Ministry of Environment and Food of Denmark
Environmental Protection Agency

Irrigation symbiosis

Local reuse of water for field irrigation

MUDP report

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Miljøstyrelsen vil, når lejligheden gives, offentliggøre rapporter og indlæg vedrørende forsknings- og udviklingsprojekter inden for miljøsektoren, finansieret af Miljøstyrelsens undersøgelsesbevilling. Det skal bemærkes, at en sådan offentliggørelse ikke nødvendigvis betyder, at det pågældende indlæg giver udtryk for Miljøstyrelsens synspunkter. Offentliggørelsen betyder imidlertid, at Miljøstyrelsen finder, at indholdet udgør et væsentligt indlæg i debatten omkring den danske miljøpolitik.

Må citeres med kildeangivelse.

Contents

1. Introduction

The report in hand is the final report for the project “Irrigation symbiosis – local reuse of water for field irrigation”, financed by the program MUDP from the Ministry of Environment and Food of Denmark.

The purpose of the project was to investigate whether it is possible to treat municipal waste water in such a way, that the valuable nutrients are kept in the water, while the problematic substances are removed by running existing treatment technologies differently and hence produce safe fertilizing irrigation water.

The idea behind the project emerged from applying circular economic thinking on wastewater treatment in residential areas surrounded by farmlands. Here both the water and the nutrients can be reused locally as valuable resources in agricultural production. This raises the question: Why bother removing the nitrogen and phosphorous from water as it is done in normal wastewater treatment, if the water is going to be used for irrigation and these valuable nutrients can be applied directly to the fields with the water. If this is possible, the local wastewater plant can be operated in symbiosis with the agricultural production at the neighboring farms, and the business model of the plant can be turned upside down - from charging money for solving a problem to generating income by providing resources.

The project has the Island of Samsø as test location. Samsø has the ambition of becoming a model island for a circular bio economy, where all biological resources are kept in closed loops, among them the resources in the wastewater. Furthermore, the intensive agricultural production at the Island with high demand of water puts pressure on the fresh water resources, as pumping too hard from the reservoir increases the risk of penetrating salt water into the reservoir.. This water challenge makes Samsø an ideal location for developing a method for the production of nutrient rich irrigation water and as a showcase for export of the solution to farming communities around the world, where water shortage is an even bigger challenge.

The project was conducted from January 2016 until February 2018 at Danish Technological Institute, Aarhus and Samsø Spildevand A/S, Nordby Plant, Samsø.
The following project partners were involved in the project:
Samsø Spildevand,
Minor Change Group,
Danish Technological Institute,
Technical University of Denmark,
Alfa Laval,
CUSS Umwelttechnik,
Air Liquide
AL-2 Teknik

2. Summary

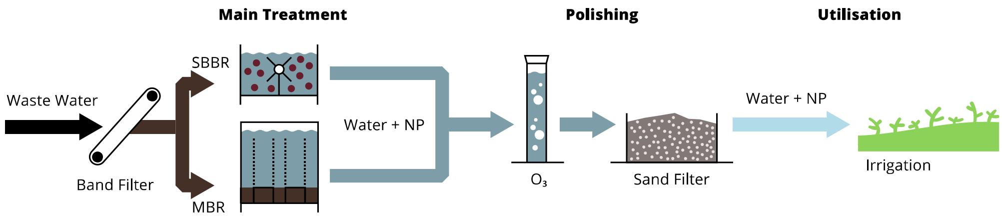
Safe nutrient rich irrigation water

It is possible to produce safe nutrient rich irrigation water from wastewater with existing treatment technologies. That is the conclusion from both trials in laboratory and test runs at Samsø in pilot scale of the proposed approach to wastewater treatment.

2.1 Approach and process

The purpose of the Irrigation symbiosis project was to develop and test wastewater treatment systems, which keep the nutrients nitrogen (N) and phosphorus (P) in the treated water during the summer growth phase, whereas the nutrients are removed from the water during the winter season. In order to obtain a high water quality for safe irrigation of crops, organic xenobiotics and heavy metals have to be removed in the process.

During winter 2016/17 a number of treatment methods were tested at a semi-technical scale at laboratories at Danish Technological Institute (DTI) with synthetic wastewater. For the main treatment, MBR (membrane bioreactor), SBR (sequencing batch reactor) and SBBR (sequencing batch biofilm reactor) were compared - and as polishing steps a reed bed and a modified sand filter coated with iron sludge. During summer 2017 the two best performing main treatment methods (SBBR and MBR) were tested in real conditions at pilot scale on the island of Samsø, with ozonation and a plain sand filter as polishing steps. Furthermore, an irrigation test with the produced water was carried out at a nearby grass field.
The figure below shows the complete pilot test.



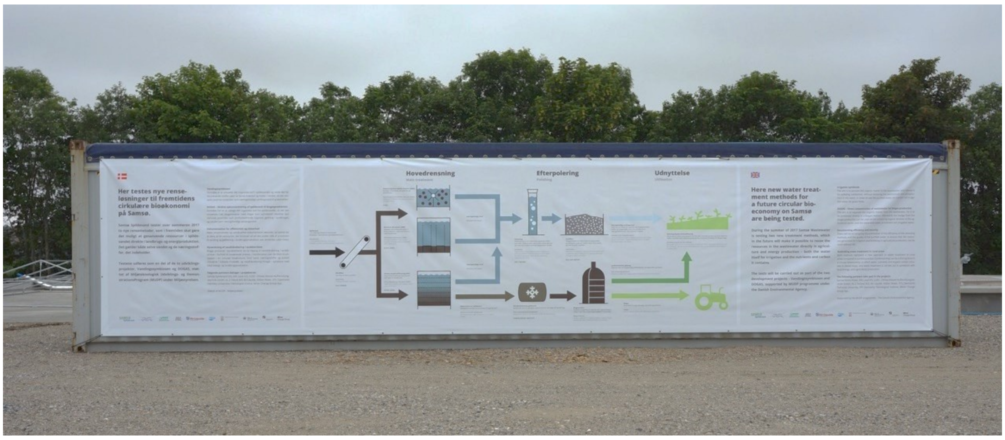
2.2 Results from lab tests

The laboratory tests proved, that it is possible to obtain a high removal of organic matter (COD) without nitrification and hence retain the nitrogen in the treated water. It is also possible to obtain a high degree of P-retention and keep it in its water-soluble form. Regarding removal of heavy metals and organic xenobiotics, SBBR was the best performing method, while SBR was as good at removing organic xenobiotics, but performed worse regarding heavy metals. With the MBR, the opposite was the case.

The polishing steps tested in lab scale proved not to be suitable for producing fertilising irrigation water. The reed bed removed a huge part of the remaining COD after the main treatments but adsorbed part of the retained N and P. The iron particles in the modified sand filter did as expected adsorb the remaining heavy metals, but unfortunately also the retained P. At the pilot scale test at Samsø it was decided to apply ozonation as polishing step for removal of remaining organic xenobiotics and a plain sand filter for withholding eventual remaining heavy metals instead.

2.3 Results from pilot scale test at Samsø

The pilot test run of the MBR and SBBR at Samsø with real wastewater confirmed the results obtained in the lab trials. After some initial operation problems the MBR proved to be the best performing technology with regard to COD removal and retention of N and P in the water fraction. Since the inlet concentrations of heavy metals and organic xenobiotics were very low at the plant at Nordby, the outlet concentration was below the detection level in most cases except nickel and . To show the depollution capacity of the plant in cases of high inlet concentrations of organic xenobiotics and heavy metals , a spiking campaign was carried out, where the concentration of selected heavy metals and organic xenobiotics in the inlet was increased with a factor 10 in relation to average values found in small municipal WWTPs. The results showed an almost complete retention of heavy metals in the sludge except for nickel, that was removed > 60 % and an almost complete removal of organic xenobiotics after both the MBR and the SBBR treatment, that was eliminated completely in the ozonation step.
This means that with normal inlet concentrations nearly no heavy metals were present in the water after the main treatment steps, and only very low doses of organic xenobiotics, which afterwards can be fully removed by ozonation.



The irrigation test was challenged by an extremely rainy summer. Hence it was not possible to detect a growth effect of irrigating the grass field. However it was possible to detect an effect of applying the nutrients with the water, as the grass at the irrigated field strip clearly was darker green.

2.4 Conclusion and perspectives

The Irrigation Symbiosis project has proven, that by running existing treatment technologies without nitrification and with low sludge age, it is possible to produce safe nutrient rich irrigation water with both biological treatment systems SBBR and MBR. With few modifications and improvements, this method can be applied in full scale, which can lead to the formation of symbiosis collaborations between farmers and wastewater companies in urban areas surrounded by farmland. On the Island of Samsø alone, Samsø Spildevand would be able to supply water equal to what is pumped up from the underground for irrigation pr. Year, which is amounts to 200-300.000 m^3.

Several hindrances have to be overcome for it to become a widespread praxis in Denmark though – like unclear and inappropriate legislative framework and mental barriers. Hence on short term the potential for the developed solution lies primarily in countries with more severe water challenges and hence a longer tradition of using treated wastewater for irrigation. Today this is often done without proper treatment and safety precautions. The Irrigation Symbiosis approach can offer an environmentally safe alternative to this praxis in an economically feasible way.

3. Dansk resume

Det er muligt at omdanne spildevand til sikkert næringsholdigt vandingsvand ved at drive eksisterende vandrenseteknologier på en ny måde - uden nitrifikation/dentrifikation og med kort slamalder. Det er konklusionen på forsøg i laboratorium og test i pilotskala på Samsø.

3.1 Formål

Formålet med projektet *Vandingssymbiosen* var at undersøge, om det et muligt at køre eksisterende vandrenseteknologier på en ny måde, så værdifulde næringsstoffer bliver bibeholdt i vandet, men stadig fjerne de problematiske stoffer, så vandet kan genanvendes som næringsholdigt vandingsvand. Svaret fra undersøgelserne og testene gennemført i projektet er et bekræftende ja.

3.2 Baggrund

Ideen til projektet er udsprunget af at lægge et cirkulær økonomisk tankesæt ned over spildevandsrensning i byområder omgivet af landbrugsland. Her vil både selve vandet og nærringsstofferne i spildevandet blive tænkt ind i det lokale ressourcekredsløb som værdifuldt input i landbrugsproduktionen. Det rejser spørgsmålet: Hvorfor bruge kræfter på at fjerne kvælstof og fosfor fra vandet, som det bliver gjort i en normal renseproces, hvis vandet skal bruges til vanding, og næringsstofferne ligeså godt kan føres direkte tilbage til markerne med vandet. Hvis det er muligt, kan lokale spildevandsanlæg blive drevet i symbiose med den omkringliggende landbrugsproduktion, og forretningsmodellen for spildevandsselskaber blive vendt på hovedet fra at være problemløsere til at være ressource-leverandører.

Projektet har haft Samsø som omdrejningspunkt. I tråd med sin profil som grøn ø, har Samsø sat sig for at blive en modelø for en cirkulær bioøkonomi. En økonomi, hvor anvendelsen af de biologiske ressourcer sker i lukkede kredsløb, så de bliver på øen og der kan skabes værdi af dem igen og igen. Det gælder også vandet og de næringsstoffer som transporteres rundt med vandkredsløbene. Vand er en knap ressource på Samsø pga. den store vandingskrævende landbrugsproduktion på øen og risikoen for at trække saltvand ind i grundvandet, hvis der pumpes for hårdt på magasinerne på en ø omgivet af hav. Det gør i en dansk kontekst Samsø til en optimal lokation for udvikling og test af Vandingssymbiose-metoden.

3.3 Projektforløb

Projektet har forløbet i to trin. hhv. udvikling og forsøg i laboratorier på Teknologisk Institut i Aarhus med syntetisk spildevand og test og demonstration i pilotskala på ved Nordby Renseanlæg på Samsø med 'rigtigt' spildevand. Desuden er der blevet foretaget en udredning af anvendelse af renset spildevand til vanding og de lovgivningsmæssige rammer for det på både national, EU og internationalt plan. Endelig blev der foretaget forsøg med vanding af det producerede gødningsvand på en græsmark i nærheden af Nordby Renseanlæg.

