC success (Fig. 1). A combination of qualitative and quantitative research methods is used to identify the configurations of social factors influencing outcomes and elucidate the underlying mechanisms of these effects.

Research goals

The aim of the project is to investigate the configurations of social factors that predict the success of collaborative projects between academia and industry in the context of sustainable (water) development. This goal will be achieved in stages:

- Identifying the key social factors that predict the success of university-industry collaboration using literature and explorative data;
- Development of the theoretical framework based on the social system concept;
- Empirical examination of various equifinal combinations of factors or conditions that contribute to the success of UIC;
- Providing practical recommendations for academic institutions, industry leaders, and policymakers on how to build collaborations for maximum effectiveness.

References

- [1] Villani, E., Rasmussen, E., & Grimaldi, R. (2017). How intermediary organizations facilitate university-industry technology transfer: A proximity approach. *Technological Forecasting and Social Change*, 114, 86–102.
- [2] Cloitre, A., Dos Santos Paulino, V. and Theodoraki, C. (2023). The quadruple/quintuple helix model in entrepreneurial ecosystems: an institutional perspective on the space case study. *R&D Management*, 53, 675-694.
- [3] Parsons, T. (1951). *The Social System*. Routledge & Kegan Paul Ltd, England.
- [4] Groen, A. J. (2005). Knowledge intensive entrepreneurship in networks: Towards a multi-level/multi dimensional approach. *Journal of Enterprising Culture*, 13(01), 69–88.

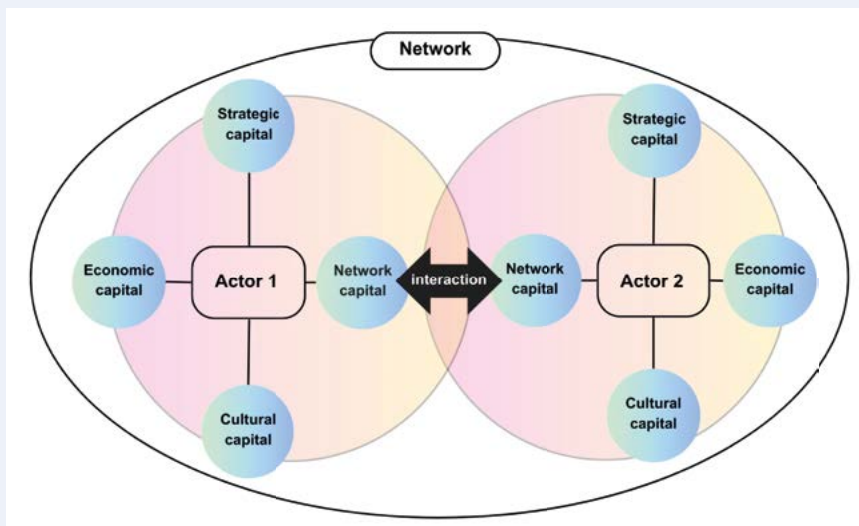


Fig 1. Dyadic Network Model from a Social System Perspective (adapted from Groen, 2005 [4]).

European projects

Research projects

- **EMPOWER**, Entrepreneurial Multidisciplinary Scientists Forging Pathways
- **Agro2Circular**, Territorial Circular Systemic Solution for the Upcycling of Residues from the Agrifood Sector
- **ConsenCUS**, Carbon Neutral Clusters by Electricity-based Innovations in Capture, Utilisation and Storage
- **STARTS 4 WATER II**, S + T + ARTS initiative (Science, Technology, and Arts) for Water/interdisciplinary collaboration for sustainable water management
- **WATER MINING**, Next generation water-smart management systems: large scale demonstrations for a circular economy and society
- **RecaP**, training the new generation of phosphorus specialists
- **NINFA**, Taking action to prevent and mitigate pollution of groundwater bodies
- **H2OforAll**, Innovative Integrated Tools and Technologies to Protect and Treat Drinking Water from Disinfection Byproducts (DBPs)
- **Water4All**, Water Security for the planet
- **SUS-SOIL**, Sustainable Soil and Subsoil Health Promotion by implementing agroecological land use and management
- **SOILCRATES**, SOil Innovation Labs: Co-Regenerating And Transforming European Soils
- **ReFarm**, Rethinking Farming and Manure management
- **Urban M₂O**, Effective Monitoring and Modelling Solutions for Data-driven Holistic Management of Urban Water Quality



S+T+ARTS 4 WATER II



EMPOWER

Entrepreneurial Multidisciplinary Scientists Forging Pathways
Onto Clean Water, Sustainable Energy and Resources

SCOPE

The objective of EMPOWER Doctoral Programme is to encourage entrepreneurship in research, resulting in a next-generation PhD: **a scientific entrepreneur** that fosters the commercialisation of scientific discoveries, generates a clear communication channel between industry and university, and creates pathways for their coexistence.

