Pilot development support & validation

NURSECOAST-II REPORT

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Morten Lykkegaard Christensen & Giacomo Messina

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The following project partner organizations contributed to the data collection and writing of this report:
Institute of Fluid Flow Machinery, Polish Academy of Sciences: Izabela Konkol, Lesław Świerczek, Ksawery Kuligowski
Natural Resources Institute Finland (LUKE): Virpi Vorne, Anu Reinikainen, Frans Silvenius, Sini Valmari
The Bogdan Janski Bure Misie Community Foundation (BMCF): Marta Płuciennik
Aalborg University (AAU): Morten Lykkegaard Christensen, Giacomo Messina
Kaunas University of Technology: Jolanta Dvarionienė, Dalia Gedgaudienė, Džiugas Dvarionas
Stockholm Environment Institute Tallinn Centre (SEI Tallinn): Tiia Pedusaar, Selma Guyon, Helen Poltimäe, Andreas Hoy

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Introduction

In Europe, tourism is the most significant sector of the blue economy regarding employment. However, very often, the inflow of tourists is seasonal, concentrating on the summer period. This holds for Northern Europe, where favourable weather conditions occur only for a relatively short period of the year. Thus, these coastal regions face seasonal variations in wastewater production. This may lead to inadequate wastewater treatment during the tourist season, when the wastewater load is high. The wastewater treatment plant (WWTP) is typically designed for the low season and is equipped to handle wastewater from far fewer people than the actual number during peak tourist periods. This results in issues such as unpleasant odours, overloaded municipal treatment plants, and pollution of the Baltic Sea. This can, for example, be a problem for the bathing water quality around tourist areas. Additionally, unpleasant odours and other issues can make the place less attractive to tourists.

Five pilot wastewater treatment plants have been installed to test new and improved wastewater solutions. The pilot plants are located in Denmark, Poland, and Latvia. The pilot plants are installed in tourist areas in order to minimize nutrient inputs into the Baltic Sea, avoid odours, lower energy consumption, and improve the capacity of already existing plants. The pilot plants used different methods to treat wastewater and manage peak tourism periods. The tested technologies include constructed wetlands, nano-bubble aeration, and the use of wastewater effluent for agricultural irrigation.

The report summarizes the pilot development support and validation, including the evaluation of methods to ensure high phosphorus removal, the efficiency of nano-bubble aeration for biological wastewater treatment, water and nutrient reuse through irrigation, biomass valorisation, and odour reduction. Besides the five pilot plants, additional work and support work have been conducted and included in the report, including IT systems for remote management of wastewater treatment plants, wastewater solution development in a tourist area (Skola Guest Harbour) and a survey study on decentralized wastewater systems.

PILOT 1: New methods for enhanced phosphorus

Author: Jānis Zviedris, Jolanta Dvarionienė

Plant site description

VNK Serviss, located in the Ventspils region of Latvia, operates and maintains 16 small-scale municipal biological wastewater treatment plants. These facilities vary in hydraulic capacity, ranging from 20 m^3/day to 400 m^3/day. Despite the differences in size, all plants use a similar flow-through system based on the activated sludge method for biological wastewater treatment.

The goal of VNK Serviss in the NURSECOAST-II project is to identify a solution for enhancing the performance of existing municipal biological wastewater treatment plants, enabling them to better cope with seasonal fluctuations in pollutant loads. These variations, driven by increased activity during peak tourist seasons, place significantly higher demands on the treatment process compared to the rest of the year.

As part of this initiative, the centralized biological wastewater treatment plant in the village of Jūrkalne, Latvia—featuring a hydraulic capacity of 30 m^3/day—has been selected as the Pilot site for testing and development.

As in other small-scale municipal biological wastewater treatment plants, the biological wastewater treatment plant in Jūrkalne faces annual seasonal overloads due to increased tourist activity, pushing pollutant levels beyond design capacity. While building an additional treatment unit for seasonal use was considered, it would raise operational costs and consumer tariffs. Instead, the nanobubble technology was installed in May 2024 as a cost-effective alternative to intensify treatment and offer more efficient oxygen transfer. A monitoring program was used to assess its effectiveness in managing seasonal pollution peaks.

The pilot site in the village of Jūrkalne, Ventspils Municipality, Latvia (Figure 1) is located on the Baltic Sea coast and has the highest coastal steep shores in Latvia. Thus, it is visited by many tourists and visitors during the tourist season. As mentioned before, this creates seasonal problems in wastewater treatment due to changing pollution levels and the inflow of wastewater into the Jūrkalne wastewater treatment plant. Jūrkalne WWTP provides centralized wastewater treatment for about 150 permanent residents daily. During the active tourist season, most of the problems are related to changes in pollutant loads, which make the capacity of existing wastewater treatment plants insufficient.

Figure 1. Pilot location in Latvia

Treatment technology

Industrially manufactured biological wastewater treatment plant BIO M-30 was built in 2015. Figure 2 presents the wastewater treatment plant in Jūrkalne.

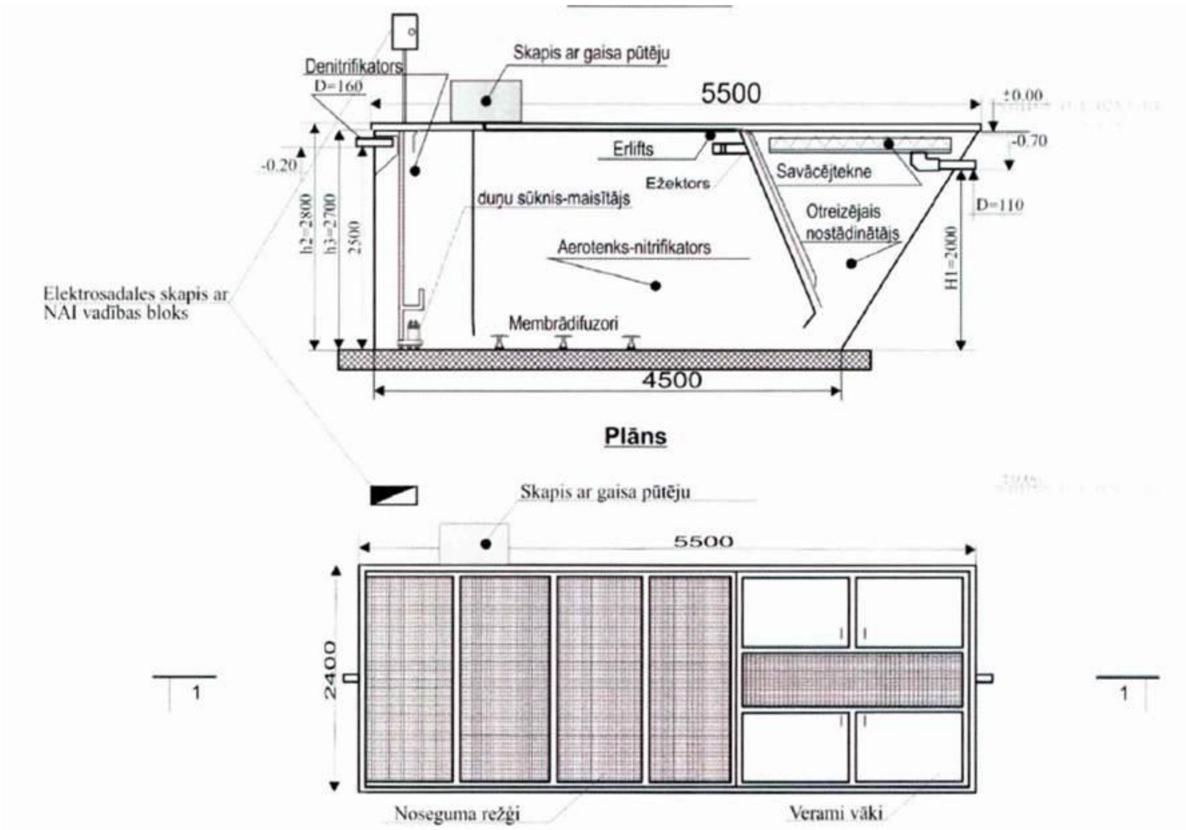


Figure 2. Diagram of the biological wastewater treatment plant BIO M-30 in Pilot 1 (Jūrkalne, Latvia), data VNK serviss.

Pre-treatment of the raw wastewater (sand, some grease, other fast sinking, or floating impurities) takes place in a primary clarifier. After mechanical pre-treatment, the effluent flows into the anaerobic (denitrification) zone of the biological treatment reactor. At the same time, activated sludge from the secondary settling tank is pumped into the denitrification zone by means of an airlift. A pump-mixer is installed in the denitrification zone to produce a homogeneous mixture of the incoming effluent and activated sludge before it enters the next biological wastewater treatment zone. From the denitrification zone, the mixture of wastewater and activated sludge flows through openings in the bulkhead into the aerobic part of the aeration tank (nitrification zone). The aeration system is supplied with air from a blower installed next to the biological wastewater treatment unit in a stainless-steel cabinet. The electrical cabinet with the control unit for the wastewater treatment plant is located next to it. The following processes are carried out in the aerobic zone: nitrification, reduction of BOD5 and COD, and activated sludge regeneration. Throughout the biological wastewater treatment cycle, a residual dissolved oxygen concentration of 2,5-4,0 mg/l and an activated sludge concentration of 2-4 g/l are maintained. After the aerobic zone, the mixture of wastewater and activated sludge flows into the secondary clarifier. The settling part of the secondary clarifier has sloping walls where the activated sludge settles out, while the upper part collects treated effluent, which flows out of the WWTP into a control well via an adjustable toothed weir. The activated sludge settled from the lower part of the secondary clarifier is returned to the anaerobic (denitrification zone) of the biological wastewater treatment plant by means of an airlift. The airlift is powered by air from an air blower.

In Table 1 (below), the design characteristics of the Jūrkalnė WWTP are presented.

Table 1. Design characteristics of the Jūraklanė WWTP (VNK Serviss, 2024).

No.	Description	Unit	Amount	Notes
1	Capacity	m^3/d	up to 30	
2	Flow:			
	min	m^3/h	0,75	
	max	m^3/h	2,0	
	COD	mg/l	210 - 740	Inlet
6	BOD_5	mg/l	150 - 350	Inlet
7	BOD_5 / COD		0,5 – 0,7	Inlet
8	Suspended solids	mg/l	120 - 450	Inlet
9	$N_{TOT.}$	mg/l	20 - 80	Inlet
10	$P_{TOT.}$	mg/l	6 - 23	Inlet
11	pH		6,5 – 7,5	Inlet
12	Temperature	^0C	11 - 25	Inlet
		Designed efficiency		
13	COD	mg/l / %	<125	Outlet
14	BOD_5	mg/l / %	<25	Outlet
15	Suspended solids	mg/l / %	<35 / 90	Outlet
16	$N_{TOT.}$	mg/l / %	N/A / 60	Outlet
17	$P_{TOT.}$	mg/l / %	N/A / 50	Outlet

Methodology

The nanobubble technology, which offers more efficient oxygen transfer, was installed in May 2024 as a cost-effective alternative to intensify the biological treatment. The solution from TECHRAS NANO ApS to boost the biological part of the wastewater treatment, potentially allowing the Jūrkalne wastewater treatment plant to be scaled down current size and more efficiently delivering dissolved oxygen to the micro-organisms that treat the polluting nutrients. The general input data for pilot calculations are assumed from worst case scenario with max inlet flow 2 m^3/h and max inlet COD concentration 1900 mg/l. A monitoring was used to assess its effectiveness in managing seasonal pollution peaks.

Data analysis

Jūrkalne WWTP provides centralized wastewater treatment for about 150 permanent residents daily. In Figure 3 the amount of wastewater Jūrkalne WWTP flow, m^3/month, 2024 is presented.

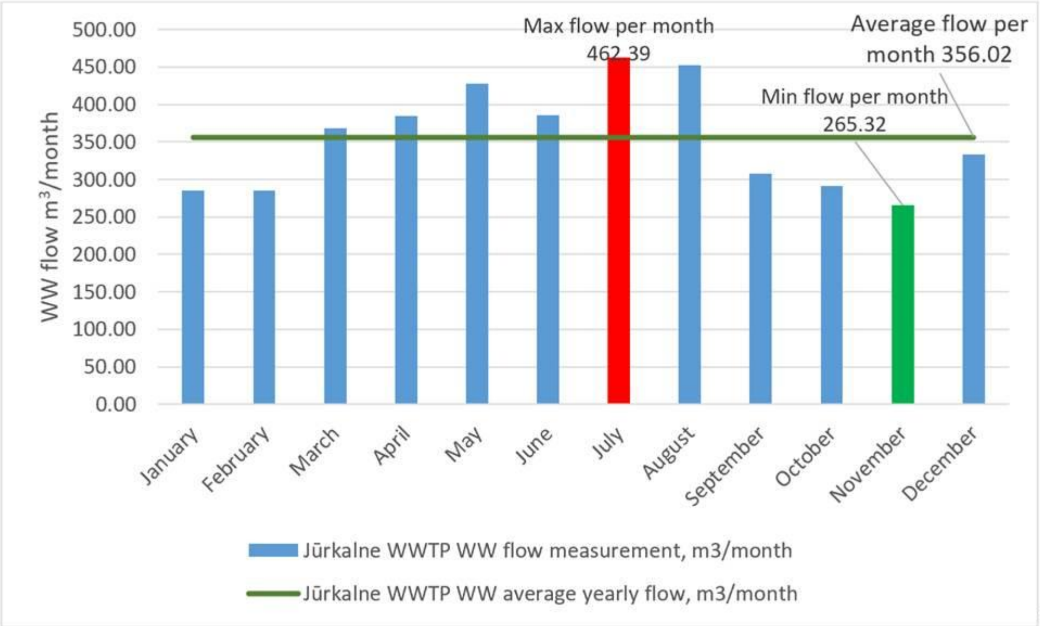


Figure 3. Jūrkalne WWTP wastewater flow measurement, m3/month, 2024 (data VNK Serviss).

The general input data for pilot calculations are assumed from a worst-case scenario in Jūrkalne WTTP, with a max inlet flow of 2 m^3/h and a max inlet COD concentration of 1900 mg/l.

Figures 4 and 5 (below) show the COD and BOD_5 concentrations in the inlet and outlet in the year 2022.

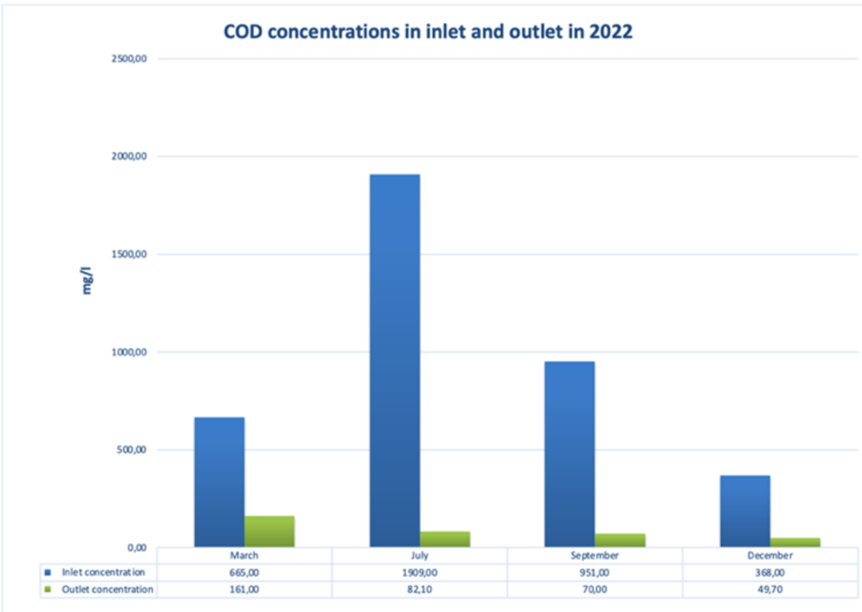


Figure 4. COD concentrations in the inlet and outlet (VNK Serviss)

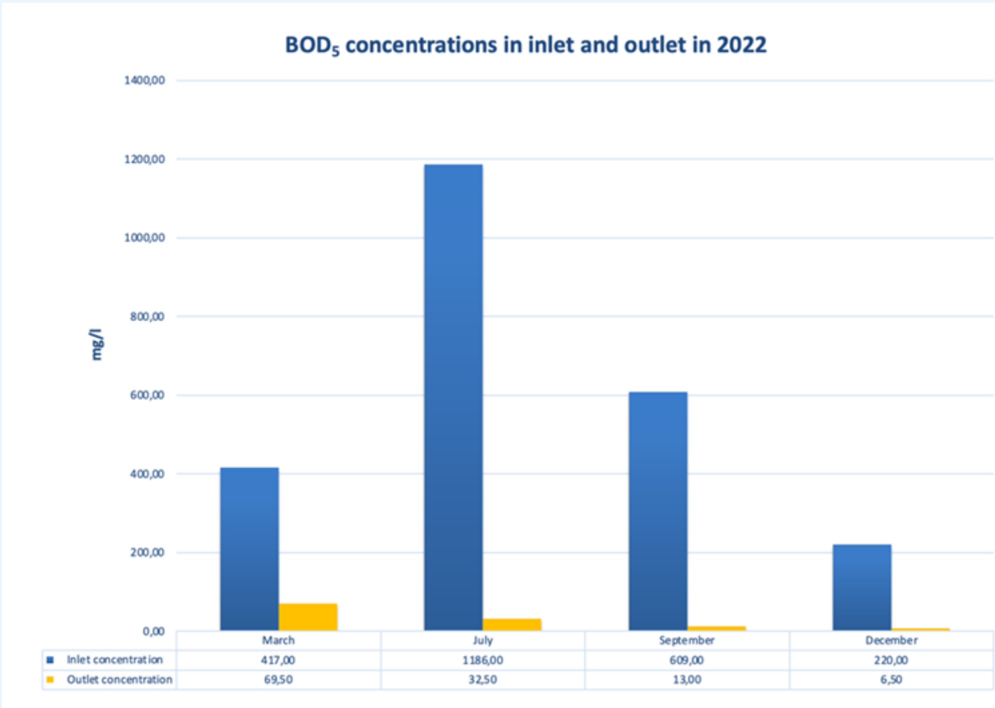


Figure 5. BOD5 concentrations in the inlet and outlet (VNK Serviss)

Discussion

Coastal tourist towns, villages, and settlements around the Baltic Sea experience significant seasonal fluctuations in wastewater generation, leading to inadequate performance of wastewater treatment systems during the busy summer months. These systems are often designed based on the needs of the low season and are ill-equipped to handle the substantial increase in wastewater produced during peak tourist periods. For example, many treatment plants are built to serve a capacity of fewer than 2000 people, which falls short of actual demand during the tourism season. This mismatch can lead to a range of issues, including unpleasant odours, overburdened municipal facilities, and increased pollution in the Baltic Sea—an ecosystem already under considerable stress.

Implementing alternative wastewater treatment technologies tailored to the specific demands of tourist areas could significantly reduce nutrient loads entering the surface waters and contribute to improving the overall health of the Baltic Sea.

One of these technologies is nanobubble technology, which has been integrated into existing biological wastewater treatment in a small wastewater treatment plant in Jūrkalnė (Figure 6). The applied technology enhances this process by injecting hundreds of billions of nanobubbles into just 1 millilitre of water, further improving the efficiency of pollutant breakdown and oxygen transfer. A decision has been made to place the nanobubble generator in the primary clarifier, before mechanically treated wastewater flows into the biological wastewater treatment phase.

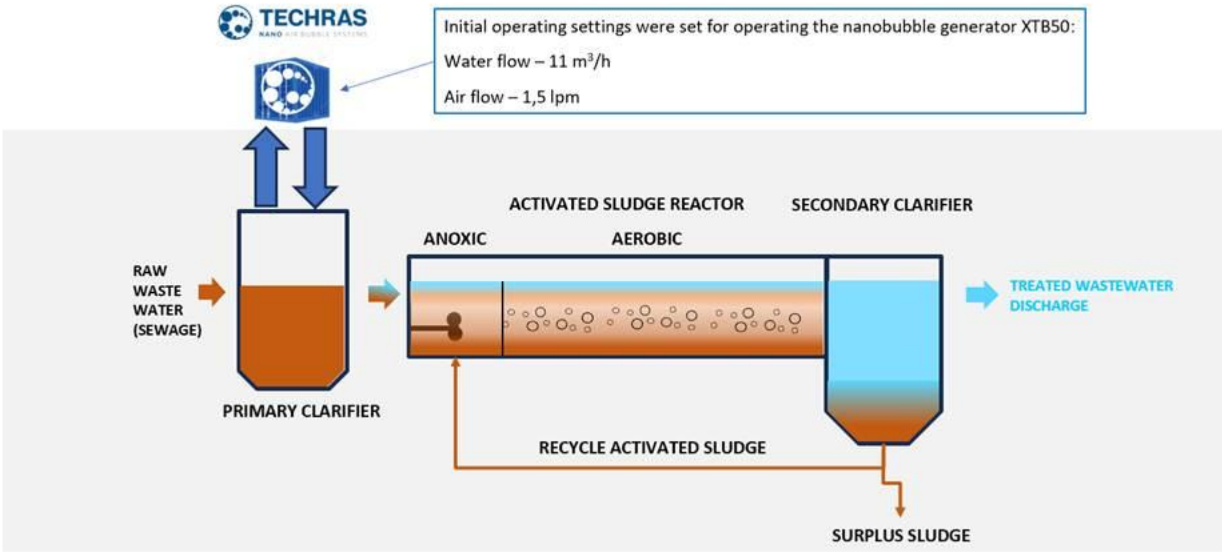


Figure 6. Solution for improvement with the nanobubble generator (TECHRAS technology, VNK Serviss)

The pilot implementation of nanobubble technology at the Jūrkalne biological wastewater treatment plant aimed to achieve the following key performance improvements:

- **Effluent Quality Compliance**: Meet the regulatory requirement of ≤35 mg/L Total Suspended Solids (TSS) in the treated effluent.
- **Odour Reduction:** Minimize unpleasant odours typically associated with overloaded treatment processes.
- **Improved Oxygen Transfer (Alpha Factor)**: Enhance the efficiency of oxygen transfer in the biological treatment process.
- **Higher Dissolved Oxygen (DO) Levels**: Increase DO concentrations in the aeration tank, particularly addressing previous challenges in maintaining sufficient levels during peak load periods.
- **Better Sludge Settleability**: Improve the settling characteristics of secondary sludge, which is essential for stable process performance.
- **Overall Effluent Quality Improvement**: Achieve measurable reductions in Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), and TSS values in the final effluent.

These indicators will guide the evaluation of the nanobubble system's effectiveness in managing seasonal pollution surges and enhancing treatment efficiency.

Lessons learned and recommendations

There are presented the observations from nanobubble technology Implementation at Jūrkalne WWTP:

4) **The application of nanobubble technology** has demonstrated highly efficient oxygen transfer, as shown by the near-complete conversion of ammonium (NH_4-N) to nitrate (NO_3-N), with nitrite (NO_2-N) concentrations remaining virtually undetectable. This is further supported by a noticeable reduction in chemical oxygen demand (COD), indicating enhanced biological activity.
4) **At the Jūrkalne wastewater treatment plant** (WWTP), the theoretical annual bio-sludge production is estimated at approximately 1.5 tons of dry solids. However, throughout 2024, no excess sludge has been removed from the process. Two scenarios could explain this:
4) **Additionally, nanobubbles offer potential for optimizing energy consumption**. Once introduced, nanoparticles can remain effective in the system for 30–60 days, suggesting that continuous operation of the nanobubble generator (NBG) may not be necessary. However, site-specific measurements are essential to determine the optimal operating schedule.

4) **Remarkably, nitrification was observed even during winter months**, when raw wastewater temperatures fell below +8 °C conditions under which nitrification typically slows or ceases. In February, the NBG was turned off to assess its residual impact. Roughly three weeks later, in early March, a rise in NH_4-N levels was detected in the effluent, suggesting that nanobubbles have a lasting effect on supporting nitrification, even at low temperatures.

The recommendations:

a. **Optimize NBG operating time for Energy Efficiency**. Optimize the operating schedule of the NBG system to reduce electricity consumption. Since nanoparticles can remain effective for 30–60 days, onsite monitoring is essential to determine the precise duration of their activity.
b. **Enable portability as a plug-and-play solution**. If nanoparticles remain active for at least 30 days, consider designing the system as a portable, plug-and-play unit that can be transferred between plants, enhancing operational flexibility.
c. **Promote conscious water usage**. Water conservation habits often lapse when people travel, influenced by a perceived sense of freedom. To reduce environmental impact, begin by educating both residents and travellers on the importance of mindful water use, regardless of location.
d. **Continue monitoring nanoparticle persistence and impact**. The delayed response in microbial activity suggests that nanoparticles, due to their buoyant nature, persist in the system and sustain microbial enhancement beyond the injection period. Ongoing monitoring and data collection are recommended to validate these initial findings with greater confidence.