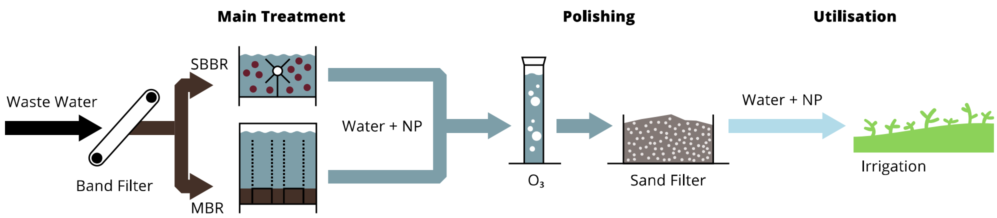
3.3.1 Forsøg i lab-skala på Teknologisk Institut

Lab-forsøgene blev gennemført over vinteren 2016/17. Der blev kørt forsøg med 3 hovedrensemetoder i semi-teknisk skala - hhv. Sequencing Batch Reactor (SBR), Sequencing Batch Biofilm Reactor (SBBR) og en Membrane Bio Reaktor (MBR), hvor der sker en omsætning af det organiske stof (COD) og organiske miljøfremmede stoffer (oMFS'er) og eventulle tungmetaller bliver tilbageholdt i slammet. Efter hovedrenseprocessen blev vandet fra de 3 processer ledt til to efterpoleringstrin – hhv. et rodzone filter og et modificeret sandfilter tilført jernslam, som kan binde tungmetaller. Forsøgene i laboratoriet viste, at det er muligt at omsætte det organiske stof og samtidig beholde en betydelig mængde kvælstof og fosfor i vandet ved at undlade at lave nitrifikation igennem lav slamalder. MBR og SBBR teknologierne viste sig at performe bedst i den henseende. Planterne i rodzonen optog imidlertid efterfølgende en betydelig del af kvælstoffet, og selvom det modificerede sandfilter effektivt fjernede tungmetaller bandt det også en stor mængde fosfor. De viste sig derfor ikke at være egnede som efterpoleringstrin. Hygieniseringen af vandet skete ved en efterfølgende UV behandling af vandet.

3.3.2 Test i pilotskala på Samsø

De to bedst performende hovedrenseteknologier MBR og SBBR blev udvalgt til at blive testet i pilotskala ved Nordby Renseanlæg på Samsø. Inden det rå spildevand blev ledt til hver af disse reaktorer, blev det filtretret for store partikler og fremmedlegemer på et båndfilter. Og som efterpoleringstrin blev der testet to nye metoder. Først blev vandet udsat for ozon for at nedbryde eventuelle rester af organiske miljøfremmede stoffer, hvor der samtidig skete en hygiejnisering af vandet. Derefter blev det ledt gennem et sandfilter, som kunne fange de rester af tungmetaller, som måtte være tilbage i vandet efter hovedrenseprocessen.

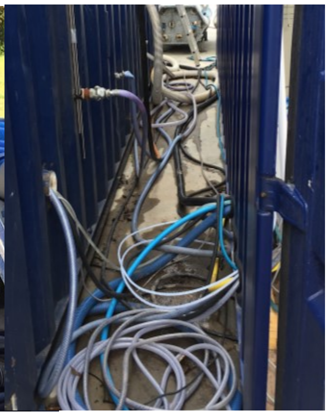
I den grafiske præsentation nedenfor ses den samlede testopstilling i pilotanlægget, som blev installeret i 2 stk.20 fods containere.



3.3.3 Forløb af pilot og analyseprogram

Pilotanlægget ved Nordby Renseanlæg på Samsø var i drift fra midten af maj til midten af september 2017. Først i 'vinterdrift' med nitrifikation som ved normal rensning for at fjerne kvælstoffet, som vil skulle ske når vandet ikke kan bruges til vanding, og derefter i 'sommerdrift' med nitrifikation. Gennem hele testforløbet blev der taget prøver af vandet, som blev analyseret for COD reduktion og fjernelse af organiske miljøfremmede stoffer (oMFS) og tungmetaller – og bevarelse af næringsstoffer (N og P) i vandet. Det blev gjort ved såkaldte koncentrationsprofiler, hvor man følger en portion vand gennem systemet ved at time prøvetagningstidspunkterne efter de estimerede opholdstider ved hvert trin.

Koncentrationen af miljøfremmede stoffer og tungmetaller er ganske lav i det spildevand, der tilflyder Nordby renseanlæg, og for nogle af stofferne lå niveauet efter renseprocessen under detektionsgrænsen. For kviksølv endda også før. For at kunne dokumentere teknologiernes reelle renseeffekt, blev der derfor lavet en spiking-kampagne, hvor der blev sendt vand med 10 gange så høje koncentrationer igennem systemet. Den blev gennemført medio september ad to omgange.
På billederne neden for ses blandetanke mm. anvendt ved spiking-kampagnerne.

3.4 Resultater og observationer fra pilotdriften

Analyseresultaterne for pilot-driften er ganske overbevisende. De bekræfter resultaterne fra laboratorie-forsøgene, at det er muligt at rense spildevand for COD og forurenende stoffer, og samtidig bevare en stor del af næringsstofferne i vandet, så det kan anvendes som gødningsvand. Desuden viste pilotdriften, at det er muligt at skifte mellem vinter og sommerdrift.

Pga. den lave koncentration af oMFS'er og tungmetaller i det 'normale' spildevand, var værdierne for nogle af stofferne ved udløb under detektionsgrænsen, hvorved det var vanskeligt præcist, at fastsætte renseeffekten. De ses ved de store udsving ved disse analyser. Spiking-forsøget viste imidlertid, at der var næsten komplet fjernelse af både oMFS og tungmetaller ved hovedrenseteknologierne. Det betyder, at der ved normale koncentrationer vil være en total fjernelse ved hovedrenseteknologierne – dvs. til under detektionsgrænsen, og dermed også grænseværdierne. Tungmetallerne bliver formodentligt bundet i slammet, ligesom det sker ved normal rensning.

Ozoneringen tager de sidste rester af MFS'er der måtte være tilbage. Men da det er forsvindende små mængder er spørgsmålet om den er nødvendig, og om det er tilstrækkeligt blot at lave en hygiejnisering af vandet med UV behandling.

3.5 Resultater og observationer fra vandingsforsøg

Der blev udpeget et areal udlagt med græs nordvest for Nordby, hvor der blev givet tilladelse til at udføre forsøg med vanding af det producerede gødningsvand. Fra midten af august til og midten af oktober 2017 blev der foretaget vanding med en 10 m^3 gyllevogn med 12 m bom med slæbeslanger – i alt 4 gange med 10.000 liter på et areal på 0,1 ha (1.000 m^2.). Dvs. at arealet er blevet tilført 40 mm. næringsholdigt vand, hovedsagelig produceret med MBR teknologien (90%) . Med et gennemsnitligt indhold af N på 60 mg/l og af P på 7 mg/l, er der blevet tilført de 0,1 ha græsmark 2,4 kg. N (24 kg/ha) og 280 g. P. (2,8 kg/ha). Da vandet blev tilført sent i vækstsæsonen, som tilmed har været meget regnfuld, har effekten ikke været så markant, at det vil være muligt at måle den på indhold af protein og kvælstof i græsset. Effekten af tilførsel af kvælstof er dog visuelt tydelig i form af en mørkere grøn nuance ved det vandede græs. Dette kan ses på højre side på billedet nedenfor.

3.6 Konklusion og perspektiver

Vandingssymbiosen har vist, at det er muligt at køre eksisterende renseteknologier uden nitrifikation og producere sikkert næringsholdigt vandingsvand. Denne metode vil med få modifikationer og forbedringer kunne foldes ud i fuld skala, hvilket kan danne grundlag for dannelse af nye symbiosesamarbejder mellem landbrug og spildevandsselskaber i byområder omgivet af landbrugsjord. Hvis det blev implementeret på Samsø ville det vand som kan produceres f.eks. svare til alt det vand som årligt pumpes op fra grundvandet til vanding på øen – ml. 200 og 300.000 m3.

Det som står i vejen for en udbredelse af et sådant vandingskoncept vil primært være uklarhed om lovgivning på området og mentale barrierer. Særlig i en dansk kontekst, hvor der ikke er tradition for at genanvende spildevandsressourcer findes en fremherskende utryghed ved det. Hvis løsningen skal implementeres på Samsø, vil vandet således kun blive anvendt til dyrkning af græs til bioraffinering og biogas – dvs. ikke til fødevarer og foder, men udelukkende non-food produktion.

Det største potentiale for vandingssymbiose-løsningen vil være i landbrugsområder i udlandet, hvor der pga. store vandudfordringer allerede i dag bliver genanvendt store mængder renset spildevand til vanding, men ofte uden tilstrækkelig rensning og sikkerhed. Der kan derfor forudses her at være et betydeligt eksportpotentiale for Vandingssymbiose-løsningen, som repræsenterer et miljømæssigt sikkert alternativ, som tilmed er økonomisk attraktiv i både etablering og drift.

4. Potential of treated wastewater for field irrigation

In order to be able to produce water suitable for field irrigation, existing legal requirements must be met.

To define quality requirements for water for field irrigation, the applicable legislative documents were reviewed regarding drinking water, wastewater and wastewater sludge in Denmark. The purpose of this review was:

- To clarify the existing permitted framework and preconditions that must be met if the treated wastewater will be used for field irrigation;
- To identify possible essential challenges
- To conclude whether essential challenges exist, and how to work with these challenges, including which public/state institutions must be involved.

4.1.1 Applicable legal requirements in Denmark

In Denmark, there are four applicable national legislative acts supervising the usage of treated wastewater:

- Ministerial order on law on environmental protection (Bekendtgørelse af lov om miljøbeskyttelse (LBK nr. 966 af 23/06/2017)[1])
- Ministerial order on water quality and control of water works (Bekendtgørelse om vandkvalitet og tilsyn med vandforsyningsanlæg (BEK nr. 1147 af 24/10/2017)[2])
- Ministerial order on wastewater permits etc. according to Danish Environmental Protection Law, Article 3 and 4 (Bekendtgørelse om spildevandstilladelser m.v. efter miljøbeskyttelseslovens kapitel 3 og 4 (BEK nr. 726 af 01/06/2016[3]))
- Ministerial order on usage of waste for agricultural purposes (Bekendtgørelse om anvendelse af affald til jordbrugsformål (BEK nr. 843 af 23/06/2017) (Sludge Act - ”Slambekendtgørelsen”)[4]).

The following chapter provides a summary of the review of the above-mentioned legislation. For a more detailed review on the relevant aspects in legislation, please see Appendix 1. For more specific information, please see the individual legislation acts (see footnotes).

Ministerial order on law on environmental protection (Bekendtgørelse af lov om miljøbeskyttelse (LBK nr. 966 af 23/06/2017))

The following conclusions can be made:

- According to Danish environmental protection law, it is not prohibited to use treated wastewater for field irrigation.

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[1] https://www.retsinformation.dk/forms/r0710.aspx?id=192058

[2] https://www.retsinformation.dk/Forms/R0710.aspx?id=194227

[3] https://www.retsinformation.dk/forms/r0710.aspx?id=180360

[4] https://www.retsinformation.dk/Forms/R0710.aspx?id=192143

- The local authority shall issue a license, unless The Minister for Environment and Food of Denmark stipulate other regulations.
- A particular license may be changed or withdrawn later.

Ministerial order regarding water quality and control of waterworks (Bekendtgørelse om vandkvalitet og tilsyn med vandforsyningsanlæg (BEK nr. 1147 af 24/10/2017))

The following conclusions can be made:
Danish Act on drinking water (Drikkevandsbekendtgørelsen[5]) is only applicable if the purpose for using water sets special (drinking water) quality requirements. In other words, it has not been stated in the act that the quality of water for field irrigation must resemble that of drinking water.

Ministerial order regarding wastewater permits etc. according to Danish Environmental Protection Law, article 3 and 4 (Bekendtgørelse om spildevandstilladelser m.v. efter miljøbeskyttelseslovens kapitel 3 og 4 (BEK nr. 726 af 01/06/2016))

The following conclusions can be made:
- The ministerial act is relevant regarding the collection and treatment of wastewater.
- The ministerial act regarding wastewater is only applicable for usage of the treated wastewater if the treated wastewater does not have an agricultural value.
- No definition of" agricultural value" can be found in the ministerial act.
- Danish Nature Agency (Naturstyrelsen) resolves matters of dispute regarding the degree to which treated wastewater has agricultural value.
- Treated wastewater without agricultural value may be discharged on ground surface if the local authority grants a license.

Ministerial order regarding usage of waste for agricultural purposes (sludge act) Bekendtgørelse om anvendelse af affald til jordbrugsformål (slambekendtgørelsen) (BEK nr 843 af 23/06/2017) ("Slambekendtgørelsen")

The following conclusions can be made:
- Industrial process wastewater with agricultural value is subject to this ministerial act, but is not specifically mentioned as "municipal wastewater".
- The ministerial act specifies requirements for sanitization and threshold values of heavy metals and organic xenobiotics both in relation to fertilization value and dry matter.
- The local authority is the institution issuing the license.

4.1.2 Relevant EU legal requirements

At the EU level, Directive 2000/60/EC of the European Parliament and of the Council of 23 October establishing a framework for Community action in the field of water policy is the most important general legislation. This directive establishes a framework for the water policy measures within the European Community.