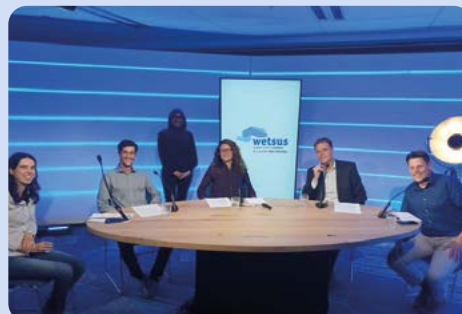
SCIENTIFIC ENTREPRENEUR

The training programme offered to the EMPOWER PhDs consists of four main interconnected parts:

- **Research:** Be a part of leading research groups equipped with cutting-edge facilities.
- **Multidisciplinary expertise:** PhDs will follow a series of courses, workshops, conferences, and interaction with fellow research group.
- **Entrepreneurship:** Opportunity to take business-related courses.
- **Personal development:** PhDs will follow a dedicated personal development programme at Wetsus.



The EMPOWER knowledge triangle.



The EMPOWER launching webinar

AT A GLANCE

FUNDING PROGRAMMES:

H2020-MSCA-COFUND-2020

TYPE OF ACTION:

Marie Skłodowska-Curie Actions (MSCA)
COFUND Doctoral Programme

DURATION:

60 months
(01 January 2022 – 31 December 2027)

COORDINATOR:

Wetsus | dr. M. Cristina Gagliano
(cristina.gagliano@wetsus.nl)

OUTCOME FROM THE EMPOWER 1ST CALL



Call open:
6 September –
29 October 2021



14 PhD projects
launched



21 external
evaluators
and experts



1001 applicants



30 supervisors



70 nationalities
76 residing countries

UNIVERSITY PARTNERS



UNIVERSITY OF TWENTE.



This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101034321

phdpositionswetsus.eu



Motivation

The 'Nutrition Targets' set by the World Health Organisation, and the 'Sustainable Development Goals' defined by the United Nations emphasize the urgency of healthy and sustainable food. As pointed out in the Green Deal of the EU, a more sustainable society requires the transition from animal-based to plant-based proteins¹. This project targets protein-containing streams in the (potato) food industry that are currently considered waste. If these proteins could be separated or fractionated effectively they provide an alternative protein sources for animal-based proteins. Apart from sustainability issues, this strategy also adds to the product portfolio of food manufacturers².

Technological challenge

In general, the protein concentration is low in the previously mentioned streams, thus effective separation and dehydration methods are needed. Because of this, extensive water removal is needed to reach appropriate starting materials for the food industry. All this asks for effective separation and dehydration technologies. It is, however, essential that the methods employed preserves protein functionality, are used to steer functionality toward different applications in food. The functionality studied in this project is the coalescence properties of oil droplets coated with these particular plant proteins. As for process conditions, special attention will be paid to the effect of temperature and the oxidation level on protein functionality. Figure 1 shows the overview of the protein separation and functionality studies.

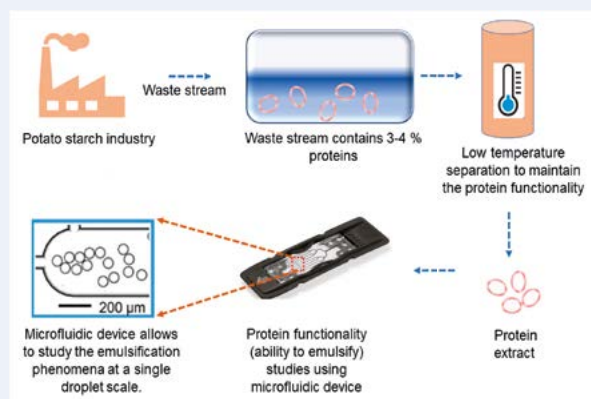


Figure 1: Schematic overview of the research project.

Measurement method

Microfluidics allow droplet formation and coalescence investigations at the millisecond time scale³ based on many observations done within a very short time. We start our investigations with the so-called coalescence chamber (see Figure 2). In the T-junction (red rectangle) droplets are formed under well defined conditions. In the coalescence chamber, the size of the droplets can be observed at various spots (green and blue rectangles, for example), which is indicative of the functionality of the protein. The droplet formation time and droplet interaction time can be systematically varied through the length of the meandering channel (in Figure 2, connecting the red and green rectangles). This allows for detailed analysis and is comparable to conditions as would occur in industrial practice. The kinetics of coalescence thus is a measure of the emulsifying behavior of the protein-coated oil droplets.

