Wetsus

Innovations

Examples 2020 – 2025

wetsus
european centre of excellence
for sustainable water technology

WATER CAMPUS
Leeuwarden

Preface

Wetsus has operated its unique cooperative innovation program on water technology since the start of the institute in 2004. Our research aims at the creation of breakthrough science & technology that contributes to solving major societal challenges and strengthens the water technology sector at the same time. In recognition of the impact and relevance of our innovation model and program, the Dutch government has appointed Wetsus as national institute for strategically important research (SBO-institute) in 2022.

The Wetsus program has led to the creation of more than 100 patents and over 35 technologies that have been demonstrated and/or applied in practice. At the same time, over 1000 high-impact scientific papers have been published in peer-reviewed journals and more than 1500 multidisciplinary-trained and application-orientated water technology specialists have been educated in the Wetsus program during the 2004-2025 period.

This book is the third edition of our series of innovation books (earlier editions were published in 2015 and 2020). In these books we illustrate Wetsus' innovative outcome by highlighting examples of the technologies developed. In this new edition, you will find a selection of innovations from the 2020-2025 period.

We are strongly committed to continue to maximize and harvest the enormous potential the unique Wetsus approach offers for a fairer and more sustainable world. We hope that our collaborative innovation mission will remain a source of inspiration for everyone connected to Wetsus.

The outcome of Wetsus as presented in this book fills us with pride and is the result of a remarkable joint effort of hundreds of people, both in Wetsus and at our participant companies and universities. We sincerely thank everyone who has, in one way or another, contributed to this success over the past 22 years.

Cees Buisman and Johannes Boonstra
Executive Board Wetsus

The effective Wetsus approach

Wetsus, European centre of excellence for sustainable water technology, is a facilitating intermediary for trendsetting know-how development. The inspiring and multidisciplinary collaboration between more than 100 international companies and nearly 30 research institutes in the Wetsus program results in innovations that contribute significantly to the solution of the global water problems. With this approach, Wetsus' mission is to foster a sustainable and fair society in a healthy and circular environment.

In the Wetsus model companies, assembled in one of the Wetsus research themes, together determine the research program. The program is executed in the Wetsus laboratory. All research, typically in the shape of four year-long PhD projects, is performed under the scientific responsibility of the participating universities. Already for two decades, 50 scientific chairs from all over Europe are involved.

The unique multidisciplinary cooperation of 50 science fields in one physical laboratory creates an enormous scientific creativity, while the close involvement of companies guarantees an application-oriented approach. To balance all interests, a dedicated Intellectual Property Rights policy is in place. This enables optimal cooperation, innovation and the commercialization thereof, and has proven to indeed lead to successful innovations. Rapid translation of Wetsus lab-inventions into real life applications is further enhanced by valorization and business development programs of WaterCampus Leeuwarden, of which Wetsus is one of the core partners.

A clear example of a sustainable and coherent solution that has quickly scaled from idea to application is BiOPhree.

01

BiOPhree – Phosphate recovery using iron oxide

In 2013, Wetsus together with several partnering companies started their research in phosphate recovery from wastewater using a new method, based on Aquacare's BiOPhree adsorption technology. Research at Wetsus tackled the fundamental challenges and improved the process, Aquacare and Haskoning developed the technology from lab to pilot. The involvement of different companies together with TU Delft, Waterschap Zuiderzeeland and STOWA eventually resulted in an efficient, selective, sustainable, and marketable phosphate recovery technology. An illustration of the effective Wetsus approach.

Phosphate (P) removal from wastewater is crucial to prevent eutrophication in surface waters and recover this limiting resource. Research on improving Aquacare's BiOPhree method, where P is adsorbed to tiny iron-oxide granules, started in Wetsus' laboratory where PhD researchers identified challenges and improved their understanding of the technology. 'Iron oxide, rust, is an excellent material to selectively adsorb P from water', Wetsus' scientist Carlo Belloni says. 'Iron oxide porous granules have a huge surface area: 1 gram of granules can have more than 100 square meters of surface area, where phosphate can adsorb'. The initial fundamental research aimed to better understand the factors influencing the adsorption, and more importantly, how to recover the adsorbed P and regenerate the rust granules. Collaborations with Mark van Loostdrecht, Geert-Jan Witkamp, and Ekkes Brück of the TU Delft all have been invaluable in these developments, amongst others. Wetsus' scientists, in collaboration with TU Delft, revealed that the larger pores in the granules contributed the most to the adsorption, since the relatively large P molecules couldn't effectively reach the small pores. In addition to surface area, the positive charge of the iron oxide granules contributed to a better selective adsorption of the negatively charged P molecules.

A feasible and sustainable technology

P adsorption technologies in and of themselves are not new, but the adsorbing materials were often only used once, whereafter they were discarded. Therefore, Wetsus develops the basic knowledge and understanding of P-recovery and reuse of the iron oxide granules by multiple regenerations, while companies such as Aquacare further develop the technology, by using and applying this fundamental understanding as a source of inspiration and new tech ideas. 'We found out that simply washing the granules with a base followed by an acid wash revealed the best results,' says Wetsus' scientist Wokke Wijdeveld. 'Although some fine tuning is needed, we proved that regeneration was possible.' According to Pim de Jager, Technical Director of Aquacare, this regeneration of the adsorbing material is crucial for a viable P adsorption technology and makes it economically feasible and sustainable.

As a team

Now that they showed the proof of principle, the time was ready to scale the technology. Haskoning played a key role in this process as well. 'We know the wastewater treatment world and the playing field of water treatment and nutrient recovery,' says Mathijs Oosterhuis, Senior Consultant Water and Resource Recovery at Haskoning. 'In addition, we are also up to date about the state of technological developments and ongoing research.'

Wetsus led the operation of an international pilot plant in Cyprus and Spain. The aim was to further improve the method by solving mechanical issues, limit chemical consumption, and identify the best regeneration strategy: what is the best pH of the alkaline and acid washes? How many chemicals are needed? This provided valuable input and improvements for a second pilot in Dronten, to further improve the process.

Both companies played a prominent role in the practical issues of building and operating the plants, collecting data and practical information how to improve the process, with a focus to eventually bring it to the market. Wetsus, on the other hand, focused on the detailed and fundamental processes of adsorption and regeneration to extend the life of adsorbents as much as possible, while also recovering phosphate. However, all parties cooperated in each other's work and supported the whole process as a team.

The golden triangle of innovation

Steadily, the technology matures and becomes more and more ready for application in the real world to eventually improve surface water quality. 'Currently we are at the end of large-scale testing at pilot level,' Oosterhuis says. The next step is to test a full-scale demo under realistic conditions at a wastewater treatment

plant. Both de Jager and Oosterhuis value the collaboration with Wetsus, where they worked closely together in a very transparent way to bring a novel technology to the market jointly. 'This collaboration with Wetsus, together with the Dutch Water Authorities, is golden,' de Jager says. Oosterhuis fully agrees: 'Working together really speeds up the process to eventually market the technology.

The collaboration between 'problem owners' Waterschap Zuiderzeeland and STOWA, companies Aquacare and Haskoning, and knowledge institute Wetsus is extremely important for success. Together they form the golden triangle of innovation.'

> Iron oxide porous granules have a huge surface area: 1 gram of granules can have more than 100 square meters of surface area, where phosphate can adsorb.

Current Innovations

Wetsus combines the practical know-how and opportunities that companies highlight, together with the fundamental understanding that universities so well deliver. In this way, much-needed innovations in the water sectors can quickly grow from idea to lab-scale implementations, and eventually to industrial-sized applications.

From spin-offs to start-ups and pilot plants to demonstration sites – this chapter highlights various successful researches that have grown from brainstorm to entrepreneurial breakthrough.

02

Capturing and utilizing CO_2 from flue gases

Wetsus scientist Sara Vallejo Castaño and her collegues from Wageningen University and Research, as well as companies like REDstack, successfully developed a process to remove, store and recover as much as 99% of the CO_2 from industrial gases. Robert de Kler, founder of Coval Energy, subsequently transforms the captured CO_2 stepwise into fatty acids, using a novel technology. 'Lipids are very versatile and can be used as a raw material for many applications, to make aviation fuel, for instance.'

> To limit global warming and compensate for emissions, we need to remove 5-50 gigatons of CO_2 from the atmosphere yearly. And with it, we could renewably source carbon for the organics industry.

'However, capturing this gas at the source, for example in industrial gases, might be more effective than from thin air.' Therefore, Vallejo Castaño and her colleagues from Wetsus, and Bert Hamelers & Philipp Kuntke from Wageningen University and Research, successfully developed a technology that removed CO_2 from flue gases. This is particularly relevant for CO_2-intensive industries, like steel and cement factories as well as refineries. The method is based on the solubility of this gas in alkaline solutions. By bubbling the flue gas through an alkaline potassium hydroxide (KOH) solution, the CO_2 present in the gas dissolves in the fluid. By subsequently increasing the acidity, pure CO_2 is released from the fluid again, harvested and used as a raw material for many applications.

Capture and regenerate

To scale the method and efficiently remove large amounts of CO_2 from industrial gases, the basic principle had to be further developed and perfectioned. One of the issues was to efficiently lower the pH in the solvent so that large amounts of dissolved CO_2 could be purified and captured. 'We aim to boost the CO_2 capturing process from the current 1 gram per hour to 100 kilogram per hour, a huge step,' says Vallejo Castaño. 'To increase our efficiency, we started using so-called bipolar membranes. With the help of electricity, these membranes can dissociate water into acidic H+ and alkaline OH- ions, creating acidic and alkaline parts.' The KOH solution with the dissolved CO_2 is led through the acid compartment, where its pH is lowered and CO_2 is released and captured. The now acidic solvent is then led through the alkaline compartment to regenerate.

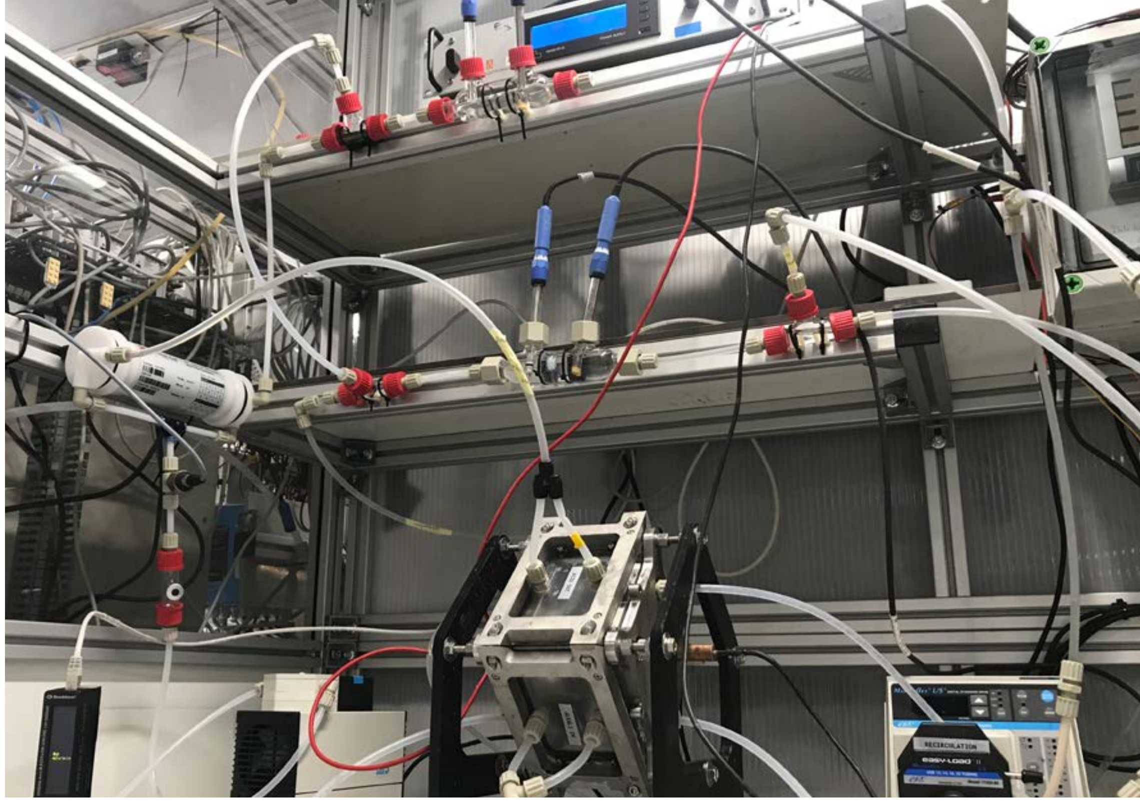
Valuable raw material

The scientists showed the proof of concept in the lab, and Vallejo Castaño is now scaling the technology with different partners, including REDstack, a company specialized in manufacturing state-of-the art electro-membrane stacks. 'Currently we have successfully tested our pilot set-up in Denmark, Romania, and Greecefor a cement and a magnesium oxide factory, as well as a refinery', she says. 'For the €13 million EU project ConcenCUS, we demonstrated that using the membrane stacks of REDstack, we could absorb more than 90% of the CO_2 emissions from flue gas, while recovering pure CO_2 from the fluid with a purity of 99%!'

Variety of applications

Scientist and founder of Coval Energy, Robert de Kler, subsequently can use this captured CO_2 as a raw material, to synthesize, for example, formic acid – a versatile compound that can be used for a variety of applications. 'We can use formic acid as an energy carrier, since it can easily be converted into hydrogen, an easy and safe route' de Kler explains. 'A very different application is to add it to manure to lower the pH. As a result, methane (CH_4) and ammonia (NH_3) stay in the manure, avoiding harmful emissions.' Benefits are huge, since farmers don't need to install expensive gas washers in animal sheds, while the manure has a much higher methane yield in biogas installations. Formic acid can also contribute to more sustainable aviation fuel. Microorganisms can metabolize formic acid, together with other compounds, like glycerine, into long-chain fatty acids, the basis of aviation fuel. Currently, de Kler is scaling the technology and produces several thousands of liters fatty acids per year, but his goal is to boost production to 10.000 tons per year.