Conclusions from Directive 2000/60/EC:
- Directive applies to water ecosystems and not agriculture. It must be ensured that the pollution of groundwater is gradually reduced.
- Directive sets requirements for emission controls of point sources based on best available techniques as well as implementation of emission limit values.

[5] https://www.retsinformation.dk/Forms/R0710.aspx?id=194227

- According to the Directive, it is not forbidden to use treated wastewater for field irrigation. On the contrary, the "sustainable water use" should be promoted, but this statement has not been specified in detail.

At EU level, a new Directive is being drafted that will regulate the minimum requirements for water quality for reuse in agriculture (Development of minimum quality requirements at EU level for water reuse in agricultural irrigation and aquifer recharge). The directive is being drafted, and it is not yet announced, when the directive is expected to be implemented.

Recently (on 10 May 2017) a public consultation analysis report prepared for the European Commission - "Policy options to set minimum quality requirements for reused water in the EU - analysis of open public consultation"[6] was published. The report summarizes the perception of different countries on both safety of reused water as well as specific aspects to be covered by EU minimum quality requirements on a very general level.

4.1.3 Reuse potential of treated wastewater in Denmark

According to the reviewed legislation, it may be concluded that treated wastewater can be used as field irrigation water in Denmark upon the permission by Danish Nature Agency and local authority. First, the Nature Agency must consider whether the treated wastewater has an agricultural value. If this is the case, the threshold values specified in Sludge ministerial act may be applied, and the local authority can give a permit.

4.2 Wastewater composition in small municipal WWTPs

The aim is to provide an overview of the composition of wastewater in small municipal wastewater treatment plants (plant < 5,000 PE) regarding the content of nutrients, nitrogen and phosphorus as well as organic xenobiotics and heavy metals, which is an integral part of the sludge act (Slambekendtgørelsen).

4.2.1 Typical composition of household wastewater according to literature

Table 1 below shows a typical content of nutrient salts, organic xenobiotics and heavy metals in household wastewater (translated excerpt from: *Teoretisk Spildevandsrensning*, Henze et al. 2006)[7]. Here Henze has made a classification of the wastewater for all parameters in thick, moderate, thin and very thin.

Table 1. Typical composition of municipal wastewater

	Unit	Wastewater type			
		Thick	Moderate	Thin	Very thin
Nutrient salts					
Total nitrogen (T-N)	mg/l	80	50	30	20
Total phosphorus (T-P)	mg/l	14	10	6	4
Organic Xenobiotics					

[6] http://ec.europa.eu/environment/water/pdf/WaterReuse2ndConsultation-Report-and-Annex-COM.pdf

[7] Teoretisk Spildevandsrensning – biologiske og kemiske processer, Mogens Henze, Poul Harremoës, Jes la Cour Jansen, Erik Arvin, Polyteknisk Forlag, 3. udgave 2006, ISBN 87-502-0942-6

Linear alkylbenzene sulfonate (LAS)	µg/l	15,000	10,000	6,000	4,000
Polycyclic aromatic hydrocarbons (PAH)	µg/l	2.5	1.5	0.5	0.2
Nonylphenol ethox-ylates (NPE)	µg/l	80	50	30	10
Bis(2-ethylhexyl)phthalate (DEHP)	µg/l	300	200	150	70
Heavy metals					
Cadmium (Cd)	µg/l	4	2	2	1
Mercury (Hg)	µg/l	3	2	1	1
Lead (Pb)	µg/l	80	65	30	25
Nickel (Ni)	µg/l	40	25	15	10
Chromium (Cr)	µg/l	40	25	15	10
Zinc (Zn)	µg/l	300	200	130	80
Copper (Cu)	µg/l	100	70	40	30

4.2.2 Actual composition of wastewater from small and medium-sized municipalities

The available analysis data for inlet water to wastewater treatment plants (WWTPs) originates from a database extract (database PULS, Danish Natural Environment Portal) for a period from 2011 to 2014, which the Danish Environmental Protection Agency made available during the first stage of this project, where this test was carried out. The interpretation of data on organic xenobiotics and heavy metals must be done with great caution, as the data foundation is small. The database is still relatively new, and far from all plants has performed analysis on organic xenobiotics and heavy metals, which is why only a few analyses are available per parameter. However, it is possible to see a certain tendency.

The project focuses on the organic xenobiotics and heavy metals, which are within the scope of the sludge ministerial act. 14 Danish WWTPs < 5.000 PE could be identified, which have carried out sampling/analyses of nutrients and some of the organic xenobiotics and heavy metals. The data for these plants create a foundation for this assessment. It is possible that the industrial wastewater is added to some of these plants. However, it was not possible to acquire information about the percentage share. The following 14 WWTPs were mentioned: Agersø, Alstrup, Bogø (Lodskerne Vest), Langø, Løjt (Brøde) Centralrenseanlæg, Morild, Odden Havneby, Råbylille Strand, Sandby, Svaneke, Thorup, Ulstrup, Øster Skørringe and Årestrup.

The tables below show an overview of the available materials for mentioned 14 WWTPs together with measurements for a period of 5 months (test period) at Nordby WWTP on Samsø:

Nutrients

Nutrient salts have been shown as average values for Total-N (nitrogen) and Total-P (phosphorus) in the following Table 2. The standard deviation has been indicated in brackets after the value.

Table 2. Average nutrient salt concentration in small municipal WWTPs

	Total-N [mg/l]	Total-P [mg/l]
Average 14 plants < 5000 PE	46 (20)	7.9 (3.1)
Nordby (Samsø)	83 (25)	9.6 (2.8)

The Total-N level at Nordby WWTP is thick, while the average level of small WWTPs and is classified moderate. Total-P content is classified between thin and moderate both in Nordby WWTP and the average of the inlet water in all small WWTPs.

Organic xenobiotics

Standard deviation has been indicated in brackets after the value. As mentioned above, there is mainly a great variation in data for organic xenobiotics and heavy metals in the PULS database. The data material is not quite large yet, and variations on individual measurement days have a significant influence on the average value, and thus result in a very high standard deviation. Inlet values for Nordby WWTP are based on 4 measurements divided across a period from May to October 2017.

Table 3. Average concentration of organic xenobiotics in small municipal WWTPs

	LAS (Linear alkylbenzene sulfonate) [µg/l]	Σ PAH (Polycyclic aromatic hydrocarbons) (11 substances) [µg/l]	Σ NPE (Nonylphenol ethoxylates) [µg/l]	DEHP (Di(2-ethylhexyl)phthalate) [µg/l]
Average 14 plant < 5000 PE	2757 (2031)	0.3 (0.3)	2.8 (2.6)	14.4 (10.7)
Nordby (Samsø)	2725 (263)	0.6 (1.0)	1.6 (1.2)	3.5 (2.4)

The average wastewater for all 14 plants < 5000 PE is classified according to Henze[8] in relation to organic xenobiotics as very thin, except PAH, which is between very thin and thin. The same may be attributed to inlet water from Nordby, but PAH here was slightly higher, which is due to the rather high concentration of Indenopyrene in one of the 4 samplings, while it was not detected in other three samplings.

Heavy Metals

The following Table 4 shows the average concentration of heavy metals in the influent of small WWTPs

Table 4. Average concentration of heavy metals in small municipal WWTPs

	Cadmium [ng/l]	Quicksilver [ng/l]	Lead [µg/l]	Nickel [µg/l]	Chrome [µg/l]	Zinc [µg/l]	Copper [µg/l]
Average 14 plants < 5000 PE	178 (168)	85 (106)	7 (7)	6 (3)	5 (3)	145 (95)	42 (26)
Nordby (Samsø)	186 (157)	21 (41)	3 (2)	7 (4)	4 (3)	169 (168)	36 (38)

The average wastewater from 14 WWTPs < 5000 PE is classified in relation to heavy metals as very thin, except copper (thin) and zinc (between thin and moderate). The same is valid for inlet water in Nordby.

4.2.3 Conclusions on Nordby wastewater composition

Nordby wastewater is generally comparable to the average indicators of wastewater received by the small Danish WWTPs < 5.000 PE.

However, the content of nitrogen is higher and is classified as thick wastewater according to literature. Thus, there is an even higher potential in keeping nutrients in water in order to use it as nutrient-rich field irrigation water.

The impact of organic organic xenobiotics in Nordby was small in all 4 analyses over a period of 4 months. The impact of heavy metals was also very small and corresponds to the average impact of small WWTPs.

Low COD can also been explained due to low flow generating a long residence time in sewer. High ammonia is somewhat unusual for a pure municipal water

5. Laboratory tests

The laboratory tests were to identify and optimize the different treatment technologies with respect to their treatment efficiency towards COD, organic xenobiotics and heavy metals while maintaining nitrogen and phosphorous. Based on the results from laboratory tests it was decided, which techniques were applied in the demonstration phase at Samsø.

5.1 Wastewater treatment technologies - setup

The following main treatment and polishing techniques were chosen for the test phase at Danish Technological Institute:

Main treatment techniques:
- SBR (sequencing batch reactor)
- SBBR (sequencing batch biofilm reactor)
- MBR (membrane bioreactor)

Polishing techniques:
- Reed bed
- Sandfilter (modified)
- UV

The selection of primary treatment techniques was based on both experiences from previous projects- the biofilm present in the SBBR, showed in the MERMISS project very efficient degradation rates of pharmaceuticals and was included here due to these results. Also, techniques as SBR and MBR are widespread and cost efficient solutions but are not commonly used in Denmark.

Establishing of reed beds are a widely-used technique in areas with low population density. In addition, a modified sand filter with added iron sludge was chosen for polishing. UV treatment was established for hygienization.

The two figures on the following page show the laboratory setup:

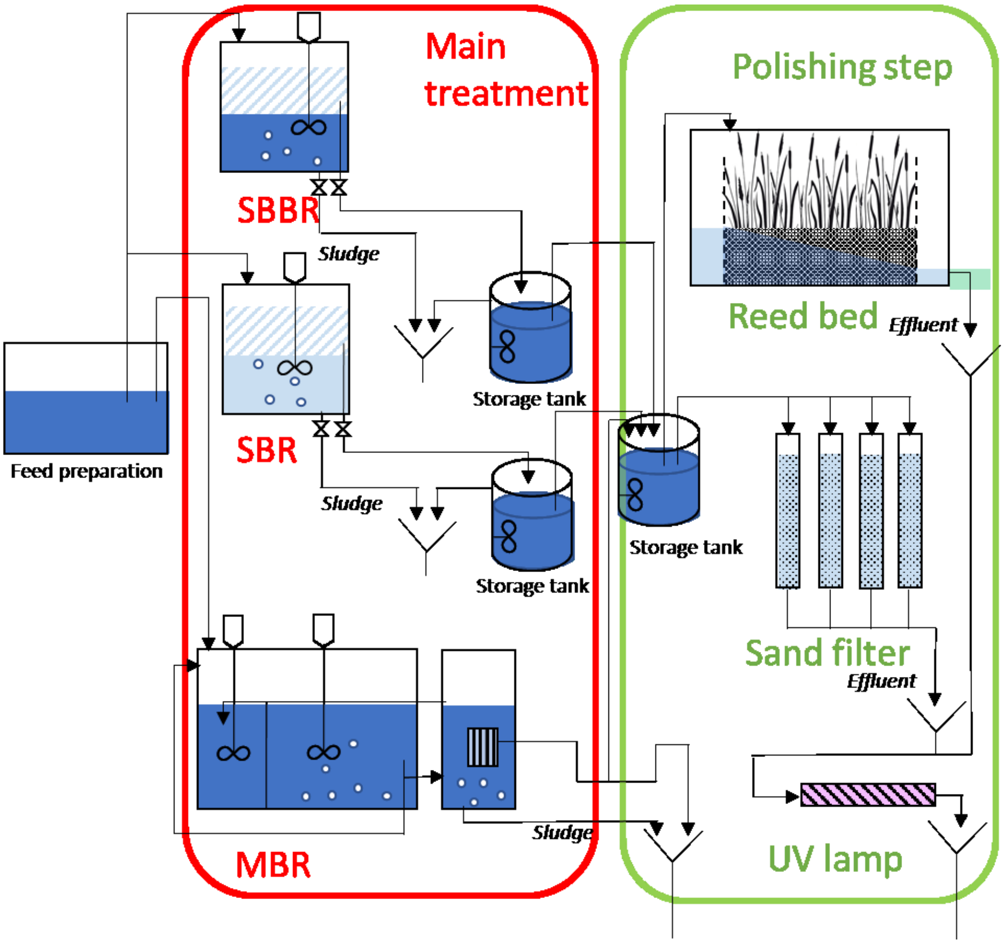

Figure 1. Flow diagram of the laboratory setup

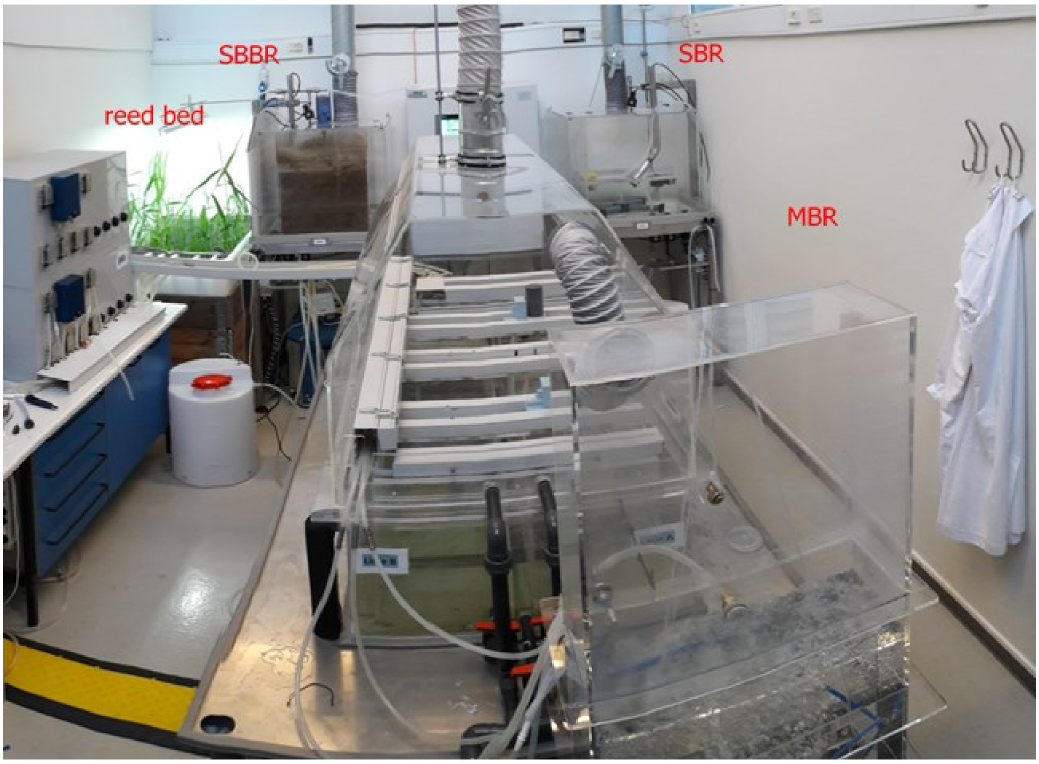

Figure 2. Laboratory setup

Synthetic wastewater and analyses

The synthetic wastewater used in all treatments was prepared following a recipe from the OECD guideline[8], modified to the nitrogen, phosphorous and COD levels, corresponding to the wastewater at Nordby/Samsø. The wastewater had the following composition:

Table 5. Composition of synthetic wastewater

	mg/l
Tryptone	124
Meat extract	123
Urea	84
di-potassium hydrogen phosphate	39
Magnesium sulphate heptahydrate	2.8
Calcium chloride dihydrate	5.0
NaCl (Salina Salt)	9.0

All chemicals were purchased at VWR Chemicals besides Urea (Merck) and natrium chloride (Salina salt).

The standard wastewater analyses (COD, T-N, NH_4-$N_{filtered}$, NO_3-$N_{filtered}$, NO_2-$N_{filtered}$, T-P, PO_4-P) were performed on a regular basis using Hach Lange cuvette tests.

Selected heavy metals and organic xenobiotics were added according the identified concentrations for small WWTPs in the PULS database (see Table 3 and Table 4). An external laboratory analyzed the heavy metals and organic xenobiotics.

5.1.1 Removal of organic xenobiotics – methods for the testing

The removal of organic xenobiotic compounds and heavy metals from treated wastewater was tested in two different setups:

- The concentration profile experiments document the actual removal of the analyzed compounds in the system at a certain time. In a concentration profile, a portion of water is followed through the plant. The sampling was performed according to the designed hydraulic retention time (HRT) of the system.
- The spiking experiments show the overall potential of the system to remove organic xenobiotics. Spiking profiles were performed the same way as concentration profiles, but with the inlet water spiked with the compounds of interest (performed in pilot scale only)

[8] OECD. (22. Jan 2001). Test No. 303: Simulation Test - Aerobic Sewage Treatment -- A: Activated Sludge Units; B: Biofilms., downloaded 20. Dec. 2016 at http://www.oecd-ilibrary.org/: http://www.oecdilibrary.org/environment/test-no-303-simulation-test-aerobic-sewage-treatment-a-activatedsludge-units-b-biofilms_9789264070424-en

5.1.2 Main treatment technologies – setup

5.1.2.1 SBR and SBBR

A sequencing batch reactor (SBR) is functioning as a conventional activated sludge treatment plant, but all processes are carried out in the same tank as opposed to e.g. activated sludge. The wastewater is supplied batch wise and undergoes a cycle of treatment processes operated by variation of stirring and oxygen. By altering these parameters, the optimal conditions for biological removal of organic carbon and nitrogen is created. During the settling phase, excess sludge is removed and the treated water is released (see Figure 3).Comparing to the conventional activated sludge treatment, less space is required and no resources are spent on establishing or operation of a settling tank or recirculation of sludge. On the other hand, the batch wise treatment of wastewater requires a buffer tank for inlet wastewater or alternating operation of the SBR.

The plant configuration and operation of a sequencing batch biofilm reactor (SBBR) resembles that of SBR in many ways. The difference between these techniques is how the biomass growths and is regulated in the reactor. While the biological conversion in an SBR is by activated sludge, which is mixed with the wastewater, plastic carriers with a biofilm is used instead in the SBBR. The plastic carriers have a large protected surface volume which favors biofilm formation and provides optimal conditions for the slow growing bacteria.
In the SBR, the bacterial composition and thereby the treatment efficiency is regulated by the sludge retention time, which is not the case in SBBR. This technique provides the opportunity to treat more specifically due to the biofilm established e.g. organic xenobiotics.

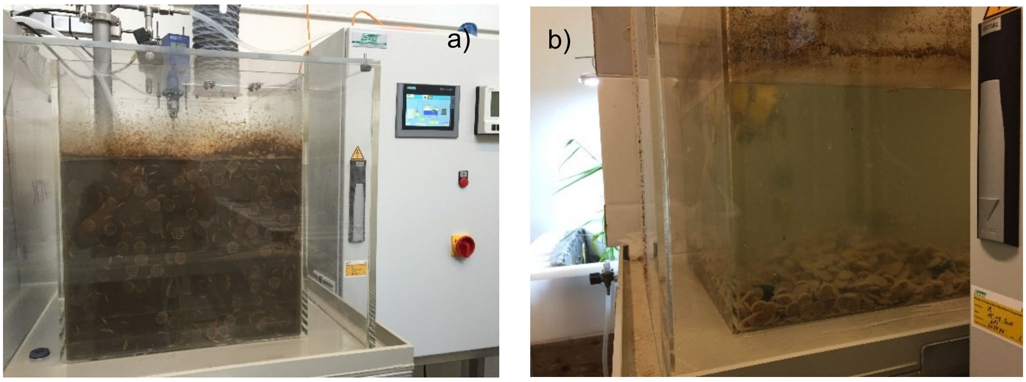

Figure 3. SBBR in aerated phase (a) and settling phase (b)

The SBR and SBBR acrylic tanks had a filling volume of 100 l and a batch cycle duration of 6 hours. The volume of water exchanged per batch and the volume of used carriers in the SBBR was modified during the test period, until an optimum operation was achieved (SBR: 31 l/batch = flow 5.2 l/h, batch period 6 hours, sludge age: 5 days, SBBR: 50 l/batch =flow 8.3 l/h, batch period 6 hours, 8.6 liter carriers). The active sludge for inoculation was collected from the aeration tank of Åby Renseanlæg, while the carriers used in the SBBR, type K5 from Anox Kaldnes with a protected surface area of 800 m^2/m^3 came from Mølleåværket/Lyngby-Taarbæk Forsyning.

The pH values in the tanks were in the range 7.1 to 8.2, while the dissolved oxygen concentration in the aerated phases was set between 6 and 8 mg/l to secure sufficient oxygen supply. The stirring in the SBR was achieved with the aeration alone, while a stirrer was used in the SBBR to ensure all carriers moving. The temperature range in the tanks was 11 – 15 °C. It was difficult to prevent varying suspended sludge concentrations (0.2 to 1 g/l in SBBR and 0.6 to 2.1 g/l in SBR) due to tubing. The main parameters for optimization were variation of the load of the plants as well as the sludge age.

5.1.2.2 MBR

The membrane bioreactor technology (MBR) combines treatment with membrane technology in a single tank. The wastewater is led to the tank, where the activated sludge is responsible for the biological conversion before the water is led through a submerged membrane, which holds back particles and sludge. The process is operated in a mode, where the membrane regularly have a break (are relaxed) for particles attaching to the surface being released by aeration.

MBR has the clear advantage that the process can operate at very high sludge concentrations compared to other sludge based technologies, and there is no need for a subsequent settling tank. As the amount of sludge is decisive for the biological activity, it is possible to obtain a very efficient biological treatment, which compared to SBR and SBBR, requires much less space and therefore economical feasible when establishing reactor tanks. However the membrane can be expensive to purchase and operate, as they require regular cleanings to ensure a functioning membrane without sludge and precipitates, and thereby maintain a stable operation.

The MBR acrylic tank had a filling volume between 80 and 100 l and a flow between 4.2 og 6.3 l/h driven by gravitation alone. The volume and flow variation was caused by increasing membrane fouling over time. The membrane was not cleaned in the operation period of 8 weeks, but extended relaxation periods ensured recovery of the membrane flux. In normal operation, the membrane relaxation time was 2 minutes after 10 minutes of operation to keep the membrane as clean as possible. The membrane was a microfiltration membrane type PVDF, with pore size of 0,2 µm. the sludge was removed on a regular basis to maintain a suspended solid concentration of around 2 g/l. The inoculation sludge was identical to the one in SBR from the aeration tank of Åby Renseanlæg.

The pH values were in the range 7.1 to 8.6, while the dissolved oxygen was above 5 mg/l always, guaranteeing enough oxygen supply for optimal bacterial growth. The stirring in the tank was ensured by aeration that was placed on the bottom of the membrane module (see

The temperature range in the MBR tank was 14 °C to 18 °C, slightly higher than in the SBR or SBBR due to the aeration pump, that caused a slight warm-up of the tank volume. It was evaluated, that this minor temperature difference of 3 °C between the different treatment methods was not critical for the comparison of the methods.

Figure 4. MBR tank normal filling height (tap water only to show the membrane module)

5.1.2.3 Regulation of biological treatment

The development of the different treatment technologies has been focusing on modifying process design and operational parameters to obtain optimal removal of relevant organic xenobiotics. In total, three pilot scale plants were developed and it was possible to vary different operational parameters e.g. variation in loading of organic xenobiotics in the plants.

Common for the biological treatment processes is, that the quantity of bacteria (sludge) determines the efficiency of the biological conversion, while the sludge age determines the different bacterial functional groups (e.g. presence of nitrifiers, denitrifiers). The sludge age reflects the average retention time for the bacteria in the tank. A relatively long sludge age is necessary to ensure that slow growing organisms e.g. nitrifiers, are present in the sludge. The sludge age must be longer than the doubling time of the nitrifiers at a given temperature for the nitrification to take place. By regulating the amount of sludge that is removed from the system, it is possible to select for certain microorganisms and thereby control which compounds are being removed.

Common for the biological treatment processes is that the quantity of bacteria (sludge) determines the efficiency of the biological conversion, while the sludge age determines the different bacterial functional groups (e.g. presence of nitrifiers, denitrifiers). The sludge age reflects the average retention time for the bacteria in the tank. A relatively long sludge age is necessary to ensure that slow growing organisms e.g. nitrifiers, are present in the sludge. The sludge age must be longer than the doubling time of the nitrifiers at a given temperature for the nitrification to take place. By regulating the amount of sludge that is removed from the system, it is possible to select for certain microorganisms and thereby control which compounds are being removed.

During the summer months when the water will be used as nutrient rich irrigation water the nutrients (nitrogen and phosphorous) should be maintained in the water, and nitrification and biological phosphorous should be avoided. Keeping a low sludge age while maintaining a high organic loading rate, can minimize the conversion of ammonia to gaseous nitrogen. During these conditions, the heterotrophic bacteria will have optimal growth conditions and thereby outcompete the autotrophic nitrifiers.