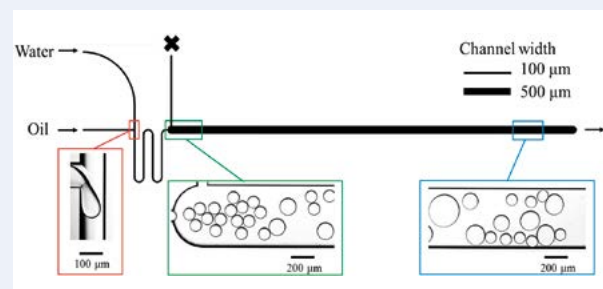


Figure 2: Schematic of the microfluidic device.

Research goals

- Study the emulsifying abilities of potato proteins using a microfluidic device and determine the optimal concentration of protein required to stabilize the emulsion.
- Investigate the effect of protein oxidation on emulsification.
- Study the effect of operating temperature during protein separation on emulsification.

References

- [1] Cué Rio, M., Bovenkerk, B., Castella, J. C., Fischer, D., Fuchs, R., Kanerva, M., & Róds, E. (2022). *Sustainability Science*, 1-19.
- [2] Liu, Z., Wu, Z., Li, R., & Fan, X. (2013) *Journal of food engineering*, 114(2), 192-198.
- [3] Hinderink, E. B., Kaade, W., Sagis, L., Schroën, K., & Berton-Carabin, C. C. (2020) *Food Hydrocolloids*, 102, 105610.



This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101034321.

SCOPE

EU project Agro2Circular aims to convert the most relevant residues in the agri-food sector (fruits & vegetables and plastic multilayers) into renewable value-added products.

An innovative route to valorise fruits & vegetables waste is conversion into the biobased and biodegradable polymer PHA. As project partner, Wetsus' focus is on green solvent extraction of PHA from PHA-rich-biomass. The recovered PHA biopolymers are pure (>98%) and of high-quality with a favourable sustainability profile. Project partners will subsequently compound the PHA into food packaging and agricultural films that will be evaluated for mechanical properties, food grade application, recycling and biodegradability.



IMPACT

- Agro2Circular aims to transform the current linear economy to be circular for fruit and vegetable residues, and for plastic multilayers.
- Wetsus' knowledge and infrastructure on PHA extraction supports the conversion of fruit & vegetable wastes into high value added PHA.

EXPECTED OUTCOME

- The innovative recycling solutions of the Agro2Circular project will be demonstrated in the region of Murcia (Spain). Boosting regional circular economic development and enabling replicability in the EU.
- Wetsus will extract PHA, which will be compounded by project partners into biodegradable food packaging and/or agriculture film prototypes.
- Wetsus will strengthen its knowledge on PHA recovery. This knowledge and experience flows to demo-scale developments that run in parallel and support scaling up to industrial PHA production.

AT A GLANCE

FUNDING PROGRAMMES:
EU HORIZON 2020 PROJECT

DURATION:
36 months (Oct. 2021 – Oct. 2024)

PROJECT BUDGET:
€ 16,8 million

COORDINATOR:
Project coordinator (CETEC) |
Fuensanta Monzó Sánchez
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Wetsus | Raquel Barbosa
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Coordinator Polymers from Water
Theme | Alan Werker
(alan.werker@wetsus.nl)

PROJECT PARTNERS

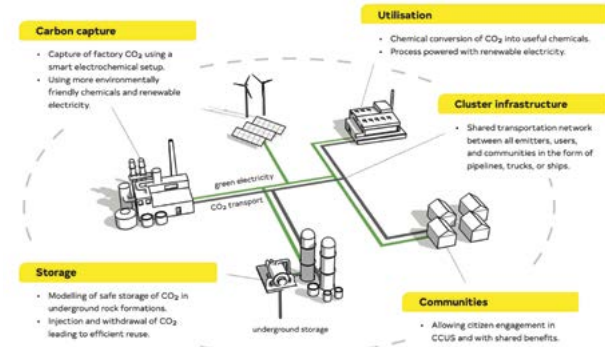
The Agro2Circular consortium consists of 41 partners from 9 EU countries, including companies, research institutes and decision makers (public, policy, financing and standardization). The focus of the project is on the Murcia region (Southeast of Spain).

PHA flakes produced at the pilot facility at Wetsus



SCOPE

The ConsenCUS project aims at showing how net-zero-carbon industry can be achieved by (1) demonstrating the techno-economic viability of green electricity-based, energy-efficient CCU innovations in an industrially relevant environment, and (2) showing how regional CO₂ networks can cost-effectively take the captured CO₂ to end users, or permanent and/or intermediate storage. Important aspects such as process modeling, costing and business analysis, as well as societal and environmental aspects will be fully addressed, clearing the way to full roll-out of technology and making industries with large CO₂ emissions neutral (net zero emissions) as soon as possible.