PILOT 3: Nanobubbles aeration efficiency tests

Author: Giacomo Messina and Morten Lykkegaard Christensen

Introduction

Nanobubble technology is a relatively new technology for wastewater treatment. A pilot-scale WWTP was installed in Næstved WWTP, Denmark, to evaluate the effectiveness of the nanobubble technology for aeration during biological treatment of wastewater. The plant in Næstved is operated by Envafors and is a large WWTP facility designed for 89,000 PE. Envafors is responsible for several WWTPs, including five located in the Næstved area. Of these five plants, two have a capacity well below 2,000 PE: Menstrup WWTP (630 PE) and Vallensved WWTP (700 PE). The original plan was to test the nanobubble technology at the pilot-scale facility in Næstved and then transfer it to Vallensved WWTP. However, data from the pilot-scale facility shows an increase in the concentration of suspended solids (organic materials) in the treated water, exceeding acceptable levels. As a consequence, it was decided not to implement the nanobubble technology on a full-scale at Vallensved WWTP; instead, another nanobubble technologies were tested at a smaller scale.

Aalborg University was involved in testing nanobubbles in a laboratory scale aeration process, aimed at measuring size, zeta potential, and oxygen concentration in nanobubbles, since it is impossible to measure these characteristics in activated sludge. More, an alternative solution to the original plan was explored, and a nanobubble generator in the shape of a rotating disk was investigated to overcome the suspended solids problem mentioned above. A literature study was conducted to understand the nature of nanobubbles and verify the obtained results regarding size, concentration and surface charge.

Treatment technology

The key element of this study was to investigate the effectiveness with which nanobubbles transfer oxygen to the water, thus allowing us to use the technology as an aeration unit. To do so, a pilot-scale plant was built at Næstved WWTP to evaluate the nanobubble generator as a method for full aeration of the biological treatment process. The setup included three IBC tanks, each with a maximum capacity of 1 m³, configured as a Sequential Bioreactor (SBR).

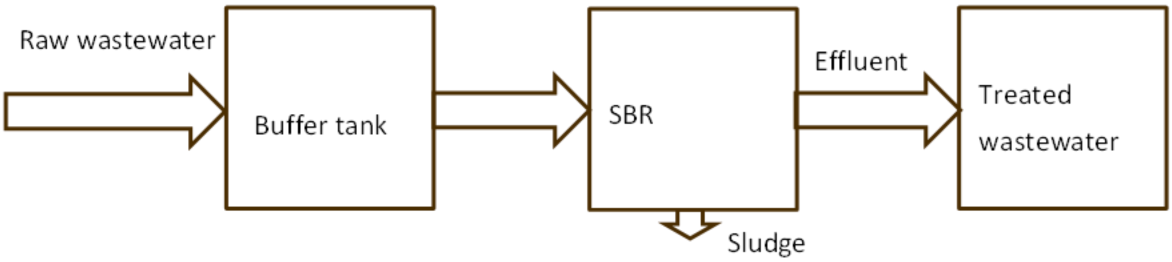


Figure 7. Sketch of the pilot plant with three tanks, each with a maximum capacity of 1 m^3. The first IBC tank is a buffer tank for raw wastewater, followed by the SBR. The treated wastewater is collected in the third IBC tank

The first tank (buffer tank) was equipped with a coarse-mesh filter to remove particles larger than 3 to 4 mm in diameter (Figure 7). After screening and sand removal at the main treatment plant, raw wastewater was pumped into the buffer tank. Heavier particles settled at the bottom and were collected separately. The surface water was then pumped into the second tank (SBR tank), passing through a fine-mesh filter with a 1.5 mm diameter (Figure 8). In the SBR tank, water was agitated using a turbine and oxygenated through a nanobubble generator. The nanobubble generator was connected as an external unit to the SBR. The wastewater in the SBR was circulated from the SBR tank to the nanobubble generator and back during the aeration periods. Before the test, the SBR was inoculated with activated sludge from the biological tank of the main WWTP in Næstved.

After the biological treatment in the SBR tank, the sludge was allowed to settle, and the resulting effluent was pumped into the third tank (treated wastewater) (Figure 7). Sludge could be retrieved from the bottom of the SBR tank. The system was designed so that the periods of aeration, no aeration, and settling could be set and controlled automatically. Various process durations have been tested and applied to optimize the wastewater treatment process.

Figure 8. Pilot plant to test nano bubble technology.

A nanobubble generator from Anzaii (ANZAIKANTETSU CO LTD, Japan, AZ-UFB-Generator, AZ-015-0286) was used for all tests (Figure 9). The nanobubble generator was based on a ceramic membrane, where air passed through the membrane and enters the water phase. With a high liquid flow across the membrane, small air bubbles were formed, and at optimal condition, nanobubbles around size of 100-300 nm were observed. This was measured in pure water, as it was not possible to detect and measure nanobubbles in wastewater due to the high concentration of other particles. Nanobubbles remain suspended in the water rather than rising to the surface as larger bubbles due to conventional aeration processes. This enhances aeration efficiency, with up to 90% of the added oxygen being transferred and dissolved in the water. Additionally, nanobubbles prevent the formation of anoxic zones and can generate free radicals, which enhance the degradation of organic materials, including micropollutants that may not undergo biological degradation. The recommendations and specifications for the unit are given in Table 2.

Table 2. Specification for the nanobubble generator unit

Gas flow	Up to 1.25 L/min at a pressure of 2 bars
Water flow	15 – 50 L/min
Recommended pump	0.06 – 0.1 kW
Carbon ceramic dimension	220 mm x 35 mm x 13 mm
Material	Transparent PVC
O-ring packing	Viton GS 170
Connection method	Adhesion or R3/4
Pipe outer diameter	20 mm

The water flow rate from the SBR tank to the nanobubble generator ranged from 5 to 30 L/min, with an aeration rate of 75 mL/min (achieved by pressurizing air to 1.5 bar overpressure). Notably, in this configuration, over 90% of the energy consumption was used for water pumping.

Figure 9. Nanobubble generator and setup

The nanobubble generator was connected to pumps and an air supply. This was done to allow for: 1) control of the air pressure to the generator, 2) measurement of air pressure and water flow, and 3) emptying of the generator unit during periods without aeration (anaerobic periods or during sludge settling).

Methodology

Experimental tests on the pilot-plant were done using the operation sequence outlined in Table 3.

Table 3. Test protocol for the SBR as an example for one of the tests preformed at the pilot-plant.

Process	Process time
Pumping from tank 1 to 2 (Aeration)	0 min
Pumping from tank 1 to 2 (Anoxic)	40 min
Aeration	60 min
Anoxic	40 min
Aeration	25 min
Settling	70 min
Pumping effluent from tank 2 – 3	15 min
Sludge removal	

Oxygen, nitrate, and ammonium concentrations are monitored online, while suspended solids and COD are measured offline. After the installation of the nanobubble generator system, inlet water samples were collected and analysed for total nitrogen (TN) and chemical oxygen demand (COD) to estimate the baseline water quality parameters. After the nanobubble generator was in function and bubbles were generated in a steady state, samples were collected in the water outlet to analyse TN, COD, and total suspended solids (TSS). To provide a better understanding and a most complete comparative context of the nanobubbles´ performance, water samples were also collected from the main treatment plant. Specifically, the comparative study was focused on the TSS outlet.

Oxygen transfer efficiency (OTE) measurements in clean water were conducted by initially cleaning the set-up from the activated sludge, carefully cleaning the water tank, filling the tank up to 300 L, and finally dissolving sodium sulphite (Na_2SO_3) in 300 L of clean water until the dissolved oxygen (DO) concentration reached 0. Initial DO was measured with oxygen sensors, and the amount of sodium sulphite used was calculated with the following formula:

$$mg\ Na_2SO_3 \approx 7.88 \times mg\ O_2$$

Then, an access of 33 or 50% of sodium sulphite was used. A total of 24 g of sodium sulphite was then added to 300 L of tap water, consequently, DO reached 0 mg/L in approximately 30 minutes. Following the deoxygenation process, the aeration device, designed to generate nanobubbles, was initiated. The working parameters for the nanobubble generation were consistently maintained at a liquid flow rate of 30 L/min, a gas flow rate of 75 mL/min of pressurized air, and a system pressure of 1.5 bar. The air used for nanobubble generation was standard compressed air supplied to the system. The increase in DO concentration within the 300 L tank was continuously monitored over time using a calibrated DO meter equipped with a data logging system. Measurements were recorded at regular 10-minute intervals throughout the aeration process. Simultaneously, the pH and conductivity of the water within the tank were also measured and recorded every 10 minutes using calibrated pH and conductivity meters to assess any potential changes in water quality during the aeration process. OTE at standard condition (SOTE) was then calculated with the following formula:

$$SOTE(\%) = \frac{SOTR}{Wo_2} \cdot 100$$

Where SOTR is the standard oxygen transfer rate [kg/h], and Wo2 is the mass flow of oxygen gas in the stream [kg/h]. They can be calculated using the following equations:

$$Wo_2 = 0.2765\ Qs$$

$$SOTR = K_L a_{20°C} \cdot C^{O_2}_{sat\,T} \cdot V$$

Where *Qs* [kg/h] is the air flow rate at standard conditions and 0.2765 is the ratio of oxygen in the gas stream at standard conditions, *V* [L] is the volume of the reactor tank, $C^{O2}_{sat\,T}$ [kg/L] is the saturation concentration of oxygen at working temperature, K_La_{20C} [1/h] is the mass transfer coefficient of oxygen at 20˚C.

At Aalborg University, a systematic study on the literature was conducted to gather information about the nanobubbles and to allow a comparative analysis with the results obtained by the experiments.

Aalborg University also conducted tests on a smaller laboratory scale nanobubble generator (ANZAI KANTETSU CO LTD, Japan, AZ-UFB-Generator, AZ-015-0286), investigating the efficiency in aeration of the nanobubbles, characterising size, zeta potential, and performing tests to evaluate the oxygen content inside the nanobubbles. The laboratory scale nanobubbles generator is a continuous flow generator, that continuously recirculate the water to ensure oxygen enrichment in a few minutes (3 minutes according to calculation). Aeration efficiency was tested by removing DO from 10 L water tank using nitrogen stripping, and then injecting 60 mL/min pressurised air at 2 atm, monitoring the rise of DO to study SOTE at 12, 20, and 25 L/min. For characterisation, nanobubbles were generated in a 10-litre tank at 12L/min and 25 L/min, the air flow was 60 mL/min. Samples were collected after 30 minutes and 120 minutes of continuous generation and were let rest for 10 minutes before starting the characterisation tests, so that microbubbles had time to leave the medium. All the samples were characterised in size and zeta potential, and the characterisation was repeated three times to ensure averaging of the data. For measuring the oxygen content, nanobubbles were generated in 10 litres of water at 25 L/min liquid flow for 30 minutes and 60 mL/min gas flow. Samples of 500 mL were then collected and let rest for 10 minutes to ensure disappearance of microbubbles. After resting, each sample was treated with 32 mg of sodium sulphite (the stoichiometric amount needed to remove DO from 500 mL of water at 25-27 °C), poured in 4 steps, to remove the DO from the medium and allow the eventual oxygen in the nanobubbles to freely flow into the water. DO was recorded over the duration of the entire experiment.

Data analysis

In the pilot plant, data show that the system effectively removes nitrogen and COD. However, the floc structure was destroyed, which reduced the quality of the treated wastewater. In the main plant, TSS in the outlet water are approximately 5 mg/L, while in the pilot plant, TSS have a higher value, attested between 50-90 mg/L, far above the legislation permit.

The dissolved oxygen concentration was monitored after the nanobubble generator was started in deoxygenated water (Figure 10). Clean water tests show that, according to calculations, SOTE has a value of 3%, which is far below the value found in literature (around 20-30%). Since the SOTE is highly dependent on the process parameters, we suspect that this can be due to the tank volume (300 L), too large for a gas flow of just 75 mL/min. Although the membrane could process a gas flow of 1.25 L/min, this was impossible due to the frequent membrane clogging from the activated sludge in previous tests.

SOTE increased with the liquid flowrate. The significant difference between SOTE calculated in the pilot plant in Næstved (around 3%) and SOTE calculated at Aalborg University relies on the different volumes of water treated; in fact, approximately the same gas flow was used to aerate 300 L in Næstved, and 10 L in Aalborg University.

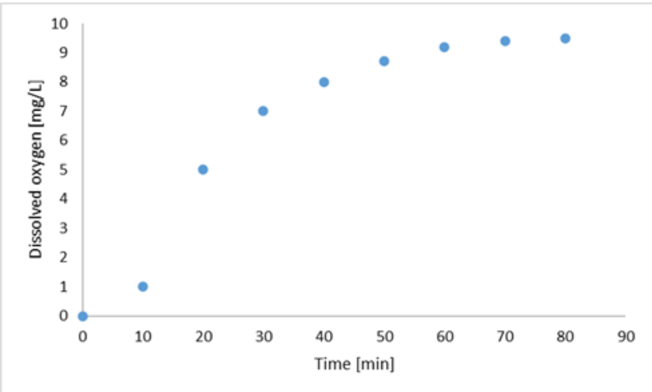


Figure 10. Oxygenation with Anzai Nanobubble generator

An experimental study at Aalborg university was done to determine the oxygen transfer efficiency (Figure 11).

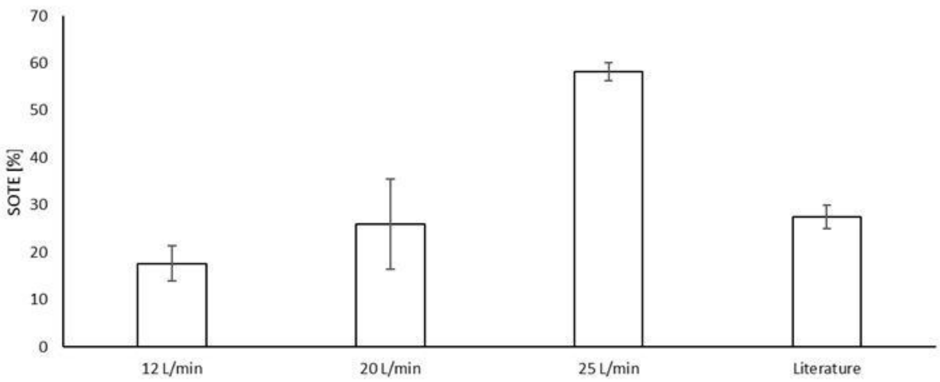


Figure 11: SOTE calculated from different pumping velocity

Discussion

The goal of the test at the pilot-scale setup at Næstved was to determine if a nanobubble generator could serve for full aeration of the biological tank during wastewater treatment. In traditional aeration, the Standard Oxygen Transfer Efficiency (SOTE) is 20-25%, meaning 75-80% of the oxygen is lost as large bubbles rise to the surface. Literature reports suggest that ceramic membrane nanobubbles can achieve a SOTE above 90%. This may particularly be beneficial for WWTPs where the biological treatment tank is undersized, as higher oxygen transfer can increase the capacity of existing plants without the need for new construction work. Depending on the energy consumption required to produce nanobubbles, this technology could also offer substantial energy savings, which was an important part of the study.

The plan was to test nanobubbles on a pilot scale and, if successful, implement them in a small full-scale plant. We operated the SBR pilot plant for a year or more and have gained valuable insights. We have observed that it is possible to remove nitrogen and COD using only nanobubbles for aeration. In addition, data from a small-scale test cell shows that the nanobubble generator is highly efficient in transferring oxygen into the water at a high flow rate. Additionally, the test shows that most of the oxygen was transferred to the water immediately or very quickly after the water passed the nanobubble generator. Nanobubbles that did not disappear after a few seconds only contributed to a small, negligible part of the total oxygen introduced to the system. One of our observations was the variation in organic load on the pilot-scale plant. This variation can be beneficial when investigating technology for areas with high loads in the summertime.

We encountered some problems with the specific nanobubble generator tested and possibly with nanobubbles in general. The nanobubble generator requires large amounts of water to be pumped to bypass the membrane, which significantly increased energy costs—more than 90% of the energy for the nanobubble generator was used for pumping water. Consequently, the energy cost was higher than that of traditional aeration, despite the higher efficiency in oxygen transfer. Additionally, the system partially destroyed sludge flocs, leading to an increased concentration of suspended solids in the effluent. This decline in the quality of treated water was unacceptable and must be solved if the technology should be used at full-scale. During operation, some of the pores for the air flow were clogged, so the air flow declined with time and thereby also the aeration rate. This increased the energy cost and lower the aeration rate. For these reasons, more technological development was required before it is mature for implementation at a full-scale plant

Pumping can be avoided by using a rotating membrane, where the rotation of the disk creates the shear force against the water that generates the nanobubbles. This may minimize the mechanical destruction of the sludge flocs and be more energy efficient than pumping water through a membrane unit. Data shows less disruption of floc structure with the rotating disk filter. Further, the energy consumption was lower, but some optimizations are still required to match the most effective aerators.

Lessons learned and recommendations

A nanobubble generator can deliver oxygen quickly and efficiently to water and sludge, making it a potentially attractive method to increase the capacity of existing small WWTPs. It is possible to use it as the sole method for aeration. Note that in other pilot plants, nanobubble generators were used as a supplement to existing aeration solutions.

When activated sludge was pumped through the nanobubble aerator, the sludge structure changed, resulting in an increase in suspended solids in the wastewater effluent. Additionally, the energy consumption was quite high. This was the most important drawback of using the solution as a sole aeration technology. Rotating disk filters are better than flow through membranes for producing nanobubbles, as both disruption of floc structure and energy consumption can be reduced.

PILOT 4: New methods for enhanced phosphorus removal and membrane filtration tests

Author: Morten Lykkegaard Christensen and Giacomo Messina

Introduction

A constructed wetland was installed at Skovsgaard Gods. The place is located in the countryside of Langeland, Denmark. It is owned by the Danmarks Naturfond (Danish Nature Foundation) and established by Danmarks Naturfredningsforening (Danish Society for Nature Conservation). The estate spans over 400 hectares, with 245 hectares used for wild grazing and nature, with cattle and wild horses living freely in nature. Skovsgaard Gods is located 10 km from Rudkøbing, the largest town on the island. Rudkøbing has a WWTP designed for 20,000 PE. Skovsgaard Gods offers nature experiences for families and nature enthusiasts. Guests visit the location primarily during the summer months, from April to September. Overnight stays are possible, but most visitors come for day trips. The site has a cafeteria. The wastewater composition varies in amount and composition during the season, depending on the type of activities (larger groups staying at the place for several days, visitors for day trips, high activity in the cafeteria).

The concept of Skovsgaard Gods as a destination offering nature activities for families and nature enthusiasts is relatively new. They began expanding their activities around the start of the NurseCoast II project in 2023. As a consequence, the amount of wastewater has increased and is expected to rise further in the coming years. Before the project, raw wastewater was collected in a septic tank and transported to Rudkøbing WWTP for treatment. With the increasing number of activities, this is not a sustainable solution. Two alternatives were therefore discussed: either pumping the wastewater to Rudkøbing (installing a sewer system) or establishing a small WWTP at Skovsgaard Gods. It was decided to establish a constructed wetland at Skovsgaard Gods. The estate is surrounded by land, allowing the placement of a wastewater treatment facility without disturbing the surroundings. Vegetables are grown on-site, and there are several fruit trees. Therefore, there is a need to irrigate the vegetables and fruit trees during the summer months. The possibility of using treated wastewater for irrigation was considered.

The constructed wetland technology has evolved over the years, now with a system that allows for water recirculation during periods of low wastewater load to keep the microorganisms alive and functional. Additionally, aeration from the bottom of the basin has been used at some constructed wetland to provide extra oxygen to the plants and microorganisms during periods of high wastewater load. These installations, known as intensified constructed wetlands, seem to be particularly ideal for locations with varying wastewater loads throughout the year or where there is a need to reduce the footprint of the WWTP.

An intensified constructed wetland was designed and installed at Skovsgaard Gods by Killian Water. It was designed to accommodate up to 60 population equivalents (PE) during the summer and 1-2 PE during the winter. The wastewater load fit well with the wetland's growth, which is most active during the summer period. The intensified constructed wetland design (Figure 12).

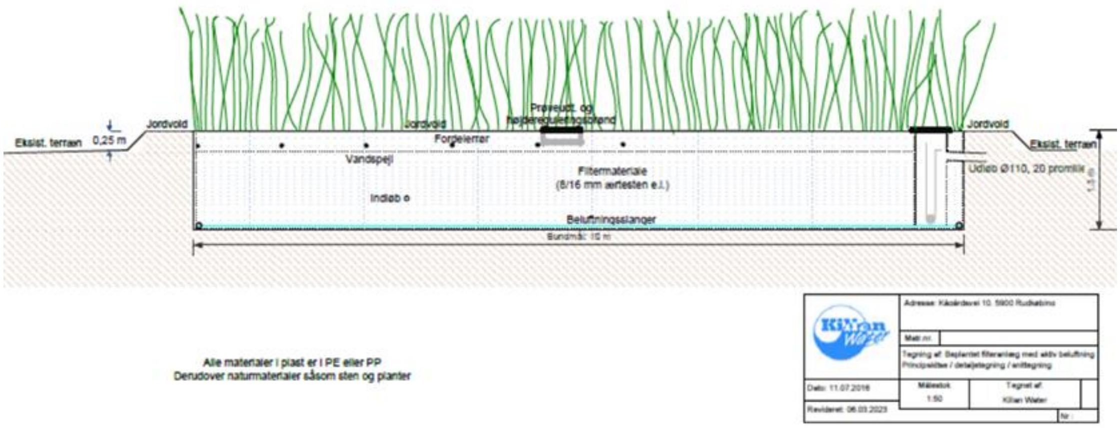


Figure 12. Principle of the constructed wetland (@ Kilian Water)

The WWTP facility was placed in a way that minimizes its visibility to visitors and mitigates potential odour issues. That was the reason for the placement behind the buildings (Figure 13).

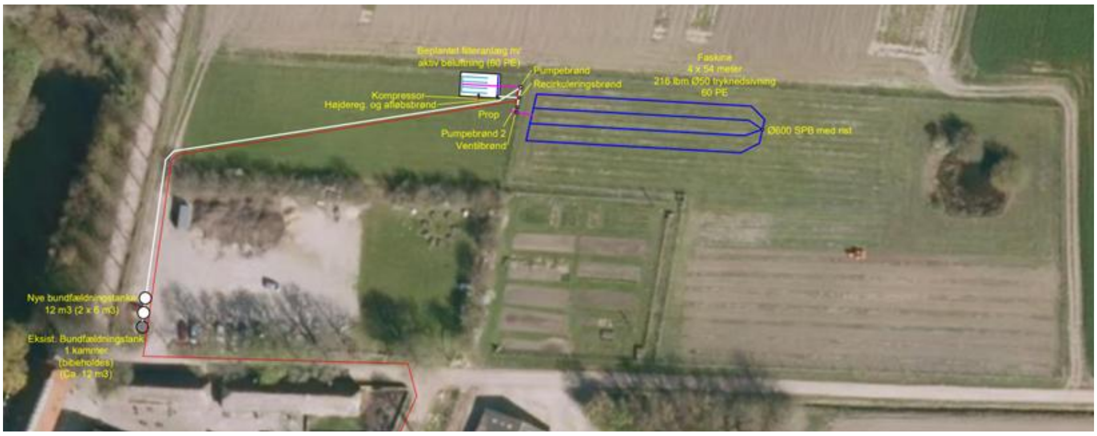


Figure 13. Skovgaard Gods with the location of the intensified constructed wetland and a zoom of the area

The design allocated 1.0 m² of constructed wetland per PE, based on the expected peak-period PE. In total, 60 m² of constructed wetland was established. The plant was positioned above an infiltration unit (Figure 14). Aeration was used in the wetland to boost mineralization processes, thereby reducing the required wetland area per PE. A small blower generates air bubbles at the bottom of the wetland, evenly distributed across the entire area. Aeration can be controlled and is limited to a maximum of 12 hours per day. A further pump was installed to recycle the effluent water back to the constructed wetland. All wastewater goes to the treatment plant. Rainwater is separated from the wastewater, is not pumped into the constructed wetland.