However, during the autumn and winter months, the treated water will be discharged to the recipient. The operational parameters will have to fit the biological processes that should take place; favoring the nitrifiers by altering the sludge age and the periodical oxygen free periods will promote denitrifiers, so that nitrogen is removed from the water. Phosphorous removal will be carried out by chemical addition.

5.1.3 Polishing technologies – setup

5.1.3.1 Reed bed

The reed bed was established in a polyethylene container (V= 650 l) with pieces of the original reed bed from Nordby WWTP. The inlet water (mixed water from MBR, SBR and SBBR outlet, 5 l/h) was supplied with a perforated pipe on top of the reed bed to ensure, that the water passed the reed bed instead of passing by in the small gaps on the sides and in-between the reed bed pieces (**Figure 5**b). The plants were illuminated with a plant lamp all day long.

Figure 5. Reed bed with watering system

5.1.3.2 Modified sand filter

The drinking water in Denmark is primarily based on extraction of ground water. Treatment of ground water for drinking water takes places at the water works, where naturally occurring compounds as ammonia, nitrite, manganese, methane etc. are removed by simple processes as aeration and filtration through sand filters

Removal of naturally occurring iron and manganese in sand filters happens through oxidation and insoluble products are formed. These settle as an iron/manganese sludge layer on top of the sand filters (see Figure 6).

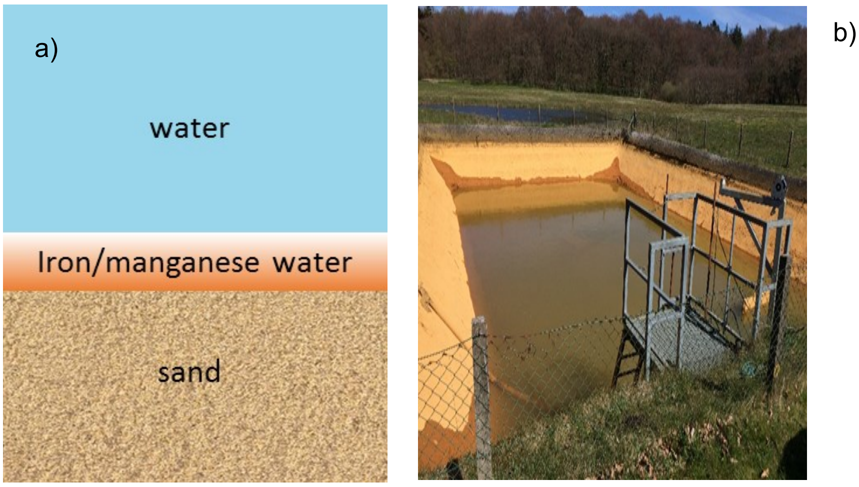

Figure 6. Settling of iron and manganese sludge after groundwater oxidation (a) and a basin with iron sludge from a Danish water work (b).

Settled iron/manganese sludge is washed out from the sand filters and must be handled as waste, resulting in additional expenses. On yearly basis, this waste sludge amounts to more than 200 tons of iron sludge and 20 tons of manganese sludge.

Binding capacity of heavy metals using the iron sludge

Removal of heavy metals from the water environment has for many decades been of focus. Among the different methods, adsorption technologies are considered the most efficient for removal of heavy metals in water. Both Fe- and Mn- oxides and hydroxides are preferred due to their high active surface area and their ability to bind different heavy metals at the same time[9,10,11].The relevant heavy metals Cu, Ni, Zn, Pb, Cd are adsorbed to iron and manganese, which are listed in legislation[12]. These heavy metals are often occurring in household wastewater and have to be reduced beyond the limit values.

Table 6. Limit values for heavy metals according Danish Statutory Order on Sludge

	mg/kg dry matter	mg/kg dry matter
Cadmium	0.8	100
Mercury	0.8	200
Lead	120	10,000
Nickel	30	2,500
Chromium	100	-
Zinc	4,000	-
Copper	1,000	-

A laboratory setup was designed for testing potential use of iron- and manganese sludge for that purpose (see figure 7) Laboratory microcosms filled with iron sludge-coated sand (two duplicates with 30 % resulting in 7 cm high coated sand layer in the upper layer or 100 % coated sand 25 cm high respective-ly) were established and operated for 6 weeks with a constant flow of 100 ml/h using the mixed outlet water from MBR, SBBR and SBR. After that period, sampling was per-formed and analyzed for the reduction of cop-per.

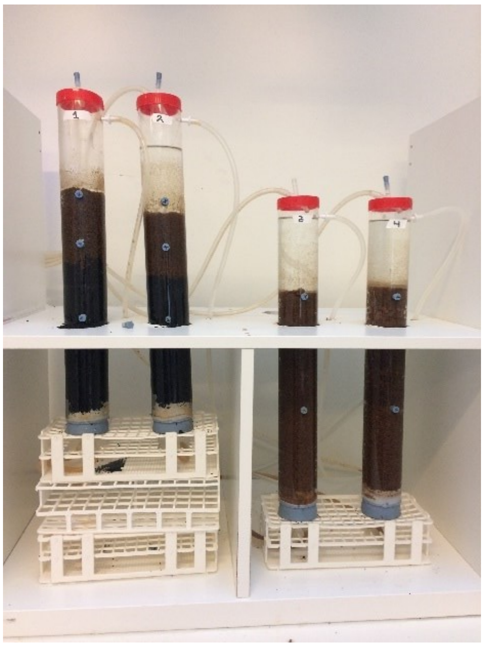

Figure 7. Laboratory setup of modified sand filters with iron-sludge coated sand.

5.1.3.3 UV

The UV treatment was chosen as a final polishing step to eliminate the potential risk from living bacteria as this technique is widely used and its effectiveness is well documented. The outlet water from reed bed and sand filters were combined, resulting in a total flow of 5,4 l/h and lead through an aquarium UV lamp (Eheim, Type 3721210, lamp type PL 7W UV-C G23) for disinfection.

9 Syed M et al, 2013 Adsorption of heavy metal ions in ternary systems onto Fe(OH)3. Korean J. Chem. Eng., 30(12), 2235-2240 (2013)

10 Zhi-liang et al 2007, Removal of cadmium using MnO2 loaded D301 resin, Journal of Environmental Sciences, Volume 19, Issue 6, 2007, P 652-656

11 Rout et al. 2009: Pb(II), Cd(II) and Zn(II) adsorption on low grade manganese ore. International Journal of Engineering, Science and Technology Vol. 1, No. 1, 2009, pp. 106-122

12 BEK nr. 843 af 23/06/2017, https://www.retsinformation.dk/Forms/R0710.aspx?id=192143

5.2 Results

In the laboratory phase of the project, the summer scenario was operated so that nitrogen and phosphorous were maintained in the water. The performance was evaluated using the common wastewater parameters as COD, total nitrogen, total phosphorus, ammonia, nitrate and nitrite. To document the removal of heavy metals and organic xenobiotics, a profile sampling was conducted; by following a portion of water through the plant. The sampling was performed according to the designed hydraulic retention time (HTR) of the system and measured changes in concentration of the selected parameters.

5.2.1 Common wastewater parameters

The common wastewater parameters were measured on a regular basis and are shown in the following figures. Figures 8 – 10 show results for the biological treatments, while figures 11 – 13 show results for the polishing steps.

Biological treatments

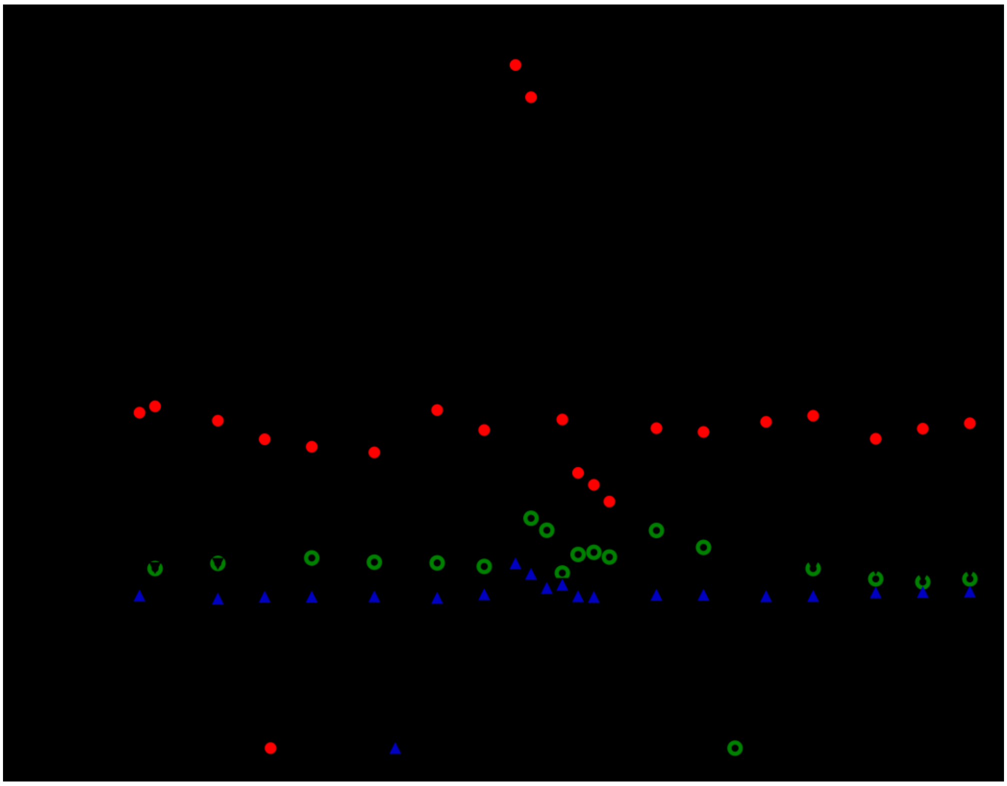

Figure 8. COD in the inlet and the outlet of the three main treatments. The dotted line indicates a change of load of the SBBR

Figure 9 shows the COD in the inlet and outlet of the different biological treatments. All treatments showed a very effective removal of the COD, and the MBR performed slightly better than SBR and SBBR. Even during peak load (three times higher than normal) all biological treatments, reduced the COD content to low levels. The load in the SBBR was increased on November 16th (flow 200 %, removal of 60 % of the carriers), as there was nitrification occurring. After that, the COD reduction in the SBBR was as effective as in the SBR.

Figure 9 shows the retention of nitrogen in the water after the biological treatment steps.

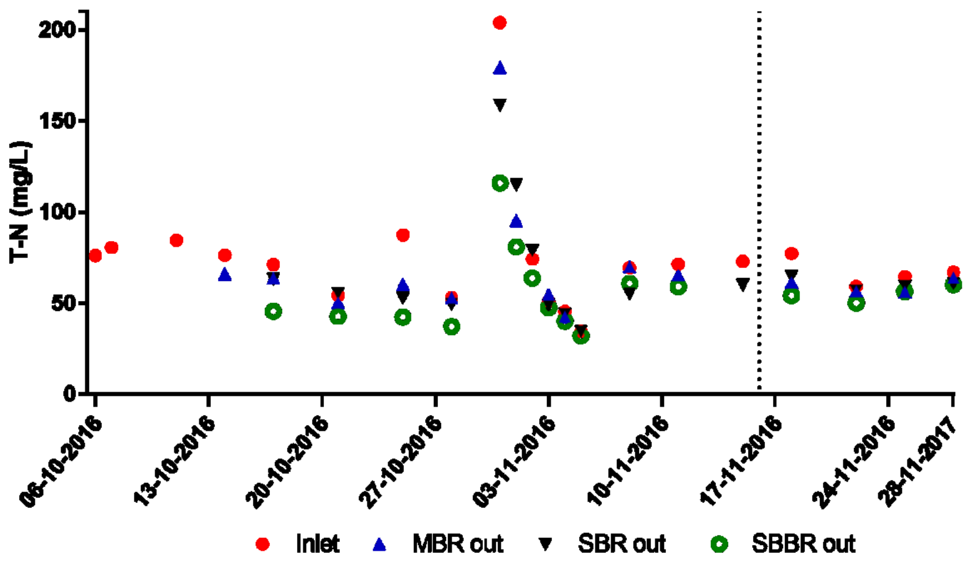

Figure 9. Total nitrogen in the inlet and the outlet samples of the three main biological treatments. The dotted line indicates a change of load in the SBBR.

The nitrogen was kept in the systems very effectively with at least 80 % retention, when the systems were optimized. Even during peak load, the nitrogen was maintained effectively in the three treatments, MBR performing best, but also with good results for SBR an SBBR. The increased loading in the SBBR (dotted line with higher flow and less carriers) did not influence the ability to keep the nitrogen in the water. The regulation of nitrification was not easy in the laboratory setup, resulting in the major part of the nitrogen being nitrate, while ammonia would be more desirable, as plants easily can assimilate ammonia. However, proof-of-concept was obtained.