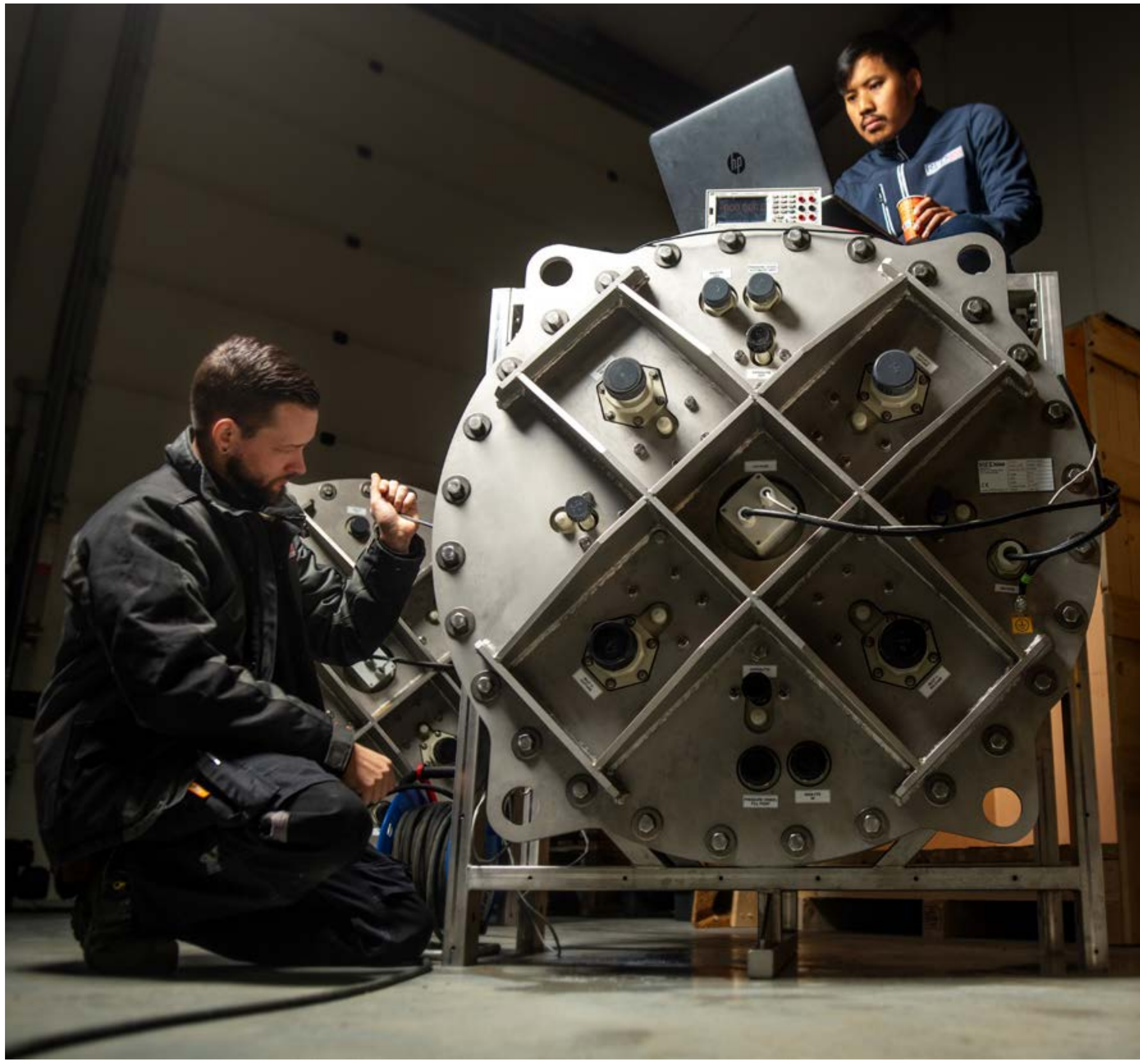
De Kler is happy with his partnership with Wetsus: 'Working with Wetsus was highly beneficial to us,' he says. 'We are a small company, and Wetsus was a valuable support partner. There is excellent communication and a lot of knowledgeable exchange. This leads to many new ideas.'



03 REDstack's evolution to a world class leader in membrane stack technology

In 2005, REDstack was founded as a spin-off from Wetsus research on Blue Energy, aimed at generating electricity from the mixing of fresh and salt water. Despite the success of the technology, the political interest in this kind of sustainable energy decreased. However, the company showed amazing resilience and has now developed into a specialist, designing and building state-of-the-art membrane stacks with numerous electrochemical applications.

> Our stacks can also be used to recover other resources, like lithium and other metals in batteries. Recovery can be close to 100%



About 20 years ago, together with partners from the industry and knowledge institutions such as University of Twente and Technical University Eindhoven, Wetsus started to revive and further develop the promising Blue Energy technology. This technique generates electricity by flowing river and sea water through a complex network of small compartments, separated by so-called ion exchange membranes. These membranes are assembled in a stack, and the success of Blue Energy was mainly due to the effective stack design. Ten years later, a scaled demonstration facility was built at the Afsluitdijk to further improve the system. During the entire research process, there was a close collaboration between Wetsus and the spin-off company REDstack. Wetsus mainly dealt with the technical development, while REDstack implemented, built, and marketed the technology.

Wealth of expert knowledge

'Over the years, REDstack perfected the membrane stack design,' says Michel Saakes, Theme Coordinator at Wetsus. 'For example, they compiled the membranes in such a way that we could use the full membrane surface area, allowing sufficient flow and a manageable pressure in the stack.' This resulted in a high efficiency stack and a low energy consumption for pumping the water through the stack. The integration of silicone seals and so-called spacers in the stack, needed to separate the membranes to create compartments, was another big improvement over the traditional designs. 'Due to these improvements, our stack uses 70 % less electricity than competing technologies,' says REDstack CEO Paula Gonzalez. However, despite the successful and sustainable way of generating electricity, Blue energy has been passed by solar energy and wind energy that have emerged on an unprecedented scale. What remained was the excellent collaboration between Wetsus and REDstack, and a wealth of expert knowledge on membrane technology.

Huge market

REDstack's and Wetsus' intricate knowledge of membranes and membrane stacks enables them to adapt or completely redesign a stack for special purposes. Wetsus' expert know-how on membranes and REDstack's expertise on stack developing and manufacturing can now be used to support other industries. 'Because we are forerunners in developing and adapting the stack technology using bipolar membranes to new applications, a huge market has opened and many companies are interested in using the REDstack units. Especially since we can also develop custom-made stacks based on specific needs,' Gonzalez says. 'For example, in some parts of the Netherlands, groundwater may contain more sodium chloride than permissible for a few months per year. That is too much for irrigation. Our stacks can effectively remove the salt and make the water suitable for agricultural use.'

> Over the years, REDstack perfected the membrane stack design. For example, they compiled the membranes in such a way that we could use the full membrane surface area, allowing sufficient flow and a manageable pressure in the stack.

Automated production

The recent development of stacks, containing bipolar membranes, has opened many additional applications, for example, carbon and ammonia capture. 'This is an evolving market, but our stacks can also be used to recover other resources, like lithium and other metals in batteries,' says Gonzalez. 'Recovery can be close to 100 %.' REDstack's unique knowledge has led to a fast-growing demand for such custom-made stacks. 'Currently, REDstack makes 40 stacks a year,' Gonzalez says. 'In March 2026, we plan to open a new automated production facility in Heerenveen, where we soon can manufacture 500 stacks per year per shift. The aim is to grow eventually to 1500 stacks per year.'

Wetsus and REDstack have been indispensable and reliable partners during these developments. Knowledge is shared, and a critical approach constantly improves the products. 'We are the eyes and ears of new developments at our spin-off', Saakes says. 'They are exceptionally skilled in what they do. I consider them the pearl of Wetsus and even Friesland.'

04 From wastewater to biodegradable plastic alternative

Using waste streams and readily available microbes, Wetsus and partners like Paques Biomaterials, and TU Delft. study processes to improve the production of biodegradable plastic made by bacteria, as an alternative to non-biodegradable fossil-based plastic. The material maintains important plastic properties, like flexibility and mechanical stability. And most importantly, it is environmentally friendly.

> We can extract up to 50 kilograms of PHA per day.

The yearly world consumption of plastic is over 400 million tons, while only 9 % is recycled or reused. As a result, millions of tons per year end up in the environment, persisting for many years and releasing micro- and nanoplastics. ‘These microplastics are of huge concern’, says René Rozendal, founder of Paques Biomaterials. ‘They accumulate in plants, reducing agricultural yield, but also in organs of humans and animals. Their presence has been associated with serious diseases, like Alzheimer, strokes and heart attacks.’ This is why Rozendal, together with Wetsus Theme Coordinator Alan Werker, collaborated to produce biodegradable plastic alternatives.

Energy reserve

‘Our former mother company Paques is world leader in biogas production from industrial wastewater’, Rozendal says. ‘However, when we were still part of Paques we were wondering if there would be possibilities to produce higher value materials than biogas.’ Scientists at the Delft University of Technology at the group of Mark van Loosdrecht, who Paques collaborated with, recognized that biopolymer producing bacteria were natively present in wastewater treatment plants, where they convert organic compounds into so-called polyhydroxyalkanoates (PHA), that they use as an energy reserve. PHA is a polymer that can be used to make biodegradable plastic. ‘By exposing these bacterial cultures to alternate regimes of food surplus and food scarcity, there is a strong selection for PHA producing bacteria,’ Rozendal explains. ‘Eventually we ended up with bacterial communities consisting mostly of PHA synthesizing species that quickly absorbed food and converted it into PHA.’ To fully focus on the promising PHA production, Rozendal and his co-founder Joost Paques started Paques Biomaterials.

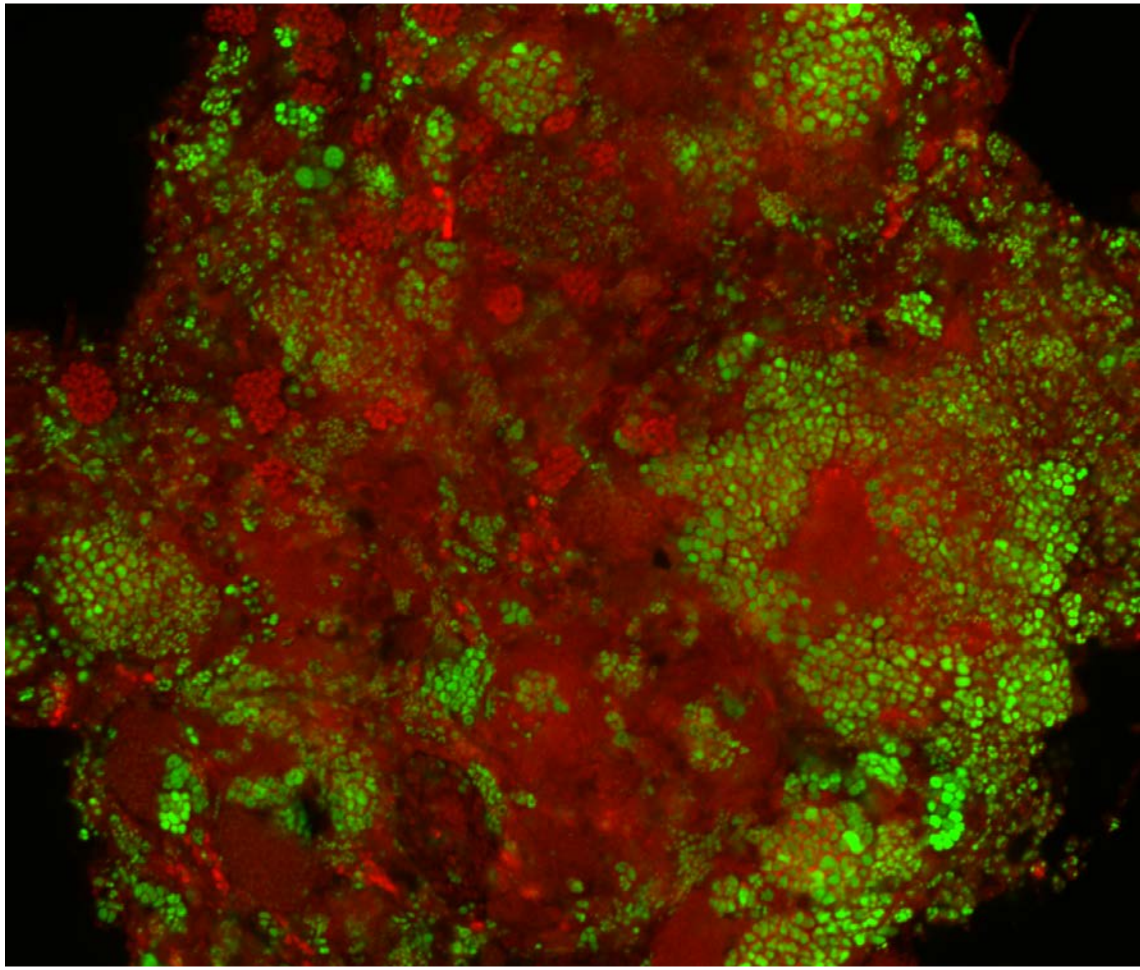
Excellent resistance

At the same time, Alan Werker worked on renewable resource recovery and focused on the same technology. 'Earlier contact with Rozendal was a seed that led to this collaboration now between Paques Biomaterials, STOWA, Slibverwerking Noord-Brabant, and Unilever to develop PHA-based plastic. Wetsus dives into technology details that will support industrial implementations,' Werker explains. The team focuses on the production steps and uses the bacteria's excellent resistance to varying food availability to their advantage. Rozendal: 'The accumulation of PHA as an energy reserve gives them an edge in surviving fluctuating food conditions over other bacteria.' The scientists start their PHA production process by using 'waste' sludge from a wastewater treatment plant, containing many bacterial species, including the ones synthesizing PHA. By feeding them in the right way with fatty acids made from organic waste, these bacteria accumulate a lot of PHA inside their cells. A fully grown dried bacterial biomass may contain up to 70% of PHA that can be extracted using a green solvent, resulting in a powder or granulate. The team further increases the value of the end product by directly using the organogel-like PHA extract recovered in the green solvents. 'This gel-like fluid can directly be used to make coatings, for example for packaging', Werker explains. 'Another route is to process the gel directly to make valued plastic products and recover the solvent at the same time.'