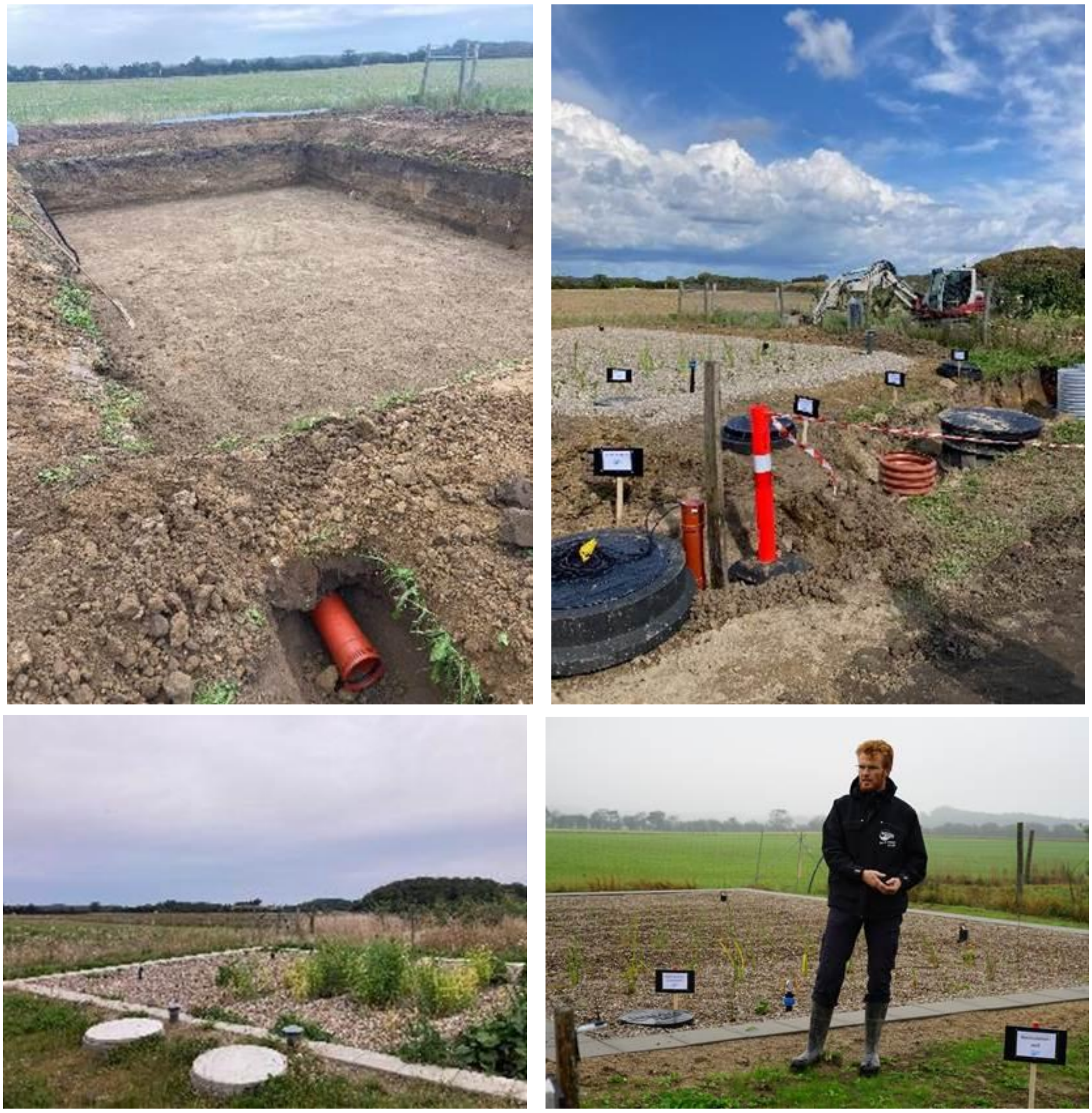


Figure 14. Pictures of the plant during and after construction in 2023. (Picture: Danmarks Naturfond)

Aalborg University participated in the pilot project for development support and validation. The part of the project consists of several components:

- Analysis of raw wastewater done after the septic tank.
- Analysis of the quality of treated wastewater.
- Input on operational properties of the plant, i.e. aeration frequency, and recirculation of wastewater effluent.
- Study on the requirements for using treated wastewater for irrigation and test of treated wastewater.
- Discussion of methods to reduce phosphorus content in the treated wastewater.

Methodology

Samples were collected at the septic tank (raw wastewater) and after treatment (effluent during the 2024 season and continued into 2025). The samples were transported to Aalborg University and analysed. Samples were collected every other week during the tourist season and less frequently outside of it. *E. coli* analysis in the treated wastewater was done at Eurofins, and the sample was taken and handled according to their procedures.

Rainfall data was obtained from Danmarks Meteorologiske Institut (dmi.dk). Danmarks Meteorologiske Institut collect weather data from across the country. Specific data on rainfall was found for Langeland, measured in millimetres of rain per week, and used to estimate the amount of water added to the intensified constructed wetlands through rainfall.

Aeration was controlled and adjusted to 4 sessions of 3 hours per day, two sessions of 3 hours per day, two sessions of 1 hour per day, or turned off entirely, depending on the wastewater load and historical data for the constructed wetland. After the first year, the aeration periods were modified based on the results.

Recirculation of treated wastewater was turned off during the tourist season, but it was used during the winter, when activity at the site was low. The energy consumption for pumping and aeration was monitored.

Raw wastewater samples were analysed by measuring pH, conductivity, turbidity (NTU), total solid, suspended solid, COD, total phosphorus (TP), orthophosphate (oP), and total nitrogen (TN)

Treated wastewater samples were analysed by measuring the same parameters as for raw wastewater, including the amount of ammonia/ammonium ions (TAN), nitrate and nitrite.

Danmarks Naturfond had an estimated number of 7,500 visitors in 2024 at Skovsgaard Gods and a water consumption of 412 m³.

Data analysis

Data for both the raw and treated wastewater were monitored. The COD varied at the inlet but was maintained around 25 mg/L, which is well below the national limit of 75 mg/L for municipal WWTP plants. The turbidity decreases as expected after filtration through the wetland bed and continues to decrease over time, possibly due to the initial leakage of small particles at the beginning of the process. The pH is higher in the effluent, while the conductivity is lower. This agrees well with the expectations.

Both removal of ammonia and nitrate were effective through the wetland, and all aeration frequencies tested gave high removal rates. However, the analysis of total nitrogen reveals a relatively high amount in the treated wastewater, with an average removal rate of 30%. Phosphorus in both the raw wastewater and the effluent exists as ortho-phosphate, and easily measurable phosphorus. The average removal rate of phosphorus is 70% if rainfall and evaporation from the constructed wetland are negligible for the measured concentration in the outlet. The average concentration of phosphorus in the outlet was 3.4 ± 0.6 mg/L. It will be beneficial either 1) to reduce the phosphorus content further or 2) to use the effluent water for irrigation.

Irrigation water should have a low number of colonies forming units (CFU) of *E. coli*. CFU have been determined during the summer period. The CFU was lower than 15, and the actual samples fulfilled the requirements for the Class B standard. This was a positive result, as extra treatment was planned to include UV treatment to ensure that the quality meets the standard. As seen in the discussion, we were not allowed to test the solution and used the water for irrigation.

During the process, it was decided to reduce the aeration duration, which did not significantly affect the treatment quality except for total nitrogen. The total removal rate increased from 10-20% with 2 hours of aeration per day to 35-50% with 12 hours of aeration per day. In comparison, 70% of the phosphorus and 80% of the COD were removed, respectively. There was no correlation between total nitrogen in the raw wastewater and the removal rate. The residence time or flow of raw and treated wastewater was not monitored.

Phosphorus reduction can be achieved using membrane technology. However, since phosphorus exists in dissolved form as ortho-phosphate, nanofiltration or reverse osmosis membranes are necessary. Some transport through nanofiltration membranes is expected, making this method less feasible for phosphorus reduction. Data with 8 membranes shows a rejection varying between 60-80% meaning that at least 20% of the phosphorus passes the membranes. The most promising technology for removal seems to be adsorption of phosphorus or adsorption by Polonite, Filtralite or LDH.

Discussion

Phosphorus and nitrogen levels were monitored in the wastewater effluent. The concentrations of phosphorus and nitrogen were significantly reduced in the constructed wetland. The aeration period did not seem to significantly influence the effluent concentrations, possibly because the number of visitors and the wastewater load did not reach 60 PE during the summer period, remaining well below that threshold. Thus, the aeration period was reduced from 12 hours per day to 6 hours per day, effectively halving the energy consumption for the compressor. Monitoring wastewater production can therefore be beneficial for plant operation, as it allows for reduced energy consumption for aeration.

The concentration of *E. coli* was measured in the effluent and was low. It was discussed whether additional treatment, such as UV-treatment, could be implemented so the treated wastewater could be used for irrigation of vegetables and fruit trees (Figure 15).

Figure 15. Area at Skovsgaard Gods with fruit trees

The wastewater effluent test shows that, without further treatment, it fulfils the requirement of the Class C standard for reclaimed water quality for irrigation with reused water (Table 4). This could be further ensured and guaranteed by establishing additional treatment.

The plan was to use drip hoses that meet Class C standards (Table 4), where the vegetables are above ground. The water should therefore meet the *E. coli* requirement of less than 1000 units per 100 ml (Table 5), but our intention was to achieve zero units per 100 ml. Monitoring was then required twice a month at an accredited laboratory during the summer period, when irrigation was required.

Økologirådgivning Danmark was contacted regarding the use of treated wastewater at Skovsgaard Gods. According to them, it was not possible as the legislation concerning the use of wastewater in Denmark is very restrictive, especially for organic production. Thus, the plan was dropped.

Table 4 Classes of reclaimed water quality and permitted agricultural used and irrigation method (quality classes for irrigation with reused water per regulation, EU 2020/741).

Minimum reclaimed water quality class	Crop category (*1)	Irrigation method
A	All food crops consumed raw where the edible part is in direct contact with reclaimed water and root crops consumed raw	All irrigation methods
B	Food crops consumed raw where the edible part is produced above ground and is not in direct contact with reclaimed water, processed food crops and non-food crops including crops used to feed milk- or meat-producing animals	All irrigation methods
C	Food crops consumed raw where the edible part is produced above ground and is not in direct contact with reclaimed water, processed food crops and non-food crops including crops used to feed milk- or meat-producing animals	Drip irrigation (*2) or other irrigation method that avoids direct contact with the edible part of the crop
D	Industrial, energy and seeded crops	All irrigation methods (*3)

Table 5 Reclaimed water quality requirements for agricultural irrigation (quality classes for irrigation with reused water per regulation, EU 2020/741).

Reclaimed water quality class	Indicative technology target	Quality requirements				
		E. coli (number/100 ml)	BOD_5 (mg/l)	TSS (mg/l)	Turbidity (NTU)	Other
A	Secondary treatment, filtration, and disinfection	≤ 10	≤ 10	≤ 10	≤ 5	*Legionella* spp.: < 1 000 cfu/l where there is a risk of aerosolisation Intestinal nematodes (helminth eggs): ≤ 1 egg/l for irrigation of pastures or forage
B	Secondary treatment, and disinfection	≤ 100	In accordance with Directive 91/271/EEC (Annex I, Table 1)	In accordance with Directive 91/271/EEC (Annex I, Table 1)	-	
C	Secondary treatment, and disinfection	≤ 1 000			-	
D	Secondary treatment, and disinfection	≤ 10 000			-	

About 2.5 cm or so every week to ten days

Lessons learned and recommendations

The intensified constructed wetland effectively ensured the high-quality treatment of wastewater. Aeration was used to enhance the degradation process. At Skovgaard Gods, good wastewater treatment was also observed over extended periods with a reduced aeration rate. Therefore, it is recommended to monitor wastewater production and effluent quality to ensure only the necessary aeration at the constructed wetland, thereby reducing energy consumption. Implementing a system to monitor the flow of raw wastewater and rainfall would be beneficial for better adapting the aeration frequency protocol to actual conditions. This could be achieved by registering visitors and the type of visitors, monitoring pumping energy, or eventually by installing a flow meter.

The effluent quality fulfilled the requirements for the Class C standard for reclaimed water quality for irrigation with reused water. Additional disinfection (UV-treatment) can be installed to reuse the treated wastewater for irrigation. Despite the EU regulation allows drip irrigation with Class C standard water, it is still not possible in Denmark. It is recommended to align the policy with the EU regulations.

PILOT 5: Aeration optimization

Author: Lesław Świerczek, Marta Płuciennik

Introduction

The mechanical-biological wastewater treatment plant (WWTP) located in pilot 5 has been operational since 2006. Due to significant fluctuations in the number of tourists throughout the year, the facility needs to be expanded and modernized to maintain high treatment efficiency amid variable and increasing wastewater loads.

In response, nanobubble (NB) technology has emerged as a promising solution for improving water treatment efficiency and was therefore implemented in the pilot 5 WWTP. Defined as gas-filled cavities with diameters around 100 nm, NBs possess unique properties such as a high surface area-to-volume ratio, negative zeta potential, and long-term stability in liquids. These features make them highly effective in applications such as flotation, aeration, and chemical-free oxidation. Compared to conventional macro- and microbubbles, which collapse rapidly, nanobubbles persist in water, thereby facilitating more efficient treatment processes. Their capacity to enhance the removal of organic pollutants, heavy metals, and improve aerobic decomposition holds significant potential.

However, several challenges are associated with the implementation of NB technology. A key issue is the limited understanding of nanobubble behaviour in complex wastewater matrices, which can influence treatment efficiency. Furthermore, inconsistencies in the literature regarding the stability and exact mechanisms of action of nanobubbles hinder their broader adoption. Economic feasibility and large-scale environmental impacts also remain insufficiently studied, raising questions about their practical applicability beyond controlled laboratory conditions.

The primary objective of introducing NB technology in pilot 5 was to assess its effect on dissolved oxygen (DO) levels in the aeration chamber. The original aeration system installed at the plant often proved insufficient, particularly during periods of high wastewater loads. Moreover, due to the ongoing development of the nearby tourist centre located in the PILOT 5 area, modernization of the treatment plant became a necessity, prompting the trial implementation of the NB system.

Nanobubble Oxygenation

The mechanical-biological wastewater treatment plant in PILOT 5 was originally designed to handle 75 Population Equivalent (PE) with a maximum wastewater flow (Qmax) of 1.5 m^3/h. However, during peak tourist season, the average number of people increases to approximately 160, compared to an off-season average of around 58.

It was observed that, especially in the summer months, the dissolved oxygen content in the aeration chamber was very low. According to scientific literature, DO levels in the aerobic chamber of a WWTP should be around 2 mg O_2/dm^3, whereas recorded values did not exceed 0.5 mg O_2/dm^3.

Due to insufficient oxygenation, seasonal variability in wastewater volumes, and a decline in treatment performance, a nanobubble oxygenation system was introduced. A 2 m^3 Micro-Nano Bubble Generator (Qingdao Aozhengnier Purification Equipment Co., Ltd) shown in Figure 16, capable of producing oxygen nanobubbles smaller than 100 nm, was installed.

a b c

Figure 16. Photos of the nanobubble generator: a - first test run, b – generator tested in IMP PAN, c – nano-oxygenated and normal water

During the reporting period, the performance of the original aeration system was compared with that of the newly implemented nanobubble (NB) system. To monitor oxygen content in the aeration chamber along with other key parameters—such as pH and redox potential at both the reactor inlet and the effluent from the aeration chamber—a dedicated monitoring system was installed at the treatment plant alongside the NB generator (CX-804 controller (Elmetron, Poland)). This setup included a control system, measurement probes, and other components enabling fully automated operation of the entire aeration process. Figure 17 shows the described components.

a b c d

Figure 17. Nano-oxygenation system components: a - circulation pump, b – monitoring device, c –probes, d – the entire setup placed in a well.

The NB aeration system was installed in place of the existing setup, with the option to easily switch between the two systems. Figure 18 shows the scheme of the NB oxygenation system introduced in the WWTP. Each aeration system was tested over a two-day period during the peak tourist season.

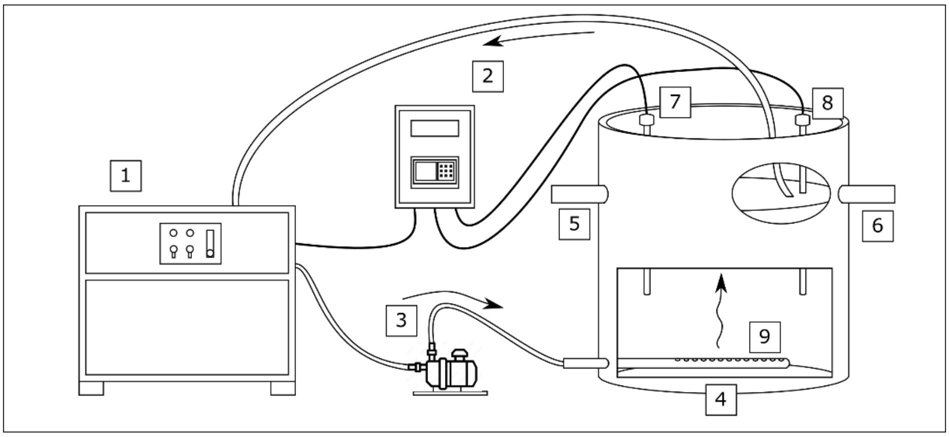


Figure 18. Nanoareation system implemented in the existing WWTP located in the Bure Misie Foundation. (1) – nanobubble generator, (2) – monitoring and control device, (3) – recirculation pump, (4) – bioreactor, (5) – wastewater inlet, (6) – wastewater outlet, (7) - pH, Red-Ox potential and dissolved oxygen probe, (8) – Red-Ox potential probe, (9) – aeration pipes

Discussion

Aeration is a critical process in wastewater treatment, supplying oxygen for biological degradation while accounting for approximately 70–80% of total energy consumption. Its effectiveness strongly depends on DO levels, which regulate microbial activity. Conventional aeration systems generate coarse or fine bubbles, with fine bubbles generally providing higher oxygen transfer efficiency due to their larger gas–liquid interfacial area.

Nanobubbles represent a promising alternative because of their enhanced mass transfer efficiency and stability. Literature reports indicate that air nanobubbles exhibit approximately 1.5-fold higher oxygen diffusion coefficients than coarse bubbles, leading to improved microbial activity and enzymatic processes. Compared with conventional fine-bubble aeration, NB-based systems have been associated with higher oxygen availability, reduced sludge production, and improved organic matter degradation. While fine bubbles are effective in enhancing nitrogen and phosphorus removal, nanobubbles have demonstrated superior performance in the removal of suspended solids and nitrogen when compared with bottom aeration.

In this study, a conventional coarse-bubble aeration system was compared with nanobubble oxygenation in an aeration chamber. The system was initially heavily loaded with organic matter, as indicated by low DO and redox potential at the outlet. After the introduction of nanobubbles, both parameters increased rapidly; however, the chamber remained overloaded after two days of operation. The application of nanobubbles resulted in an average 35% increase in DO concentration, confirming their high oxygen transfer efficiency. Despite a significantly lower air flow rate (0.3 m^3/h for the NB generator versus 60 m^3/h for the conventional blower), both systems showed comparable energy consumption, highlighting the substantially higher mass transfer efficiency of nanobubbles. Nevertheless, to fully meet the oxygen demand of the treatment system, longer operating times or a higher-capacity NB generator would be required. Although nanobubbles improve oxygen delivery, they do not provide sufficient hydrodynamic shear to control biofilm thickness, indicating that combined operation with mechanical aeration or optimized recirculation is necessary for stable long-term performance.

Lessons learned and recommendations

The primary objective of the PILOT 5 installation was to enhance the efficiency of an overloaded wastewater treatment plant, which faces increased load during summer months and receives effluents from food production facilities. Introducing NB aeration significantly improved oxygen transfer, enhanced wastewater parameters and reduced odours, confirming the high oxygen transfer efficiency of NB systems despite comparable energy consumption to conventional aeration.

However, the pilot also revealed key operational challenges. Unlike traditional blowers, nanobubbles do not generate sufficient turbulence to maintain proper sludge mixing, leading to potential sludge accumulation and reduced treatment efficiency. This highlights the need for hybrid solutions. It is recommended to combine nanobubble aeration with mechanical mixing or traditional blowers to ensure both oxygenation and adequate biomass circulation. Additionally, using NB aeration in the primary settling tank could enhance the breakdown of fats and organics, reducing the load on the biological treatment stage. Overall, nanobubble technology shows strong potential as a supplemental or alternative aeration method, but further system integration and optimization are required to address limitations related to mixing and sludge transport.

PILOT 5: Effluent irrigation

Author: Ksawery Kuligowski, Izabela Konkol

Wastewater effluent irrigation

The goal of the study was to verify the wastewater effluent (WE) as a nutrient-holding irrigation medium in ryegrass cultivation, which is:

1. To examine the plant growth response as a function of effluent application rate in 3 subsequent growth months
2. To examine nutrient (Nitrogen) use efficiency (NUE) as compared to the control treatment and relative agronomic effectiveness (RAE) as compared to the reference fertilizer in 3 subsequent growth months

Methodology

The following steps were applied during the spring and summer of 2025 (Figure 19).

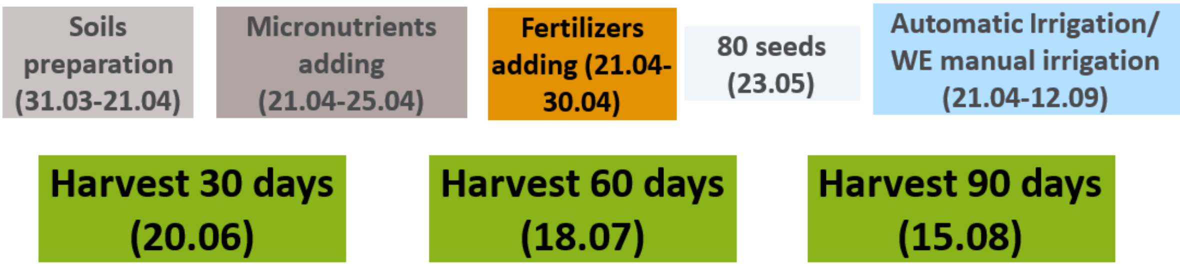


Figure 19. Greenhouse experiment set-up progress scheme

The following wastewater effluent (WE) from the Pilot 5 plant has been used (Table 6):

Table 6. Basic characteristics of the wastewater effluent (WE) used

Parameter	Unit	Influent	Effluent (Limit)	% Change
BOD	mg O_2/ L	604	130	- 78.50
COD	mg O_2/ L	2 845	268 (150)	- 90.60
Kjeldahl N	mg N/ L	80	123	+ 53.75
Ammonium N	mg N-NH4/ L	76	84	+ 10.50
Nitrites N	mg NO_2/ L	0,127	0,022	- 82.70
Nitrates N	mg NO_3/ L	0,520	0,360	- 30.80
Total P	mg PO_4/ L	30	6 (5)	- 80.00
Total N	mg N/ L	157	207 (40)	+ 31.85

Figure 20. Wastewater effluent (WE) seen when watering seeds and the greenhouse facility

The following fertilizer materials were used as reference ones (Table 7):

- UBG – Urine Based Granules (Sanitation360/ Sweden), 100 g N/ kg
- CMG – Cow Manure Granulated (Commercial), 49.3 g N/ kg

Table 7. Fertilizer application loads and dosing

Fertilizer	Application Loads	Dosing
WE	**58 – 275 kg N/ ha**	Right before seeding and 2 x/ month thereafter (volume restrictions)
UBG	20 – 370 kg N/ ha	Right before seeding
CMG	20 – 370 kg N/ ha	Right before seeding

Results and discussion

Below is shown the plant´s response to increasing application loads, broken down into 3 subsequent. Next, the plant N content and N use in kg/ ha are presented. Finally, both Nutrient Use Efficiency and Relative Agronomic Effectiveness are calculated and presented in Table 8.

1. Ryegrass yield responses after 30 days

Across all fertilizer materials, ryegrass yields at 30 days were relatively low compared to later harvests, reflecting early growth stage limitations.

- Wastewater effluent (WE): WE showed a strong, almost linear positive response to increasing N application. Yields rose steadily from ~0.15 g TS/pot at 0 kg N/ha to ~1.3 g TS/pot at 300 kg N/ha, suggesting good short-term N availability in the effluent.

- Urine-based granules (UBG): UBG produced a sharp early peak (~1.0 g TS/pot) at the lowest N addition (~25 kg N/ha). However, yields declined progressively with increasing dosage and dropped close to zero at the highest N rate. This pattern indicates potential salt or ammonium toxicity at elevated application rates, or overly rapid N release surpassing the crop's early uptake capacity.
- Cow manure granulate (CMG): CMG increased modestly, reaching ~0.65 g TS/pot at intermediate N rates (100–200 kg N/ha). At high rates (>250 kg N/ha), yields diverged, with a small recovery at 350 kg N/ha. This suggests slow N mineralization, with limited immediate availability at day 30.

2. Ryegrass yield responses after 60 days

Ryegrass biomass increased dramatically for all materials by day 60, reflecting active tillering and improved nutrient uptake.

- WE again showed a consistent, monotonic increase from ~0.3 g TS/pot up to ~1.9 g TS/pot. While the magnitude of increase was lower than for UBG or CMG, the response remained stable and predictable, indicating controlled N supply without toxicity.
- UBG produced the highest yields among all treatments and time points, reaching nearly 5.7–6.0 g TS/pot at 100–150 kg N/ha. However, yields declined at higher doses, confirming that excessive N release continues to suppress growth after the optimal window.
- CMG showed moderate yields (~2.0 g TS/pot initially) with improvement to ~3.0 g TS/pot at 250 kg N/ha. The pattern indicates progressive mineralization, with N becoming more available as the manure decomposes.

3. Ryegrass yield responses after 90 days

At 90 days, growth patterns diverged noticeably across fertilizers, reflecting longer-term nutrient release dynamics and possible soil feedback effects.