Figure 10 shows the retention of phosphorous in the biological main treatments.

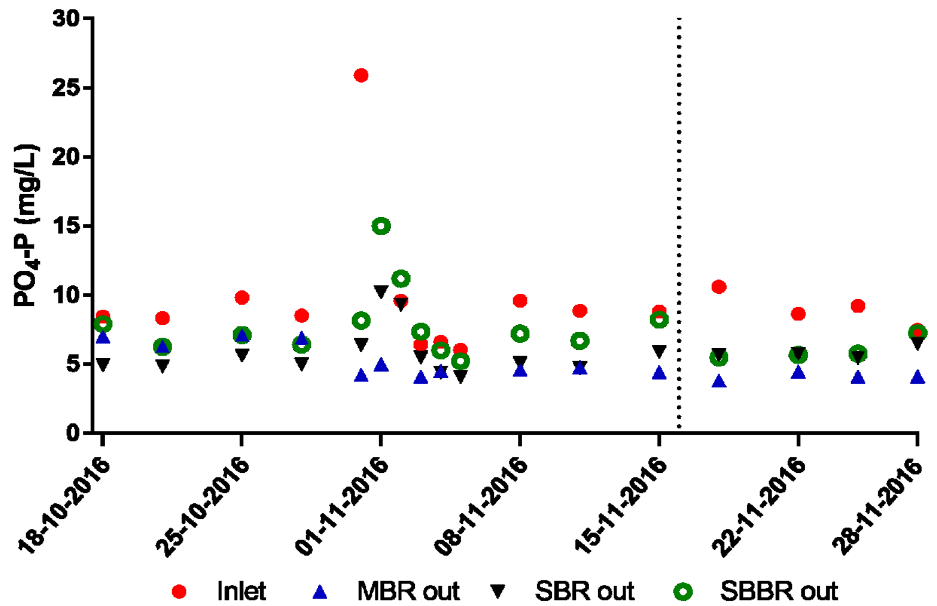

Figure 10. Phosphorous in the inlet and the outlet of the three main treatments. The dotted line indicates a change of load in the SBBR

The phosphorous retention was above 50 %. In most cases, the retention was better in the SBR and SBBR than in the MBR. The increase of the load in the SBBR again did not influence the phosphorous retention.

Polishing steps

The COD reduction in the polishing steps is shown in the following

Figure 11. The tested technologies included the reed bed and iron-sludge coated sand was added to the sand filter.

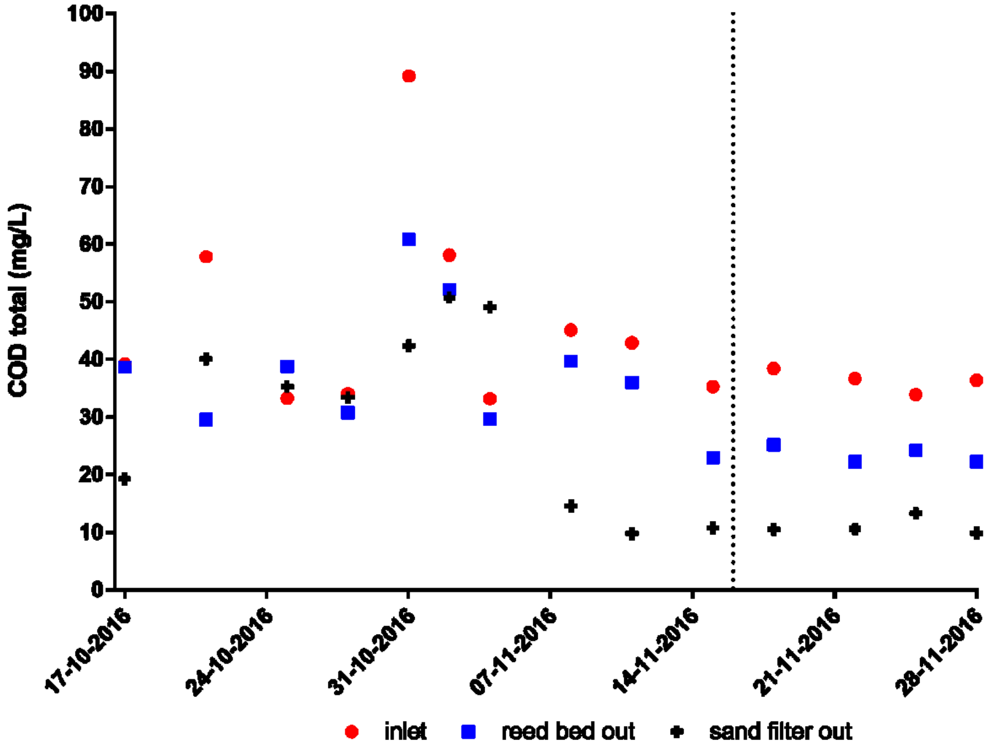

Figure 11. COD removal of the remaining COD in the polishing steps

The remaining COD from the biological treatments (mixed water from the three outlets) was treated in the reed bed or the sand filter. The reed bed showed the best removal ability of the two systems. Both polishing techniques reduced the remaining COD to a very low level.

Figure 12 shows the total nitrogen retention in the polishing steps.

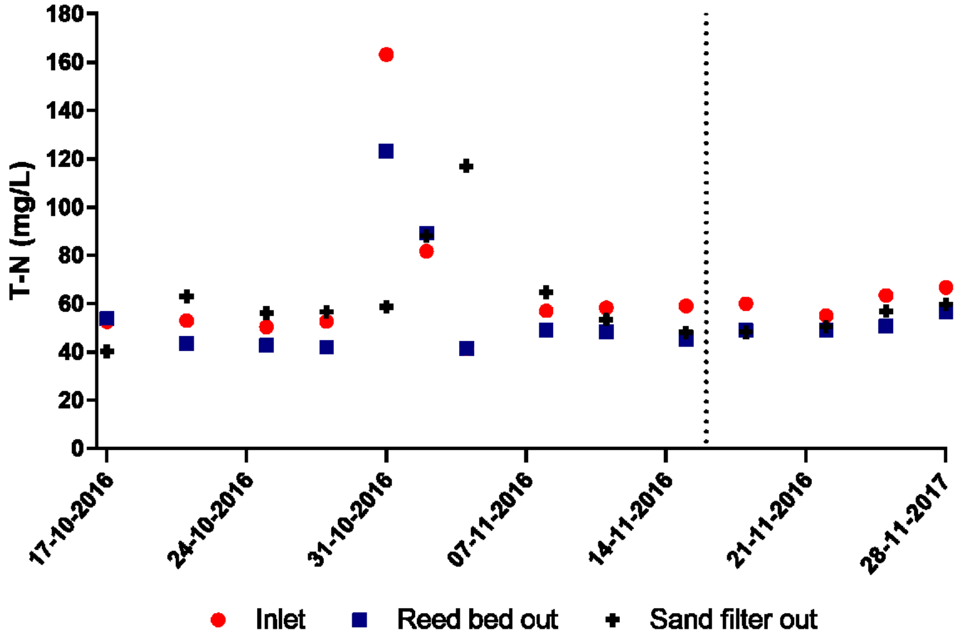

Figure 12. Total nitrogen in the inlet and the outlet of the polishing steps

The nitrogen concentration in the outlet samples of both polishing methods was close to the inlet concentration and stable performance was obtained. In some cases, the outlet concentration was slightly higher than the inlet concentration, which shows the uncertainty of the sampling and analysis methods.

Figure 13 shows the phosphorous retention in the polishing steps.

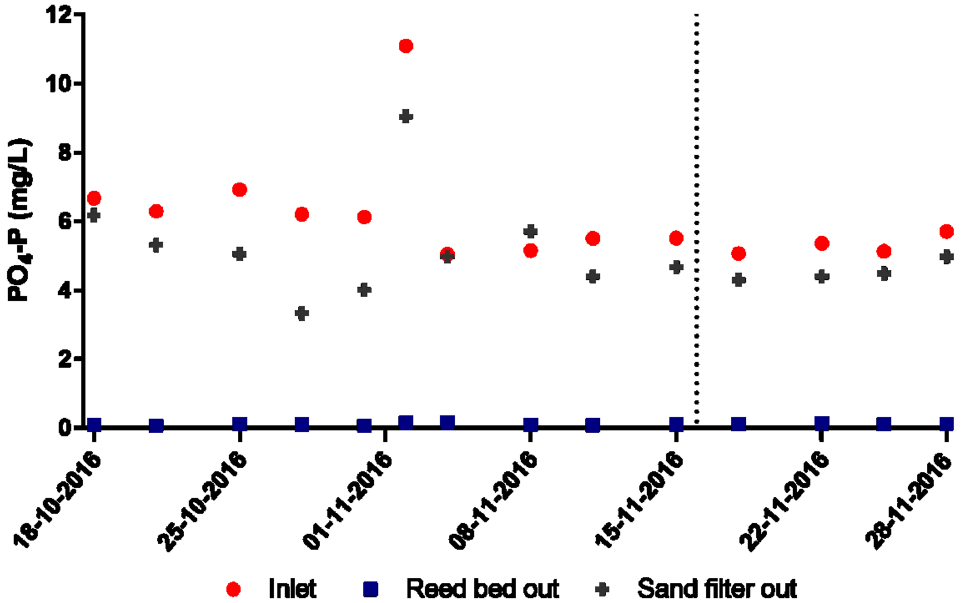

Figure 13. Phosphorous retention in the wastewater

The phosphorous retention in the outlet water from the reed bed was very good, while all phosphorous was bound in the sand filter. In summer scenario, the modified sand filter is not suitable due to the removal of phosphorous from the water.

5.2.2 Removal of organic xenobiotics

The removal of xenobiotic organic compounds and heavy metals from treated wastewater is crucial before reusing the water for field irrigation. The removal was tested in a profile sampling of the biological main treatment steps. The concentration profile experiments show the actual removal of the analyzed compounds in the system at a certain time, according to the HRT of the system.

Biological treatment

In Figure 14 and Figure 15 the removal of selected organic xenobiotics and heavy metals is shown. The substances were selected corresponding to the Danish Statutory Order on Sludge apart from DEP, which was used instead of DEHP. DEHP is water insoluble and therefore very difficult to add, sample and analyze, as it tends to stick to surfaces. It was decided to add DEP instead, so that the results should be more reliable.

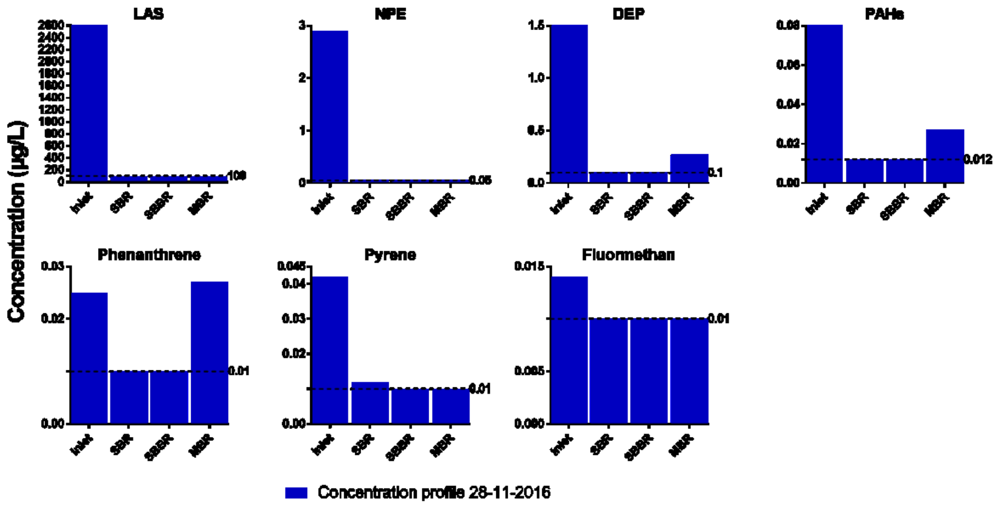

Figure 14. Reduction of organic xenobiotics in the biological main treatments. The dotted lines mark the detection limit of the analysis

Data for mercury are not available, as the concentration was below detection limit in the inlet. The organic xenobiotics analyzed were removed effectively in the main biological treatment steps. No removal of phenanthrene in the MBR was observed, as similar levels in outlet samples were detected. In the case of fluoromethane, the inlet concentration was only slightly above the detection limit. In the outlet of all biological treatments, the concentration was below the detection limit.