Crucial scaling step

Now the proof of principle, and lab scale extraction was firmly established at Wetsus, the team took the next step by scaling the technology. In Emmen, in May 2025, a new large pilot facility to extract PHA from bacteria was opened. 'This Caleyda Extraction Facility (CEF) is a crucial scaling step for Paques Biomaterials', says Rozendal. 'We can extract up to 50 kilograms of PHA per day.' Besides testing the process at a larger scale, this plant also allows Paques Biomaterials to extract enough PHA for customer trials, for example for textile fibers or agricultural products. When successful, Paques Biomaterials has reserved a 3-hectare plot in Emmen for construction of the full-scale extraction plant.

For the success of the project, Wetsus was a crucial link. Rozendal: 'Wetsus excels at combining academic research with industrial relevance. This is essential for the success of these types of projects, as in-depth PhD research helps us understand the fundamental details needed to refine and perfect the technology.'



A fully grown dried bacterial biomass may contain up to 70% of PHA.

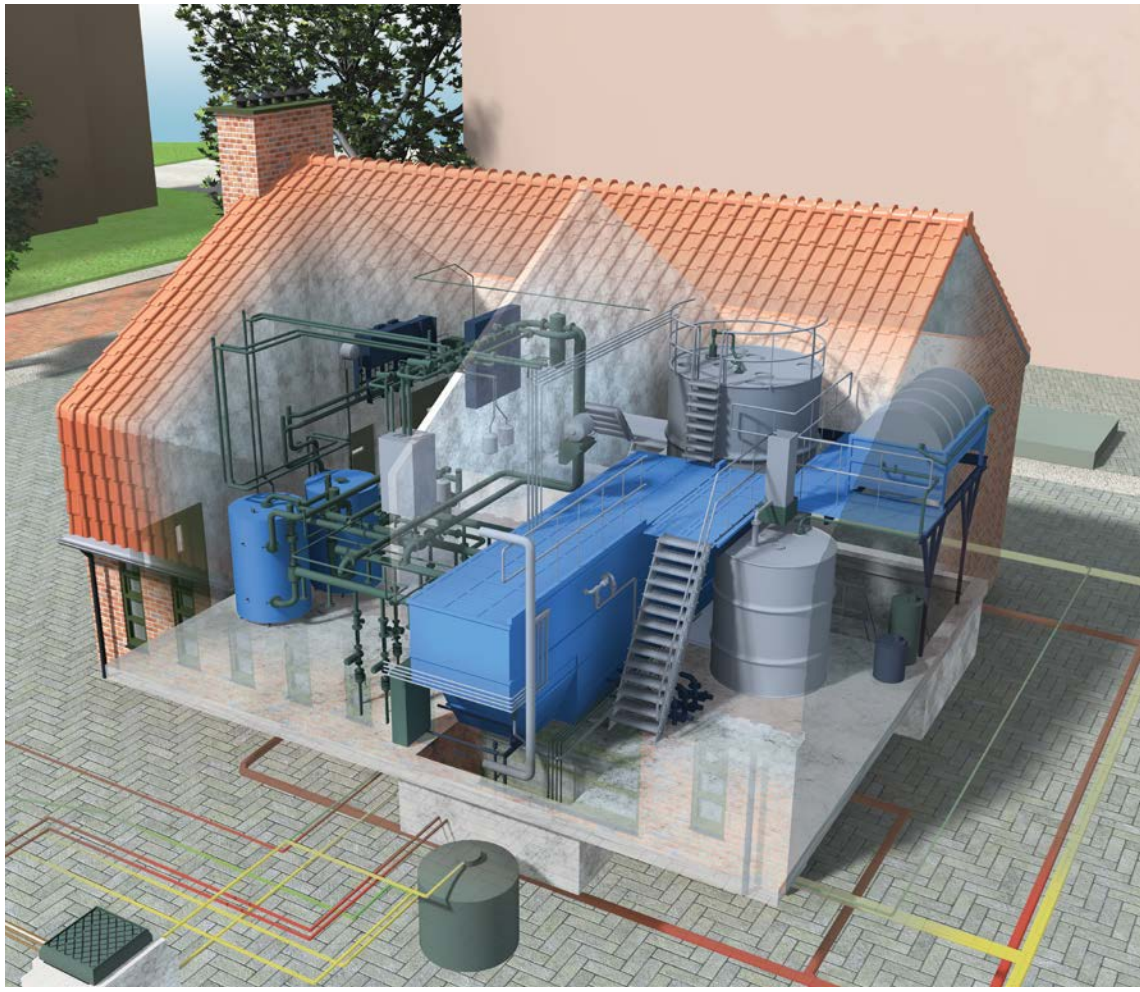
05

Effective removal of micropollutants from grey water using nanofiltration

Micropollutants, like pharmaceuticals and substances in personal care products, are challenging to remove from wastewater. Together with Univeristy of Twente, companies DESAH and NX filtration, Wetsus scientist Sam Rutten developed a method to effectively deploy nanofiltration technology in wastewater treatment plants.

> As polluted water is pressed through fiber membranes, most bacteria and even microplastics can't pass – making the water ultra clean and safe to drink.

Micropollutants are emerging contaminants that include residual medicines, components in cosmetics, pesticides, and industrial chemicals. These chemicals are difficult to remove from water and this has resulted in more pollutant discharge in surface waters. Many micropollutants are persistent and accumulate in the environment, causing health effects in humans and animals. For example, they may promote cancer and disrupt the hormonal system. Today, even pristine groundwater sources used for drinking water have already become contaminated with these compounds. In the future, micropollutant concentrations are expected to increase in the environment and in drinking water sources. The EU's Urban Wastewater Treatment Directive aims at a removal of at least 80% of many of those compounds from wastewater during the coming years.



Ultra clean

The removal of micropollutants in current wastewater treatment plants is difficult. Wastewater treatment plants mostly use microorganisms in oxygen-rich conditions to purify the water. 'In source-separated sanitation concepts, this treatment is also applied to greywater, which includes all wastewater from households except for toilet water,' Sam Rutten, Scientific Project Manager at Wetsus, explains. 'But these microorganisms can't break down part of the micropollutants.' To meet EU criteria for micropollutant removal, Wetsus teamed with Erik Roesink, and Joris de Grooth, amongst others, from Twente University, where a so-called capillary nanofilter for water treatment had been developed. This filter consists of a collection of tiny hollow fibers of less than one millimeter in diameter, with semi-permeable walls. Polluted water is pressed through the fibers, letting water and small ions pass, while retaining micropollutants and bigger ions. 'Also, most bacteria and even microplastics can't pass,' Rutten says. 'This makes the filtered water ultra clean and safe to drink.'

Real-life pilot plant

However, it was unknown if the complex cocktail of contaminants in greywater would interfere with the effective operation of the nanofilter. Therefore, together with DESAH and NX filtration, Rutten tested whether micropollutants could be effectively removed from greywater under realistic conditions. He first experimented in a real-life pilot plant in Sneek, where separate wastewater treatment of 232 households is used in practice. Here, they tested the robustness and integrity of the membranes of the nanofilter. 'This test facility is run by DESAH and is a perfect location to test new methods,' Sybrand Metz, technical director at DESAH, says. 'You may run into very practical issues, like membrane fouling or obstructions of the system.' Eventually, the tests in Sneek were successful, and the scientists were ready for the next scaling step.

Large-scale testing

With lessons learned from Sneek, Rutten and his colleagues went to Sweden for large-scale testing of the concept in a grey water treatment plant, where they incorporated the nanofilters into a newly-built treatment system. In the new set-up, the grey water was first treated by anaerobic and aerobic bacteria. This step broke down the organic compounds, after which the water was led to the nanofiltration unit to remove micropollutants and microorganisms. The clean water resulting from the filtration was separated from a concentrated waste stream of contaminated water. To further break down the chemicals in this waste stream, it was directed towards an ozonation unit, where the pollutants were oxidized, and subsequently led back to the first bacterial compartment. 'This oxidation loop helped to make the persistent (micro)contaminants easier to degrade by the microorganisms,' Rutten explains. 'Thanks to this loop system, micropollutants were further degraded by microorganisms and we were able to reach the EU clean water targets, without waste production.'

The successful implementation of nanofiltration in large-scale water treatment plants is a strong example of cooperation between Wetsus and companies like DESAH and NX filtration. 'Thanks to Wetsus' extensive network of scientists and companies, information is shared, while fundamental knowledge can be combined with novel technologies and subsequently tested', Metz says. 'By joining forces, we have an edge over the competition. This is the great strength of Wetsus.'

06

Saving drinking water by better leak detection

To detect leaks in their water pipelines, drinking water companies use sensors to measure pressure and flow. However, it often takes too long before a leak is actually discovered. The Smart Water Grids Group, led by Doekle Yntema, Theme Coordinator at Wetsus, together with TU Eindhoven and spin-off company HULO, designed and developed a model to improve leak detection based on pressure and flow sensor data.

> It can easily take a month of searching before a leak is found. Using our software, we can find it within a day.

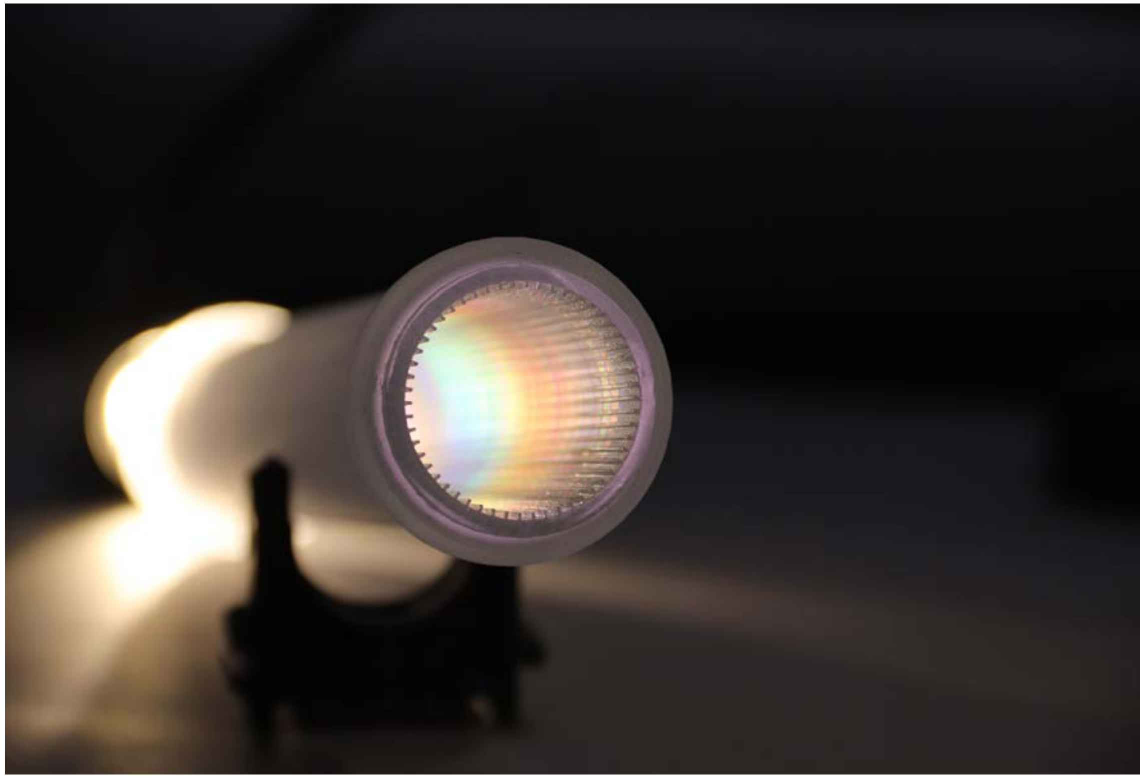
Worldwide, about 30-50% of all drinking water is lost due to pipe leaks. The Netherlands is doing great with less then 5% losses, due to a relatively good monitoring of the water network. ‘Drinking water companies use sensors that detect pressure and flow, generating a massive amount of data to check for leaks in their pipe system, but there are many false-positives’, says Frank van der Hulst, co-founder of Wetsus spin-off company HULO. ‘In addition, despite the extensive monitoring, discovering the exact location of a leak often takes too long.’ Therefore, Wetsus and HULO and several drinking water companies are designing models for improved monitoring, making it cheaper, more reliable, and effective.

New approach

Typically, drinking water companies use patterns in daily water use as a basis for leak monitoring. Deviations in user patterns, like the known peak in the morning, a dip at night, and a peak after the Saturday’s football match, could indicate a leak. But water use can also change due to unknown user factors, that have nothing to do with a leaking pipe. This causes many false positives. Improving water network monitoring should address better leak detection, with less false positives, in addition to a better assessment of the exact leak location. This is what Wetsus and HULO aim for by smart use of existing data. ‘Drinking water companies generate a wealth of data by using pressure and flow sensors from their water network. With the right data processing, large improvements can already be made in monitoring the system,’ says Wetsus Theme Coordinator Doekle Yntema. ‘As a first important step, we decided to focus on the water network itself, instead on water use patterns.’