- WE maintained a modest but consistent pattern, with yields rising to ~1.4 g TS/pot at 250–300 kg N/ha. The lack of a strong late-season response suggests WE is largely depleted of plant-available N by this stage, consistent with fast N availability earlier in the cycle.
- UBG had a secondary performance peak (~3.2 g TS/pot) at ~225 kg N/ha, and a very high late peak (~4.7 g TS/pot) at 350 kg N/ha. This rebound indicates a slower-release fraction becoming available later, which aligns with the partial stabilization of nutrients in granulated urine products.
- CMG yields peaked around ~3.8 g TS/pot at ~125 kg N/ha but declined steadily afterwards. This suggests CMG mineralization rates may have peaked earlier (between days 60 and 90), after which either N became limiting or other factors (competition, soil microbial immobilization) constrained growth.

4. Comparative material performance

Early season (30 days): UBG provides strong early N but risks toxicity at higher doses, WE provides steady and reliable N for early growth, CMG underperforms due to slow mineralization.

Mid-season (60 days): UBG offers the largest yield potential, outperforming all other fertilizers, CMG catches up as mineralization accelerates, WE remains stable but yields are moderate.

Late season (90 days): UBG re-emerges as the highest yielding product at high application rates, WE yields plateau due to early nutrient exhaustion, CMG peaks early and then declines.

5. Comparison with other studies

The trends observed align well with previous glasshouse studies on ryegrass fertilization:

Urine-derived fertilizers

Similar studies report:

- Very high N availability due to urea hydrolysis and ammonium formation.

- Strong early growth at moderate rates.
- Growth suppression at high application levels due to elevated conductivity, ammonia toxicity, or pH shifts.
- These match the sharp early peaks and high-dose decline seen here at 30 and 60 days.

Wastewater effluent

Published work on effluent irrigation shows:

- Consistent but moderate biomass accumulation.
- Yield increases proportional to N loading.
- Reduced benefit over long growth periods due to early N depletion.

This corresponds closely to the monotonic but moderate WE responses across all three harvests.

Cow manure granulates / composted manures

Other ryegrass studies show:

- Slow but continuous N mineralization.
- Yields improving substantially between 30 and 60 days.
- Plateaus or declines after 90 days as mineralization slows.

This matches the observed mid-season peak and late-season decline in the CMG treatment.

Overall conclusion

The three fertilisers exhibit distinct N-release and ryegrass-growth signatures:

- UBG is the highest-performing fertilizer when applied at moderate rates, with both early and late growth benefits, but becomes inhibitory at excessive N loads.
- WE provides predictable, steady N release suitable for early and mid-season growth, with minimal risk of toxicity.
- CMG acts as a slow-release fertiliser that performs best from mid-season onward but shows diminishing returns later in the growth cycle.

Together, the results confirm previously observed behaviour of these fertilizer classes in controlled ryegrass systems, with clear implications for dose optimization and timing in practical applications

Across all three growth stages, the nitrogen (N) plant content and N use patterns closely mirrored the yield dynamics observed previously, revealing clear differences in N-release behaviour among the three fertilizer materials. Wastewater effluent (WE) consistently produced moderate but stable N concentrations in plant tissue (generally 22–30 g N/kg TS) across all months and dosages, and its N use increased steadily with dosage but remained comparatively modest (peaking around 20–30 kg N/ha), matching its steady yet moderate yield response. In contrast, urine-based granules (UBG) generated very high early plant N contents at low rates after 30 days (>50–65 g N/kg TS), followed by a steep decline at high doses—reflecting early N oversupply that corresponded with toxicity-linked yield depression in the first month. By 60 days, UBG showed a second strong rise in plant N content (up to ~30 g N/kg TS) and the highest N use values among all fertilizers (peaking near 80 kg N/ha), aligning with the exceptionally high mid-season yields previously observed. At 90 days, UBG maintained moderate tissue N levels (15–22 g N/kg TS) but again showed a sharp increase in N use at very high N loads, consistent with the strong late-season yield rebound. Cow manure granulate (CMG) consistently displayed low to moderate plant N content across all months (typically 10–20 g N/kg TS), with only minor increases at higher dosages, and N use remained low to moderate throughout (generally 10–25 kg N/ha). These patterns confirm CMG's slow-release behaviour and correspond to its gradual yield increase by day 60 followed by plateauing or decline by day 90. Overall, UBG delivered the highest N uptake and strongest yield responses at optimal doses but showed toxicity at high early applications, WE provided balanced N delivery and stable growth, and CMG supplied N slowly, supporting moderate and delayed biomass production.

Table 8. Nutrient Use Efficiency for 3 materials and Relative Agronomic Effectiveness for 2 materials

Growth	Dose [kg N/ ha]	NUE [%]			RAE [%]	
		CMG	WE*	UBG	WE*	UBG
30 days	20	103,5	270,9	486,2	136,5	288,1
	70	171,6	386,9	732,9	159,5	306,7
	120	205,2	433,6	610,4	146,3	232,8
	170	264,7	446,8	168,5	147,3	73,6
	220	271,2	444,5	188,8	142,3	77,8
	270	282,6	653,6	127,9	125,8	59,6
	370	499,2		-85,6		2,4
60 days	20	210,6	197,3	142,8	85,4	78,2
	70	248,0	253,1	436,6	84,2	154,2
	120	319,2	366,2	607,7	122,2	168,8
	170	281,7	311,6	1153,1	118,7	328,3
	220	246,8	368,9	1434,0	94,8	442,3
	270	394,6	381,0	1127,7	112,7	248,2
	370	326,7		657,9		177,6
90 days	20	16,9	63,7	-1,5	103,2	84,2
	70	58,5	80,2	279,3	48,9	239,3
	120	268,3	159,7	111,7	95,0	57,5
	170	173,2	61,4	99,3	94,7	72,9
	220	70,5	138,8	324,3	99,2	248,9
	270	140,8	181,4	290,5	196,2	162,1
	370	43,4	0,0	784,2		616,4

The Table 8 shows the results of the following calculations:

NUE (%) = $(N_i - N_{ctrl})$ x 100/ctrl

RAE (%) = (N_i/N_{ref}) x 100

So NUE literally denotes **how much over** is the given material's N use than the control treatment, and RAE shows the **ratio of the given material's N use as compared** directly to the reference material.

Across the three growth stages, Nitrogen Use Efficiency (NUE) and Relative Agronomic Effectiveness (RAE) reflected the contrasting nutrient-release behaviours of the wastewater effluent (WE), urine-based granules (UBG), and cow manure granulate (CMG), and were largely consistent with the yield and N-use patterns previously observed.

During the first 30 days, UBG exhibited very high NUE values (270–650%), driven by disproportionately high early N uptake at low to moderate doses, although this was accompanied by yield suppression at the highest application rates, resulting in negative RAE at the upper end. In contrast, WE displayed moderate NUE values and high RAEs (>400–700%) at most rates, reaffirming WE's availability of readily utilizable N and its stable early yield response. CMG showed lower NUE (70–200%), matching its slower mineralization and weaker early biomass production.

By 60 days, UBG again delivered the strongest overall agronomic performance, achieving very high RAE values (600–1430%) and high NUE (250–380%), directly corresponding to its peak ryegrass yields and highest N use of all materials at this stage. WE maintained moderate NUE and RAE, reflecting continued but not excessive N availability and a stable yield curve, whereas CMG generated moderate NUE.

By 90 days, UBG continued to show variable but often high RAE values (up to ~780%) at mid-to-high N dosages, consistent with its late-season biomass rebound, while its NUE declined due to diminishing marginal yield gains relative to N input. WE maintained moderate NUE and RAE, mirroring its stable but modest late-season yield plateau. CMG recorded the lowest NUE values (typically <100%), consistent with its limited late-season growth after earlier mineralization had slowed. Overall, the NUE and RAE profiles reinforce that UBG is the most agronomically potent material when applied at optimal rates and timings, WE is the most stable and predictable across months, and CMG provides delayed but weaker overall benefits due to gradual N release.

Lessons learned and recommendations

1. Urine-based granules (UBG) delivered the highest agronomic performance overall, producing the greatest mid-season yields, the highest N uptake, and the strongest RAE values, but only when applied at moderate rates. High doses caused early phyto-toxicity and reduced NUE during the initial growth period.

2. Wastewater effluent (WE) provided the most consistent and predictable response across all months. Its moderate but stable NUE and relatively high early RAE were directly linked to steady N availability and the absence of toxicity, making WE a reliable option for uniform growth without risk of over-fertilization.

3. Cow manure granulate (CMG) acted as a slow-release fertilizer, with low early NUE but moderate improvements by 60 days as mineralization progressed. However, its performance declined again by 90 days, demonstrating limited late-season N supply and generally lower agronomic value compared with UBG and WE.

4. Integrating yield, plant N content, N use, NUE and RAE patterns shows that UBG is best suited for rapid biomass production, WE supports stable growth across time, and CMG provides delayed but weaker benefits, confirming that fertilizer N-release dynamics strongly dictate ryegrass performance under glasshouse conditions.

5. Practical implications

- Generally, you need a water permit to irrigate plants with this type of water.
- You need to consult the Council of Ministers of the Environment regarding the conditions that must be met when discharging wastewater into water and soil.
- The quality standards set out in the EU regulation must be met. It's brand new, effective June 2023.
- This regulation classifies water, depending on its use, into four water quality classes: A, B, C, and D.
- A class is the most restrictive; it can be used to irrigate plants eaten raw, such as tomatoes (but the water cannot be poured directly onto the fruit; an irrigation system is required).
- Microbiological and physicochemical tests are required.
- Of course, there must be no E. coli or parasites.
- If it doesn't meet the requirements of class A, lawns, ornamental plants, or energy crops are optional.

PILOT 5: Hydrophyte biofilter treatment efficiency – design & technical support, seasonal loads effects on treatment, biomass valorisation and odours reduction

Hydrophyte biofilter treatment efficiency

Author: Izabela Konkol

Introduction

The use of hydrophyte-based biofilters offers an effective, sustainable method for wastewater and stormwater treatment. These systems utilize aquatic plants to absorb nutrients, trap sediments, and support microbial activity that breaks down pollutants.

Efficient biofilter performance begins with proper system design. This includes selecting suitable hydrophyte species (e.g., Phragmites australis, Typha latifolia), optimizing flow rates, and configuring substrate layers to ensure adequate retention time and nutrient uptake. Site-specific factors such as climate, water quality, and space availability are also crucial in system planning.

Well-designed hydrophyte biofilters can achieve high removal rates of nitrogen, phosphorus, suspended solids, and heavy metals. Typical efficiencies include:

- Nitrogen: 40–80%
- Phosphorus: 30–70%
- Total Suspended Solids (TSS): up to 90%
- Heavy metals: variable, depending on species and load

Ongoing technical support ensures long-term efficiency. This includes monitoring system performance, plant health, hydraulic functionality, and periodic maintenance such as sediment removal or vegetation management. Advanced support may also involve remote sensing, water quality testing, and optimization of operational parameters.

In conclusion, hydrophyte biofilters, when properly designed and supported, provide a cost-effective, eco-friendly treatment solution adaptable to various environmental conditions.

Wastewater treatment system before modernization

The wastewater treatment infrastructure in Osada Burego Misia was originally based solely on the Bioekol-Mini 75 treatment plant, constructed in the early 2000s. The system was designed to handle domestic wastewater and partially biodegradable effluents from local food production (e.g., cheese dairy, meat processing, and planned bakery).

Original System – Bioekol-Mini 75

The core parameters of the Bioekol-Mini 75 installation were as follows:

- Daily flow capacity (Qd): 15 m^3/day
- Peak hourly flow (Qmaxh): 1.5 m^3/h
- Maximum permissible pollutant loads:
  - BOD_5: 4.5 kg O_2/day
  - COD: 9.0 kg O_2/day
  - TSS: 5.4 kg/day
  - Total Nitrogen (TN): 0.9 kg/day

- Total Phosphorus (TP): 0.112 kg/day

The technological layout consisted of a three-zone septic tank providing mechanical pretreatment through:

- Sedimentation (4–8 hour retention time),
- Sludge accumulation and partial anaerobic digestion,
- Scum retention zone, occupying approx. 20% of the sludge zone volume.

Need for modernization

Over time, the original system became insufficient to meet actual operational demands, especially during summer peak loads, where the domestic wastewater alone exceeded the design capacity by over 150%. In addition, the food processing effluents placed significant strain on the system, with pollutant loads surpassing permissible values:

- BOD_5: 106.9%
- COD: 118.2%
- TSS: 96.9%
- TN: 95.5%
- TP: 61.8%

Although these effluents are largely biodegradable, their variable inflow patterns and high organic concentrations created operational challenges and treatment inefficiencies. As a result, it became necessary to modernize and expand the system to ensure regulatory compliance and stable operation.

Modernized system – hybrid constructed wetlands

In response, the treatment facility was upgraded by introducing a second treatment stage: a hybrid hydrofit-based biofilter system, providing biological purification of both domestic wastewater and pre-treated industrial effluents.

After mechanical and partial biological treatment in the Bioekol-Mini unit, the wastewater is evenly distributed to the constructed wetlands based on flow rate.

At this stage:

- Domestic wastewater is largely free of easily settleable solids.
- Food industry effluents are pre-treated and do not contain fats or colloidal organic matter like starch or slurry.

The biological treatment is carried out in a hybrid system composed of:

- Two vertical subsurface flow beds (SSVF I and II) – designed for oxygen-rich conditions, efficient organic matter removal, and nitrification.
- One horizontal subsurface flow bed (SSHF) – offering longer retention times, reduced oxygen levels, and optimal conditions for denitrification and removal of persistent pollutants.

Key purification processes include:

- Filtration, sorption, oxidation, and reduction,
- Microbial activity within the biofilm supported by plant roots and rhizomes,
- Intermittent surface loading of vertical beds to improve aeration and treatment efficiency.

The vertical flow beds (SSVF) enhance organic matter degradation and ammonia oxidation, while the horizontal bed (SSHF) supports nitrogen removal through denitrification and facilitates further reduction of hard-to-degrade compounds, including pharmaceuticals and priority substances.

The original Bioekol-Mini 75 system was no longer sufficient under increasing organic and hydraulic loads, especially from seasonal domestic wastewater peaks and local food processing. The modernization and expansion of the system through the addition of hybrid constructed wetlands significantly improved treatment capacity and process stability, allowing the facility to meet environmental standards and adapt to varying wastewater inflow conditions.

Monitoring - 2024

During the summer tourist season of 2024 (Table 9), a series of monitoring activities was carried out at the wastewater treatment plant operating in Osada Burego Misia. The monitoring was conducted every 1–2 weeks with the primary objective of assessing the treatment efficiency of the existing Bioekol-Mini 75 system prior to its planned modernization.

Sampling and analyses were performed at two specific monitoring points:

1) the first point was located at the primary settler, representing wastewater after mechanical treatment;
2) the second point was positioned at the outflow from the Bioekol-Mini 75 system, representing wastewater after biological treatment.

The evaluation focused on key wastewater quality parameters to determine the system's effectiveness in removing pollutants under peak seasonal loading conditions.

Tested Parameters:

- Suspended Solids (SS) [mg/L]
- Total Nitrogen (TN) [mg/L]
- Total Phosphorus (TP) [mg/L]
- Chemical Oxygen Demand (COD) [mg O_2/L]
- Biochemical Oxygen Demand (BOD_5) [mg O_2/L]

To meet environmental discharge standards, the treated wastewater should not exceed the following values:

- SS: 50 mg/L
- TN: 30 mg/L
- TP: 5 mg/L
- COD: 150 mg/L
- BOD_5: 40 mg/L.

Table 9. Monitoring results in summer season 2024.

Parameter	Unit	Primary Settler – Avg (SD)	After Mini75 – Avg (SD)	Limit Value	Criterion met
Suspended Solids	mg/L	16 ± 10	8 ± 4	50	Yes
Total Nitrogen	mg /L	210 ± 23	182 ± 40	30	No
Total Phosphorus	mg/L	15 ±3	12 ± 1	5	No
COD	mg/L	1407 ± 349	616 ± 298	150	No
BOD	mg/L	431 ± 171	121 ± 45	40	No

The monitoring campaign conducted in the summer of 2024—prior to the modernization of the facility—clearly indicates insufficient treatment performance by the existing Bioekol-Mini 75 system.

Although mechanical and biological stages together significantly reduced pollutant concentrations, the final effluent quality still failed to meet regulatory standards in several key areas:

- Total Nitrogen and Total Phosphorus remained far above acceptable thresholds, indicating ineffective nutrient removal.
- Both COD and BOD_5 values were significantly elevated, confirming incomplete degradation of organic matter.
- Only Suspended Solids levels remained within permissible limits.

The variability of the results, as indicated by high standard deviations—particularly for COD and BOD_5—further suggests unstable system performance, likely due to hydraulic and organic load fluctuations, as well as the limitations of the existing treatment technology.

These findings provide quantitative evidence supporting the need for modernization. The inability of the Bioekol-Mini 75 system to consistently treat both domestic and food-processing wastewater to compliant levels necessitated the implementation of an enhanced, hybrid hydrofit-based treatment solution.

Monitoring 2025

Following the modernization of the wastewater treatment system in Osada Burego Misia, a second phase of monitoring was conducted in the period from April to June 2025 (Table 10), prior to the peak summer tourist season. The aim of this monitoring was to assess the performance of the upgraded system, now enhanced with a hybrid constructed wetland (hydrophyte biofilter), and to evaluate its effectiveness in treating both domestic and food-processing wastewater.
Sampling was performed at three measurement points at intervals of several weeks.

- Point 1 remained located at the primary settler, representing wastewater after mechanical treatment.
- Point 2 represented the outflow from the Bioekol-Mini 75 unit, i.e., after biological treatment.
- Point 3, newly added in this monitoring phase, was located at the final outflow from the hybrid constructed wetland, representing the overall effluent quality of the entire treatment system.

The following parameters were tested, as in season 2024:

- Suspended Solids (SS),
- Total Nitrogen (TN),
- Total Phosphorus (TP),
- Chemical Oxygen Demand (COD),
- Biochemical Oxygen Demand (BOD_5).

Table 10. Monitoring results before the summer season 2025.

Parameter	Unit	Primary Settler – Avg (SD)	After Mini75 – Avg (SD)	After wetland – Avg (SD)	Limit Value	Criterion met
Suspended Solids	mg/L	181 ± 59	5 ± 1	41 ± 52	50	Yes
Total Nitrogen	mg /L	161 ± 43	55 ± 7	170 ± 38	30	No
Total Phosphorus	mg/L	34 ± 15	21 ± 3	5 ± 1	5	Yes
COD	mg/L	3824 ± 2743	942 ± 828	294 ± 23	150	No
BOD	mg/L	985 ± 383	182 ± 51	164 ± 41	40	No

The results from this second monitoring phase confirm that the modernization of the treatment system—including the integration of a hybrid constructed wetland—led to a marked improvement in pollutant reduction compared to the pre-modernization state. Substantial decreases were observed in suspended solids, organic matter (COD and BOD_5), and phosphorus levels. For example, suspended solids dropped from an average of 181 mg/L after mechanical treatment to just 41 mg/L at the final outlet, remaining within permissible levels.

However, despite these improvements, several parameters still failed to meet effluent quality standards:

- Total nitrogen levels remained significantly elevated in the final effluent (170 mg/L), exceeding the limit of 30 mg/L.
- COD and BOD_5 values, although significantly reduced compared to earlier stages, also exceeded the required thresholds.

These results suggest that while the wetland system is contributing to additional pollutant removal, its full treatment capacity may not yet be realized. It is important to consider that the constructed wetland is still in its early stages of ecological development, with hydrophyte vegetation in the process of root expansion and biomass formation. This biological maturation is critical for the establishment of effective microbial communities responsible for nutrient removal, particularly nitrogen via denitrification.

Given the above, it is recommended that continued monitoring be maintained throughout the 2025 summer tourist season, when hydraulic and organic loads will reach their peak. Further observation will provide insights into the stabilizing performance of the wetland system and help determine whether additional optimization is necessary.

Biomass valorisation to bioethanol

Author: Lesław Świerczek

Bioethanol production from renewable biomass has emerged as a key strategy in reducing dependency on fossil fuels while simultaneously addressing the growing challenge of organic waste management. Among various substrates, lignocellulosic biomass—such as agricultural residues, food industry waste, and energy crops—offers considerable potential due to its abundance and high carbohydrate content. One underexplored source of lignocellulosic material is the plant biomass generated in constructed wetlands which routinely produce organic-rich residues during their operation.

Ethanol fermentation is a biological process in which simple sugars are converted into ethanol by microbial action, typically involving yeast strains. While easily fermentable sugars are readily converted, lignocellulosic substrates are more complex due to their structural composition—mainly cellulose, hemicellulose, and lignin. These components form a rigid matrix that is highly resistant to enzymatic degradation, posing a significant barrier to efficient bioethanol production.

Pre-treatment is a critical step in bioethanol production from lignocellulosic materials. It facilitates the breakdown of complex plant structures, making cellulose more accessible for enzymatic hydrolysis. Common methods include mechanical treatment (e.g., shredding), chemical processes (acidic or alkaline hydrolysis), thermal methods such as steam explosion, and combined approaches like organosolv treatment. The goal of pre-treatment is to maximize sugar release, enhance conversion efficiency, and minimize the formation of inhibitory compounds.

Despite ongoing research and development, the conversion of lignocellulosic biomass into ethanol remains challenging due to processing costs and variability in biomass composition. Nevertheless, valorising plant biomass from constructed wetlands contributes to the circular bioeconomy by integrating renewable energy production with sustainable wastewater treatment.

The aim of presented study was to assess the potential of vegetation harvested from a contracted wetland as a substrate for bioethanol production. However, due to the slow growth rate and limited biomass yield of hydrofit vegetation, an alternative substrate—wheat straw—was used in experimental trials aimed at evaluating the bioethanol production process. Wheat straw, with its well-documented composition and higher availability, served as a model lignocellulosic substrate for validating the fermentation and pre-treatment protocols developed in this study.

Bioethanol production methodology

Biomass pre-treatment

In the biomass valorisation study, a representative lignocellulosic substrate was used to qualitatively assess pre-treatment strategies relevant to bioethanol production. The experimental approach considered commonly applied pre-treatment concepts aimed at improving the accessibility of cellulose prior to enzymatic hydrolysis and fermentation.

Two general pre-treatment pathways were evaluated: a pressure-assisted treatment in an aqueous environment and a combined pressure–thermal treatment with alkaline support. These approaches reflect widely used methods in lignocellulosic bioethanol research and were selected to examine their qualitative influence on substrate structure and downstream process feasibility.

Following pre-treatment, the biomass was subjected to standard enzymatic hydrolysis and subsequent fermentation using established laboratory-scale procedures. Basic physicochemical characteristics of the substrate were determined to support a general assessment of biomass suitability, without focusing on quantitative performance indicators.

Enzymatic hydrolysis

After biomass pre-treatment, enzymatic hydrolysis was applied to convert accessible polysaccharides into fermentable sugars using commercially available cellulolytic enzymes under standard laboratory conditions. This step was used to qualitatively evaluate whether the applied pre-treatment approaches effectively enhanced substrate accessibility.

The hydrolysis stage served as a functional link between pre-treatment and fermentation, allowing verification of process continuity without focusing on quantitative conversion metrics. Analytical measurements were used solely to support general process evaluation and were not reported in detail.

Bioethanol fermentation

Following enzymatic hydrolysis, alcoholic fermentation was carried out using conventional yeast-based processes commonly applied in bioethanol production. This stage aimed to verify the technical continuity of the conversion pathway from pre-treated biomass to ethanol rather than to quantify fermentation performance.

Fermentation proceeded under controlled conditions to enable the transformation of fermentable sugars into ethanol, after which the product was recovered using standard laboratory-scale separation methods. The process was evaluated qualitatively, focusing on operational feasibility and process stability.

Low-Temperature Pressure Pre-treatment

The effectiveness of low-temperature pressure pre-treatment was evaluated based on glucose concentrations in the hydrolysates, measured using high-performance liquid chromatography (HPLC). Analysis of the results revealed a positive correlation between hydrolysis time and glucose yield. A 24-hour enzymatic hydrolysis was shown to be insufficient for effective cellulose-to-glucose conversion. However, no clear positive effect of increased pressure on glucose yield from wheat straw was observed. Despite this, all hydrolysates were subjected to alcoholic fermentation in accordance with the methodology described earlier.

The findings indicate that variations in pressure applied during low-temperature pre-treatment did not lead to a clear qualitative improvement in ethanol production. Minor differences observed between treated and untreated biomass may be associated with process-related effects, such as partial material loss during depressurization, rather than with enhanced conversion efficiency.

Overall, the applied low-temperature pressure pre-treatment did not demonstrate a distinct advantage in improving sugar availability or downstream fermentation performance. The results suggest that, within the tested process framework, this pre-treatment approach has a limited influence on the effectiveness of lignocellulosic biomass conversion.

High-temperature pressure pre-treatment

Alkaline-assisted pre-treatment was found to qualitatively enhance
cellulose accessibility by partially modifying the lignocellulosic structure, thereby supporting enzymatic hydrolysis. Increasing the intensity of the applied pre-treatment improved substrate accessibility only up to a certain extent, while excessively harsh conditions were associated with reduced process effectiveness, likely due to the formation of inhibitory by-products originating from lignin degradation. These inhibitors may negatively affect both enzymatic conversion and fermentation, indicating that moderate pre-treatment conditions represent a more robust and feasible approach for lignocellulosic biomass valorisation.