The removal of the selected heavy metals is shown in Figure 15. The heavy metals were removed at least 50 % in all cases in the water fraction except for copper in the MBR and nickel, which only was removed slightly in the SBR and SBBR.

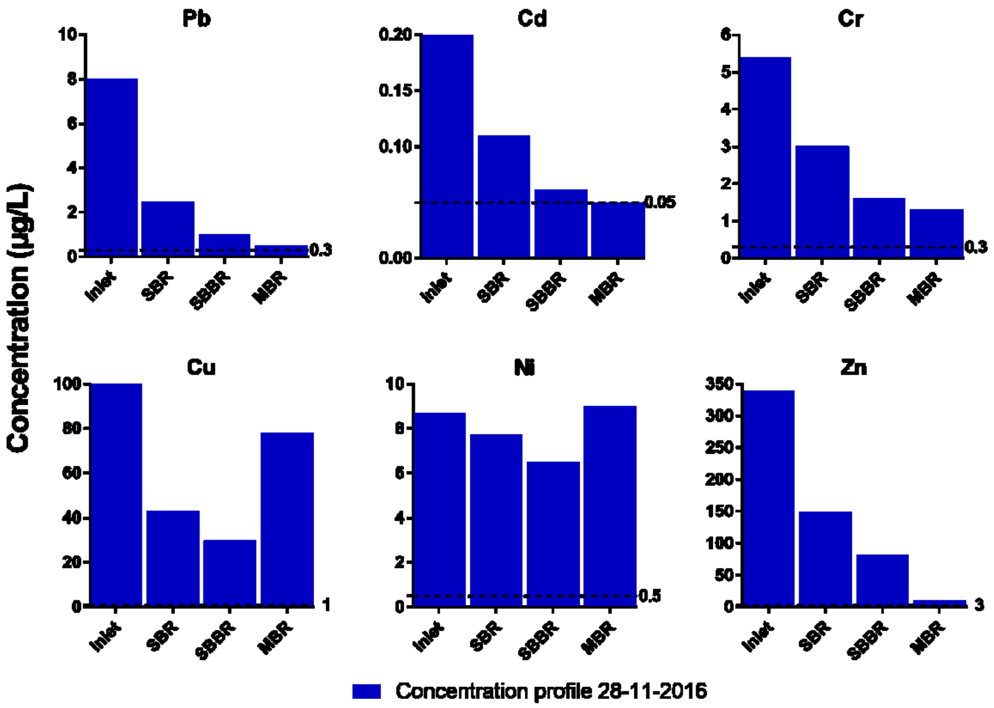

Figure 15. Reduction of heavy metals in the main treatments. The dotted lines correspond to the detection limit of the analysis of the different heavy metals.

Polishing steps

The removal of micropollutants in the polishing steps are only shown for the heavy metals, as the organic micropollutants were removed to below detection limit in the biological treatment.

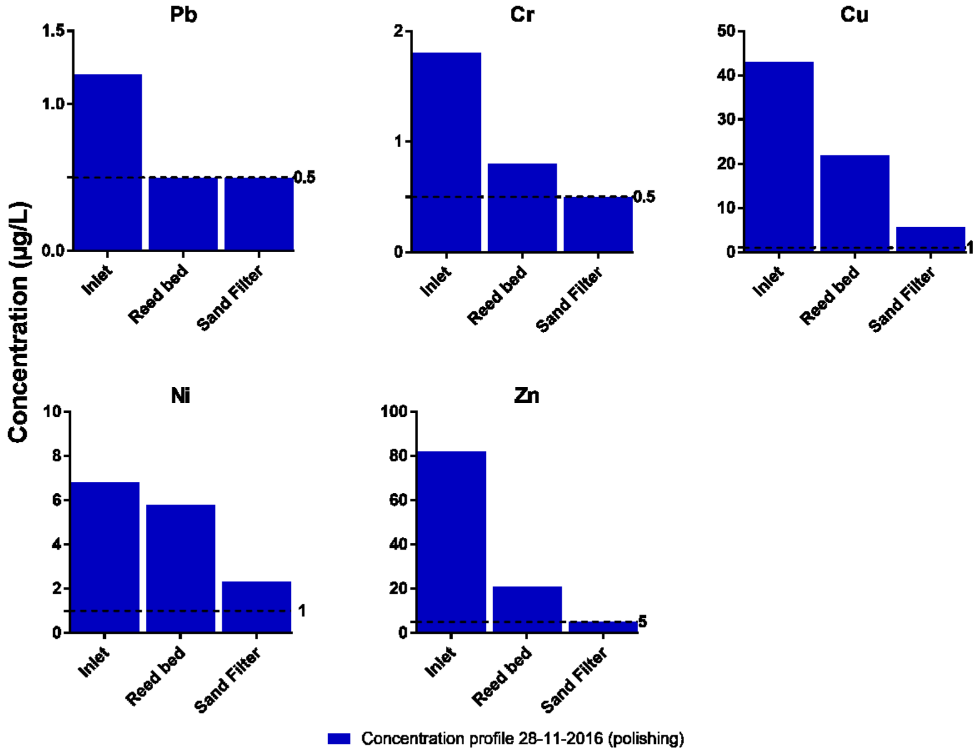

Figure 16. Removal of heavy metals remaining after biological treatment

Both polishing steps were quite effective to remove the remaining heavy metals after the biological treatment with the sand filter having been clearly superior to the reed bed.

5.2.3 Results from the modified sand filter

The sand filters were in operation 6 weeks before backwashing. The effluent samples were taken before and 24 hours after backwashing, respectively. Measurements of copper were carried out and represent the expected behavior of the heavy metals.

The results for copper absorbance are shown in table 7.

	Before backwashing		**After backwashing**	
	Cu concentration [mg/l]	**Cu reduction [%]**	**Cu concentration [mg/l]**	**Cu reduction [%]**
Inlet concentration	0.184		0.273	
Effluent (30 % iron sludge)	0.226	-22.8	0.215	21.2
Effluent (100 % iron sludge)	0.184	0.0	0.166	39.2

Table 7. Copper removal in the modified sand filter microcosm.

The iron-sludge coated sand filter microcosms showed no capacity to adsorb copper prior to backwashing. The backwashing process improved the copper removal potential to 21 % and 39 % in the microcosms with 30 %- and 100 % iron coated sand, respectively.

The results indicate that it is most likely the iron-sludge rather than the biomass on the sand particles adsorbing the copper. The copper adsorption potential was almost doubled by increasing the coated sand particle depth from 7 to 25 cm (30 % and 100 % coated sand). It is assumed that a sand filter with a depth of 150 cm will adsorb the majority of the copper as well as other heavy metals in wastewater. However, these sand filters should be backwashed every 2 to 3 weeks, as carried out at water works, because a longer period of continuous operation causes a thick biofilm on the sand particles and reduces the copper adsorption potential of the sand filter.

As the modified sand filters also remove the phosphorous apart from heavy metals, it was decided not to establish this technique in the modified form but only as a conventional sand filter in the demonstration phase at Samsø.

5.2.4 UV treatment results

The effect of UV treatment on live bacteria in the effluent from sand filter and reed bed was measured using the colony count method at 22 and 37 °C (DS/EN ISO 6222:2000)[13] on duplicate samples from before and after the UV treatment.

	Colonies per plate							
Sample	Dilution factor						Concentration [CFU/ml]	Reduction [%]
[Tekst]	10^0	10^1	10^2	10^3	10^4	10^5		
In 1 (22 °C)	-	-	-	9	26	0	3.15E+05	
In 2 (22 °C)	-	-	-	8	1	3	1.08E+05	
In 1 (37 °C)	-	-	-	40	0	1	3.69E+05	
In 2 (37 °C)	-	-	-	4	1	0	4.55E+04	
Out 1 (22 °C)	nc	63	19	-	-	-	7.45E+03	97.6
Out 2 (22 °C)	nc	71	12	-	-	-	7.55E+03	93.0
Out 1 (37 °C)	81	8	1	-	-	-	8.11E+02	99.8
Out 2 (37 °C)	27	10	1	-	-	-	3.42E+02	99.2

Table 8. Colony counts on plates with inlet and outlet samples from UV treatment, calculations of resulting colony forming units (CFU) per ml and percentage reduction of bacteria in the treatment. (nc = not countable)

The reduction of live bacteria was in the range of 93 to 99.8 %. The growing of bacteria especially on the 37 °C plates (potentially disease-promoting bacteria) indicated, that the retention time of the water in the UV lamp should be prolonged or the lamp strength enhanced to eliminate the last few percent of living bacteria. There is no doubt that the method is sufficiently effective when dimensioned correctly.

13 https://webshop.ds.dk/en-gb/standard/ds-en-iso-62222000

5.2.5 Conclusions on which treatment technologies are chosen for demonstration phase

It was decided to use MBR and SBBR as main biological treatment technologies in the demonstration phase on Samsø, as these two techniques are very different in their approach. The SBBR was chosen rather than the SBR, because of the high removal capacity for hardly degradable pharmaceuticals in a project focusing on hospital wastewater treatment.
As polishing steps, ozonation and sand filters were tested in pilot scale. Ozonation was chosen as a safety precaution to ensure complete removal of organic xenobiotics if the biological approaches were less efficient than anticipated. Also, a conventional sand filter solution without iron-sludge coating was established to keep the phosphorous in the water. The iron-coating of sand showed promising results but it is anticipated that further focus on development of this approach should be carried out before a pilot scale solution is constructed.

5.2.6 Organic xenobiotics adsorption test with PE granulate

The ability of plastic to adsorb organic xenobiotics is described in literature[14,15,16] and suggests that a more active use of this capability should be investigated further. The following experiments should clarify, whether it is possible to remove the organic xenobiotics from the wastewater using plastic granulate and regenerate the plastic absorption capacity by ozone treatment. A lot of ozone could be saved that way, because only the organic xenobiotics on the plastic granulate had to be treated instead of the whole wastewater volume, which contains some more organic matter than the organic xenobiotics.

A two-part experiment was performed. In the first part, the sorption capacity of polyethylene granules (PE granulates) was studied by adding them to a water solution containing two PAHs (phenanthrene, pyrene) and nonylphenol (NP). In the second part, the PE granulates were ozonized to regenerate their sorption capacity.

In the first part of the experiment, 0.466 g of PE granulate (38 granules) was added to 1 liter solution (water added 100 µg/L of both PAHs and 300 µg/L NP). Every 24 hour, the solution was analyzed and replaced by fresh solution of xenobiotics. In the second part of the experiment, half of the PE granulates were ozonated (19 granules) in water at a concentration of 30 mg O_3/L for two hours. After ozonation, the PE granules were kept in 500 ml of the micro pollutant solution as well as the untreated pellets were kept under the same conditions. The micro pollutant solution was again analyzed and replaced by fresh solution after 24 hours.
The PAHs and NP concentrations were determined by HPLC chromatography with fluorescent detection (FLD detection at 260 nm excitation and at 380 nm and 410 nm emission) and UV detection (λ=230 nm for DAD).

The results in **Figure 17** show, that removal of PAHs and NPs could be achieved with PE granulate in a period of 4 days without minor change of efficiency over time. The pyrene removal was higher than the removal of phenanthrene and NP. The results for NP removal fluctuated between 40 and 80%.

After ozone treatment (day 5), the ozonated PE granulates had similar sorption capacity for phenanthene and pyrene as the non-ozonated (control) ones. In both cases, the removal had decreased slightly compared to the first 4 days. An explanation could be, that the PE granulate had reached a saturation point, or the removal was limited due to the diffusion of PAHs and

14 H. Hirai et al.: Organic micropollutants in marine plastics debris from the open ocean and remote and urban beaches, *Marine Pollution Bulletin* 62 (2011) 1683–1692

15 Teuten, E. et al.: Potential for plastics to transport hydrophobic contaminants, *Environ. Sci. Technol. 2007, 41, 7759-7764*

16 Mato, Y. et al., Plastic resin pellets as a transport medium for toxic chemicals in the marine environment, *Environ. Sci. Technol.* 2001, 35, 318-324

NP inside the granulate. However, the NP adsorption capacity of the ozonated granulates was improved compared with the non-ozonated PE granulates. The reason may be, that NP was removed from the surface of the plastic granulate by ozone and new NP could be sorbed (increased capacity). But on day 6, the removal was again high for the non-ozonated PE granulates. The overall results showed that PE granulates can adsorb PAHs and NP, however these compounds might penetrate the granulates rather than only be adsorbed to the surface. This could explain the insufficient regeneration of sorption capacity of PE granulate by the ozone treatment.