Excellent division of tasks

To focus on the water network was a new approach, that proved successful thanks to an excellent division of tasks and communication between Wetsus and HULO. 'Wetsus develops algorithms and formulas to extract information, like possible leaks, from the massive amounts of data supplied by drinking water companies,' Yntema explains. 'HULO and Wetsus discuss the best way to incorporate these formulas into a model that gives relevant information about the water network.' HULO then validates the model with real data from existing water networks. For example, if there is a known leak somewhere, they check if the program can detect it based on the collected data. Preliminary results show that these models result in fewer false positives, while they responds within 10 minutes of the leak's occurance. The search area where the leak is to be located, from source to user, could also be reduced to 1-5 % of the total. 'In the Middle East, specialized search teams can check about 2 kilometers of pipeline per day', says Frank van der Hulst. 'It can easily take a month of searching before the leak is eventually found. Using our software, we found it within a day!' Wetsus and HULO are now further developing and refining the model step by step. Using AI and plans to collect data from water meters in people's homes, are important for a different perspective and a consequent better understanding of the dynamics of the water network.



More precise leak detection

Although many sensors are already used, sensors placed at strategic locations in pipes are needed for a more precise leak detection. This may eventually allow the deployment of fewer sensors. Research from TU Eindhoven and Wetsus is currently determining the optimal locations for sensor placement and where they give the best information about water network dynamics. 'Eventually we want to be able to predict leaks, so we can prevent them from actually happening', says van der Hulst. 'Wetsus' research is of a very high standard, so I am very confident we will manage to do this.'

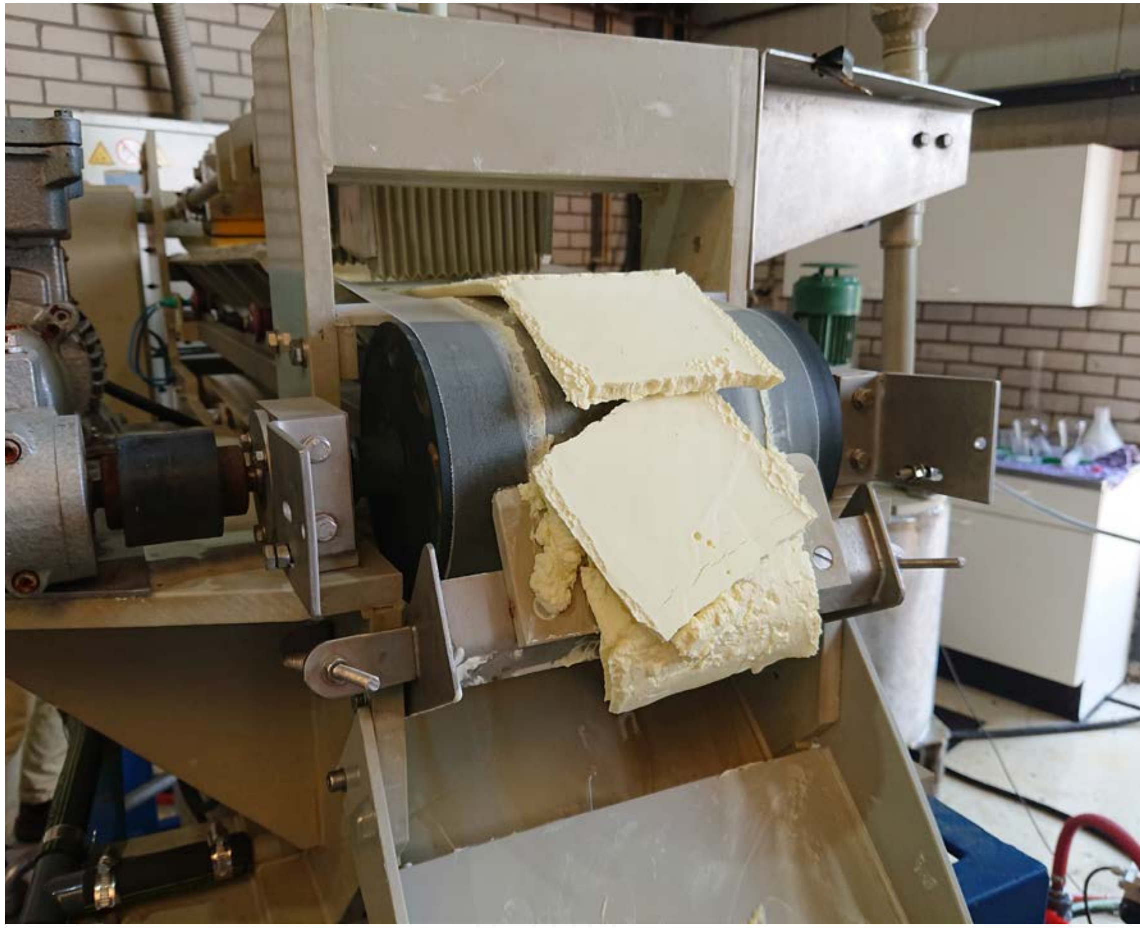
Van der Hulst values his 'fantastic collaboration' with Wetsus: 'Besides high-quality science, aimed at solving actual problems, the teamwork with Wetsus, drinking water companies and the end user is very effective, and results can be quickly transferred to the market.'

07 Treating waste streams using a new water-based separation technology

Together with Wageningen University and Research and Cool Separations, a company specialized in low-temperature separation technologies, Wetsus developed a process to recover lactose from cheese whey. This byproduct of the cheese industry can now be retrieved using less energy and a higher yield. The process is now validated successfully at an industrial scale and can also be applied to other industrial waste streams.

> low-temperature separation used 30 to 60% less energy, while achieving a higher yield.

Cheese production results in whey as a byproduct, a liquid containing salts, proteins, and lactose. From this side-stream, the proteins are recovered and the remaining lactose is collected by evaporation and slow cooling crystallization, resulting in the formation of lactose crystals that can be harvested. 'This is quite an energy-intensive process, while not all lactose is recovered,' says Ruben Halfwerk, scientific project manager at Wetsus. 'To improve energy efficiency and remove lactose from whey, *eutectic freeze crystallization* (EFC) technology seemed a promising candidate.' This separation technology starts by slowly cooling the liquid. The water will freeze, and the dissolved salt and lactose molecules will be pushed into the unfrozen liquid, where concentrations will consequently increase. Eventually, the liquid will become saturated and lactose crystals will form. Halfwerk: 'At this point, you have a three-phase system: pure frozen water, crystallized lactose that can be retrieved, and a remaining concentrate.'



Traditional method

On paper, EFC as a means of separation was not expected to be a viable alternative to current evaporation technology. At the low operating temperatures crystal growth would be slow, with smaller crystals formed. Halfwerk's tests revealed that crystals were indeed smaller than by evaporation, but that the crystallization was not as slow as expected. 'Crystallization was faster, due to a higher lactose saturation of the fluid,' Halfwerk explains. 'That pretty much compensated for the lower temperatures.' The ambitious next step was to test EFC on the waste stream after the crystallization process where lactose had been removed by the traditional method of evaporation and cooling. That stream still contains 20% lactose, in addition to some minerals, proteins and salts. Currently, it is difficult to further process and is mainly used as a cattle feed supplement. Though, Halfwerk managed to optimize the method and retrieve up to 85% of the remaining lactose by using EFC. A big success.

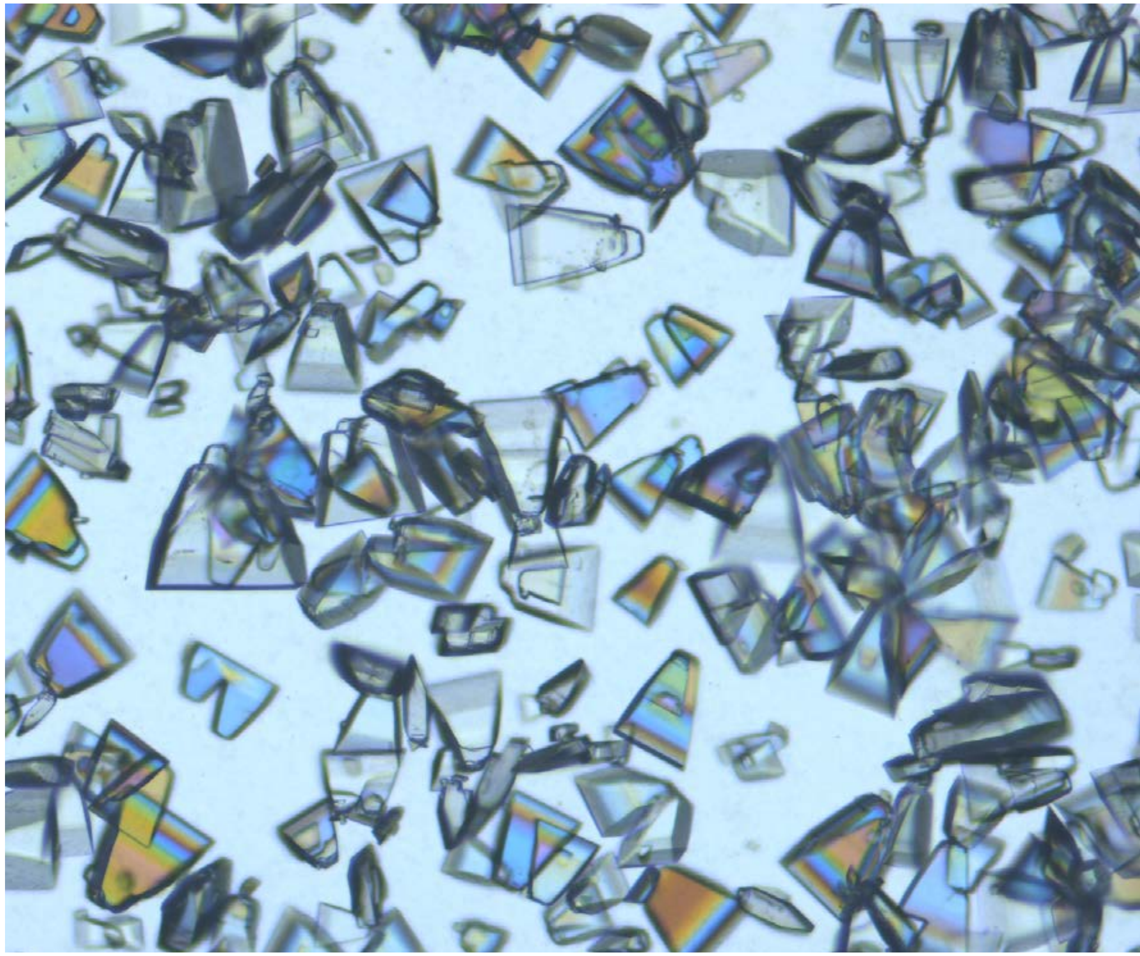
Semi-industrial level

Together with Albert van der Padt from Wageningen University and Research, and the company Cool Separations, specializing in scaling and commercializing separation technologies, the final step was to scale the process. 'This pilot plant phase was done in close collaboration between Wetsus and our company,' says Lei Fan, COO of Cool Separations. 'Together we configured and ran the plant and showed the proof of principle at a semi-industrial level, based on the methods developed by Wetsus.'

Besides developing a theoretical framework and an optimized procedure with the EFC technology, Halfwerk also evaluated its costs and efficiency compared to the traditional evaporation method. He found that the low temperature separation used 30-60% less energy, while achieving a higher lactose yield, a better separation and a cleaner waste stream. Fan: 'This makes EFC very attractive for potential clients to replace the existing energy-consuming evaporation separation.' In addition, it shows that this technology can be applied to other applications in the food industry. According to Halfwerk, the EFC separation has huge potential and is widely applicable to separating components in different waste streams, from the mining sector to the food sector.

Applying the technology

Fan sees the collaboration with Wetsus as a game changer for both parties. During regular meetings important information was exchanged, while Wetsus and Cool Separations complemented each other almost perfectly. 'Wetsus has done excellent research, which formed the basis of applying the technology for this application,' Fan says. 'The concept could then be applied for large-scale production using our pilot facilities, where we could use industrial-scale machinery for validation.' This made the scaling-up process much more efficient: without research at Wetsus, scaling the method would have required a lot of trial and error, while the outcome would have been more uncertain. Fan: 'Thanks to the collaboration with Wetsus, we are currently the only company that can offer a low-temperature solution to recovering lactose with EFC on an industrial scale.'



EFC separation has huge potential and is widely applicable – from the mining sector to the food sector.

08

Senor data fusion: effective, affordable, and indirect contami-nant measuring

Measuring contaminants in water can be challenging because the sensors, able to detect specific compounds, are often unavailable or too expensive. Wetsus and Wageningen University and Research came up with a solution to this problem and, together with partners at aqa.earth, developed a successful and widely applicable concept: measuring concentrations of difficult-to-gauge substances indirectly, and with high precision using a set of simple, affordable 'standard' sensors.

> It is complex and expensive to measure specific components, therefore we use standard sensors and models supplemented with AI, to fill in the missing information.

Measuring contaminants in water is of great importance to governments and many industries. For example, water monitoring by water boards, and contaminant measurement is crucial. A widespread problem is the ongoing pollution of surface water with nitrogen (N) and phosphorus (P) from agricultural origin. The water boards monitor the larger waters for these pollutants, but the frequency is low due to costs, while the more vulnerable, small water bodies are not measured at all. Worryingly, the Netherlands has failed to meet EU criteria for clean surface water for many years.

Challenging and costly

To reliably measure environmental contaminants can be complicated. It requires specific sensors that can measure such compounds, a time- and money-consuming process. Though in a roundabout way, it can be done. 'Grundfos, a Danish company that develops chlorination systems for drinking water, came up with the idea of indirectly measuring chlorate, an unwanted substance in the chlorination process,' says scientist Martijn Wagterveld, Coordinator of Monitoring and Quality at Wetsus. 'The idea was to use a combination of simple measurements, for which sensors are available and cheap, such as pH, temperature, and conductivity. Based on the data generated, chlorate concentrations could possibly be estimated. To determine if this could work, we set up a Wetsus project that would eventually lead us to the technology on which aqa.earth is built.'