Discussion

The study assessed the potential of lignocellulosic biomass for bioethanol production using wheat straw as a model substrate representative of vegetation harvested from constructed wetlands. The results confirmed that appropriate pre-treatment of lignocellulosic material is a prerequisite for effective enzymatic hydrolysis, as untreated biomass does not readily undergo cellulose conversion. Alkaline-assisted pre-treatment was identified as particularly advantageous, as it promotes partial lignin disruption and improves substrate accessibility. Comparative evaluation of different pre-treatment approaches indicated that moderately intensified processing conditions enhance enzymatic conversion, while excessive treatment offers no additional benefit. Although biomass availability from constructed wetlands may be limited, the findings suggest that its valorisation through similar pre-treatment and conversion pathways could be technically feasible, provided that sufficient substrate quantities are available.

Local nutrient-rich substrates and biogas pathway: feasibility perspective

Author: Izabela Konkol, Lesław Świerczek

Biogas production through anaerobic digestion represents one of the most relevant local waste-to-energy options for Osada Burego Misia, especially given the availability of on-site organic substrates. Three main feedstocks were identified:
• cattle manure (~300 tons/year),
• kitchen waste (~30,000 L/year),
• greenhouse residues (~200 kg/year, e.g., tomato plants).
Despite relatively modest quantities, their combined biogas potential was assessed through laboratory methane fermentation tests to verify real biodegradability and expected methane yields.

Figure 21. Kitchen waste.

Laboratory assessment of substrate biodegradability

The substrates were investigated using batch methane fermentation tests with a controlled inoculum-to-substrate ratio (I/S = 2 on a VS basis). To ensure stable anaerobic conditions, reactors were operated under mesophilic temperature (40°C), flushed with nitrogen before startup, and supplemented with blank controls to correct for background methane formation. Substrate and inoculum proportions were calculated based on total solids (TS) and volatile solids (VS), ensuring comparable organic load across all trials. Fermentation gas was captured in sealed, water-displacement cylinders, preventing gas dissolution and guaranteeing accurate volumetric readings.
These tests provided comparable and standardized methane performance data, supporting later evaluation of technical feasibility and realistic energy conversion potential.

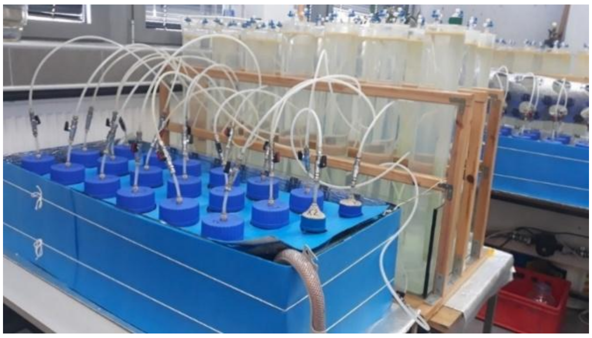


Figure 22. Batch – fermentation system

Daily measurements of biogas volume and composition were conducted at a consistent time interval. Gas quality (CH_4, CO_2, and trace gases) was analyzed using a portable biogas analyzer whenever the accumulated biogas exceeded the minimum required volume. At low gas outputs, final samples were verified using gas chromatography. Fermentation continued until daily biogas production fell below 1% of cumulative yield, marking the effective biodegradation endpoint under standardized conditions.

Total solids and volatile solids were determined gravimetrically following Standard Methods. VS values were also obtained for all substrates after pretreatment; however, as VS expresses only the proportion of volatile to non-volatile mass, these results indicate relative composition rather than actual solubilization or chemical transformation. Thus, VS alone cannot be used to infer substrate degradation pathways or structural modification.

Results

Cattle manure showed moderate but stable gas production, with methane content of 56.84% in the biogas. The control-corrected cumulative yields were:

- Per tonne fresh mass: 8.65 m^3 CH_4/t FM and 15.22 m^3 biogas/t FM
- Per tonne dry mass: 82.41 m^3 CH_4/t DM and 144.97 m^3 biogas/t DM
- Per tonne organic dry mass: 137.34 m^3 CH_4/t oDM and 241.62 m^3 biogas/t oDM

Kitchen waste proved to be a much more energy-rich substrate. Methane concentration in biogas reached 62.62%, and the average, control-corrected yields were:

- Per tonne fresh mass: 125.81 m^3 CH_4/t FM and 200.91 m^3 biogas/t FM
- Per tonne dry mass: 455.85 m^3 CH_4/t DM and 717.70 m^3 biogas/t DM
- Per tonne organic dry mass: 510.49 m^3 CH_4/t oDM and 803.72 m^3 biogas/t oDM

For tomato vines (greenhouse residues), methane productivity was determined at 185 m^3 CH_4/t dry mass. Assuming a dry-matter content of 18%, an organic fraction of 80% of DM, and an average methane share of 55% in the biogas, this corresponds approximately to:

- Per tonne fresh mass: 33.3 m^3 CH_4/t FM and 60.5 m^3 biogas/t FM
- Per tonne dry mass: 185.0 m^3 CH_4/t DM and 336.4 m^3 biogas/t DM
- Per tonne organic dry mass: 231.2 m^3 CH_4/t oDM and 420.5 m^3 biogas/t oDM

Overall, the results confirm that all three locally available substrates are suitable for anaerobic digestion, with kitchen waste showing the highest specific methane potential, tomato vines offering a valuable seasonal co-substrate, and cattle manure providing a stable base feedstock for continuous operation.

Overall feasibility outlook

The methane fermentation experiments performed in this study were conducted in batch mode. Such laboratory tests should be understood as fundamental screening tools: they do not model continuous digester operation, but they reliably determine the biodegradability of substrates and their technical suitability for biogas conversion before any investment decisions are made.

Based on the experimentally determined specific biogas yields, the three locally available substrates could generate a total of approximately 10,600 m^3 of biogas per year. This corresponds to an estimated installed electrical capacity of only around 8–12 kW for a micro-scale combined heat and power (CHP) unit, depending on methane content and engine efficiency.

Such capacity remains significantly below the typical economic threshold for even the smallest agricultural biogas systems (usually >30–50 kW). In addition, the low annual mass of tomato vines and seasonal variability in their availability further reduce the feasibility of steady digestion without supplementation by external feedstocks.

Therefore, despite confirmed biodegradability and favorable methane characteristics of kitchen waste and manure, the volume of substrates available at Osada Burego Misia is insufficient to justify the construction, operation, and maintenance of an on-site digester. The scale would not ensure stable operation nor financial return within realistic payback horizons.

From a sustainability and circular-economy standpoint, the most rational pathway is not local digestion, but logistic cooperation with an external biogas facility, where substrates can be directed for efficient recovery of energy and nutrients under optimized, continuous-scale conditions. In this configuration, Osada Burego Misia contributes to renewable energy generation without incurring investment, regulatory, operational, or maintenance burdens associated with owning a biogas installation.

Testing the IT system for remote management of the WWTP BMCF

Author: Marta Płuciennik

Introduction

The Pilot 5 facility is located in Poland, at the Bure Misie Settlement (Figure 23), which is the seat of the Bure Misie Community Foundation. It is located in Nowy Klincz, at a distance of ca 50 km from the Baltic Sea.

The Bure Misie Settlement is home to nearly 50 people with disabilities. It is also a place that attracts many visitors during the summer season, with a large campsite and several holiday cottages located on its grounds. The settlement is located away from other buildings, which allows for a break from urban noise, such as traffic. However, this remoteness also brings certain challenges – including those related to wastewater treatment.

Figure 23. The Bure Misie Settlement (photos: BMCF)

The previously existing wastewater treatment plant at this site has been extended and modernised as part of the NURSECOAST-II project of the Interreg Baltic Sea Region programme. Commissioning of the new treatment plant took place in October 2024.

It currently consists of: primary settling tanks, a bioreactor with an installation well, a pumping station, a well with valves separating the effluent into the wetland, two vertical beds (constructed wetlands), a horizontal bed (constructed wetland), a measurement well, and absorption wells. Nanobubble technology is also being tested. The wastewater treatment system used at Pilot 5 has been described in the previous chapters.

No one works on the WWTP permanently in the Bure Misie Settlement. This means that, apart from a brief on-site inspection once a day, there is no one there to notice failures immediately after they occur. This also means that there is a risk that a blower, pump or power failure could only be noticed the following day. The solution was to use a system that would itself inform people of breakdowns. Preferably by sending a message to their phone. At the stage of the design of the WWTP, requirements were made for the contractor to use an IT system that would allow real-time monitoring and managing the pumping stations and gate valves at the WWTP.

IT system

The treatment plant was equipped with the Bumerang Smart system.

The selected contractor connected the Bumerang Smart system to the control cabinets (Figure 24):

- of the pumping station "P3" located behind the septic tank.
- of the collection well where the wastewater is distributed to the wetland, through special valves.

Figure 24. Pumping station P3 (left) and collection well (right) at the Bure Misie Settlement wastewater treatment plant. (photos: Płuciennik M., BMCF)

The Bumerang Smart monitoring and management system is a proprietary system of the 25-year-old company Ecol Unicon from Gdańsk, Poland (Figure 25). This system enables remote control and management of the operation of monitored objects of rainwater infrastructure and water and sewage infrastructure. Bumerang Smart also allows for the planning and recording of all events and service actions, and additionally allows for the archiving of notes and photos.

The system can be used to control: wastewater pumping stations, retention tanks, separators and settling tanks, BIOFIT wastewater treatment plants, odour neutralisation systems, and measuring chambers.

Monitoring systems and remote control systems are delivered together with the equipment manufactured by Ecol-Unicon, but can also cooperate with other sanitary network facilities.

Figure 25. Logo of the Bumerang Smart system from Ecol-Unicon

The capabilities of the BUMERANG SMART system and the potential benefits of its use:
- real-time insight into the operating parameters of a given facility and reduction of the number of local facility inspections,
- remote control of water and sewage network elements,
- signalling of emergency conditions,
- display of a map with marked objects and current and forecast weather at a given location
- more accurate servicing schedule,
- greater environmental safety
- minimised risk of flooding and floods,
- reduced costs - reduced number of people directly involved in operations,
- easier work due to possible suggestions of actions in emergency situations,
- ongoing recording and archiving of process data,
- quick access to collected data,
- easier creation of current and periodical reports.

The range of capabilities of the BUMERANG SMART system at the WWTP of the Bure Misie Settlement:

a) Per the P3 pumping station facility:

a.1 Monitoring:

- for pumps:

- signalling whether the pumps are operating in automatic or manually controlled/stop mode,
- indication of user-activated pump stop,
- indication of pump failure and pump inverter failure,
- information on the number of starts per day,
- information on operating time for a given day;

- information on break-in (opening the well without unlocking the security alarm),

- information on failure due to lack of power supply,

- indication of GSM communication problems,

- date and time of the last data update (last reading by the system)

- information about the current level of sewage in the well and an alarm if this value exceeds the minimum (dry-running) and maximum (overflow) levels or if the floats controlling the level of sewage fail;

The well chamber also has room for a third pump - once this has been installed, it will be possible to monitor its parameters in the same way as for pumps 1 and 2.

a.2 Management:

- possibility of setting alarm levels, maximum and minimum sewage levels in the well;
- control: possibility of remote activation and deactivation of individual pumps, possibility of blocking operation of selected pump(s), deactivation of floats, resetting of start-up counters and pump operation times on a given day.

b) Per the collection well facility:
   b.1 Monitoring:

- status of gate valves 1, 2, 3 - possible status for each of them: open, closed, failure
- information on break-in (opening the well without unlocking the security alarm),
- information on failure due to lack of power supply,
- indication of GSM communication problems,
- date and time of the last data update (last reading by the system);

   b.2 Management:

- control: ability to open and close individual valves remotely.

Methodology and data analysis

The main objective of the study was to verify the functionality and reliability of the Bumerang Smart monitoring and management system under real operating conditions. The scope included:

- testing bidirectional control of wastewater treatment plant equipment,
- logging operational and alarm data,
- remote management of wastewater distribution to a constructed wetland.

The tests were conducted under real operating conditions. The system was tested under varying weather conditions, including temperatures below 0°C. Variation in plant load was observed, depending on resident numbers.

The first step was to test the bidirectional functionality of the control system — that is, whether a manual change made on-site at the wastewater treatment plant is correctly reflected in the online interface, and whether a change made remotely (online) results in the appropriate physical response of the corresponding element at the wastewater treatment plant. 100% of the control functions were tested, all of which worked correctly. The response time was below 15 seconds.

In March 2025, a maintenance inspection was carried out on the facilities connected to the monitoring and management system. The inspection was conducted by Ecol-Unicon, the equipment supplier. The tests confirmed the full functionality of the pumping station, the collection well, the control cabinets, and the Bumerang system.

Permanent (24/7) use of the Boomerang system at the wastewater treatment plant began in October 2024. From October 2024 to June 2025, changes in the operation of the pumping station and collection well were made exclusively online.

During the use of the system, wastewater was remotely directed to specific treatment beds. In particular, the vertical beds were switched off during sub-zero temperatures.

While testing the system, the following data were also collected:

- pump operation characteristics (number of activations), which makes it possible to estimate the volume of raw wastewater. (The treatment plant is equipped with a measurement system for treated wastewater, located after the constructed wetlands. While this is valuable information, it does not provide a complete picture of the treatment plant's performance when using constructed wetlands. The volume of raw and treated wastewater will differ due to evaporation and rainfall),
- any emergency situations.

The data on the number of pump activations per month is presented in Figure 26.

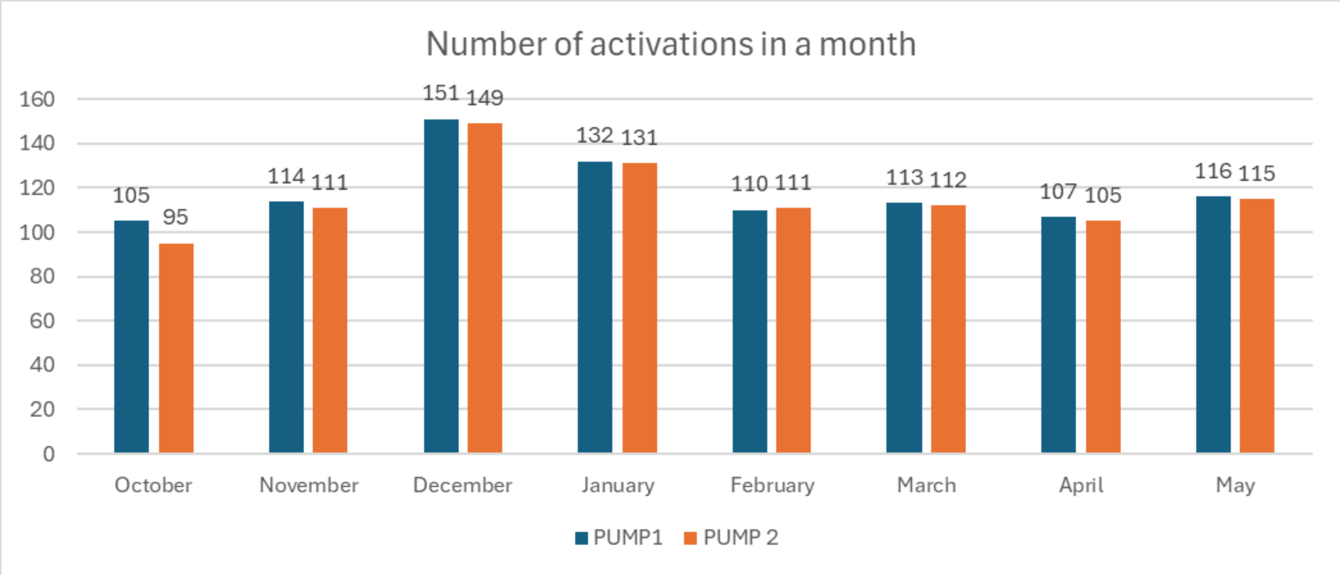


Figure 26. The data on the number of pump activations per month

The data on pump activations provides a reliable estimate of the actual volume of raw wastewater generated, independent of external influences such as evaporation from constructed wetlands (Figure 26). The pumps operate alternately, but if one of them fails, the other one automatically takes over the full load. Analysis of the collected data indicates an increased water usage in the Bure Misie Settlement during December, which correlates with the holiday season and a higher number of visitors to the site.

During the study period, the following alarms were recorded for Pumping Station P3:
- power outage of the telemetry module – 41 times
- 400 VAC power failure – 37 times
- break-in (opening of the hatch without prior code entry) – 18 times

For the collection well, the following alarms were recorded:
- GSM communication failure – 54 times
- power failure – 30 times
- gate valve failure – 30 times (coincided with power failures)

The most frequent issues involved power supply and GSM communication. Power outages were typically short-lived and required only resetting the breakers in the main power cabinet. To prevent future occurrences, an electrician improved the parameters of the power supply system in April 2025, resulting in a noticeable improvement. No action was taken regarding the GSM communication interruptions, as similar issues occur sporadically in the area beyond the wastewater treatment plant. The opening of the collection well hatch without prior code entry was due to human error (incorrect sequence of system checks during on-site rounds at the treatment plant). The hatch is secured with a padlock and was not accessed by unauthorized individuals.

The partner online meeting

On 21 January 2025, a webinar entitled “Pilot 5: Testing the IT System for Remote Management of the WWTP” was held (Figure 27). The meeting was organised on the Google Meet platform and participants received an invitation by email.

The online webinar was attended by representatives of the project partners:

- The Szewalski Institute of Fluid-Flow Machinery Polish Academy of Sciences (IFFM PAS),
- Natural Resources Institute Finland (LUKE),
- The Bogdan Janski Bure Misie Community Foundation (BMCF),
- VNK serviss LtD.
- NK forsyning
- and Paweł Roman - technical expert from Ecol Unicon, who deals with the Boomerang Smart system on a daily basis.

Present, therefore, were partners involved in the cases from the pilot investments from 4 countries.

This online partner meeting consisted of two parts:

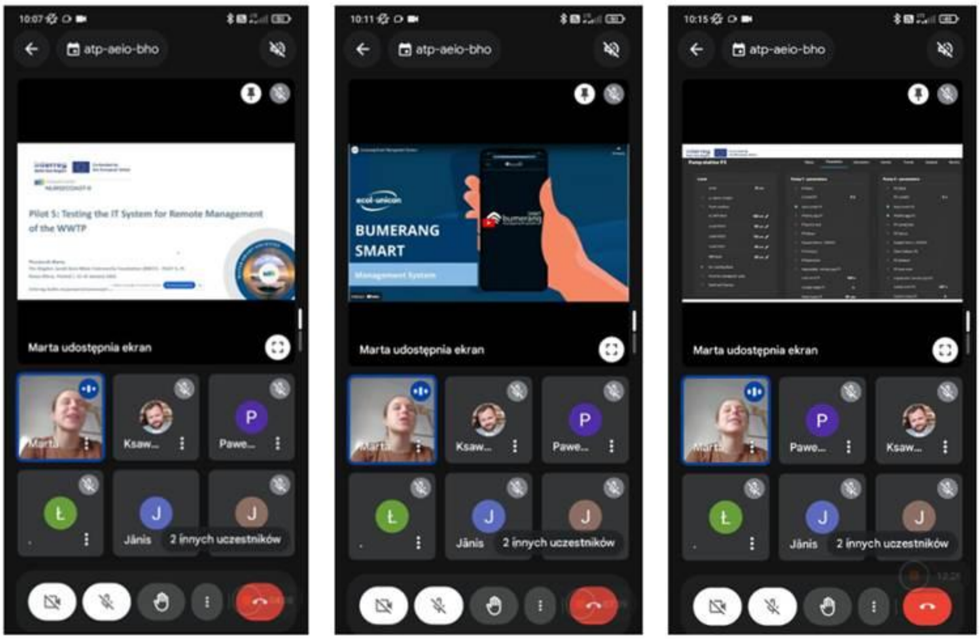
- Case Study: a presentation of the extent to which the Bumerang System has been introduced at Pilot 5, what possibilities it offers and a summary of 3 months of testing the system (Marta Płuciennik, BMCF),

- presentation of other possibilities of the Bumerang system not used at Pilot 5 (Paweł Roman, Ecol-Unicon) and a Q&A session and discussion among all partners.

AGENDA:

1. Welcoming participants and introduction (purpose of the webinar + discussion of the meeting structure)
2. An animation presenting the Bumerang Smart system (https.//www.youtube.com/watch?v=zoUpoZeg79Q, duration 0:0:44)
3. The roles that IT can play in wastewater treatment plants
4. Challenges of managing a WWTP in Pilot 5
5. Facilities that are located in the WWTP at Pilot 5
6. Presentation of the various capabilities of the monitoring system on the example of Pilot 5 facilities (screenshots, video of moving through the program, description), including: objects, map, parameters, analysis.
7. Summary of three months of system testing
8. Presentation of other capabilities of the Bumerang Smart system, not used in Pilot 5, based on examples of other wastewater treatment plants
9. Discussion on what distinguishes the Bumerang Smart system from other remote management solutions for wastewater treatment plants
10. Q&A session and discussion between meeting participants
11. Summary

The meeting lasted 1h 45minutes. In the discussion, webinar participants asked about, among other things, interactions with SCADA systems, system security, limitations of the technology, real-life examples and best practice, and further opportunities for IT system development at Pilot 5.



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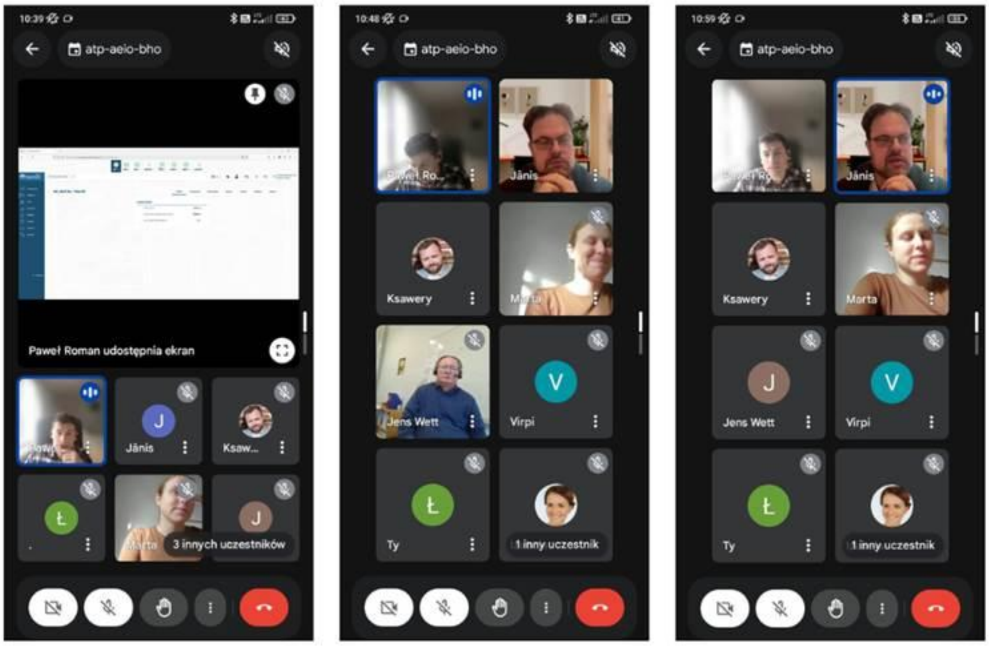


2.

Figure 27. Online meeting.

A great value of the webinar was the interactivity, which provided a field for discussion and sharing the experiences of people from different countries. The system used at Pilot 5 can be implemented at other wastewater treatment plants and adapted to local needs. At wastewater treatment plants located in tourist areas around the Baltic Sea, there is a big difference in wastewater volumes during the tourist season and the off-season. Therefore, the use of an IT system at these WWTPs can be very helpful in managing these wastewater treatment plants more efficiently.

Discussion

The objective of the pilot tests of the Bumerang Smart system was to evaluate the functionality nd reliability of remote supervision and control of selected components of the wastewater treatment plant under actual operational conditions. The system demonstrated stable and consistent performance. The IT platform enabled continuous monitoring of selected operational parameters of the plant, as well as detection of system alarms.

Data related to pump activation frequency provided a reliable basis for assessing changes in the volume of incoming wastewater, independently of external factors such as evaporation in the constructed wetlands.

Analysis of the collected data indicated that during the winter season, particularly in December, water consumption in the Bury Miś Settlement increased slightly, correlating with a higher number of guests during the holiday period.

System alarms were also monitored, most commonly related to power outages and GSM communication disruptions. While power issues occurred relatively often, they were short-lived. Electrical upgrades carried out in April 2025 helped reduce the number of such incidents, positively impacting the overall stability of the treatment plant's operation.

The tests confirmed that bidirectional communication between the control system and on-site devices functioned correctly. This enabled immediate response to system events and failures, significantly reducing the time required for service interventions.

During system operation, remote management included, among other things, the distribution of wastewater across individual constructed wetland beds, allowing for adaptation of the plant's operation to prevailing weather conditions.

Overall, the implementation of the Bumerang Smart system led to a significant improvement in the supervision and management of the treatment plant, resulting in faster response times to operational incidents. Remote access to data and the ability to control equipment off-site enhanced both user convenience and environmental safety.