How do we envision Net-zero CO₂ clusters

EXPECTED OUTCOME

- Highly efficient CO₂ capture process in alkaline blends (capture rate >90%; specific energy needs 1.4 GJ/t CO₂; levelized capture cost <€20 per tonne CO₂);
- Novel electrochemical regeneration producing a high purity CO₂ stream (>96%);
- Electrochemical conversion of CO₂ to added-value products (formate) at competitive costs;
- Highly replicable solution - Demonstration on-site in three major plants (cement, magnesia production; oil refinery), at a scale of 0.1 tCO₂/h;
- Design of net-zero CO₂ clusters with an highly integrated technological, environmental, and societal approach.

AT A GLANCE

PROGRAMME:

H2020-EU LC-SC3-NZE-5-2020 (Competitive, Low Carbon and Circular Industries)

EU CONTRIBUTION: € 4.3 million

DURATION: 48 months (01/03/2021 – 28/02/2025)

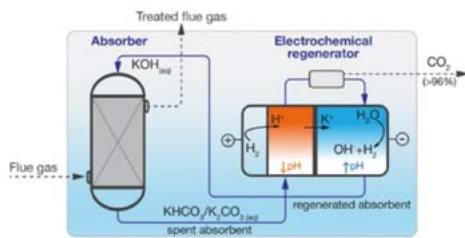
CONTACT DETAILS:

Project coordinator |

Dirk Koppert | New Energy Coalition
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Wetsus project leader |

Sara Vallejo Castano
(sara.vallejocastano@Wetsus.nl)



CO₂ capture via alkaline absorption and electrochemical regeneration

PROJECT PARTNERS



STARTS 4 WATER II

S + T + ARTS initiative (Science, Technology, and Arts) for WaterInterdisciplinary collaboration for sustainable water management

SCOPE

- S+T+ARTS4Water facilitates interdisciplinary co-reflection with professional artists by means of collaborative art residencies, international educational workshops, exhibitions, conference & network activities that bring artists, researchers, stakeholders and ICT experts together to tackle specific local and corporate water challenges and to speculate on future visions of water management.
- This initiative offers the opportunity to embrace the principles of the New European Bauhaus. By incorporating sustainability, aesthetics and inclusiveness into the tackling of water challenges, the community involvement can be improved during technology development for a more responsible innovation process.
- In this project, Wetsus and its industrial partners (Waterschap de Dommel, Bright Spark, NTK, IPF) will provide scientific and technological support for an artist residency (10 months) that works on a dedicated water challenge under the collaboration with the Waag future lab. At the end, an art installation responding to a certain technology development and water challenge will be created and exhibited worldwide for a wider impact on the society.

IMPACT

- Through 20 artists residencies, 80 meetings, 5-day summer School, more than 15 events, 15 showcases at local level, 3 large exhibitions, and 6 labs at local level, more than 15.000 people reach
- Exhibitions at 2025 UN Ocean Conference (Nice), the Love Tomorrow Conference during Tomorrowland Festival, Ars Electronica 2025

EXPECTED OUTCOME

- Contribute towards new narratives and knowledge sharing on water management and raise awareness on pressing challenges within Belgium, the Netherlands, Slovenia, Croatia, Ireland, France, Austria, and Italy



Credit picture: Territorial Agency, Oceans in Transformation

S + T + ARTS

SCIENCE + TECHNOLOGY + ARTS



AT A GLANCE

FUNDING PROGRAMME:

HORIZON 2020-STARTS4WATERII

Type of Action :

Artist residency & exhibition

DURATION: 84 months

22 months [Jan 2024-Oct 2025]

Residency phase [Sept 2024-May 2025]

Exhibition phase [May 2025-Oct 2025]

PROJECT PARTNERS



CONTACT

Project coordinator | Zeynep Birsel |

Waag future lab

Coordinator Wetsus | Xiaoxia Liu

Xiaoxia.liu@wetsus.nl

S+T+ARTS 4 WATER II



This project has received funding from the European Union's Horizon 2020 research and innovation programme.

starts.eu

WATER MINING

Next generation water-smart management systems: large scale demonstrations for a circular economy and society

SCOPE

The WATER-MINING project aims to provide examples for real-world implementation of the Water Framework Directive to help the transition to Circular Economy. Demonstrations of innovative technologies in Cyprus, Spain, Portugal, Italy and The Netherlands will be built to show novel efficient ways to reclaim nutrients, minerals, energy and water from industrial and urban wastewater and seawater.