Very accurate

The principle of indirect measurements is simple: by gauging numerous variables using inexpensive 'standard' sensors, it is theoretically possible to accurately estimate the concentration of a particular substance. The challenge is deciding which sensors are the most informative and effective to deploy. In addition, it is particularly complicated to calculate the concentrations of the target compound using the data generated by the sensors. Research by Wetsus and, amongst others, Karel Keesman from Wageningen University and Research found that by using just a few sensors, measuring temperature, pH, conductivity and UV A absorption, it was possible to reliably calculate chlorate concentrations with a deviation of only a few percent. 'To come to such a good approximation, you need a lot of data, in addition to models, supplemented with AI to fill in missing information', Wagterveld explains. Eventually, the method Wetsus developed worked well and was ready to deploy.

> Building a model that describes reality, without having to understand all details, is much more cost-effective.

Business case

After this initial success, Wagterveld and technology developer and Wetsus theme participant Mateo Mayer set up a spin-off company, aqa.earth. They aimed at monitoring, predicting and improving environmental monitoring quality by using the same indirect measurements. Though this time focused on the agricultural sector. They specifically aimed at monitoring nitrogen (N), phosphorous (P) and organic compounds (OC) in water, through measurements in soil, air, and rural ditches. 'It is complex and especially expensive to measure these compounds based on individual samples in a laboratory,' Mayer explains. 'Therefore, we use standard sensors measuring temperature, conductivity, and 5 different light colors, including UV-C at 280 nm.' The scientists then calibrated these measurements with direct N, P and OC laboratory analysis data using physics-based models, sensor-data-fusion algorithms, and AI. This resulted in very accurate estimates for N, P and OC from agricultural sources. Mayer: 'Because conditions differ largely between different sites, we need to do these calibrations for each location.' But the big advantage is that the scientists can now monitor continuously, a huge improvement compared to the current low frequency measurements as performed by the Dutch water boards. And on an EU level, the relevance of the technology is already being seen, as the sensors are applied in large projects like Urban M2O and H2O4All.

Tremendous impact

The Wetsus approach to start using indirect data and AI-based algorithms has a tremendous impact on the way of thinking. Mayer: 'I was always dedicated to get data and facts aimed at a better understanding of processes, before building a model. But building a model that describes reality, without having to understand all details about a process, is so much more cost-effective.'

09

CO_2 removal from seawater using membranes

About 3.5 years ago SeaO2 was founded as a spin-off from Delft University aiming at large-scale CO_2 removal from the ocean to slow down global warming and ocean 'acidification'. Wetsus contributes with expertise on state-of-the-art membranes that play a key role in the technology. 'By the end of this year, our pilot plant will remove 250 tons of CO_2 from sea water', says Founder and CEO Ruben Brands. 'By 2045 we aim for a total removal of 1 billion tons of CO_2 from the sea.'

Since the Industrial Revolution, human CO_2 emissions have increased, with concentrations rising from 280 to over 420 ppm. The oceans absorb around 33% of anthropogenic CO_2 emissions and hold the majority of carbon within the fast carbon cycle. This has led to a slight decrease in pH, from 8.2 to 8.1 on average. Increased emissions and a consequent further pH reduction may potentially affect marine life in the future. According to Ruben Brands, it is crucial to reduce atmospheric CO_2 and reach carbon neutrality to combat climate change and reduce the impact of dissolved CO_2 on the ocean's pH. 'To reach carbon neutrality by 2050, cutting emissions is not enough,' he says. 'In addition, we must remove about 10 gigatons of CO_2 annually.' SeaO2 is aiming to remove CO_2 from seawater, store it or reuse it as a raw material for different products. Due to much higher concentrations of this gas in seawater, removal from the ocean is a more efficient way of carbon capture than directly from the atmosphere. 'The concentration of CO_2 in seawater is about 150 times higher than in air, making ocean-based removal potentially more energy-efficient,' Brands explains. 'Therefore, capturing and removing this gas from water is more energy efficient than, for example, Direct Air Capture.'

> The concentration of CO_2 in seawater is 150 times higher than in air. Capturing it from water is more energy efficient than direct air capture.

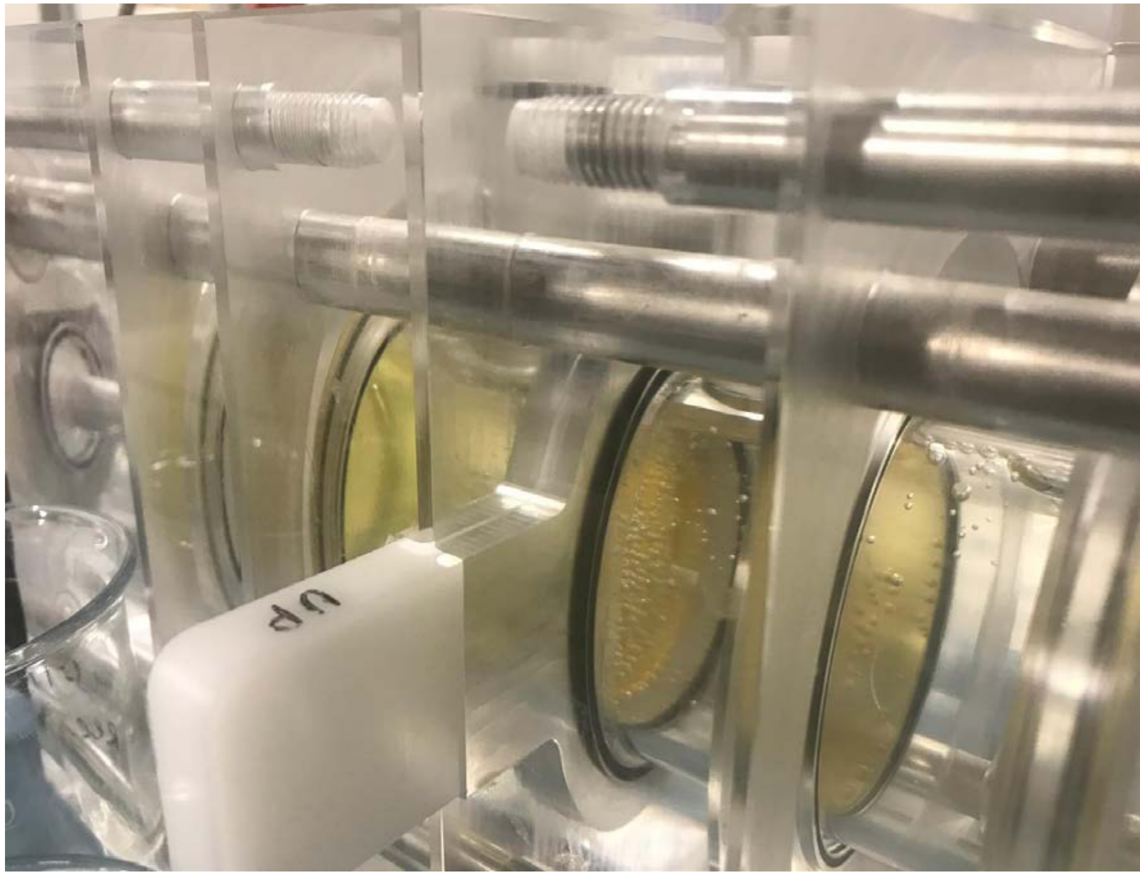
State-of-the-art membranes

The development of the newest generation of membranes has led to many new applications and technologies. They play a key role in SeaO2's technology to capture CO_2 from seawater. As does the initial research done at Wetsus in collaboration with David Vermaas from TU Delft. Wetsus scientist Sara Vallejo Castaño still contributes with crucial knowledge on how to use these membranes efficiently. The core of their technology is a patented electrochemical process, where a collection of state-of-the-art membranes, with different properties, such as anion-selective, cation-selective and bipolar membranes, are put together in a stack. In the first step, seawater is dissociated to create an acid and a base. 'To achieve this, different reactions happen in the multiple compartments between the membranes', says Asvin Sajeev, Chemical Engineer at SeaO2. 'By controlling ion flows through ion-selective membranes, we can create acidic and basic compartments'

When the pH is lowered, you can get pure dissolved CO_2, which can be extracted from the seawater by applying a vacuum. The extracted gas is then compressed, stored, or utilized for other applications. The CO_2-stripped seawater is returned to the ocean after neutralizing it with the base produced earlier. This enables the ocean to absorb more CO_2 from the atmosphere to complete the cycle.

Further cost reduction

SeaO2 sees different business opportunities for a viable operation, including permanent storage in geological structures, generating high-quality carbon credits. However the gas can also be used as a raw material for green methanol synthesis, or even net-neutral aviation fuel. Finally, the technology can be licensed to companies to reduce their CO_2 footprint. Due to the efficient technology, costs are relatively low; 30-40% lower compared to alternative methods, like Direct Air Capture, and will be between 100 and 300 euro's depending on the scale of the plant. 'We can achieve a further cost reduction by partnering with energy companies that use sea water to cool or desalination installations', says Brands. 'Integration of our plant and using part of their infrastructure could save up to 25% on energy costs. These decreasing costs make it competitive and interesting for companies in a booming market.'



> Using state-of-the-art membranes, the costs of recovery are 30 to 40% lower to alternative methods.

Upcoming Innovations

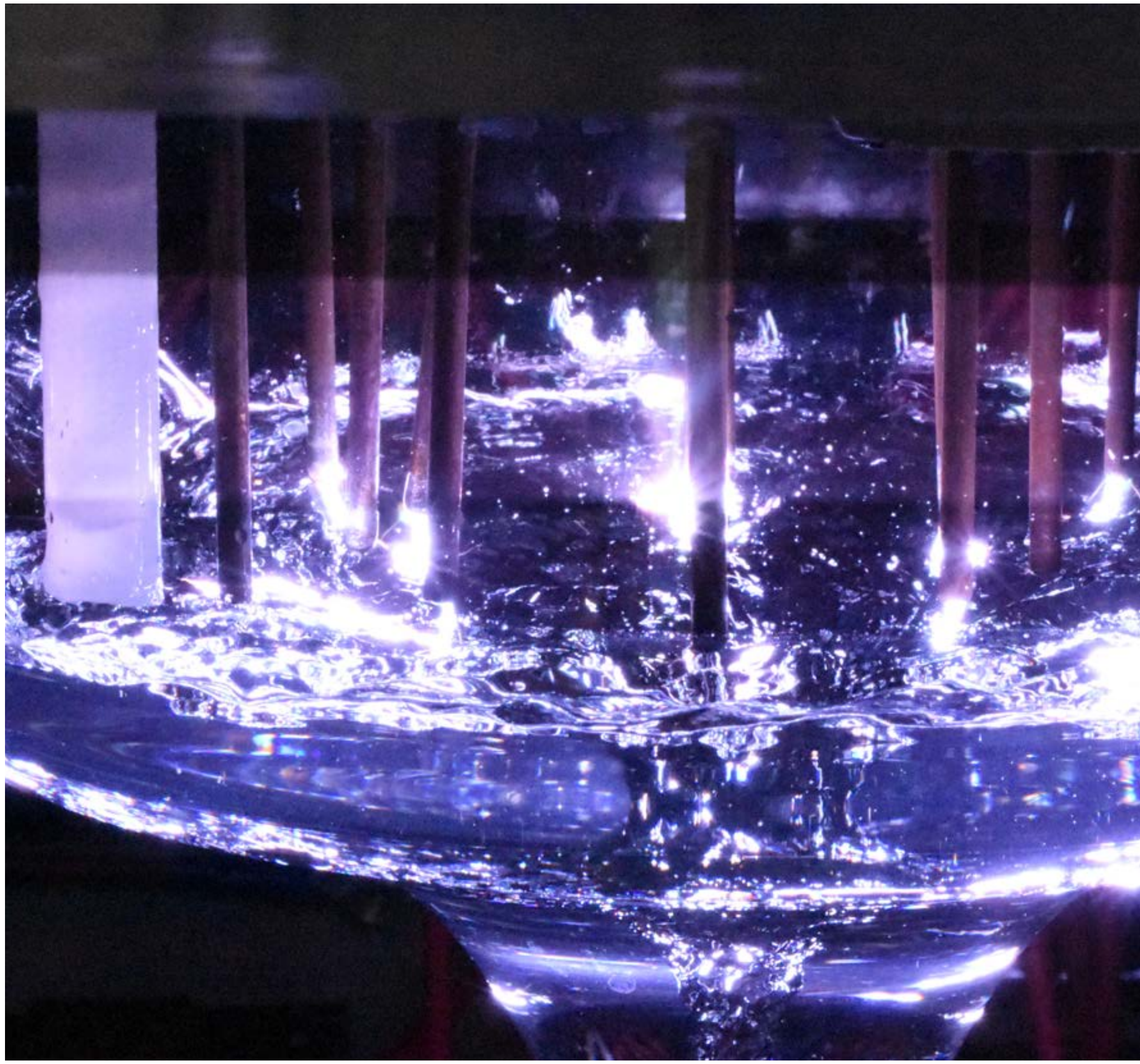
Wetsus accelerates innovation. Our ecosystem allows for quick transfer of lab-scale tests to pilots and demonstration sites. Here we present you the up-and-coming technologies that are about to highlight their potential on a new level.

10

PFAS degradation using lighting in a vortex

PFAS pollution poses an increasing environmental problem due to its persistence and toxic effects. Roman Klymenko, postdoc researcher at Wetsus and researchers at Graz University of Technology, developed a novel technology to effectively degrade PFAS in water. By using a combination of plasma discharge and a so-called hyperbolic vortex for improved mixing and gas dissolution, he was able to degrade almost 100% of the PFAS present. Together with the municipality of Leeuwarden, the water boards and Wetsus, a pilot is being built to treat the PFAS-polluted groundwater at air force base Leeuwarden.

> The two molecules together stayed longer at the surface of the fluid, resulting in a much better degradation. As a result, after about an hour of treatment, almost all PFAS, short and long chain, were degraded.