Looking ahead, further development of the system may bring even greater benefits, particularly in the context of fluctuating plant loads and seasonal variability. It is worth noting that the conducted studies did not yet cover the peak tourist season.

Lessons learned and recommendations

The use of the IT system has proven to be highly beneficial for BMCF. During the testing period, it significantly shortened the response time to power outages, thanks to alarms being sent via SMS. Additionally, data archiving revealed how frequent this issue was. As a result, the decision to improve the power supply system for these facilities led to more stable and reliable operation of the wastewater treatment plant.

The use of the Bumerang Smart system so far has demonstrated that it is a useful and necessary system for the wastewater treatment plant at the Bure Bear Settlement. It contributes to the efficient and more effective operation of the wastewater treatment plant.
Further benefits could come from expanding the IT system by connecting more objects at the WWTP to the Bumerang Smart system. The most significant benefit here for Pilot 5 would be to further improve the monitoring of the facilities, which enables, for example, a faster response in the event of breakdowns and other unexpected situations.

It is recommended to expand the IT system. The expansion can be divided into two parts:

- the part related to the conversion of the "old" Bioekol-Mini 75 wastewater treatment plant;

- the part that is behind the constructed wetland.

However, the scope and timing of the further expansion of the IT system is dependent on the financial conditions of the BMCF and will be carried out in several stages.

Extension of the existing system with the existing and planned facilities at the 2006 treatment plant, which at the present time performs pretreatment functions for wastewater with a higher pollutant load (from food processing):

- the existing primary settling tank will serve as a pumping station (P1) feeding the wastewater to the RB bioreactor (as a function of time) with dry-running protection and 2 alarm levels - 2 monitored pumps and with remote management via the Bumerang Smart system;

- planned sewage pumping station P2 - 1 pump monitored and with remote management via the Bumerang Smart system;

- probes for pH, dissolved oxygen, temperature, redox potential and conductivity are currently installed in the bioreactor, the data is currently readable in real time on site.

Analysis of the data collected in this way will allow the aeration in the bioreactor to be optimised and the settings of the nanobubble generator to be adjusted accordingly. This data will allow process optimisation.

Behind the hydrophytic beds, there is a measuring well with a meter for the amount of treated wastewater. The flow meter in the well is connected to the Kama eco Group Sm-03 monitoring station, which collects and archives data, but reading the data requires presence on site. In the future, it is planned to connect the existing system so that this data can be read remotely. A solution that would allow this data to be checked via a single online platform would be preferred.

The proper functioning of the entire wastewater treatment plant minimises the risk of discharging wastewater with nutrient levels that are too high. Monitoring of individual components and the ability to remotely manage some of them therefore increases environmental safety.

Archipelago solution development at Skola Guest Habour, LUKE

Authors: Virpi Vorne, Anu Reinikainen, Frans Silvenius ja Sini Valmari

Introduction

The guest marina in Barösund, Ingå (Finnish: Inkoo), is a popular tourist destination in the Finnish archipelago during the summer season. The port area and its functions have been developed over the past few years, and further development is planned. As a result, the current wastewater system's capacity has become insufficient during the high season. During the summer months, up to 12 times more wastewater is generated compared to the winter, as the area receives 100–200 tourists daily. Excess wastewater has been directed to a holding tank and transported from there to the Ingå municipality's central wastewater treatment plant, 35 km away, for further treatment. The Barösund guest marina needs a new wastewater system that can withstand large seasonal fluctuations.

At the beginning of the project, it was assumed that the large volume of greywater in the area was the main issue. Potential solutions are needed to determine whether greywater should be separated and where it could be directed in an area with both rocky and, in places, clayey soil. The project’s kick-off meeting was held on-site, and based on the recommendations of the project partners and external experts, it was concluded that the composition of the wastewater should first be analyzed.

Methodology

Wastewater sampling

Wastewater samples were taken three times during the peak season in July 2023 from the influent to the current Wehoputs 30 treatment plant. A WehoPuts 30 (capacity 4,5 m^3/d) is a biological chemical small-scale treatment plant, which works on the batch principle. The three samples collected in July were consistent in quality and likely representative of the peak season. In addition, one sample was taken from the treated effluent. Based on the results (Table 14), the treatment plant did not meet the minimum removal efficiency requirements for decentralized wastewater treatment systems, as set out in Section 4 of the Government Decree on Treating Domestic Wastewater in Areas Outside Sewer Networks (157/2017). According to the decree, the required reductions are at least 90% for organic matter (BOD_7), 85% for total phosphorus, and 40% for total nitrogen.

Based on the peak season sampling, greywater did not dilute the wastewater; instead, the wastewater was relatively concentrated. During the July sampling events, no significant amounts of grease were detected in the influent; the measured concentrations ranged from 13 to 23 mg/l. During the project's kick-off meeting, it was estimated that grease from the restaurant could hinder the operation of the treatment plant. The restaurant's grease trap has been emptied regularly, as indicated by the water sample results. According to the effluent sample, the plant removed organic matter to a level close to the required standard, but only about half of the phosphorus was removed. A considerable amount of suspended solids escaped the treatment process, and no nitrogen removal was observed.

Table 11. Wastewater sampling results of the Barösund treatment plant, Wehoputs 30.

Barösund treatment plant Wastewater analysis	Influent 10.7.2023	Influent 11.7.2023	Effluent 11.7.2023	Influent 19.7.2023	Unit
Ammonium Nitrogen, NH4-N	110	120	100	110	**mg/l**
Total Nitrogen, N	130	140	140	140	**mg/l**
Total Phosphorus, P	17	19	10	19	**mg/l**
Total Phosphorus, P, soluble (CSE)		16	6,6	14	**mg/l**
Total Suspended Solids	170	210	230	190	**mg/l**
pH	7	7	7,7	7,1	
Conductivity 25 C	220	230	220	220	**mS/m**
Alkalinity	14	14	13	13	**mmol/l**
BOD-7-ATU, Biological oxygen demand	750	770	180	690	**mg/l**
CODCr, Chemical Oxygen Demand	1300	1300	570	1200	**mg/l**
Fats, Oils and Grease (FOG)					
- Total hydrocarbons	23	16	5,9	13	**mg/l**
- Mineral oil	<0,5	<0,5	<0,5	<0,5	**mg/l**
- Calculated FOG content	23	16	5,9	13	**mg/l**

According to the ELY Centre, an environmental permit must be obtained for a wastewater treatment plant if the plant's designed load exceeds 100 population equivalents (PE), in accordance with Section 1 of the Government Decree on Environmental Protection (713/2014). PE (Population Equivalent) is a unit used to estimate the organic load produced by one person, and the calculation uses a value of 70 g BOD/person/day (Table 12). Based on the results of the July sampling, the Barösund treatment plant therefore requires an environmental permit.

Table 12. Wastewater treatment plant load calculation

Samplings	Flow Rate (m^3/d)	BOD (kg/d)	PE
With July 2023 monthly average flow	10.9	8.1	116
With maximum flow	16	12	170

Environmental Permit application

The Municipality of Ingå, with Ramboll, initiated the environmental permitting process for a wastewater treatment plant. Finnish law requires a permit for plants treating ≥100 population equivalents (PE); this plant was designed for 170 PE, so a full permit was necessary. As the applicant was a municipality, the application was submitted to the Regional State Administrative Agency (AVI).

The application included:

- **Facility details**: location, capacity, treatment process, diagrams, and technical specifications.
- **Emissions and impacts**: wastewater volume and quality, treatment targets (e.g., BOD <15 mg/l, phosphorus removal), compliance with regulations, and mitigation of air emissions, noise, and odours.
- **Discharge**: receiving water body details, impact assessment, and measures to prevent contamination.
- **Contingency planning**: emergency response for overloads, outages, and failures.
- **Sludge and waste management**: handling, disposal, and responsibilities.
- **Environmental context**: nearby residents, protected areas, Natura 2000 considerations.

- **Sustainability assessment**:
    - *Environmental*: low nutrient discharge, minimal marine impact, seasonal discharge planning.
    - *Social*: transparent communication, safety procedures, public updates.
    - *Economic*: local treatment cost benefits, public sector execution.

Attachments included maps, site plans, process diagrams, discharge site details, noise/odour assessments, ecological surveys, zoning excerpts, and a list of affected landowners. Preparation took several months.

Environmental Permit process

The permit officer assessed whether the submitted materials were sufficient and appropriate for decision-making purposes. If any essential information was missing, such as a more detailed estimate of the plant's emissions or contact details of neighbouring property owners, the applicant was requested to supplement the application within a specified deadline.

A request for additional information was a standard part of the process in cases where the application materials were incomplete. It did not indicate a problem but ensured that the decision could be made based on accurate and adequate information. However, supplementing the application delayed the processing, so it was in the applicant's best interest to respond promptly and provide the requested additional documentation to the authority.

Public notification and hearing procedure

By law, the application must be publicly announced to allow stakeholders to comment. The authority publishes a 30-day notice summarizing the project on municipal notice boards, its website, and in a local newspaper. The notice includes applicant details, project description, location, document access, and instructions for submitting opinions. If needed, it may also announce a public hearing, though this is rare for small plants.

In addition, affected parties, such as neighbouring property owners and water body owners, receive direct notifications informing them of their right to express views. They were encouraged to submit any objections in writing by the specified deadline (Table 13).

Table 13. Stakeholder mapping.

Stakeholder Group	Role/Concern
Local residents	Environmental concerns, access rights
Summer residents	Use of marina, aesthetics, odour, children's safety
Commercial ferry operators	Safe navigation near pipe installation
Fishermen (zander spawning)	Seasonal disturbance of the spawning area
Water co-operative (joint water area)	Legal water area usage and rights
Municipality of Ingå	Project owner, applicant, communicator
Consultant (Ramboll)	Technical and environmental documentation
ESAVI (Regulator)	Permit review and compliance enforcement

Stakeholders could raise concerns, such as odour, ecological risks, or legal rights, or propose conditions for acceptance. Key issues included:

- **Ecology**: Risk to zander spawning in May at the discharge site.
- **Marine use**: Outfall near ferry route and marina; safety and aesthetics.
- **Transparency**: Requests for access to assessments and emergency plans.
- **Cumulative impacts**: Long-term nutrient loading and eutrophication.
- **Legal rights**: Questions on easements and shared marine areas.

Authorities also provided statements:

- **ELY Centre**: Assessed water body condition and proposed stricter limits if needed.
- **Municipal authorities**: Reviewed environmental and health impacts.
- Other bodies (e.g., fisheries, zoning, rescue) were consulted as necessary.

After the consultation period, objections and statements were sent to the applicant, who could respond or amend the application (e.g., add odour controls). This hearing process helped define permit conditions.

Responses and mitigation actions by the applicant:

- Construction scheduled outside zander spawning season (May–June).
- Navigation impact assessed; pipe will be buried and marked, no ferry disruption.
- Public emergency protocols submitted.
- Additional water quality data and projections provided.
- Rights clarified with joint water area representatives.
- Community meetings emphasized compliance with EU/national standards and efficient treatment.
- Continuous monitoring promised; immediate response to anomalies.
- Annual performance and water quality summaries to be published for transparency.

If necessary, the authority could also negotiate preliminary permit conditions with the applicant to ensure they were both effective and feasible.

It had already taken 1.5 years to reach this stage (Figure 28).

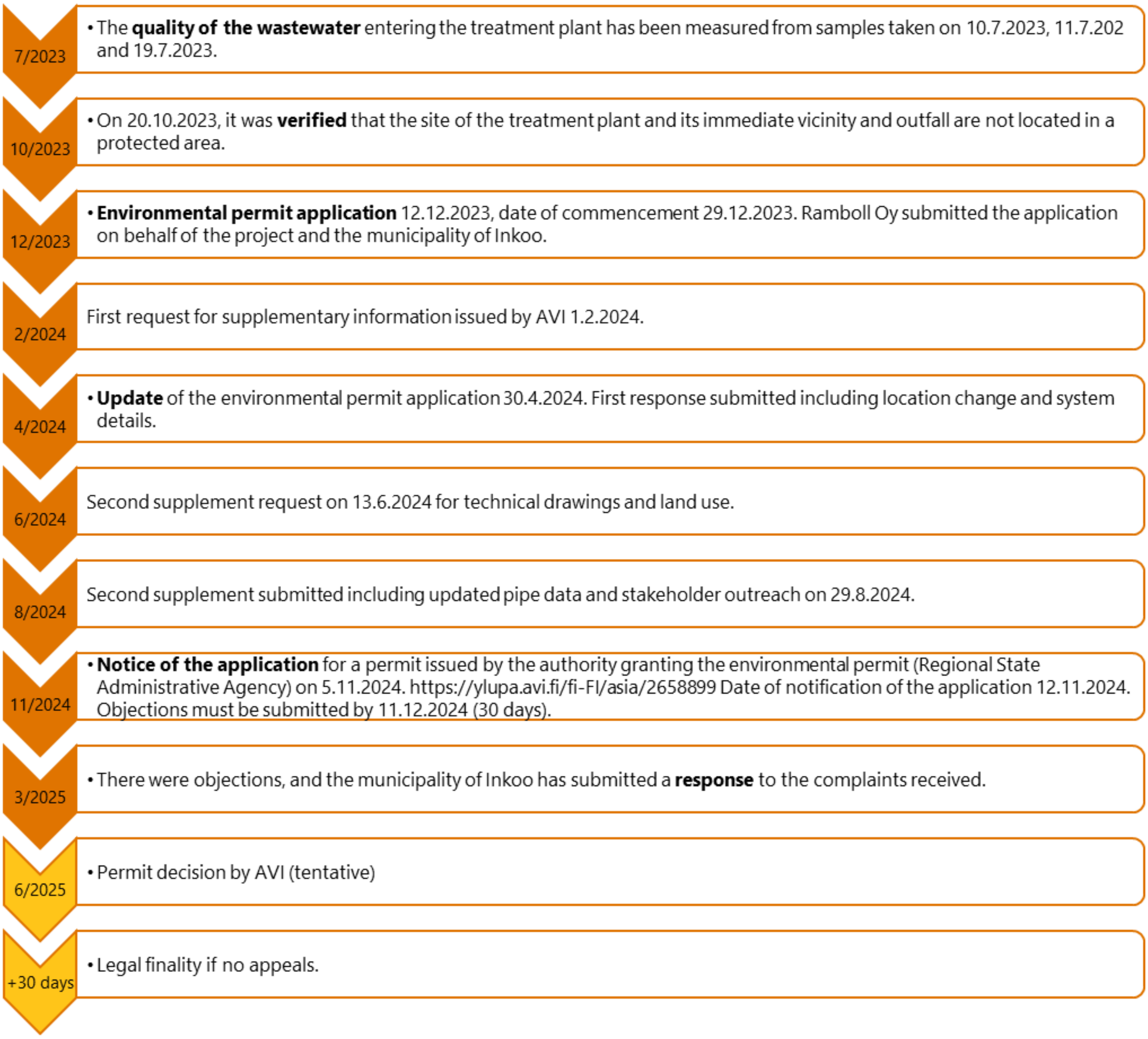


Figure 28. Events on the 2023-2025 timeline.

Permit consideration and decision-making

After the hearing phase, the authority evaluated the application and feedback against Environmental Protection Act criteria: compliance with environmental standards, use of best available techniques (BAT), and protection of water quality. For the 150 PE plant, biological-chemical treatment with nutrient removal was required. Typical limits included BOD <10–20 mg/l and phosphorus <1 mg/l, with possible nitrogen limits for Baltic Sea discharges.

The permit decision included conditions such as:

- **Continuous monitoring** with remote sensors.
- **Quarterly reporting** to AVI and public disclosure.
- **Annual reviews** of performance and corrective actions.
- **Adaptive management** for exceedances.
- **Public feedback channels** for complaints.

Permits are usually granted with conditions unless the project violates critical restrictions. In this case, approval was expected as the plant met technical and environmental requirements.

Permit validity:

Environmental permits are generally granted indefinitely but include a review requirement after 5–10 years (typically 7–10 for small plants). The operator must submit an updated report, and conditions may be revised to reflect new regulations.

The final decision is signed by the competent authority, municipal environmental board or AVI, and published after public announcement. All concerned parties receive the decision.

Notification of the decision, legal validity, and follow-up actions

After the decision, the applicant and all notified parties receive the permit and an appeal notice. Appeals must be filed within 30 days to the Vaasa Administrative Court; if none are submitted, the permit becomes legally binding. Appeals suspend implementation unless an interim enforcement permit is granted, though this is rare for small plants. The court may uphold, amend, or revoke the permit; further appeal to the Supreme Administrative Court is possible but uncommon.

Once valid, the operator can construct and commission the plant under permit conditions, obtain any additional building permits, and notify authorities upon start-up. During operation, compliance is monitored through annual reports and inspections by municipal and ELY authorities. Violations can lead to corrective orders or enforcement measures. Permits are indefinite but subject to review (typically after 10 years) or amendment if operations change significantly.

Comparison with other cases

While similar in scope to other small-scale rural wastewater projects in Finland, this case stands out due to:

- Marine discharge in a designated spawning area
- Complex land and water ownership arrangements
- Intensive seasonal load variation

For comparison, several municipalities (e.g. Loviisa, Parainen, and Kemiönsaari) have also implemented small-scale modular wastewater treatment systems for seasonal villages or marina clusters. These cases generally feature simpler inland discharge routes and more consolidated land ownership, allowing for faster permitting. In contrast, Barösund's discharge into a biologically sensitive marine area and overlapping private water rights created multiple legal and ecological challenges.

The need to coordinate with an unorganized water co-operative, address spawning zone impact, and model nutrient dispersion in a tidal marine environment significantly extended the project duration. Furthermore, community expectations regarding transparency and risk mitigation were heightened due to the tourism profile of the site. Thus, Barösund provides a valuable reference for similarly situated communities operating in coastal or ecologically sensitive zones.

- Marine discharge in a designated spawning area
- Complex land and water ownership arrangements
- Intensive seasonal load variation

Data analysis

Selecting the best available technique

As the environmental permitting process progressed and additional clarifications and requirements emerged, various equipment options were evaluated to meet the needs of the Bärosund Guest Marina. The assessment primarily considered treatment efficiency and suitability for significant seasonal variations. Discussions were held with both equipment manufacturers and the local water cooperative, and potential risks were also evaluated.

In the validation of the best available technique, purification efficiencies were compared in percentages. In addition, the contents of the treated effluent were calculated, allowing these values to be assessed against both legislative and site-specific requirements. The purification efficiencies of the package treatment plants are primarily based on CE-certified testing results.

The prices in cost-benefit calculations are indicative only and are intended to provide a general estimate of the investment and operational costs associated with different wastewater treatment solutions. Installation costs are varied depending on factors such as ground conditions. Operational costs did not include potential additional expenses, such as premature pump failures or other unexpected technical issues.

Regarding sludge removal frequency, the calculations tend to underestimate the required frequency for systems operating at very low capacity. This was because the calculation method was based on the volume of sludge generated relative to the storage capacity, without accounting for the functional requirements of the equipment that might necessitate more frequent sludge removal.

In the market study and negotiations with equipment suppliers, the following wastewater treatment systems were considered suitable for the significant seasonal variations at the Barösund guest marina:

Wehoputs small-scale treatment plant 150.

Wehoputs 150 is a biological-chemical batch treatment plant for domestic wastewater from multiple properties or 150 people, designed for year-round use (Figure 29). Treatment plants are manufactured in the factory ready to be installed and ready for operation. Only sewer and electrical connections are made at the construction site.

Delivery includes: A fully installed and operational treatment unit, GSM remote monitoring system, Optional accessories (ordered separately), WehoPuts precipitation chemical, and anchoring kit.

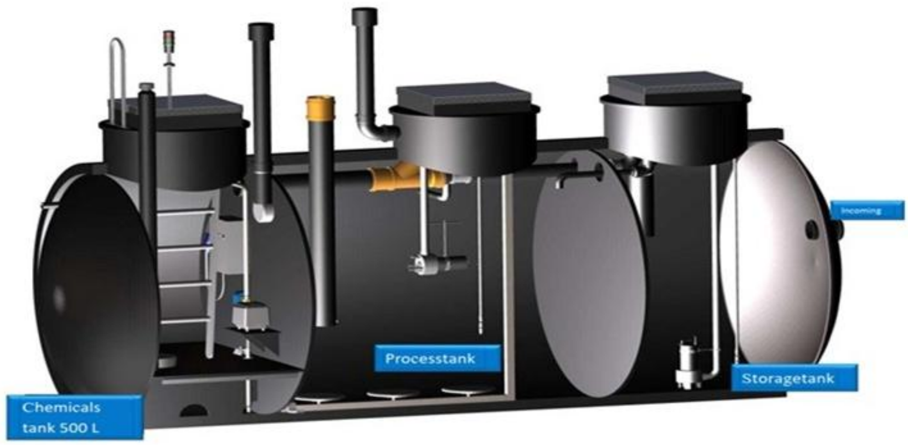


Figure 29. Wehoputs treatment plant

The WehoPuts wastewater treatment plant is a bio-chemical domestic wastewater treatment system intended for year-round use. All wastewater is directed into the treatment plant without separate pre-treatment. Treated water then flows or is pumped to the discharge point.

1. Treatment process

The WehoPuts treatment plant works on a batching principle SBR (Sequenced Batch Reactor), treating a certain batch of wastewater at one time. The treatment is based on a biochemical process, where the microbes living in the activated sludge decompose the organic matter in wastewater, while the chemical deposits the phosphorus.

The cleaning process is divided into different stages: aerating, chemical feed, settling, and removal. These stages are carried out in sequence inside the process tank. Control of these stages is carried out automatically through the control unit. After an electrical outage, for example, the treatment plant will automatically resume the process from the interrupted stage.

2. Wastewater batch accumulation

Wastewater is directed into the storage tank without separate pre-treatment. From the storage tank, the wastewater is pumped into the process tank. Once the wastewater level in the process tank reaches the start-up level, the process starts.

3. Aerating and chemical feed

The compressor in the machine room aerates the wastewater. Aerating promotes biological decomposition and the oxidation of nitrogen compounds into nitrate. At the end of the aerating phase, a chemical is added to the wastewater. Phosphorus compounds are separated from the wastewater using a chemical.

4. Nitrogen removal and settling

Aerating is stopped, and sludge slowly settles to the bottom of the process tank. The treated, nutrient-free water gathers on top. The nitrate-form nitrogen is reduced to nitrogen gas.

5. Removal of treated water and residue sludge treatment

After settling, the treated water is then discharged. Residue sludge is regularly transferred to the sludge bag. Sludge may be composted with other organic household waste. Alternatively, it can be removed using a vacuum truck.

Vestelli BioKube Mars 6000 x 2 Wastewater System (Continuously operating wastewater Bioreactor)

BioKube Mars systems are prefabricated solutions, delivered to the customer ready to install as Plug & Play and ready for use. BioKube Mars systems are internationally certified according to the highest standards.

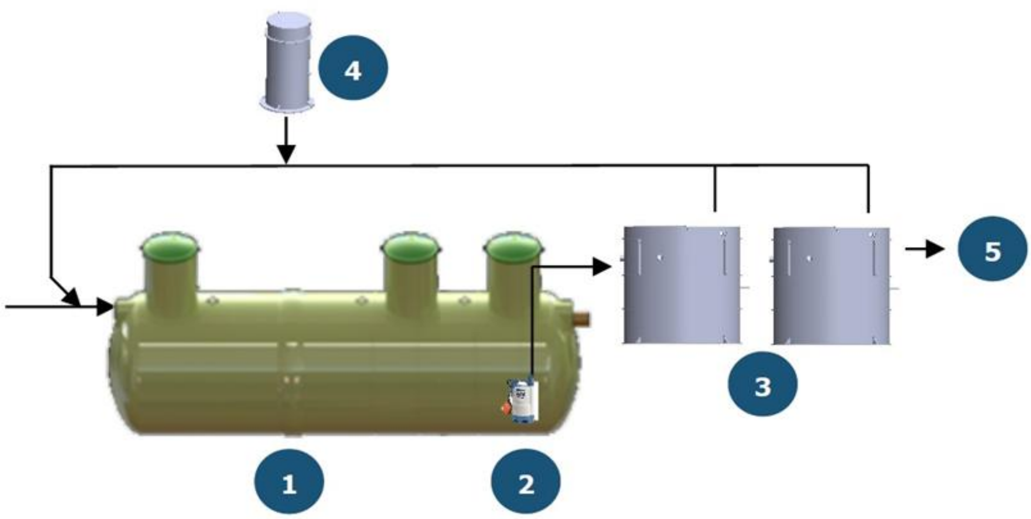


Figure 30. Vestelli BioKube Mars 6000 x 2 Wastewater System.