In this project, Wetsus will investigate and develop a suitable phosphorus (P) recovery method for waste water treatment plants (WWTP) that use NEREDA® technology and discover synergies with Kaamera Nereda® Gum extraction. Furthermore, two technologies for phosphorus removal and recovery will be demonstrated in Cyprus and Spain. Reversible P adsorption on iron-oxide resins (BioPhree), and a vivianite crystallization technology called ViviCryst.



Kaamera extraction plant Zutphen Picture: Waterschap Rijn en IJssel

IMPACT

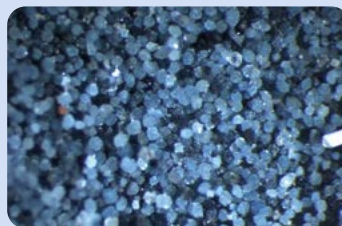
- P-removal to ultra-low levels will prevent biofouling on membrane systems treating WWTP effluent
- P removal will prevent eutrophication of water bodies receiving WWTP effluent
- P recovery from wastewater will provide the EU with its own source of this critical raw material

EXPECTED OUTCOME

- Best practice developed for P recovery for NEREDA® plants in combination with Kaamera extraction
- Feasibility of BioPhree and ViviCryst demonstrated for P removal and recovery
- Economic evaluation and best method for a BioPhree and ViviCryst combination determined



BioPhree installation. Picture: Aquacare



Recovered vivianite crystals. Picture: Wetsus

AT A GLANCE

FUNDING PROGRAMMES:

H2020-EU.3.5.4.

H2020-EU.3.5.2.2.

TOTAL FUNDING : €16.9 MILLION

DURATION:

48 MONTHS

1 SEPTEMBER 2020 – 31 AUGUST 2024

PROJECT PARTNERS



CONTACT

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Communication leader | Nicole Heine | DECHEMA
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Coordinator Wetsus | Wokke Wijdeveld
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BACKGROUND

Phosphorus (P) is a vital input for agricultural production but current agricultural practices are overexploiting and wasting the earth's P reserves. In addition, there is a large flow of P from agriculture to surface waters, where eutrophication severely deteriorates ecosystems. Hence, P is polluting the environment, while at the same time valuable P resources are lost. Important steps towards a circular P economy includes restructuring the P governance and developing novel P management solutions at regional and global scales.

AT A GLANCE

TOTAL FUNDING:
€ 4.3 million

DURATION:
48 months (01/03/2021 – 28/02/2025)

COORDINATOR:
Project coordinator |
Jacob Reardon (SDU) (jare@sdu.dk)
Wetsus |
Thomas Prot (thomas.prot@wetsus.nl)

STRATEGY

RecaP will address these needs by creating a new generation of P specialists to become multi-disciplinary 'knowledge brokers' ensuring transformative changes in P sustainability in the EU. ESRs will focus on capture and recycling of P from wastewater and freshwater systems, novel P recovery techniques, strategies to improve crop

utilization of P, novel freshwater restoration techniques, as well as barriers and enablers to policy and economic transformation to support recycling. All activities are connected to one another in order to create novel insights that can help create new P governance.

EXPECTED OUTCOMES



PROJECT PARTNERS



The RecaP project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 956454.

SCOPE

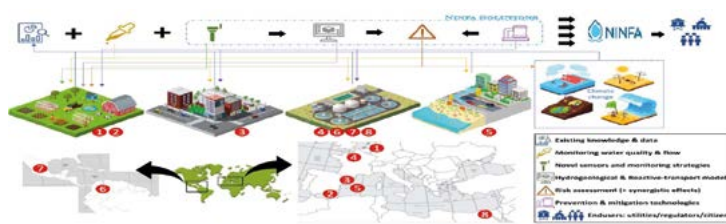
NINFA will provide an innovative approach that relies on an early-warning decision support system and knowledge base (NINFA Platform) and a set of innovative and cost-effective monitoring, modeling, and treatment solutions, taking into account diverse pollutants (salinity, nutrients, and organic micropollutants) and synergistic effects derived from climate and global changes, with the objective of preventing groundwater contamination, protecting its quality, and enhancing its resilience.

IMPACT

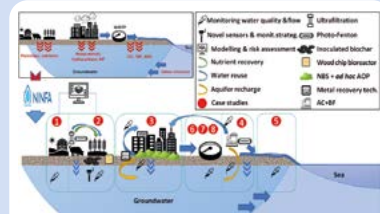
- Develop novel sensors with high resolution (1m) and accuracy (water flow $\pm 10\%$ deviation and salinity $\pm 10\%$ deviation).
- Optimize HyGenTox Chip sensor for the automated detection of toxic pollutants in groundwater system.
- Optimize the groundwater withdrawals, identifying by modelling the reduction rate and the best locations to limit groundwater abstraction.
- Remove 80% of hydrocarbons and microplastics from wastewater by developing and validating trains of treatment technologies.