PFAS are a group of toxic and persistent man-made chemicals that consist of a lipid-soluble tail composed of carbon and fluorine and a water-soluble head group. The strength of the carbon-fluorine bond makes it one of the most persistent chemicals. Since the 1950's it has been used in a wide variety of industrial and consumer products, like cosmetics, pesticides, non-stick cookware, raingear, fire-fighting foam and many others. Due to their widespread use and discharge, it has accumulated in the environment and poses increasing health risks. 'PFAS is used in many sectors, but no technology can effectively degrade these chemicals', says Klymenko. 'Using membranes, PFAS can be removed from wastewater, but there is no cost-effective solution for dealing with the resulting concentrated PFAS waste stream.' Another approach is to adsorb PFAS using activated carbon, however, at higher concentrations, this method becomes costly due to the need for thermal regeneration at temperatures exceeding 1,400 °C. Klymenko, amongst others in collaboration with Jakob Woisetschläger from Graz University of Technology, successfully developed an effective and affordable technology to degrade PFAS.

Enhanced mixing

The basis of Klymenko's PFAS degradation technology is plasma, high-energy ionized gas molecules that are very reactive and able to break the fluorine-carbon bonds of PFAS. This plasma also reacts with air, forming highly reactive oxygen and nitrogen species (RONS) such as hydroxyl radicals, ozone, and many others that also contribute to PFAS breakdown. 'Since these reactions mostly occurs in the air, while the PFAS is in the water, its degradation should be enhanced by dissolving and mixing these RONS into the water,' Klymenko explains. 'We eventually found a technology originating from Austria that proved to be very efficient: the creation of a vortex when water flows through a so-called hyperbolic Schauberger funnel. Due to the large surface area between air and water, combined with vortex dynamics, this design enables highly efficient oxygen dissolution and mixing. It also showed excellent suspension of the plasma-created RONS into the water.

Almost all PFAS degraded

'By creating short energetic plasma pulses in the air above the water surface, RONS are formed in an energy-efficient way,' Klymenko explains. 'In addition, plasma discharge bombards the water surface with energetic charged particles that can easily break carbon-fluorine bonds.' Most PFAS is degraded at the surface by plasma discharge, especially the long-chain PFAS. The shorter chain PFAS are mostly degraded in the bulk by RONS, and that's where the efficient mixing of these very reactive molecules using the hyperbolic funnel is crucial. However, there was a problem. Although the system worked very well for the longer chain PFAS, the degradation was close to 100%, shorter chain PFAS were formed during this process and increased in concentration. Klymenko proposed adding a surfactant with a positively charged head group that would electrostatically stick to the negatively charged head group of PFAS. Klymenko: 'The two molecules together stayed longer at the surface of the fluid, resulting in a much better degradation. As a result, after about an hour of treatment, almost all PFAS, short and long chain, were degraded.'

Testing at the airbase

The technology has great potential and currently a pilot plant with a capacity of 1 m^3 per hour is being built to treat PFAS-polluted soil at the firefighter practice spots at the air force base in Leeuwarden. 'Fire extinguishing foam contains a lot of PFAS', says Maurice Tax, CEO at Bright Spark. Tax was involved in Wetsus from the very beginning and his company aims to apply fundamental scientific knowledge to solve practical problems. He appreciates working with Wetsus because of the open communication and the excellent research being done. When PFAS became a hot topic, he realized that Klymenko's plasma technology could offer a solution to PFAS pollution. Tax: 'At the air force base, we plan to remove the polluted ground surrounding the firefighter practice spots, rinse it, and subsequently destroy the PFAS-containing water in the pilot plant.' When successful, the technology is ready to address the PFAS problem at a large scale.

Photo: Ingrid Schauberger

11

Nutrient recovery from human manure: closing nutrient cycles

Closing nutrient cycles is crucial for food security. That's why Wetsus scientist Chris Schott and Wageningen university and Research are working on recovering nutrients from human manure by redesigning the traditional sanitation system. By separating toilet water from other household wastewater, combined with decentralized water treatment systems, nutrients, can be recovered and reused in agriculture, closing cycles. This design will be applied in the development of Spoordok, a new sustainable urban district of 2000 living units to be built in Leeuwarden.

Current food production is far from circular and therefore unsustainable. Farmers import feed and nutrients from the other side of the world, for example phosphorus from Northwestern Africa. Animals convert this nutrient into dairy products, meat, and manure. Part of it is reused by farmers to fertilize their crops, but legal limits apply to avoid excess phosphorus to wash out from the soil, harming the environment. As a result, there is a substantial surplus of manure. Also, human manure adds to the massive waste of nutrients that are discarded through the sewage system. After treatment in wastewater plants, a big part eventually ends up in a solid fraction, sludge, that is incinerated and the ashes used for asphalt. 'Currently, very few nutrients are actually recovered. It's unethical to extract nutrients from abroad, and eventually make asphalt from it,' says Chris Schott. 'The whole system is aimed at mass production, ignoring quality and environmental impact.' According to Schott, too many resources are wasted at high economic and environmental costs. Since we can't grow crops healthily without these crucial compounds, closing nutrient cycles and recovering nutrients, like phosphorus, from manure is essential to guarantee food security.

Nutrient-rich waste stream

Recovering nutrients requires the collection and processing of manure. For animal manure, successful collecting and recovering efforts are being made, but human manure still is wasted. Schott: 'If we want to be circular, we need to reuse human manure.' Therefore, he aims at reusing this resource, but current sanitation systems add too much water, making it more difficult to extract valuable compounds. To make more concentrated waste streams, a system change is needed. 'By implementing vacuum toilets, that use substantially less water than ordinary toilets, while separating this so-called blackwater from the toilet from other wastewater, like shower and dishwasher water, we end up with a concentrated nutrient-rich waste stream,' Schott explains. 'A next step involves the use of decentralized wastewater treatment systems, where resources are recovered.'

Sustainable urban district

To test if separated sanitation combined with decentralized wastewater treatment is working at a large scale, knowledge from a 'green' demonstration neighborhood in Sneek, consisting of 200 homes, is being applied to the development of Spoordok, a new sustainable urban district in Leeuwarden. Jeanet van Dellen, Senior Advisor Economic Affairs of Leeuwarden municipality and closely involved in developing Spoordok, considers Wetsus' involvement in the project crucial to achieve the sustainability goals in the field of water technology. 'They are an important partner because of their expertise in sustainability and closing cycles, especially the water cycle,' she says. The first phase to close the water cycle and recover resources is separating blackwater from greywater. These streams will then be treated separately using different technologies. Most micropollutants, like pharmaceutical residues and micro-plastics, end up in greywater. By using state-of-the-art technologies, like aerobic treatment combined with nanofiltration, most of these pollutants can be removed, resulting in a liquid stream of drinking water quality.

Excellent relationship

Blackwater contains most nutrients and organic materials, which can be recovered by anaerobic digestion. During this microbial digestion, calcium phosphate granules are formed which can easily be retrieved and used in agriculture as a phosphate-rich fertilizer. The nitrogen present in the effluent can be recovered by so-called strippers and scrubbers. The 'stripping' phase converts the dissolved ammonium into ammoniac gas. The 'scrubber' phase recovers this NH_3 using acid, converting it back to ammonium. The remaining effluent, containing potassium, can be used for irrigation.

Van Dellen is more than satisfied about Wetsus' input and their involvement in designing Spoordok: 'Wetsus is of great economical interest for the region, and there has been an excellent and successful relationship between Wetsus and Leeuwarden since it was founded, she says. 'Our collaboration has always been very pleasant and Wetsus has been an invaluable partner with crucial contributions to the design of Spoordok.'

> Closing nutrient cycles and recovering nutrients from manure is essential to guarantee food security.

12

An improved desalination technology with many applications

To address an increasing shortage of fresh water, Wetsus improved the desalination of salt water. Using reversed osmosis 80% of fresh water and 20% brakish waste was made. In a second, innovative step, a combination of smartly stacked membranes separated the different ions present in the waste stream, preventing the formation of salt deposits. This boosted fresh water yield to 97% and reduced salty waste to only 3%. The technology also has large implications for side-stream management in the food industry.

> Our approach was to rethink the problem: what if we could prevent scaling, simply by separating the troublemaker compounds.

An improved desalination technology with Due to an increasing world population, fresh water demand is increasing rapidly, and producing drinking water from salty water is becoming more common. Reversed osmosis (RO) is the standard method to desalinate water. This technology works by pressing salty water through a membrane, allowing the passage of water, while retaining dissolved components like ions and organic substances. Usually, this results in 80% of fresh drinking water and 20% concentrated waste stream. The high salt concentration in this waste stream may result in scaling, the deposition of salts, like calcium sulfate ($CaSO_4$) and calcium carbonate ($CaCO_3$). These deposits may clog the membranes and consequently disrupt their function. With the huge quantities of fresh water needed, the waste fraction is altogether considerable and difficult to process and reuse.

Limiting factor

'Salt scaling has always been a limiting factor in RO,' says Jan Post, Program Director at Wetsus. 'Our approach was to rethink the problem: what if we could prevent scaling, simply by separating the troublemakers—like calcium and sulfate ions—from each other?' Post and his colleagues came up with a process scheme, based on an idea by

FujiFilm, to boost the freshwater yield, while reducing the salty waste stream. Together with, amongst others, Huub Rijnaarts and Harry Bruning from Wageningen University and research, they set out to investigate the innovative idea. 'The solubility of different salts varies greatly, for example, sodium chloride (NaCl) dissolves very well, while $CaSO_4$ easily deposits, limiting RO performance', Post explains. 'The idea was to take the salty waste stream from the RO and separate the Ca^{2+} and SO_4^{2-} ions from each other, so no $CaSO_4$ deposits can be formed.' Ion-exchange membranes play a key role in the technology: an electrical current drives the ions towards a membrane that allows the passage of some ions, while blocking others. In a first step, a membrane selectively removes and separately collects single-charged ions, like Na^+ and Cl^-, from the salty waste stream. The remaining fluid is directed towards a so-called electrodialysis metathesis membrane unit (EDM), where membranes selectively remove Ca^{2+} and direct it towards the Cl^- collecting unit. Similarly, SO_4^{2-} ions are transferred to the Na^+ unit. 'The resulting salts, $CaCl_2$ and Na_2SO_4 stay in solution, since they both have a very high solubility', Post says. 'With our technology the original waste stream has been converted into >80% desalinated water and only 10% Na^+ and 10% Cl^- type brine solutions. We can now increase the overall freshwater yield from 80% to 97%, while the waste stream has diminished from 20% to 3%!'

Right tool

The technology may have important applications not only for improving desalination efficiency, but also for waste stream management and the recovery of salts, especially in the food industry. 'At FrieslandCampina, we are dealing with a salty side stream after the proteins, sugars, fats and some salts have been removed from cow's milk to make our products', Kaustub Singh, membrane specialist at FrieslandCampina says. 'It contains a variety of ions ranging from sodium, calcium, chloride to phosphate. EDM technology might just be the right tool to manage and valorize this stream.' Currently, this side stream is used in cattle feed, which is a low-value application, while there is only a limited market. Singh sees EDM as a highly promising technology to pre-treat these salt rich side streams to extract useful chemicals such as NaOH and H_2SO_4 for use in FrieslandCampina's own production processes, thereby reducing raw material costs and help close resource loops. 'Once we have a better understanding of whether EDM is feasible in our processes, we will need a technology partner to build first proof-of-concept pilots to prove the concept on larger scale', Singh says. 'In the future a close collaboration with Wetsus as our knowledge partner together with a technical partner could pave the way for effective waste management, something which our company is actively pursuing.'

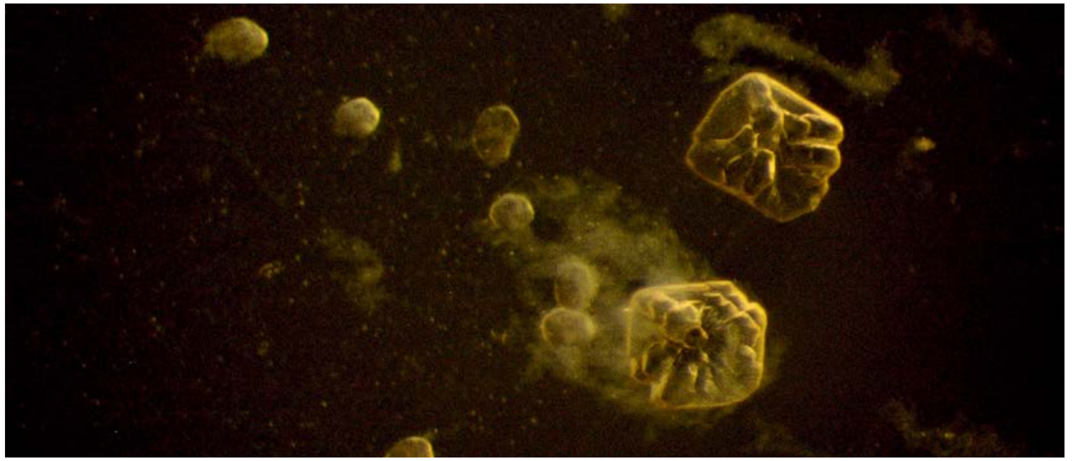
> With our technology, we increased the freshwater yield from 80% to 97%, while the waste stream has diminished from 20% to 3%

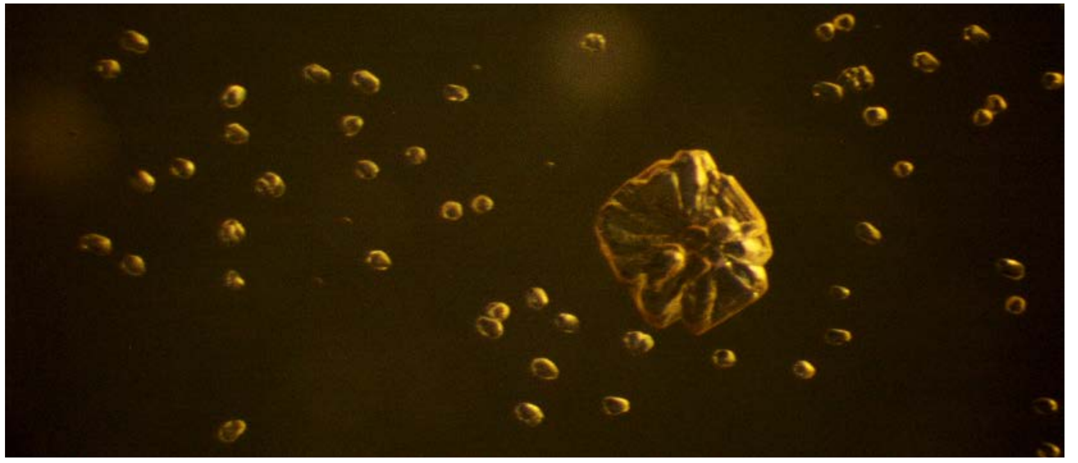
13

Safer drinking water by using magnets

A magnetic field can influence bacterial communities in water, enhancing drinking water safety and reducing the deposition of calcium crystals in pipes. Wetsus scientist Dr. Xiaoxia Liu is unraveling the mechanisms and applying the knowledge found to develop a chemical-free water treatment technology. Liu: 'We have seen that a weak magnetic field has a positive impact on the bacteria population in drinking water, by inhibiting pathogenic species and promoting 'good' bacteria.'