Description of the Wastewater System

1. **Settling Tank – 40 m³**
   Wastewater from the property is directed into a three-compartment settling tank, where solids heavier than water settle at the bottom of the compartments and grease accumulates on the surface.
2. **Equalization Tank – 5 m³**
   The equalization tank contains a pump that regulates the flow of water into the treatment process.
3. **Mars 6000 Wastewater System**
   An integrated wastewater treatment system with two tanks, where biological compartments and intermediate clarifiers alternate. The system detects the incoming volume of wastewater and aerates the biological compartments accordingly. The Mars 6000 recirculates activated sludge back to the beginning of the process, enhancing the system's resilience to varying loads. The bacterial culture can withstand even months of idle operation.
4. **Activated Sludge Recirculation**
   The activated sludge from the wastewater system is recirculated via a sewer inspection well located in front of the settling tank, back to the beginning of the process. At the same time, polyaluminum chloride (PAC) is added to the settling tank to precipitate phosphorus.
5. **Post-Clarification Discharge**
   After post-clarification, the water is directed either to soil infiltration or surface discharge (Figure 30).

Comparison of the performance, cost-effectiveness and environmental impact of selected wastewater systems

When comparing the Vestelli Biokube 2x Mars 6000 to the WehoPuts 150, both systems show excellent removal of organic matter and phosphorus. However, the Biokube system achieves significantly better nitrogen removal (70% vs. 50%) and is more cost-efficient across all removal categories. On the other hand, the WehoPuts 150 has a lower total climate impact (2,263 kg CO_2 vs. 3,728.4 kg CO_2), while the Biokube system has a lower total eutrophication impact (48.22 kg PO_4 vs. 73.26 kg PO_4). These results suggest that Biokube offers better treatment performance and cost-efficiency, whereas WehoPuts may be more favourable in terms of climate-related emissions (Table 14).

Cost-benefit and environmental impact results are calculated based on an average yearly load equivalent to 50 people (on-season 200, off-season 20). The results are indicative and may vary depending on how comprehensively the equipment suppliers have included costs and material expenses in the data collection. The treatment results are based on values provided by the equipment suppliers.

Table 14. Comparing Wehoputs 150 and Biokube 2x Mars 6000 equipment.

X	WehoPuts 150	Vestelli Biokube 2x Mars 6000
X	Biological plant, Uponor, Finland	Biological plant, Vestelli, Finland
X	Microbiological degradation, chemical fixation of P, sedimentation	Biological-chemical
Efficiency		
BOD removal:	97%	97%
COD removal:	92%	89%
Suspended solids:	90%	90.4%
Nitrogen removal:	50%	70%
Phosphorus removal:	90%	94.6%
Daily capacity ranges		
Inflow range:	7 - 22.5 m3	0 - 40 m3

BOD inflow in day:	900 - 9000 g	0 - 13400 g
Nitrogen inflow per day:	280 - 2800 g	0 - 3740 g
Phosphorus inflow per day:	44 - 440 g	0 - 580 g
Outflow		
BOD concentration:	10 mg/l	10 mg/l
COD concentration:	58.7 mg/l	80.7 mg/l
Suspended solids:	46.7 mg/l	46.7 mg/l
Nitrogen concentration:	46.7 mg/l	28 mg/l
Phosphorus concentration:	1.3 mg/l	0.8 mg/l
Dimensions		
Outer dimensions:	13.7 x 3.6 x 3.6 m	21 x 3.3 x 2.4 m
Net dimensions:	12.9 x 2.6 x 3.1 m	21 x 2.3 x 2.2 m
Construction materials	Polyethylene: 3900 kg	Glass fiber: 1600 kg
Sludge formation cycle		
Maximum sludge capacity:	5.48 m3	13.3 m3
50 persons sludge per year:	9.3 m3	9.3 m3
Sludge needs to be removed:	After every 7 months	After every 17 months*
Usage		
Electricity annually:	4062 kWh per year	8380 kWh per year
Chemicals:	1848 kg per year (PAX)	1300 kg per year (PAC)
Investment costs		
Equipment:	100 000 €	99 500 €
Installation:	10 000 €	18 000 €
Investment total:	110 000 €	117 500 €
Usage costs		
Electricity annually:	487 €	1 006 €
Desludging per year:	255 €	105 €
Chemicals usage:	7700 €	3 250 €
Maintenance 1000 €/6 months:	2 000 €	2 000 €
Total usage cost per year:	10 442 €	6 361 €

Total costs		
Construction annualized:	2 200 €	2 350 €
Annual usage costs:	10 442 €	6 361 €
Total costs per year summed:	12 642 €	8 711 €
Cost-Efficiency		
Efficiency of removing BOD:	14.27 € / kg	9.83 € / kg
Nitrogen removal efficiency:	98.89 € / kg	48.67 € / kg
Removing of Phosphorus:	349.62 € / kg	229.19 € / kg
Environmental impact*		
Climate impact of construction:	140.1 kg CO2**	262.8 kg CO2**
Eutrophication imp. of constr.:	10.3 g PO4**	43.2 g PO4**
Usage impact to climate:	2123 kg CO2	3465.6 kg CO2
Usage impact to eutrophication:	73.25 kg PO4	48.18 kg PO4
Climate impacts summed:	2263 kg CO2	3728.4 kg CO2
Eutrophication summed:	73.26 kg PO4	48.22 kg PO4

*For capacity comparison only. Sludge removal at least once per year is recommended, to ensure manufacturer stated highest wastewater treatment efficiency.

**All impact values are reduced to annual impact rates for best comparison.

Both the Uponor WehoPuts 150 and the Vestelli Biokube 2x Mars 6000 are compact, high-efficiency wastewater treatment systems designed for small communities or seasonal properties. However, their performance under very low load conditions during winter—a critical factor for seasonal use such as cottages, resorts, or small communities—can differ significantly.

The WehoPuts 150 system is known for its simplicity and reliability, but it may face challenges during extended periods of low inflow, especially in cold climates. Biological treatment processes can slow down in low temperatures, and without sufficient organic load, the microbial community may become inactive or unbalanced. This can lead to reduced nitrogen removal efficiency and potential odour issues during reactivation in spring. The system does not have a built-in standby or energy-saving mode, which may result in unnecessary energy consumption during off-season periods.

In contrast, the Biokube Mars 6000 system is specifically designed with modular operation and standby functionality. According to manufacturer documentation, the system can operate in a “stand-by mode” during periods of low occupancy, which helps maintain microbial activity while reducing energy use. This feature is particularly beneficial in winter when wastewater inflow is minimal. The Mars system’s modular design also allows for partial operation, meaning only one of the two units may run when demand is low, further improving energy efficiency and system longevity.

While both systems perform well under normal conditions, the Biokube Mars 6000 offers superior adaptability for off-season, low-load winter operation due to its standby capabilities and modular design. This makes it a more robust choice for properties with highly variable seasonal usage. The WehoPuts 150, while effective, may require more careful management or supplemental heating in cold, low-load conditions to maintain optimal performance.

Discussion

The environmental permit process in Finland is extremely demanding and, in some cases, unreasonable, especially when it concerns a small treatment plant with a population equivalent (PE) of just over 100. Furthermore, in cases with significant seasonal variation, such as the Barösund marina, the permit process should be simplified. In this case, the area is only active during the summer, and for the rest of the year, there are only a few dozen residents, just a handful in winter. The processing time for the environmental permit application is far too long and causes unnecessary environmental burden and financial loss, as the sludge has to be transported 35 km to the central wastewater treatment plant in Ingå.

When selecting the best technology and equipment, it is also important to consider factors that may not be reflected in numerical comparisons. At a nearby site, Hotel Barö, the Biokube Mars 6000 system is in use. It has operated flawlessly, and the water analysis results significantly exceed the purification requirements. By coordinating chemical purchases and maintenance activities with other local operators, time and money can be saved, especially when benefiting from their experience and expertise. Therefore, when choosing equipment, emphasis should be placed on the maintenance agreement as well as the supplier's customer service capabilities and accessibility, particularly in case of problems. If the supplier has a local office, for example, it is a major advantage.

Furthermore, in the context of sustainable tourism, Ingå has made notable progress in adopting sustainable tourism practices by following Visit Finland's criteria and promoting eco-friendly actions, local engagement, and regional economic benefits. Challenges remain, particularly in infrastructure development and visitor awareness.

A Scola restaurant model based on local, seasonal ingredients, such as fish, grains, and berries, embodies sustainable values while supporting the local economy and food culture. An adjacent store featuring local producers further extends these values, promoting community resilience, cultural connection, and authentic visitor experiences.

In the project, sustainable tourism criteria have been developed for archipelago areas based on Visit Finland's guidelines, with a specific focus on the needs of guest marinas. The criteria address ecological, socio-cultural, and economic aspects: minimizing environmental impact, supporting local communities, and enhancing regional economic benefits. Guest marinas are recognized as key players in advancing sustainable tourism in the archipelago.

However, the current Visit Finland criteria do not explicitly address wastewater management, which is critically important in archipelago regions due to their ecological sensitivity and limited infrastructure. Sustainable wastewater treatment, through decentralized and nature-based solutions such as constructed wetlands and biofiltration systems, can not only prevent harm but actively support ecosystem restoration. These solutions should be integrated into the criteria so that tourism infrastructure, including guest marinas and accommodations, can truly align with the principles of regenerative tourism.

Lessons learned and recommendations

1. Conduct Water Analyses Early

Performing water quality analyses at the beginning of the project is highly recommended. The results can be surprising and may significantly influence the choice of wastewater treatment solutions. Early testing helps ensure that the selected system is appropriate for the actual conditions.

2. Understand Environmental Permit Requirements

If the population equivalent (PE) exceeds 100 people, the site requires an environmental permit. This process is demanding and may involve multiple additional studies and clarifications. Appeals can delay the permit approval, and in some cases, such as in Ingå, it may take up to 1.5–2 years to obtain the permit.

3. Carry Out a Thorough Risk Assessment

A comprehensive risk analysis is essential. It can reveal potential issues that were not initially anticipated, allowing for better preparedness and more resilient system design.

4. Clearly Define Roles and Responsibilities

The responsibilities and authority of the water cooperative's key personnel must be well documented. It is also crucial to have clear procedures in place for handling disruptions or emergency situations.

5. Promote Sustainable and Regenerative Tourism

Developing sustainable tourism in the area requires close cooperation among all stakeholders. The shared goal should be to foster regenerative tourism that not only minimizes environmental impact but also contributes positively to the local ecosystem and community.

Report on decentralised wastewater systems in Moonsund Archipelago, Estonia

Authors: Tiia Pedusaar, Selma Guyon, Helen Poltimäe, Andreas Hoy

Introduction

This chapter focuses on the Moonsund Archipelago, also known as the West Estonian Archipelago, located in the eastern part of the Baltic Sea. Covering an area of 3,933 km², it is home to approximately 40,700 residents (Statistics Estonia, 2024). The principal islands within the archipelago are Saaremaa, Hiiumaa, Muhu, and Vormsi. Compared to other countries around the Baltic Sea, Estonia's density is relatively low: 31.8 persons per square kilometre, while in Germany it is 235.8 and in Poland 119.4 persons per square kilometre (Eurostat, 2025). Saaremaa's density is even lower than the Estonian average: around 11.7 persons per square km.

Saaremaa concentrates the majority of the tourism activities in the Moonsund Archipelago. In 2024, Saaremaa welcomed over 286,000 overnight stays, a slight decrease from 292,000 in 2023 (Puhka Eestis, 2025). While this indicates a stable interest in the island, Saaremaa's tourism represents only a small fraction of Estonia's overall tourism activity. For context, Tallinn alone accounted for nearly half of all overnight stays in the country (Puhka Eestis, 2025). A notable characteristic of Saaremaa's tourism is its pronounced seasonality. In July 2024, the island experienced a peak with approximately 62,500 overnight stays, whereas January saw fewer than 10,000 (Puhka Eestis, 2025). This sharp contrast highlights the seasonal nature of tourism in Saaremaa, like other coastal areas around the Baltic Sea, where the highly uneven, seasonal influx, rather than the overall load, poses a challenge to wastewater treatment systems.

Wastewater discharging service on the island of Saaremaa

Estonia has a population of 1.3 million, of whom around 83% use public water supply and wastewater systems (Ministry of Climate, 2018). Around 200,000 are self-supplied. In 2019, Saaremaa municipality had a population of 20,775, of whom around 88% were connected to the public wastewater treatment system (Liiv et al, 2018). The rest of the population has its own system, including septic tanks.

There are nine wastewater discharging points in Saaremaa, all operated by Kuressare Veevärk AS, but only four are used: Kuressaare, Orissaare, Kärla, and Leisi (Arm, 2021). All four are situated in Saaremaa Parish (see Map 2). According to regulations, a septic or storage tank can be emptied only by the service provider who has a contract with the water company for wastewater discharge (Saaremaa Municipal government, 2019). The statistics about the amount of wastewater discharged are not publicly available. It is known that 5891 m^3 of wastewater was discharged in Saaremaa County in 2019 (Arm, 2021). However, these data may not be accurate, as reporting discharge amounts became obligatory only in 2020.

There are several deficiencies in the discharge system. One of them is that there is no system in place to register dischargers, which complicates monitoring. This can lead to a situation where the service is provided by unauthorised companies that discharge wastewater into improper places. Moreover, local authorities lack an overview of on-site treatment facilities and the amount of wastewater generated, making it challenging to plan the capacity of discharge points. Incorrect planning is one of the primary reasons why many discharging points are out of use, necessitating the transportation of wastewater over impractically long distances, which increases the cost and harms the environment (Arm, 2021).

The price for wastewater discharge service starts from 14 euros per m³ (however, an additional cost for transport distance is applied). However, the wastewater cost for sewage systems ranges from 3 to 6 euros/m3, depending on the municipality and whether it is serving inhabitants or legal entities (i.e., companies) (Kuressaare Veevärk, 2023). Hence, the discharging service costs are much higher for those not connected to the public wastewater system.

Report structure

A two-part analysis has been done to assess the state of decentralised wastewater systems on the Moonsund Archipelago. A first questionnaire provided an initial overview of decentralised wastewater systems, focusing on accommodation providers of the island of Saaremaa. To complete this overview, in-depth interviews were conducted to analyse whether the wastewater treatment systems of tourist facilities ensure environmental and health safety. A cost-effectiveness analysis was then conducted to determine the potential costs associated with achieving the desired water quality level in the area. Finally, lessons and recommendations are drawn from this analysis and presented.

Questionnaire of decentralised wastewater systems

Methodology

The objective of the survey was to assess the condition of on-site wastewater systems, the technologies used, daily maintenance practices, and investment needs for collecting and treating wastewater from households providing tourism services in Saaremaa County. The questionnaire was developed based on the Ministry of Climate's recommendations, but modified to consider the specific needs of the NURSECOAST-II project. Further feedback was collected from Saaremaa County. As the questionnaire's target group was tourism enterprises (Map 1), their information and contact data were collected from the "Visit Estonia" website in May and June 2023. Blue dots denote tourism service providers in Saaremaa, and red areas indicate agglomerations with a public sewerage system (Map 1).

Map 1. Tourism service providers in Saaremaa County (blue dots) and agglomerations (red areas)[1]

[1] Source of the map: Tiia Pedusaar, with a map from the Land and Spatial Development Board, https://geoportaal.maaamet.ee/eng/Web-Maps-p35.html

In August 2023, information on small ports (marinas) was obtained from the State Port Register database. Due to their connection to the public wastewater system, the tourism enterprises in the city of Kuressaare were excluded from the potential sample.

The questionnaire was completed online by emailing links to 120 accommodation providers, 27 caterers and 8 small ports. In total, the questionnaire was sent to 155 tourism service providers. Before sending the link, the survey was tested. The questionnaire could be answered under a business name or anonymously. The questionnaire was activated on September 15, 2023, and data collection ended on November 6, 2023. The response rate was 23.3 % (34 answers). Of them, 44% responded by business name. The list of questions is in Appendix 1.

Data analysis

Most respondents were active in the accommodation sector, but in many cases, this is combined with other services (marina or catering). The vast majority of tourism facilities are relatively small, with 71% of respondents able to accommodate 20 visitors at a time. As expected, tourism is highly seasonal; only a third of the tourism facilities operate year-round in Saaremaa. 2/3 of respondents are open only for some months during the year. Among those who operate seasonally, 23% are open only in the summer months (June, July, August), while most facilities are open from April/May to September (32%) or October (41%). According to the state port register, the number of marina users fluctuates between 70 and 3,000 people during the navigation period (Sadamaregister, 2023).

Wastewater systems

The most used onsite wastewater systems are septic tanks with a leach field (41% of respondents) and storage tanks (32% of respondents). 12% of respondents reported an individual plant with a leach field, and the treatment method is based on activated sludge or biofilm technology. Some respondents reported septic tanks with a sand filter field; others reported onsite systems combined with the possibility of accessing a public sewer.

The average storage tank volume is approximately 5 m³; the most common material is plastic or fibreglass (80%). The septic tank volume is highly variable, ranging from 1 to 30 m³, with an average of approximately 8 m³. The most common leach field size (79% of respondents) is 15-30 m2 or 31-60 m². The average amount of wastewater generated per season was 9 m³ (minimum 1 m³, maximum 55 m³).

Everyday maintenance of onsite wastewater systems

Storage tanks are emptied frequently: half of the respondents empty them at least once a month. Two respondents emptied the system even more frequently but also admitted the need for reconstruction of wastewater systems to reduce costs. Half of the system's owners claim to empty their septic tanks at least once every 6 months. Only two respondents said they empty their septic tanks more seldom than once a year. In most cases, the activated sludge is taken to a regional wastewater plant: 67% of respondents claim this. 15% of respondents store it on their own land/premises, and 18% are unsure where it is taken.

Construction time and need for reconstruction

Most of the surveyed tourism enterprises' wastewater systems were built relatively recently: 47% between 2001 and 2010, and 29% after 2010. 18% of the respondents reported that the wastewater system was built between 1991 and 2000. Most of the systems have also been reconstructed; however, in many cases, this is unknown, possibly due to changes in ownership or management at the facility.

When discussing the need to reconstruct the wastewater system, 64% of respondents did not see a reason, while 36% believed it was necessary. The questionnaire asked about reasons for the need for improvement of the system by giving three options: My drinking water is at risk/or the drinking water well is polluted; The existing wastewater treatment system is depreciated; The coastal sea bordering my property needs protection) and provided an opportunity to add other reasons. Of the predetermined reasons, the old wastewater system that needs reconstruction was most often chosen (67% of respondents), followed by the need for coastal sea protection (50% of respondents). Only one mentioned that their drinking water is threatened.

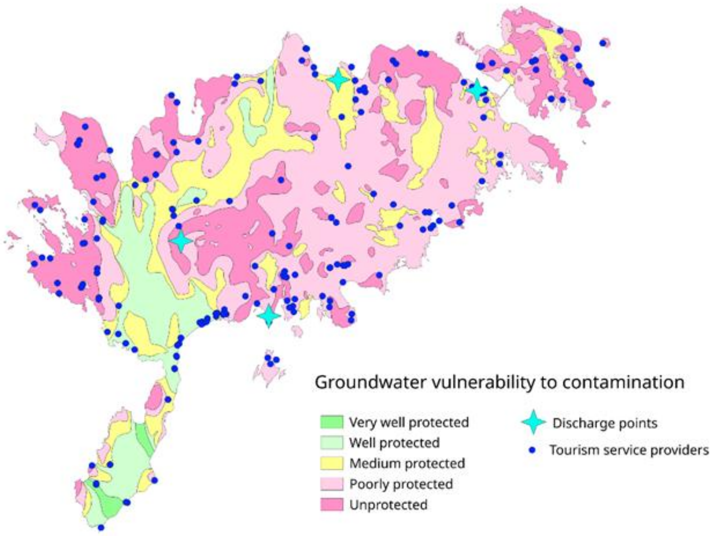
Other reasons claimed were that the storage system is located on a neighbour's premises, that the septic cleaning service is too expensive, or that they are unsure how well the system works. Additionally, a marina mentioned a problem with caravans, as they have limited options for pumping wastewater from caravan septic tanks. One respondent expressed a desire to join the public sewer system.

75% of those who estimated the potential cost of reconstruction thought it was more than 5,000 euros, while 25% thought it was between 2,500 and 5,000 euros. As expected, most respondents (72%) would expect to receive at least 60% of the financial support from the municipality or state to reconstruct their onsite wastewater system. Still, some respondents claimed that no financial support is necessary.

Source of drinking water

Drinking water quality is closely related to the wastewater treatment systems in rural areas without sewerage systems. For this reason, we asked where tourism service providers get their drinking water. Approximately 77% of the respondents obtain their drinking water from deep wells (groundwater), and around 9% from dug wells (shallow wells). The remaining enterprises have access to the central water system. Typically, the groundwater quality is superior to that of the dug wells on the island.

Due to its geology, the Moonsund Archipelago is renowned for its poorly protected groundwater. 71.5% of Saaremaa County's territory is defined as an area where groundwater is unprotected or poorly protected. In these areas, groundwater is particularly vulnerable to pollution. Most tourism service providers are located in unprotected or poorly protected aquifers (Map 2).



Map 2. Groundwater vulnerability to contamination and location of tourism service providers who received the questionnaire in Saaremaa County[2]

[2] Source of the map: Land and Spatial Development Board. (2025). X-GIS 2.0 [ise34R2r]. Land and Spatial Development Board of Estonia. https://xgis.maaamet.ee/xgis2/page/link/ise34R2r

Discussion

The survey achieved a response rate of 23.3%, which is reasonable given the sensitivity of the topic and the specific target group. Recent challenges in the tourism sector, including the Covid-19 pandemic, the energy crisis, high inflation and geopolitical uncertainty, may have reduced willingness to respond. The results provide a representative characterisation of the target group, which consists mainly of small accommodation providers operating on-site wastewater systems and lacking access to the public sewer network. The findings also confirm the strong seasonality of tourism on the island, with peak activity occurring between May and October, particularly in June, July and August.

Conventional septic tanks with leach fields and storage tanks are the predominant wastewater solutions on the island, accounting for 73% of the systems. This aligns with previous studies, such as the 2014 Infragate report on on-site wastewater systems in Estonia and the 2023 CleanEst study in the Viru sub-basin of Eastern Estonia[3].

The survey identified several shortcomings, including the need for frequent and costly septic tank emptying and high wastewater transport costs resulting from the limited number of discharge points. Notably, 18% of respondents were unsure where their wastewater is discharged, raising concerns about environmental awareness and potential non-compliant disposal practices.

While the survey results provided valuable insights, several issues required further investigation through on-site visits and interviews. Firstly, the survey only included responses from those who have relatively recent (post-1991) wastewater systems. It is likely that those with older, underperforming systems did not participate, as they tend to respond less. The Saaremaa Development Plan 2019–2030 highlights the widespread issue of outdated, self-built, or non-compliant systems (Saaremaa Municipal government, 2019). On-site inspections will provide a better understanding of the condition of these older systems. Secondly, groundwater on the island is vulnerable to pollution from septic infiltration systems and leaky storage tanks. Since groundwater is the primary drinking water source for the island, it is critical to focus on its protection and sustainable use. Interviews and on-site visits will enable a more accurate assessment of drinking water quality, primarily through direct sampling and analysis of groundwater near wastewater treatment systems. This will help identify potential contamination risks and inform necessary improvements.

[3] Infragate report: https://kliimaministeerium.ee/sites/default/files/documents/2021-10/Hajaasustuste%20reovee%20kohtk%C3%A4itluss%C3%BCsteemide%20inventuuri%20aruanne_0.pdf; CleanEst Life project study: https://lifecleanest.ee/sites/cleanest/files/2023-06/LIFE%20CleanEST%20uuringu-%20ja%20seireplaan%202023-2027.pdf

In-depth interviews with owners of small wastewater systems

Methodolody

The interviews aimed to further assess the pollution load from the wastewater treatment systems of tourism establishments in Saaremaa during the tourist season and off-season. The study will give an overview of the compliance of wastewater treatment technologies with Estonian legislation and the efficiency of systems under peak summer loads and minimum off-season loads. The quality of drinking water and compliance will also be assessed. Lastly, the interviews will examine the need for renovation in cases of non-compliant systems. The interviews will help determine whether the water treatment systems of tourist facilities ensure environmental and health safety and whether they are compatible with Saaremaa's geological and environmental conditions.

Site surveys, data collection, sampling and advice to water treatment operators were carried out by Aqua Consult Baltic OÜ[4]. The surveys were conducted in three visits during the summer tourist season: 22-23 July, 26-28 August and 13 October 2024. Thirty-one tourist establishments were visited. In each establishment, interviews were conducted with a representative, systems were checked, and wastewater and drinking water samples were taken. Wherever possible, advice was provided during the visit to ensure that water treatment systems were operated correctly and maintained.

The interest and involvement of treatment operators in the survey varied widely. For the most part, the operators were cooperative, shared the necessary data to facilitate the study, and expressed interest in improving the performance of the treatment plants. However, for some tourist establishments, it was challenging to obtain accurate information, and the managers were not interested in carrying out the visit or improving the cleaning processes.

Accredited samplers took samples of fresh, waste, and drinking water. Many of the treatment systems were subjected to wastewater soakage in the case of wastewater samples, which did not allow for an adequate analysis of the effluent sample. The sample was taken from the best available site, as decided by the accredited sampler. Samples were analysed in certified laboratories.