EXPECTED OUTCOME

- Develop a cost-efficient monitoring strategy based on the integration of existing sensors and analytical approaches with innovative tools.
- Assess the existing sources and pathways of groundwater pollution, by testing and validating hydrogeological and reactive transport models.
- Develop preventive measures to protect the quality of groundwater, soils, and receiving water bodies by optimizing and validating different trains of technologies.
- Develop a risk assessment methodology to ensure that reclaimed water aquifer recharge (together with other pollution prevention/mitigation strategies) does not cause substantial harm to the ecosystem.
- Develop and validate an integrated early-warning decision support system for efficient and holistic groundwater management and protection.



Development and validation of NINFA Solutions and Platform in case studies



NINFA systemic approach against GW exploitation and contamination

AT A GLANCE

FUNDING PROGRAMME:

Union's Horizon Europe 2021

EU CONTRIBUTION: € 3.9 million

DURATION: 42 months

1 Nov. 2022 – 30 April 2026

PROJECT PARTNERS



CONTACT

Project coordinator |
 ACONDICIONAMIENTO
 TARRASENSE ASSOCIACION
 (LEITAT)

Wetsus project leader |
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SCOPE

Water purification and disinfection are crucial processes to provide safe water to citizens. Still, low quality of water sources, caused by increasing contamination of soil/freshwater, makes this goal very challenging. When chlorine disinfectant reacts with organic matter in water, disinfection byproducts (DBPs) are produced. They have a severe impact on the environment and human health, even at low concentrations. Effects on human liver activity and neurotoxicity were already reported, but formation, presence, and impact are still not well understood. The H2OforAll project aims to assess main DBPs sources and fate by developing fast, cost-effective, and accurate sensor monitoring devices and modelling their spread through drinking water distribution systems. In addition, DBPs toxicity and environmental impact will be studied in this project, and measures are proposed to protect the drinking water chain.

IMPACT

DBPs toxicity and environmental impact will be studied and measures will be proposed. Breakthrough water treatments to remove DBPs or avoid their formation will be developed, paying attention to their life cycle analysis, costs and risks. A Central Knowledge Base with reliable data on the occurrence of DBPs in the EU and their effects will be created to increase awareness and engagement of society and governmental organizations about these drinking water contaminants and favour new policy responses and guidance.

EXPECTED OUTCOME

- A better understanding of DBP formation and transmission pathways, allowing adequate measures to prevent/minimize production.
- New disinfection technologies and cost-effective water quality sensors provide real-time information on drinking water quality from sources to supply.
- A central knowledge base with information about DBPs
- Prevention plans to protect drinking water will be developed



Figure 1: Disinfection Byproduct (DBPs) formation pathways



Figure 2: Real-time information on drinking water quality

AT A GLANCE

FUNDING PROGRAMMES:

HORIZON 2.6.7

TOTAL FUNDING : € 3.45 million

DURATION: 36 months

1 November 2022 – 31 October 2025

PROJECT PARTNERS



CONTACT

Project coordinator | Luisa Durães

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Project coordinator | Rui Martins

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Coordinator Wetsus | Martijn

Wagterveld

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SCOPE

The Water4All Partnership - Water Security for the Planet - is co-funded by the European Union within the frame of the Horizon Europe programme (a key funding programme for research and innovation). The objectives are to tackle water challenges as means to face climate change, help to achieve the United Nations' Sustainable Development Goals, and boost the EU's competitiveness and growth.



Water4All Strategic Research Agenda

ACTIVITIES

A broad range of strategic, research and innovation, and practice-oriented activities will be implemented, including support to start-up creation, capacity building through training (from vocational education to PhD programmes), and demonstration sites & living labs.



Water4All Activities

AT A GLANCE

FUNDING PROGRAMME:

HORIZON-CL6-2021-CLIMATE-01
HORIZON-CL6-2023-CLIMATE-01

INITIAL BUDGET: € 86 million

INITIAL FUNDING: € 26 million

TOTAL FUNDING RESERVED FOR PARTNERSHIP: € 126 million

DURATION: 84 months

1 June 2022 – 31 May 2029

PROJECT PARTNERS

Gathering over 90 partners from 33 countries from Europe and beyond, from the whole water Research, Development and Innovation chain, including the province of Fryslân, the municipality of Leeuwarden, CIV Water, CEW, Water Alliance and Wetsus.