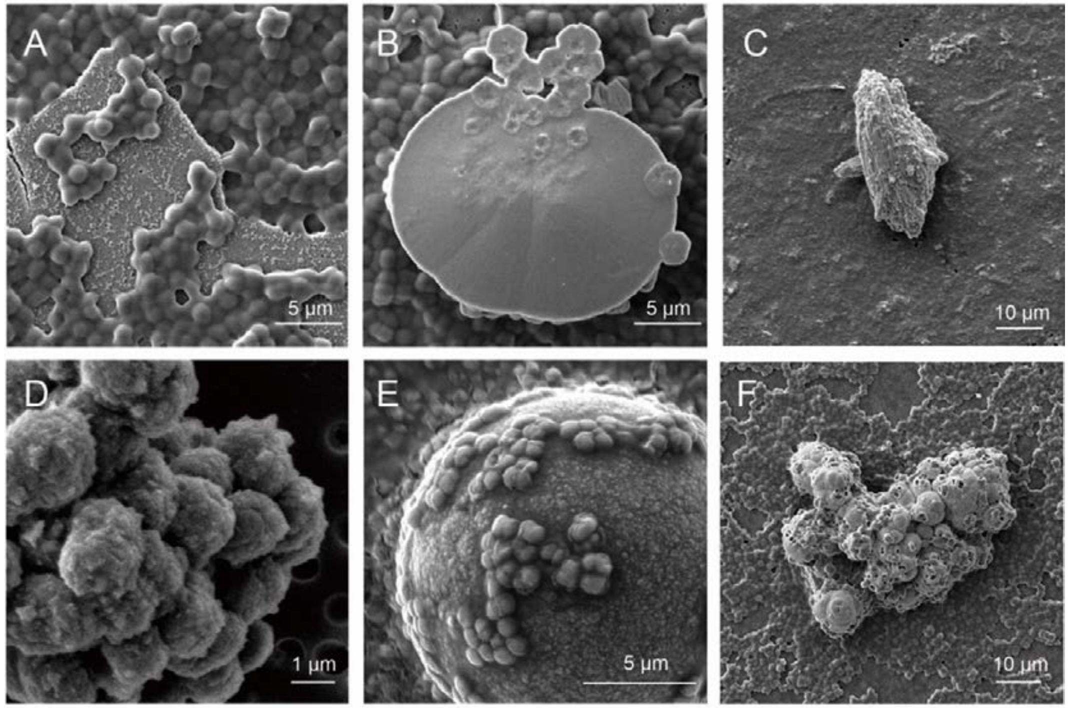
> Reducing scaling by applying a magnetic field was considered a miracle.





Without and with treatment.

Safe drinking water is a basic necessity. In most Western countries, water treatment is effective and guarantees safe drinking water. However, despite state-of-the-art water treatment, drinking water does contain many species of bacteria. Under exceptional circumstances, pathogenic species might even be growing, for example during warm summers or when the water stagnates in the pipes due to a technical failure. 'Our main aim is to make drinking water biologically stable, meaning there are very few pathogens grow in it,' says Liu. 'Although most drinking water is safe, we want to improve this even more and prevent growth of unwanted bacteria.' Traditionally, companies aimed to remove as many microbes as possible from drinking water, but this makes it more vulnerable to the growth of harmful bacteria due to the lack of competition between bacterial species. According to Liu, it could be beneficial to keep and promote the presence of 'good' bacteria, to inhibit the growth of harmful ones and magnets could play a key role. Such a microbiological approach could also address the issue of the deposition of calcium crystals by bacteria inside water pipes, so-called scaling.



Beneficial effects

Already during the 1970's, water treatment using magnets was patented. Extremely strong magnetic fields changed the microbiology of water, but it was not further developed due to a lack of understanding of the underlying mechanisms. Some years later, the effect of water core magnets – weakly magnetized steel encasings filled with spring water – on the microbiology of water and consequent scaling in industrial cooling towers was observed by the research company of Johann Grander in Austria. Grander showed that scaling and fouling in cooling towers of industries was strongly reduced by applying their devices in water pipes. 'At that time, the reduced scaling by applying a magnetic field was considered a miracle,' says Georg Huber, research director at IPF, the research company of the Grander GmbH. 'But a scientific explanation was lacking.'

Competitive advantage

That all changed when IPF joined the Wetsus Theme 'Applied Water Physics'. Together with a group of scientists covering a wide multidisciplinary field, the secrets of water, and the physical impact of water core magnets were elucidated step by step. Recently, Liu's research, in collaboration with Gernot Zarfel of the Medical University Graz, and Willibald Loiskandl from BOKU, has revealed that weak magnetic fields selectively promote the growth of harmless, low nutrient-adapted bacteria. This gives them a competitive advantage of the high-nutrient adapted pathogenic bacteria. Eventually, this increases the safety of drinking water. The advantage of magnetic treatment is that it's not an 'end-of pipe' approach, but that it improves drinking water before it reaches the consumer. In addition, the method is sustainable, since it doesn't require any chemicals, and it is very energy efficient and easy to implement: a couple of magnets can simply be applied to the drinking water pipes.

Developing science

Liu also found a scientific explanation why weak magnetic fields reduced scaling in water pipes and industrial cooling towers. Liu: 'We discovered that even a weak magnetic field interferes with a bacterial enzyme involved in calcium metabolism. As a result, crystals formed by these microorganisms are smaller and can be flushed away more easily. So, calcium deposits and consequent pipe clogging are prevented.'
Huber is very enthusiastic about the developing science to explain the impact of magnets on water quality. According to him, Wetsus has played a catalyzing and crucial role in understanding more about the effects of physical water treatment in general and the effect of magnetic fields on water quality in particular. 'Wetsus has the network and financials needed to solve big questions', he says. 'Bringing scientists from different disciplines together to jointly work on a complex issue, promotes collaboration, and encourages them to look beyond the borders of their own field. I highly appreciate Wetsus' excellent management and group leading skills, where a clear organization structure and logic decision making is continuously practiced.'

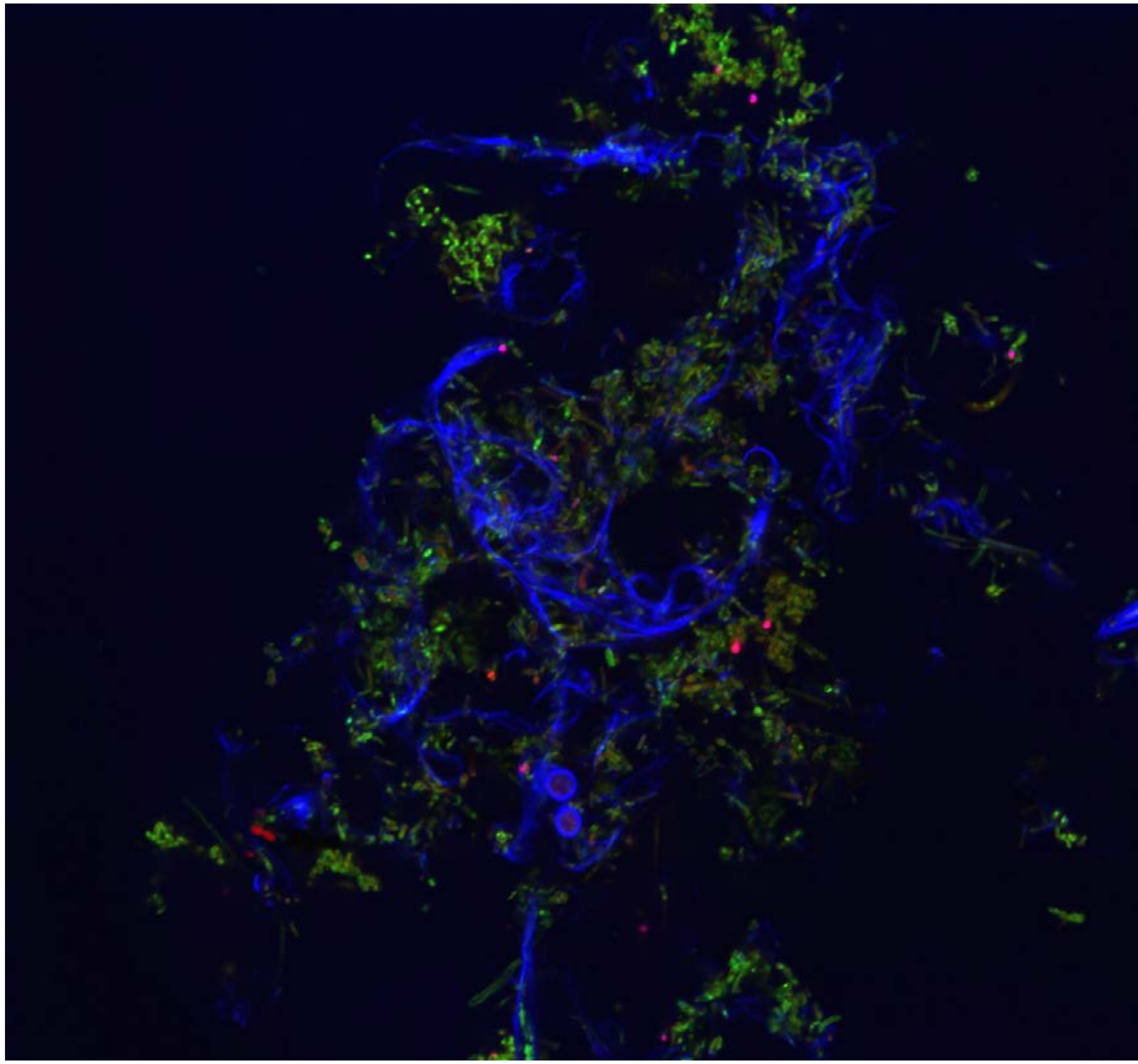
> The method is sustainable, very energy efficient and easy to implement.

14 Sustainable sedimentation using natural flocculants

The wide-spread use of oil-based polymers to increase sedimentation speed, for example in wastewater, is unsustainable and impacts the environment. Therefore, Wetsus, Paques, Wageningen University and Research and other partners have developed the production of a green alternative. The new polymer is efficiently made by bacteria, sustainable, non-toxic and biodegradable. Its production is also relatively inexpensive.

> An urgent change in policies towards using more sustainable polymers, replacing PAM, is needed.

Flocculants are substances used to increase sedimentation, for example in wastewater treatment, the mining or the dredging industry. Most flocculants consist of polymers, long molecules that trap small particles, like clay, and eventually form bigger clumps that settle to the bottom, clearing the water. Many industries need quick sedimentation, and flocculants reduce the sedimentation time drastically: minutes instead of hours or even weeks. The most commonly used flocculant is polyacrylamide (PAM). Its worldwide use is growing and well over 2 million tons per year with an estimated value of over 5 billion dollars per year. 'PAM is an unsustainable oil-based material, it is possibly toxic, and the environmental fate is unknown', says Carlos Contreras Davila, Wetsus Theme Coordinator Natural Flocculants. 'Considering the vast amounts of flocculants used and their potential environmental risks, an urgent change in policies towards using more sustainable polymers, replacing PAM, is needed.'



Nature-based solution

Together with Paques and Pentair-X-Flow, Wageningen University and Wetsus started looking for more sustainable flocculant alternatives that are easy to make at a low price. As so often, the best solutions are provided by nature itself. Bacterial communities that are present in wastewater are usually able to synthesize different polymers, the so-called extracellular polymeric substances (EPS). These polymers mainly consist of proteins and polysaccharides, with a high molecular weight and a negative charge, similar to PAM. These characteristics make them possible replacements for the unsustainable and potentially toxic PAM polymer.