Drinking water samples were analysed for manganese, total iron, NH_4, NO3 and NO_2 ions, pH, turbidity, color, Escherichia coli, enterococci and coliform bacteria at the Estonian Environmental Research Centre (EEA) laboratory. The effluent samples were analysed for BHT_7, COD, suspended solids, total nitrogen and total phosphorus at the Environmental Analysis Laboratory of the University of Tartu. The data were summarised and evaluated using a spreadsheet program. A summary report was prepared, which included a summary table of the survey results and analyses, as well as an assessment of the treatment plants' performance and compliance; however, this report is not publicly available.

[4] https://aquaconsult.ee/

Data analysis

Wastewater research

Load volatility

During the tourist season, wastewater treatment plants' loads are high, but low or non-existent during the off-season. Average summer and peak loads (Mid-summer and other single days of very high attendance) vary significantly.

As wastewater generation in tourist facilities is not measured, it was calculated as a proportion of the number of visitors. While the average daily consumption of drinking water and the amount of wastewater generated per person are approximately 80-100 litres per day in residential areas, they are significantly lower in tourist establishments. It depends very much on the season and the amount of food prepared on-site. This calculation estimated 35 litres of wastewater per person per day.

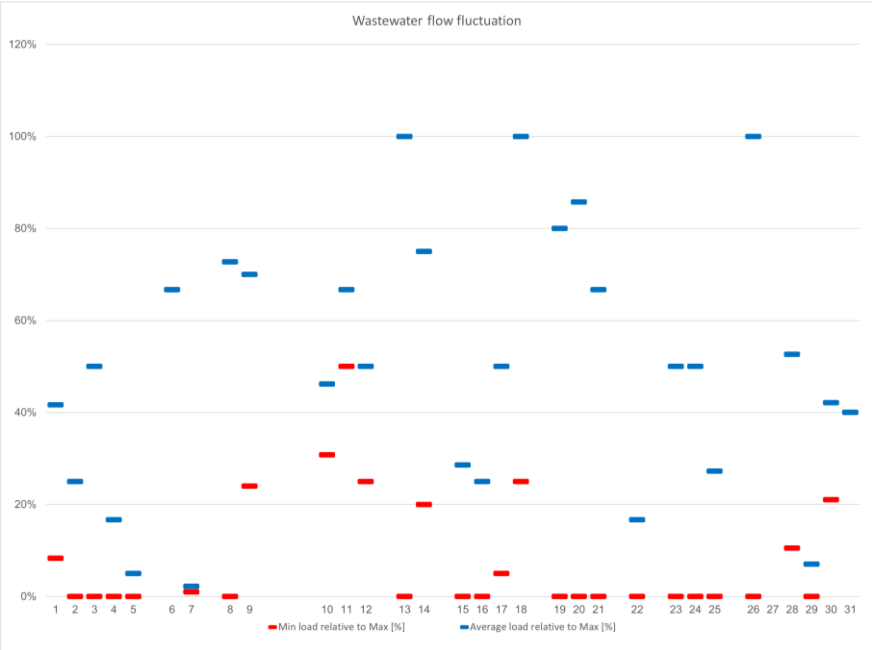


Figure 31. Variability of wastewater generation – summer average and winter (minimum) flows as a proportion of summer maximum flows.

As shown in Figure 31, flows exhibit significant variability. The summer peak flow is significantly higher than the average for the same period in almost all tourism businesses. In the low season, however, flows are very low. Most tourist establishments in Saaremaa County are closed during winter, resulting in significant fluctuations in the wastewater load. Typical wastewater treatment systems for tourist facilities include septic tanks with leach fields, individual plants with leach fields (utilising activated sludge), and storage tanks.

In the vast majority of tourist facilities, wastewater is discharged. If there is an activated sludge scrubber in front of the soak-off, the water to be soaked is already pre-treated. However, combining a septic tank with a leach field is also a common practice. As the purification capacity of septic tanks is very low, such treatment is not recommended in unprotected or poorly protected groundwater areas, and it is not legally required. In analysing the treatment performance of the technology, it was assumed that a septic tank installed on a mostly aggregate bed would exhibit treatment performance similar to that of a soil filter septic tank (Figure 32).

Wastewater is also collected in fully compliant storage tanks and discharged to a larger treatment plant.

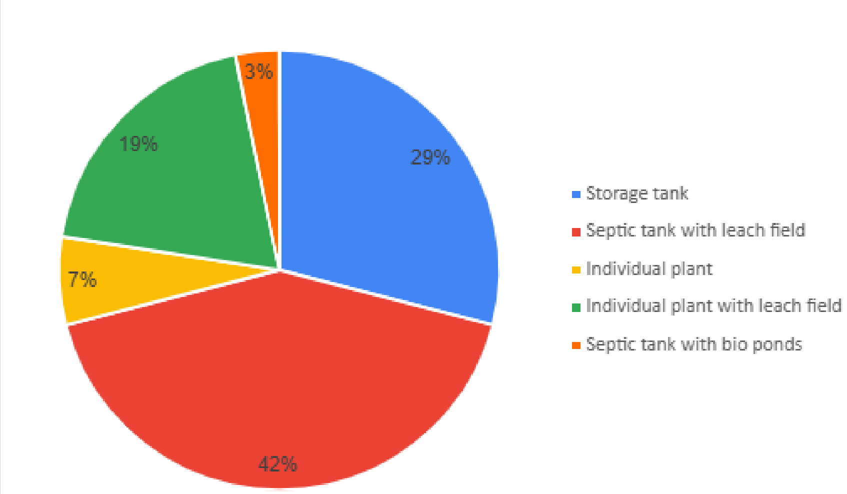


Figure 32. Wastewater treatment technologies for tourism enterprises.

During the site visits, wastewater and effluent samples were taken from the treatment plants. Sampling effluent from the wastewater treatment plants was only possible in cases where a sampling point could be established in the effluent. In the case of septic tanks, the tank itself also serves as a treatment step to a certain extent. However, sampling is only possible after the previous treatment step (usually the septic tank outfall), i.e. the inlet to the septic tank. Thus, only 7 out of 42 samples from the wastewater treatment plants could be assessed for the quality of the effluent discharged into the environment, and four of these samples comply with the thresholds.

In areas with weakly protected or unprotected groundwater, wastewater containing faecal matter must undergo biological treatment before being discharged through diffuse groundwater infiltration (percolation) (Ministry of Climate, 2019). Thus, in areas with weakly protected and unprotected groundwater, it is suitable to use storage tanks (and wastewater disposal) or to impregnate after biological treatment (e.g., activated sludge).

The technical compliance of wastewater treatment plants with legal requirements was also assessed. Based on the applicable criteria, 55% of the treatment plants were found to comply with legal design requirements, while 45% did not. One of the key requirements is that the year-round infiltration depth should be at least 1.2 m above the highest groundwater level. Site visits indicated that several leach fields may not meet this requirement; however, due to the lack of long-term groundwater monitoring data, this criterion could not be fully assessed and was therefore excluded from the compliance evaluation.

An additional assessment examined whether the installed treatment capacity was adequate for the pollution load generated during the summer tourist season. This assessment compared the average number of summer visitors with the design capacity of the treatment plants, based on available technical documentation. For many tourism establishments, however, operators were unable to provide documentation or were unaware of it. In such cases, treatment plant capacity was estimated by the sampler and specialist using observations and data collected during the site visit. For example, a vertical soil filter or similar leach field was estimated to require approximately 4 m² of filter area per person's pollution load (Kuusik et al., 2023).

The results of the visits indicate that 32% of wastewater treatment plants have a pollution load from average summer visitors that is broadly aligned with their design capacity. In 29% of cases, adequacy could not be assessed due to insufficient information on storage tanks. By contrast, 39% of treatment plants receive a summer pollution load that exceeds their design capacity, with exceedances becoming more pronounced during peak summer days.

The figure below shows the estimated share of average summer visitor arrivals to tourism businesses in the estimated project load of wastewater treatment plants. Based on the figure, nearly half of the wastewater treatment plants have a number of visitors in summer that is significantly higher than the treatment capacity of the plant (Figure 33). Compared to the maximum days of summer visits, the wastewater pollution load of most tourism facilities significantly exceeds the treatment capacity of the treatment plant.

During visits to tourist businesses' treatment plants, several solutions were observed, indicating that wastewater was bypassing the treatment plants or that the storage tanks were not being emptied legitimately. Unfortunately, this cannot be verified, and therefore, such suspicions are not included in this report.

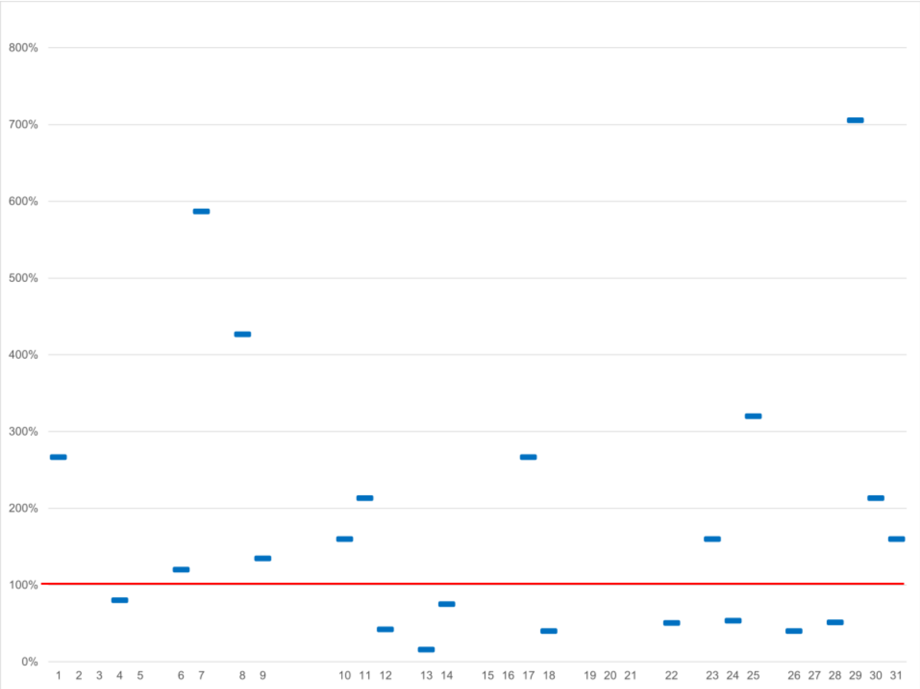


Figure 33. Average number of visitors in the tourist season based on the estimated treatment plans' load

Drinking water survey

Drinking water samples were taken by an accredited sampler during the visit to the tourist establishments. In 65% of cases, the drinking water sample does not meet the legal requirements. The highest exceedance is for microbiological contamination, with 42% of samples failing to meet the requirements. The limit values for iron and manganese were also exceeded (36% and 20% of samples analysed, respectively). In cases where iron and manganese levels are exceeded, a corresponding iron and manganese supplement is required.

Discussion

Almost all treatment plants use soil percolation, thereby avoiding the discharge of effluent to a distant water body, watercourse, or ditch. Presumably, the main reason for using such a system is that there is no obligation to obtain a water permit for the impregnation of up to 5 m^3 of wastewater, according to Section 188 (6) of the Water Act (Parliament of Estonia, 2019). Additionally, the construction of long wastewater pipelines is often expensive.

A very large part of Saaremaa is located in an area with unprotected or weakly protected groundwater. It is, therefore, necessary to implement biological treatment of wastewater, according to Section 8(1) of Regulation

No.61, as in practice, wastewater from water treatment plants is often not separated from other flows (Ministry of Climate, 2019). This means that the parameters of the wastewater after biological treatment must meet the following requirements: BHT7 ≤ 40 mg/l, KHT ≤ 150 mg/l and Hg ≤ 35 mg/l, according to Section 3 (3) of Regulation No.61 (Ministry of Climate, 2019).

The main concern for tourist establishments was not so much information on cleaning solutions but finding the financial means to install cleaning technology. It is estimated that the investment needed to install a wastewater treatment system to serve 30-60 people is 20,000 to 40,000 €. Saaremaa has many tourist facilities, and several businesses have pointed out that they can barely meet ends. According to several estimates, increased spending on water treatment technology could lead to the closure of several businesses. Given these financial constraints, the following cost-efficiency analysis will closely examine the relationship between costs, scale, and treatment needs to better understand where investment would be most efficient and feasible.

Cost-Efficiency Analysis

Methodology

Cost-efficiency of upgrading small wastewater plants

A cost-efficiency analysis evaluates the potential costs of achieving the desired water quality level in this area. This analysis is based on in-depth interviews conducted with the owners of small wastewater plants, as well as expert opinion from the consultancy company that facilitated these interviews.

A total of 31 tourism facilities were included. Approximately one-third of these facilities are located within 500 m of the sea, and a further 25% are within 1 km, indicating a potentially higher risk of impact on coastal waters. Around 40% of the facilities are located farther inland, where the direct impact on seawater quality is lower. The sample represents approximately 17% of tourism facilities operating in Saaremaa outside Kuressaare, which is served by a public wastewater system. Given the lack of previous studies focusing on wastewater issues in Saaremaa's tourism sector, the sample is considered representative.

Compared to water use and scarcity issues, wastewater treatment, particularly on islands and isolated households, has not received much attention in the scholarly literature. It is published separately from the water use and demand topics (Ricart et al., 2023). The wastewater studies have concentrated on management strategies of septic tanks, as this is the most common technology used on islands (see, for example, Wells et al., 2016; Margeta, 2019). Septic tanks are prohibited in some rural regions due to concerns over groundwater quality. Then, different technical options are considered for wastewater treatment, but the solutions need to be tailored to the specific wastewater stream, as these contain different pollutants (Zhang et al., 2025).

A cost-efficiency analysis is typically applied to find the most cost-effective option to achieve a specific objective. However, it is more easily applicable to some aspects of water issues, while it is more difficult to apply to ecological issues (UNDP, 2013). In typical cost-efficiency analysis, cost is calculated in relation to measurable effect, for example, per kilogram of nitrogen mitigated (Wood et al., 2015; Martin & Johnson, 2019).

Data analysis

In the case of Saaremaa, on-site inspections revealed that nearly half of the wastewater plants (45%) did not comply with legal requirements. The main issue is that most of Saaremaa has unprotected or poorly protected groundwater. As no official data are available, we have used the map of tourism facilities (Map 2) to obtain a rough estimate of the tourism facilities located in the area of unprotected or poorly protected groundwater. Based on the map, it is about 85%. If a facility is located in an area with unprotected or poorly protected groundwater, it is required by law to have a storage tank or a biological treatment system. A septic tank with a leach field is not suitable in this case. The investment cost of the biological treatment plant ranges from € 20,000 to € 40,000, which includes both equipment and construction costs. The estimated total costs for compliance with legal requirements related to wastewater are presented in Table 15.

Table 15. Estimated costs of replacing septic tanks with biological treatment

	Number of facilities	Cost per facility	Total costs
Replacement of septic tanks in unprotected or poorly protected areas	Around 62 tourism facilities (183 facilities outside the public sewage system, 85% of them on unprotected or poorly protected groundwater areas, 40% of them relying on septic tanks)	Mean: 30,000 euros (estimated range: 20,000 – 40,000 euros)	2 million euros

Discussion

There are many issues with the investment. Firstly, according to the interviews, facility owners are willing to invest only around 2,000 – 3,000 euros in a wastewater treatment system, while the estimated costs are around ten times higher. The tourism sector has faced several crises in recent years, including the Covid-19 pandemic, rising energy prices, and a decline in tourism due to its proximity to Russia. Hence, the tourism facilities hope to get investment support for wastewater systems, which is difficult to provide under the current budget cuts. In addition, this investment alone does not fulfil the objective, as biological treatment needs specialised knowledge to run efficiently after installation. Tourism providers in Saaremaa are small and cannot hire specialised experts. An option would be to offer them a service, specifically in the first years of biological treatment operation, where wastewater treatment experts visit the facility periodically to ensure its proper operation. However, this would increase the costs even further.

However, the potential impact of these investments on water quality remains unclear. In terms of drinking water, tourism facilities are required to test their water quality annually, and to date, no issues have been reported. The drinking water samples collected as part of this project met the requirements. The potential effect on seawater quality resulting from replacing septic tanks with biological treatment plants is also unclear. The general impact of tourism facilities on seawater quality in Estonia is likely rather limited, as the main load of nutrients is caused by agriculture (Ministry of Climate, 2024). A similar trend holds for the Baltic Sea, as agriculture contributes about 70-90% of nitrogen and 60-80% of phosphorus (HOLAS3, 2023). The highest nitrogen surpluses around the Baltic Sea are found in Denmark, Germany, and Poland, which are also characterised by high levels of animal husbandry and crop production (HOLAS3, 2023). This situation may differ significantly in other regions, depending on factors such as agricultural production, settlement density, and tourist load. For example, human settlement impacts on water quality in some coastal areas are very significant. In Cape Cod, USA, it has been estimated that approximately 70% of the nitrogen entering coastal waters comes from household septic systems (Martin & Johnson, 2019).

Lessons learned and recommendations

Tourism businesses in Saaremaa County face persistent challenges in managing wastewater due to the region’s highly seasonal tourism activity. Many establishments currently rely on septic tanks with soil infiltration systems, even in areas with unprotected or poorly protected groundwater. According to current regulations, these systems are not suitable and must be replaced with biological treatment technologies that provide more reliable environmental protection. However, transitioning to biological treatment systems is not a simple technical upgrade. It requires significant financial investment as well as ongoing technical support. Many tourism operators lack the necessary skills to manage and maintain these systems—particularly during the seasonal spring restart, when biological processes need to be reactivated after winter dormancy. Even technically compliant systems may fail to meet performance standards without proper support.

To ensure effective implementation, financial support schemes (e.g., grants or subsidies) must be paired with structured technical assistance. This could include local expert networks, maintenance contracts with wastewater professionals, or public-private partnerships to provide operational support, especially in the first years of system adoption.

Effluent sampling should also be made more systematic. Treated wastewater should be monitored after the biological treatment stage and before it reaches the soil or the receiving water body. Matching treatment plant capacity to actual pollution loads—particularly during peak tourist seasons—is critical, as is enforcing regular maintenance and compliance with legal standards.

Although drinking water quality currently meets regulatory requirements—a prerequisite for tourism operators to receive seasonal licenses—the impact of new wastewater treatment systems on seawater quality remains unclear, considering the role of agriculture. Further monitoring and research are necessary to determine whether improvements in on-site wastewater treatment result in measurable benefits for the surrounding marine environment. That said, existing evidence suggests that agricultural runoff plays a more significant role than tourism-related wastewater in affecting the quality of coastal waters.

In summary, improving wastewater management in Saaremaa requires a coordinated and well-supported transition from outdated septic systems to compliant biological treatment solutions. This must be backed by both investment and capacity building to ensure long-term effectiveness and protect both groundwater and coastal ecosystems.

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Conclusion

The pilot studies highlight innovative solutions and practical recommendations for improving efficiency and environmental protection.

Key steps before installing a new wastewater treatment system:

1. **Conduct early water analyses** – initial testing ensures the chosen solution matches actual conditions.
2. **Understand permit requirements** – approval can take years, plan accordingly.
3. **Perform comprehensive risk assessments –** identify potential issues early to build resilience.
4. **Define roles and emergency procedures** – clear responsibilities are critical for smooth operation.
5. **Foster stakeholder cooperation** – collaboration supports sustainable and regenerative practices.

Successful implementation requires financial support (e.g., grants or subsidies) combined with structured technical assistance, such as expert networks, maintenance contracts, and public-private partnerships—especially during the first years of adoption.

Different technologies have been installed and tested. Nanobubble aeration ensures highly efficient oxygen transfer, enabling nitrification even in cold conditions and can be used as a portable unit. Constructed Wetlands are a simple solution, but clear. Intensified wetland with Real-Time Aeration Control can optimize aeration rates and reduce energy use while maintaining effluent quality. IT-Based Management Systems enable remote monitoring, faster issue resolution, and overall process optimization.

Reusing treated wastewater for irrigation can be an attractive solution, but it requires compliance with the EU Water Reuse Regulation. A water permit is mandatory, and strict quality standards apply. Microbiological and physicochemical testing is required, ensuring zero E. coli and parasites.

Appendix 1

Questionnaire on onsite wastewater systems

Dear recipient of the survey,

You are invited to participate in a survey to assess the condition of the local wastewater treatment system. The study aims to find out the condition of the small local treatment plants related to tourism in Saaremaa Municipality. The study is carried out in the context of the international project Nursecoast (https://interreg-baltic.eu/project/nursecoast-ii-interreg-baltic-sea-region/), funded by the Interreg BSR programme. The project deals with small wastewater treatment plants along the Baltic Sea, where the tourist season leads to fluctuations in wastewater quantities. Estonia's project partner is the Stockholm Environment Institute Tallinn Centre (SEI Tallinn), whose field of activity is conducting applied research related to the environment (https://www.sei.org/centres/tallinn-et/).

The results of the survey are analysed and a sample of treatment plants is drawn up, where, with the consent of the owner, an on-the-spot inspection is subsequently carried out. The study is necessary for local authorities to have a reliable overview of the local wastewater treatment systems used in their administrative territory and their condition, in order to prevent the spread of pollution to groundwater and surface water.

The data will be stored on the SEI Tallinn server until the end of 2030 and the results of the analysis will be shared with Saaremaa municipality. The results of the study are not used by the municipality to impose coercive measures, but to formulate wastewater treatment policy, including the planning of subsidies.

It takes no more than 15 minutes to answer the questions. When answering questions, be guided by your best knowledge. If you manage several properties related to tourism, please respond to the property where the wastewater load is highest.

If you have any questions, please contact the project coordinator: Tiia Pedusaar, phone: 5097744, email: tiia.pedusaar@sei.org.

Thanks for taking the time to respond!

Survey for assessing the condition of the local wastewater treatment system of the property

1. **Business name and address (answering is not mandatory):** ____
2. **Tourist service offered:** Accommodation ; Catering ; Small port

   (Explanation: please tick all correct answers)
3. **Maximum possible number of visitors:**

   _____beds in case of accommodation

   _____seats in case of catering

   _____guests during navigation period in a small port
4. **Time of provision of tourist service (navigation period for small ports):**

   year-round; seasonal
5. **In the case of seasonal service provision: the period during which you provide the service (from which month to which month):**___________________________
6. **How is the treatment of wastewater generated on the property solved?**

   storage tank;

   septic tank and leach field;

   on-site treatment plant and leach field;

   septic tank and sand filter;

   no treatment;

other (please specify)_________________

7. Year of construction of the property's wastewater treatment system:

earlier than 1980;

1980-1990;

1990-2000;

2000-2010;

later than 2010;

unknown

8. Time of reconstruction of the wastewater treatment system of the property:

earlier than 1980;

1980-1990;

1990-2000;

2000-2010;

later than 2010;

unknown ;

reconstruction has not been carried out

9. **Amount of wastewater generated (m3/month):** ____

Explanation: In the case of seasonal operation, please indicate the average monthly wastewater amount generated per season

10. Description of the wastewater treatment system of the property:

1.4 Storage tank:

Capacity of the storage tank (m3)_________________________

Storage tank material:

plastic;

fiberglass;

metal;

concrete

2.4 Septic tank and leach field:

Septic tank capacity (m3)________________________________

Dimensions of the leach field:

up to 15m2;

15-20 m2;

30-60m2;

over 60m2

3.4 On-site treatment plant and leach field:

Type of on-site treatment plant:

Biological treatment system based on activated sludge;

Biological treatment system based on biofilm;

other

Dimensions of the leach field:

up to 15m2

15-20 m2

30-60m2

over 60m2

4.4 Septic tank and sand filter:

Septic tank capacity (m3)__________________

Sand filter dimensions:

up to 15m2;

15-20 m2;

30-60m2 ;

over 60m2

11. Frequency of emptying of the storage tank:

more often than once per month;

once per month;

once per quarter;

once in half year;

once per year;

less often than once a year;

has not emptied

12. Where are the residues from the maintenance of the wastewater treatment system taken?

to a regional wastewater treatment plant;

you store on the territory of your property (e.g. in a field) ;

you are not aware of where the waste will be taken

13. Source of drinking water on the property:

deep well;

shallow well;

other (please specify)___________

14. **Do you see the need to improve/rebuild your wastewater treatment system?** Yes; No

15. If you answered yes to the previous question, what are the reasons for the need for improvement?

(Explanation: Choose the answers that are important to you)

My drinking water is at risk/or the drinking water well is polluted

The existing wastewater treatment system is depreciated

The coastal sea bordering my property needs protection

Other (please specify)------------------------------

16. **How much do you estimate the cost of rebuilding or constructing a wastewater treatment system?** Up to 2500 euros ; 2500 – 5000 euros; over 5000 euros; can't say

17. If the state or municipality offers assistance for the refurbishment and construction of wastewater treatment systems in the future, at what minimum level of state or local government participation is the owner interested in streamlining the system in the future?

support for the streamlining of systems is a minimum of 15%;

support for the streamlining of systems is a minimum of 30% ;

support for the streamlining of systems is a minimum of 45% ;

support for streamlining systems is a minimum of 60%

Other ______________________

18. Are you willing to participate in an on-site inspection, where the condition of your treatment plant will be assessed by a water supply and sewerage engineer and, if necessary, will also give advice?

Yes

No

If you agree, please let us know your email