Global coverage Water4All partnership

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SCOPE

According to the EU Soil Strategy, around 60 to 70% of the soils in the European Union are not healthy and suffer from severe degradation processes. The degradation processes primarily affecting the topsoil are also depleting the subsoil's (> 0.3 m) health, reducing their ecosystem services delivery. SUS-SOIL is a 4-year project adopting a multidisciplinary approach that will develop a set of 15 Subsoil-Living Labs (LLs) to inventory, analyze and benchmark different agroecology management approaches and land uses and their impacts on the subsoil spatial variations and dynamics.

AMBITION

The main ambition of SUS-SOIL is to promote the sustainable management of soil by considering subsoil health and its ecosystem services, fostering the agroecological transition in rural and urban areas across Europe.

ACTIVITIES

- Creation of an agroecological subsoil management network between 15 Living Labs.
- Create a standardized protocol to sample sub-soil layers in accordance with previous EU soil monitoring initiatives.
- Characterize soil biological, chemical and physical properties of European subsoils.
- Assess sustainability of topsoil management on the subsoil.
- Wetsus will organize the LL of The Netherlands and organize pilot experiments that will assess agricultural sustainable practices on subsoil.



Map of Living Labs and partners of SUS-SOIL



Soil profile (0 – 1.5 m) in the Veluwe (Netherlands)



AT A GLANCE

FUNDING PROGRAMME:
HORIZON.2.6 - Food, Bioeconomy
Natural Resources, Agriculture and
Environment

TOTAL FUNDING: € 6 million

DURATION: 48 months
1 October 2024 – 30 September
2028

PROJECT PARTNERS



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SOILCRATES

SOil Innovation Labs: Co-Regenerating And Transforming European Soils

SCOPE

Today, an estimated 60-70% of soils in the EU are (severely) degraded due to unsustainable land use practices and pollution. However, advancing towards sustainable agriculture remains challenging. The SOILCRATES consortium includes 21 partners, including farmers, research institutes, governmental agencies and companies across The Netherlands, Ireland, France and Spain. SOILCRATES partners will work together on the tasks defined by the EU Mission 'A Soil Deal for Europe', creating four Living Labs that will produce pilot experiments and knowledge transfer activities with a bottom-up approach.

AMBITION

The main ambition of SOILCRATES is to create sustainable and dynamic Living Labs and to monitor and promote soil health and biodiversity.

ACTIVITIES

- Create four interconnected Living Labs to inspire a shift towards a living soil centered agricultural system.
- Develop a standardized and accessible soil health monitoring scheme on applied management practices.
- Co-create and utilize practices, tools and strategies for improving soil structure and soil biota.
- Facilitate knowledge transfer, participatory approaches, and policy recommendations.
- Wetsus will focus on evaluating soil ecosystem services and on assisting the interconnection between Living Labs by providing scientific support.



AT A GLANCE

FUNDING PROGRAMME:

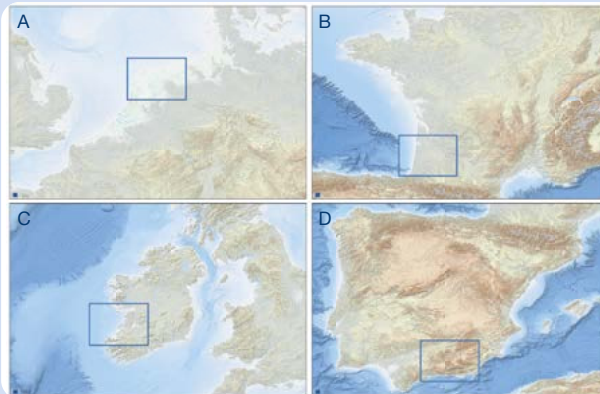
HORIZON.2.6 - Food, Bioeconomy Natural Resources, Agriculture and Environment

TOTAL FUNDING: € 12 million

DURATION: 48 months

1 October 2024 – 30 September 2028

PROJECT PARTNERS



Locations of SOILCRATES Living Labs: A, North of the Netherlands, B Landes, France, C Southwest of Ireland and D Granada, Spain

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SCOPE

Rethinking Farming and Manure management (ReFarM) aims to contribute to sustainable agriculture by developing and implementing technology which locally improves the valorization of animal manure. The ReFarM project aims to implement technological solutions to convert manure from waste into products such as fertilizer alternatives, soil improvers and renewable energy in the form of biogas. The recovered products can replace current products derived from primary resources such as fertilizers from mining, organic substrates from peat extraction and fossil fuels. The local reuse of resources minimizes emissions and damage to the local environment, as well as soil contamination from the emissions-intensive extraction of primary resources.