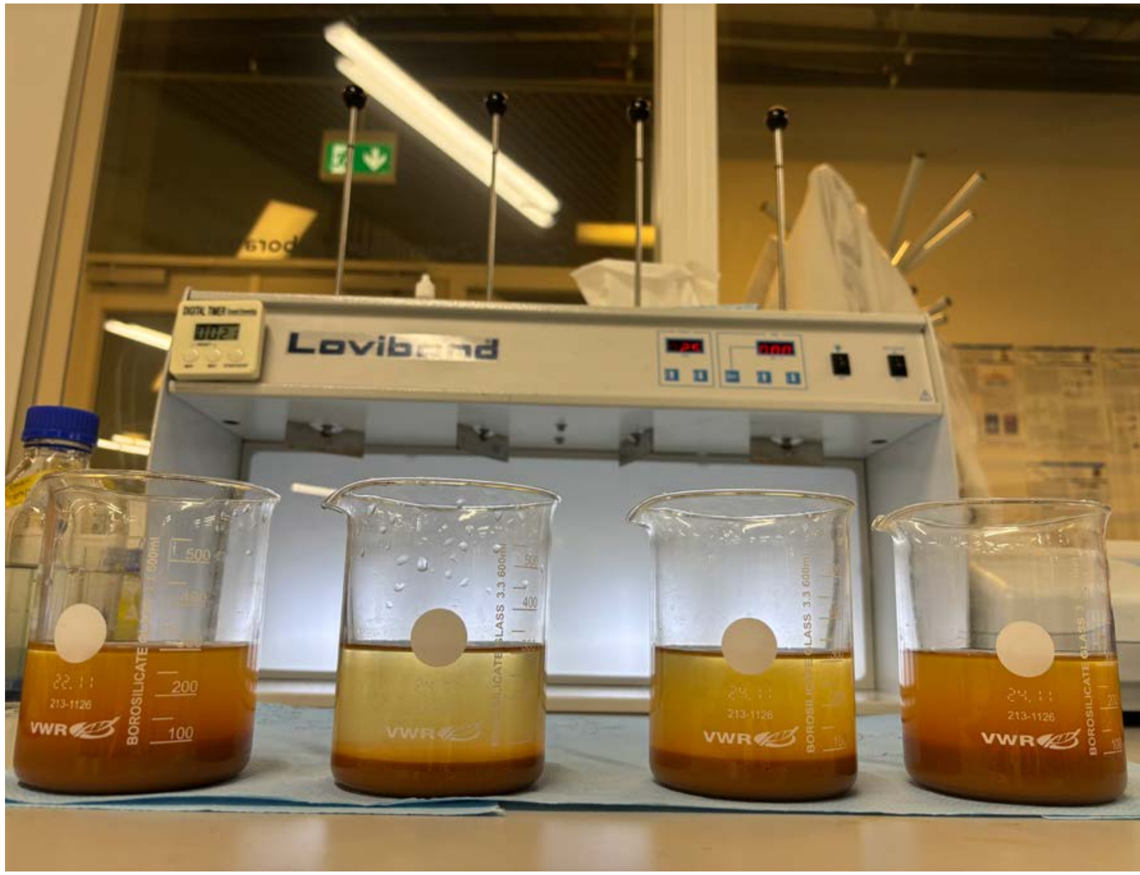
Natural flocculants

The great thing about EPS is that it can be produced efficiently in operating wastewater treatment plants that handle industrial waste streams. Wetsus, in collaboration with Wageningen University and Research's Hardy Temmink, Huub Rijnaarts and Dainis Sudmalis, found out that manipulating the environmental conditions inside the reactor, like keeping the concentrations of organic matter high and those of nutrients like nitrogen low, bacteria produced a lot of EPS. 'The low amount of nutrients prevents bacteria from growing, while the large amount of organic material supplies them with a lot of food. Consequently, they excrete high amounts of EPS that can be harvested,' Contreras explains. 'The beauty of the method is that instead of degrading and oxidizing organic matter from waste streams into carbon dioxide, the bacteria now make polymers that can be used as natural flocculants.'

Toxic waste

'For Paques it is the challenge to make economically attractive, high-quality products. Working together with Wetsus and other partners was a huge benefit,' says Carla Frijters, Process technologist & Development Manager Natural Flocculants at Paques. 'In the green flocculant project, we worked successfully together on the technology to synthesize EPS in lab reactors. Then, Paques developed a special reactor for the production of EPS.' The technology is efficient and low-

> Instead of degrading organic matter from waste streams into CO_2, bacteria now make polymers that can be used as natural flocculants.



cost compared to other green alternatives. Frijters sees several options on how to market the polymer: 'Bacteria can synthesize EPS in our specially designed reactors, whereafter the polymer is harvested and sold. Another possibility is to incorporate the reactor inside a wastewater treatment plant. Then, EPS can be continuously produced and directly applied to flocculate small particles.'

Cheapest option

But she still sees some hurdles to replacing PAM with EPS. 'Currently, the price for the sustainable EPS is still a bit higher than the oil-based PAM, that goes for about 3-5 euro per kilogram.' The price of EPS should definitely be more competitive. Another bottleneck is that there is no legislation yet to limit the use of PAM as a flocculant and as a result companies mostly choose the cheapest option. Another issue is the relatively undefined content of EPS. Although EPS is a natural and biological degradable mixture of bacterial polymers, companies need by law to show its content and characteristics. Frijters: 'We will need to do toxicity and biodegradable tests to solve this.' Nevertheless, she is very optimistic that the hurdles will be taken and that EPS will be a large success, with major positive environmental impact.

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While this book features interviews with several representatives of our projects, we are deeply aware that many more voices and contributions have played a crucial role in shaping the outcomes. Not all of them could be mentioned within the chapters, but their input, guidance, and commitment have been equally indispensable. This dedicated section is therefore meant to extend our sincere gratitude to all who have been involved – directly or indirectly – in the innovations that emerged from our program.

The effective Wetsus approach

1. BiOPhree – Phosphate recovery using iron oxide
The development of the BiOPhree technology has been a true team effort over many years. The first steps were taken by Prashant Kumar, the first PhD at Wetsus to work on this topic. He was followed by Carlo Belloni, who drove the research further towards scientific understanding and application. The baton has now been passed on to Yuwei Huang, who is already making excellent contributions to this work. The scientific foundation was strengthened through the collaboration with TU Delft, in particular with professors Mark van Loosdrecht, Ekkes Brück, and Geert-Jan Witkamp, who provided invaluable academic guidance. From the very beginning, Leon Korving, as theme coordinator of the P-recovery theme, has been one of the key drivers of this research.

The international pilot plants in Cyprus and Spain required ingenuity and persistence; here, Wokke Wijdeveld played a crucial role in operating and troubleshooting the installations under challenging conditions. The pilot sites and support were kindly provided by the Larnaca Sewerage and Drainage Board (LSDB) and Sorigué. The subsequent pilot in Dronten, made possible thanks to the support of STOWA and Waterschap Zuiderzeeland, marked an important step towards real-world application. We gratefully acknowledge the support of the European Union's Horizon 2020 research and innovation programme through the Water Mining project. The close collaboration with Pim de Jager (Aquacare) and Mathijs Oosterhuis (HaskoningDHV) has been essential in scaling the technology from the lab to the field.

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Current innovations

2. Capturing and utilizing CO_2 from flue gases
We would like to thank the ConsenCUS project for providing financial support and all the consortium members for the fruitful discussions and collaborative research developed in the framework of the project, particularly we want to thank Michele Tedesco former scientific project manager at Wetsus, Pim Fredrix from NEC (New Energy Coalition), Professor Philip Loldrup Fosbøl from DTU (Denmark Technical University), Professor Mijndert van der Spek from HWU (Heriot-Watt University), and collaborators from CERTH (The Center for Research and Technology, Hellas in Greece).

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3. REDstack's evolution to a world class leader in membrane stack technology
REDstack has transformed into a stack designing and constructing company based on the knowledge gained from two decades of research on salinity gradient energy. REDstack is a strongly technology driven company with a very dedicated technical staff that is in close contact with Wetsus. University supervisors who have contributed are professor Kitty Nijmeijer and Doctor Zandrie Borneman (University of Eindhoven), professor Wiebe de Vos, professor Wim Brilman and Doctor Antoine Kemperman (Twente University), professor Cees Buisman and professor Bert Hamelers (Wageningen University) and Doctor David Vermaas (University of Delft).

Part of the research was carried out within the framework of the European project REvivED. REvivED has received funding from the European Union's Horizon 2020 research and Innovation programme under grant agreement No 685579.

4. From wastewater to biodegradable plastic alternative
Connecting the dots that make innovations requires that the founding ideas are somehow made available in a melting pot that stews with the opportunity for the 'cooks' (focused motivated researchers) to brew. Wetsus created such a melting pot in the establishment of the research theme Biopolymers from water in 2017. Municipal wastewater can be a renewable resource for commercial supply chains of bioplastics. The pot is warmed by the member organizations and academic institutes with individuals – supporting, contributing, challenging, and motivating – while being stirred and spiced by a team of dedicated researchers – so thanks to STOWA (with actively involved water authorities – Waterschap Brabantse Delta, Wetterskip Fryslân), Paques Biomatertials BV, Slibverwerking Noord-Brabant (SNB), Unilever, TU Delft (Prof.s Mark van Loosdrecht and Robbert Kleerebezem), TU Eindhoven (Prof.s Kitty Nijmeijer and Zandrie Borneman), Maastricht University (Prof. Andrij Pich)

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6. Saving drinking water by better leak detection

The smart water grids research theme exists since 2009, and since a lot of developments into better asset management, improving inspection technology, developing data science and other new innovations are made. First of all this would not be possible without the long standing help of our current members PWN, Vitens, Acquaint, Brabant Water, Evides, Wavin, HuLo and our former members Oasen and Applus. And of course to the representatives of these companies: Thank you all for your critical and positive attitude ensuring a dynamical and creative research vision, without you this research theme would be a lot less interesting and rewarding! The research projects in this theme resulted in 2 Spinoff companies actively implementing the discovered inventions and methods. The water companies are actively adopting new methods and delivering valuable information bringing the research projects much further and Wavin (Orbia) is together developing a new kind of water carrier by active involvement and upscaling research to a pilot phase. All this would not be possible without the openness and willingness of these companies to work closely together in new research directions, and implementing the research outcomes into real applications.

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7. Treating waste streams using a new water-based separation technology

We thank the participants of the research theme "Dehydration" for the fruitful discussions and their financial support. Special thanks for Coolseparation bv. for hosting and co-organising the pilot test at their location. Furthermore we like to thank prof. Albert van der Padt of Wageningen university and dr. Jaap van Spronsen from Coolseparations bv. for their academic input and supervision.

8. Senor data fusion: effective, affordable, and indirect contaminant measuring

Although Wetsus has been working for many years with sensors and models, the Sensoring theme participant, Grundfos, planted the seed for sensor data fusion to detect and monitor low concentrations of chemical species indirectly. Edwin Ross was the first student to work on this topic, with Karel Keesman as promotor and Hans Stigter as supervisor from Wageningen University. Mateo Mayer from Easymeasure BV played an important role by producing optical sensors required for the research, but also in the modelling of industrial processes.

This cooperation in the Sensoring theme proved to be very successful and laid the foundation for Wetsus spin-off aqa.earth. The same sensor fusion approach has been included in the research of multiple projects in the former Sensoring theme, supported by the aforementioned companies, Evoqua and Shell. And even to date, in the Monitoring & Quality theme, supported by partners: Brabant Water, Deep BV, Vitens, muRata, EasyMeasure BV, aqa.earth, Omrin, Waterkracht, Wageningen University, Groningen University, Delft University of Technology, Eindhoven University of Technology, and University of Twente. Two PhD projects run in Horizon Europe projects: H2OforAll (ID: 101081963) and UrbanM2O (ID: 101180710).

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9. CO_2 removal from sea water using membranes

The concept idea was initially developed by Wetsus PhD alumni Rezvan Sharifian under the supervision of Martijn Wagterweld, scientific project manager from Wetsus and Professor David Vermaas from TU Delft. The project leading to this application has received funding from TKI Energie. We would also like to thank the participating companies of the research theme "Sustainable Carbon Cycle" for the financial support, as well as the companies, the supervisors, the former and current PhD students, and the Bachelors and Master's interns for fruitful discussions and their research contributions to the development of the technology.

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Upcoming innovations

10. PFAS degradation using lighting in a vortex
We would like to thank the Wetsus laboratory support team for their assistance, and give special thanks to the students Harmen, Esther, Manuel, and Leticia for their contributions. We are also grateful to the members of the research theme Applied Water Physics for their valuable discussions and suggestions. We sincerely thank our financial partners for their generous support, which made this research possible. In particular, we are deeply grateful to Waterschap De Dommel for their valuable input, to Schauberger Natur for supporting this research, and to Bright Spark B.V. for guiding the research focus toward PFAS-related challenges, providing continuous support, and supplying a wide range of PFAS-contaminated samples from various locations, which were essential for the experimental work.

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12. An improved desalination technology with many applications
This innovation in improved desalination technology evolved from many years of research within the Wetsus program on electrodialysis and other electrochemical processes. The idea of using metathesis to prevent salt scaling had long been discussed in theory, but it was the chemical-free process developed by FujiFilm that sparked the collaboration and allowed the concept to mature into a practical solution. We gratefully acknowledge the dedication of Kecen Li, PhD candidate at Wetsus, whose research was central to this development. We also thank Dr. Harry Bruning and Prof. Huub Rijnaarts from Wageningen University for their scientific supervision and support, which were instrumental in guiding the work to high-quality results. From industry, we express special thanks to FujiFilm, and in particular Abdulsalam Alhadidi, for initiating the project and sharing essential knowledge at the start. We also thank REDstack, whose advanced stack engineering was crucial to the success and further development of the process. This work was carried out within the Desalination & Concentrates theme of Wetsus. We warmly thank all participating companies, including Evides Industriewater, Evides Drinkwater, PWN, Waternet, SUEZ, FrieslandCampina, K+S, Pentair, and Pure Water Group, whose continued support and collaboration made this achievement possible.

13. Safer drinking water by using magnets
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14. Sustainable sedimentation using natural flocculants
The research on the dedicated production of microbial flocculants is performed in the Wetsus Natural Flocculants theme. In 2018, a proof-of-principle of EPS overproduction with open cultures was done as part of the PhD research of Victor Ajao under the supervision of Hardy Temmink. The developments continued with the PhD research of Evelyn Antunes, Berke Kisaoglan and Bohan Chen. This research is made possible with the support of the theme members Pentair X-Flow and Paques, with special thanks to Leo Vredenbregt and Carla Frijters for the fruitful collaboration. We thank Evides who also supported the proof-of-principle research. The demonstration with industrial waste(water) as feedstock was funded by the Netherlands Organization for Scientific Research (NWO) (grant number 19336) performed by Carlos Contreras Davila who also worked part-time at Paques on the technology development. Lastly, we would like to thank the research supervisors Hardy Temmink, Cristina Gagliano and Carlos Contreras Davila from Wetsus; Dainis Sudmalis, Huub Rijnaarts and Harry Bruning from Wageningen University; Boelo Schuur from University of Twente; and all the MSc and BSc students that contributed to this topic in the past seven years.

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