IMPACT

- Secondary resources in animal manure will be valorized
- Phosphorus and nitrogen will be turned into products for precise farming
- Harmful emission will be prevented and a more circular farm-based system developed with little transport of wet manure
- Soil demands guide the treatment process of manure

EXPECTED OUTCOME

- A mobile pilot installation with user experiences under four different circumstances
- A demonstration unit in full scale combined with field experiments providing insights into fertilization and presence of Compounds of Emerging Concern
- LCA and business model studies will identify the benefits of new technology, and soil and manure management



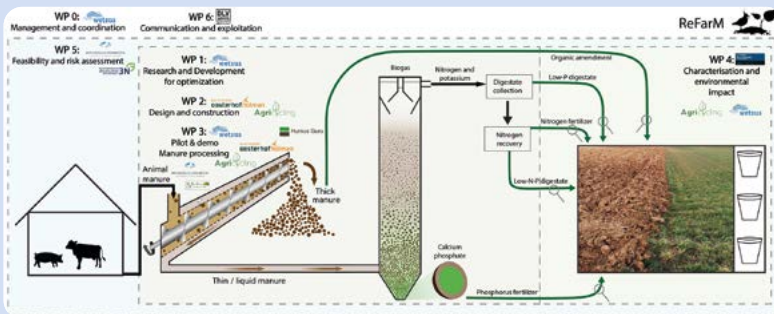
ReFarM aims for a circular system in farming to make agriculture more sustainable.

AT A GLANCE

FUNDING PROGRAMME:
Interreg Deutschland Nederland
TOTAL FUNDING: € 5 million

DURATION: 48 months
1 June 2024 – 30 May 2028

PROJECT PARTNERS



Overview of the activities of ReFarM.

CONTACT

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SCOPE

Urban M₂O's main objective is to create and demonstrate tools to merge and integrate data from different sources across the urban water system, supporting a 'whole system monitoring approach' addressing the multifaceted pollution threats to water quality. These solutions include market-ready, cost-effective monitoring technologies enhanced by AI-methods, identifying proxies for pollution indicators, and fit-for-purpose modeling tools (digital twins and data sharing platforms), extrapolating information from monitoring data at the city/catchment scale. Integrating these two approaches will enhance the value of the collected, openly available information, bolstering the development and implementation of data-driven water quality management plans. In this project, Wetsus will develop and benchmark AI-enhanced monitoring technologies at 3 pilot locations in Barcelona, Copenhagen, and Zürich, attract external technology developers, and integrate the developed monitoring technologies with a digital twin of urban water systems.



Representation of the Urban M₂O solution

IMPACT

- Enhance urban water quality, better guidance for policy-making and prioritization by integrated urban water quality monitoring management plans
- Sound, safer, and risk-based urban water quality management supported by evidence-based, enhanced holistic monitoring, modeling, and digital solutions
- Increase uptake of digital tools in the water sector to support water management decisions for all stakeholders

EXPECTED OUTCOME

- Validated AI-enhanced sensors provide real-time surface and groundwater quality information
- Tailored guidance for planning and implementation of data-driven pollution management plans
- Fit for purpose digital twin of urban water systems and pollution management plans

AT A GLANCE

FUNDING PROGRAMME:

Horizon-CL6-2024-Zeropollution-02

TOTAL FUNDING: : €6.62 million

DURATION: 48 months

1 June 2025 – 31 May 2029

PROJECT PARTNERS



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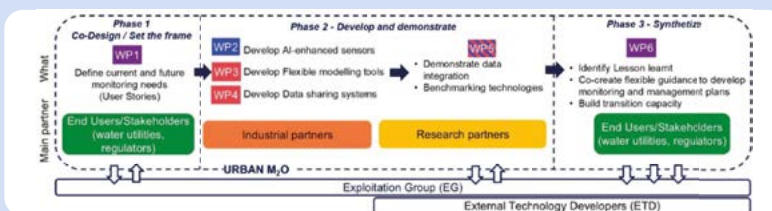
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Development phases of the Urban M₂O project



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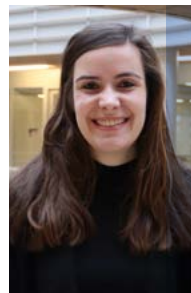
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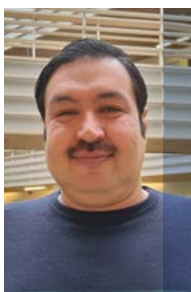
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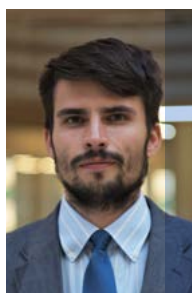
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Wetsus, European centre of excellence for sustainable water technology is a facilitating intermediary for trend-setting know-how development. Wetsus creates a unique environment and strategic cooperation for development of profitable and sustainable state of the art water treatment technology. The inspiring and multidisciplinary collaboration between companies and research institutes in Wetsus results in innovations that contribute significantly to the solution of the global water problems.