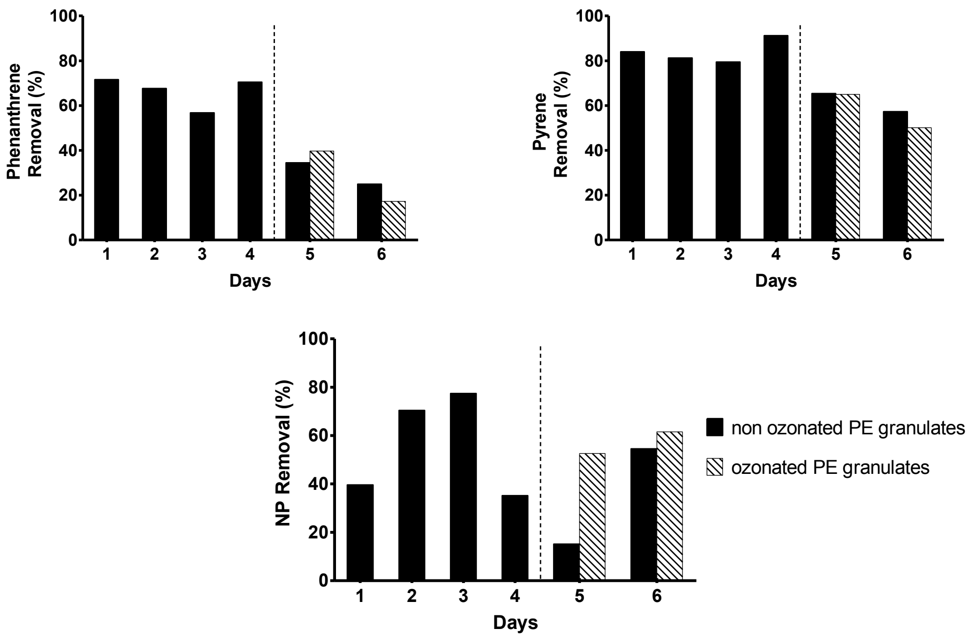

Figure 17. Removal (%) of phenanthrene, pyrene and NP (nonylphenol) from water by PE granulates.

5.2.7 Micro plastic

It was not possible to carry out reliable micro plastic analyses as the analysis methods were and still are under development in Denmark and foreign countries, which is described in the recently published report[17]. In the case of MBR though, all micro plastic particles > 0.4 µm should be retained in the sludge fraction due to the membrane cutoff. In the case of SBR and SBBR it is still unclear, which percentage of micro plastic will end in the sludge. Most likely, more micro plastic will be retained in the sludge of the SBR than the biofilm-based SBBR approach. Several studies describe, that a very high percentage (> 90 %) of micro plastic is retained in the wastewater treatment plants of the EU countries, however, the numbers given in the articles are to be interpreted with caution because of high uncertainties of the used methods for micro plastic analyses[18,19,20]. Especially very small particles < 20 µm are very difficult to analyze, but it is still uncertain, whether particles of that size affect the recipients even at rather low occurrence[17].

17 http://mst.dk/media/143341/partnerskab-om-mikroplast-i-spildevand-2017.pdf

18 Magnusson, K (2014).: Mikroskopiska skräppartiklar I vatten från avloppsreningsverk, IVL Svenska Mijöinstitutet, rapport nr. 2208

19 Mintening, S., Int-Veen, I., Löder, M., Gerdts, G. (2014):Mikroplastik in ausgewählten Kläranlagen des Oldenburgisch- Ostfriesischen Wasserverbandes (OOWV) in Niedersachsen, http://www.dwa-bayern.de/tl_files/_media/content/PDFs/LV_Bayern/Abschlussbericht_Mikroplastik_in_Klaeranlagen-3.pdf

20 Vollertsen, J., Hansen, A. A. (2017): Microplastic in Danish wastewater, Environmental Project No. 1906, The Danish Environmental Protection Agency, https://www2.mst.dk/Udgiv/publications/2017/03/978-87-93529-44-1.pdf

6. Pilot scale setup at Samsø

The possibilities of the pilot scale phase at Samsø were to operate the chosen treatments with the real wastewater from Samsø and upscale the MBR by a factor of 10. It was decided to have a short trial period with the winter scenario with full nitrification/denitrification to observe how long the transition period from winter to summer scenario will last, which gave additional great value beyond the projects settings. The whole trial at Samsø lasted for 5 months, starting in May 2017.

6.1 Wastewater treatment technologies - setup

The treatment technologies tested on Samsø were established in two 20 feet containers plus a 40 feet container for the sand filter.
The following main treatment and polishing techniques were chosen for the demonstration phase in Nordby/Samsø:

Pretreatment technique:
- Belt filter

Main biological treatment techniques:
- SBBR (sequencing batch biofilm reactor)
- MBR (membrane bioreactor)

Polishing techniques:
- Ozonation
- Sandfilter

SBBR and MBR techniques were chosen as main treatment technologies based on the results from the laboratory tests. A belt filter removed larger particles before the wastewater entered the main treatment step to enhance the performance of the membranes in the MBR. As polishing treatments ozonation and a sand filter were tested. Ozonation was selected as a safety precaution to ensure complete removal of the organic xenobiotics. A sand filter without iron sludge coating was chosen, because the phosphorous was retained in the modified sand filter with iron sludge coating.

The following Figure 18 shows the setup in the demonstration phase:

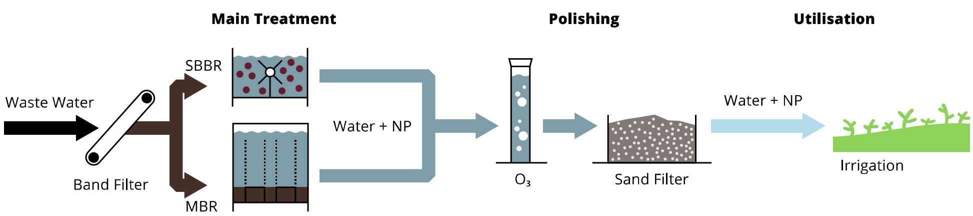

Figure 18. Setup in demonstration phase at Samsø

6.2 Main treatment technologies – setup at Samsø

6.2.1 Belt filter

An AL-2 belt filter with a filter band, pore size 150 μm (see Figure 19) was used as a prefiltration step to prevent membrane clogging in the MBR. The belt filter was dimensioned to continuously produce a flow of minimum 260 l/h to feed the tanks. The water was pumped from the full scale SBR reservoir tank containing water after sand/grease treatment of the Nordby WWTP. The belt filter operated very stable during the whole experimental period. The outlet water from the filter was pumped to both MBR and SBBR.

Figure 19. Belt filter installation at Samsø

6.2.2 MBR setup

An Alfa Laval MBR pilot scale system was used for MBR treatment of wastewater. The system was mounted in a 20' container with the MBRs (two similar lines) at the end, where roof can be liftet to inspect the MBR reactor tanks.

Figure 20: The MBR container.

The pilot plant consisted of components and prefabricated piping ready for operation when installed and connected to the local water streams and power supply systems.

The container system included a feed section, two anoxic/aeration-MBR tanks with an aerated volume of approximately 0,9 m^3 in each of them. In each membrane tank, a hollow sheet membrane filtration module (

Figure c) was installed as well as an incorporated PLC/MCC. The pilot plant was intended for semi-automatically controlled MBR production in non-Ex classification zones.

Figure 21. MBR pilot scale system, Alfa Laval. a) Membrane module; b) inside the container with indication of the two parallel lines.

The membrane modules had a membrane area of 9m^2 in each of the two lines. The installed membrane type were microfiltration membranes with high permeability that allowed operation by gravity. Microfiltration membranes remove almost all suspended solids and particles larger than 0.2 µm (smallest bacteria are around 1 µm).

The plant was operated with nitrification and denitrification during the first period. Table 9 shows the main operating parameters during this period:

Parameter	MLSS [g/l]	SRT [d]	HRT [h]	pH	Temperature [°C]	Flux [LMH]	Pressure on membranes [mbar]
Range	0.2 – 1.2	2 - 10	10 - 30	5.4 – 7	18 - 22	8.5 – 14.5	10 - 30

Table 9. Operation data during initial standard MBR (N/DN) operation. Mixed liquor suspended sludge (MLSS), sludge retention time (SRT), hydraulic retention time (HRT), pH, temperature and flux (LMH=l/h/m^2)

In that period, the pH dropped below 7 - even down to 5.43. The reason was most likely the due to each othernitrification combined with a low C/N ratio (BOD/N ratio down to 2) that might have occurred because of high retention time in the buffer tank and the effect of the belt filter. Low pH is also due to the low hardeness of Norby water and from time to time high N-NH4 content. This is typically resulting to low pH and furthermore there was no return of alkalinity from denitrification.

In the second period, the denitrification tank was shut down and the feed was installed directly to the membrane tank (see figure 22).

Figure 22. MBR –the two parallel lines – membrane tanks

Some challenges occurred in this operation mode, as the new sludge did not grow and nitrite was observed. At the same time the flux through the membranes declined due to the poor sludge effect. Table 10 shows the operation parameters in the second period.

Parameter	MLSS [g/l]	SRT [d]	HRT [h]	pH	Temperature [°C]	Flux [LMH]	Pressure on mem-branes [mbar]
Range	0.2 – 1.2	2 – 10	10 – 30	6.9 – 7.9	18 - 22	4 - 10	30 – 40*

Table 10. Operation data on MBR (no DN); Mixed liquor suspended sludge (MLSS), sludge retention time (SRT), hydraulic retention time (HRT), pH, temperature and flux (LMH=l/h/m^2) operation. *The pressure on the membranes was mainly around 30 to 40 mbar except right after extended relaxation.

PH improved during the summer operation as denitrification was ceased while the sludge retention time was decreased. The membrane flux was compromised (see Figure 23) and the occurrence of nitrite confirmed that nitrification was partly stopped. Nitrosomonas have a higher kinetic as nitrobacter and for this reason there should be no $N0_2$ present.The reason is probably an inhibition of nitrobacter due to a high concentration of ammonium. Nordby WWTP has a quite high N-ammonium concentration, and with a low biomass concentration in the MBR a limited amount of nitrite oxidizing bacteria is present, which easily can be inhibited by ammonium.

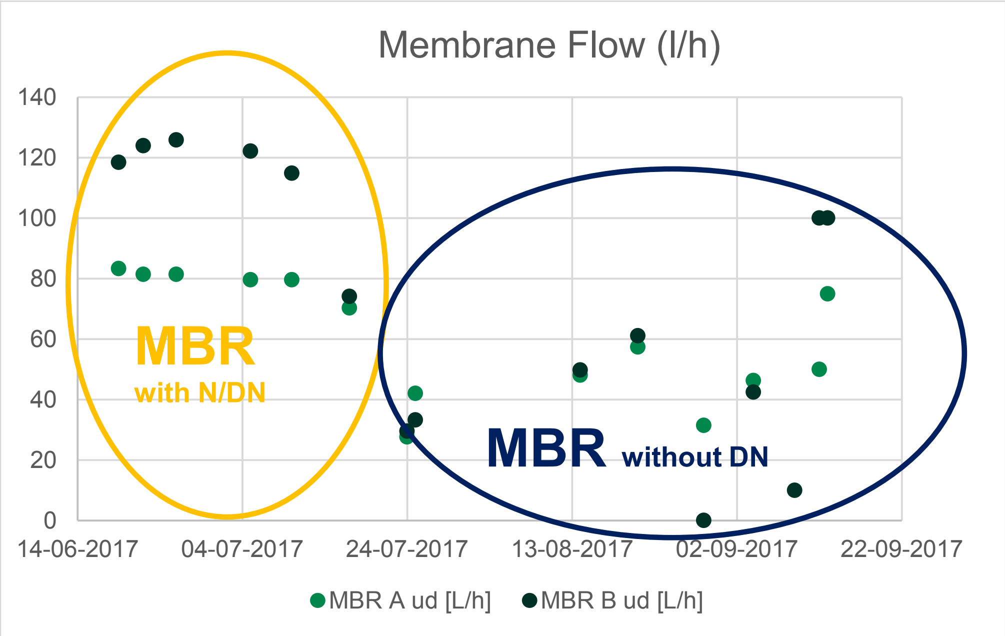

Figure 23. Membrane flow in both MBR lines A and B

6.2.3 SBBR setup

The SBBR tank from the laboratory test was transferred to Samsø for the pilot scale phase. The operation volume was 100 l with a flow of 10 l/hour and a batch length of 6 hours (resulting in 60 l water/batch). The sludge age was set to 5 days in the startup phase (winter operation with nitrification/denitrification at the give temperature of 13.8 – 17.2 °C) and 2 days from 22/6-2017, where the operation was changed to summer scenario without nitrification/denitrification (temperature range 17 to 19.8 °C). The carriers were transferred from the laboratory tests (volume 8.6 liter).

The pH was between 6.9 and 8.0 in the whole operation period, the temperature in the tank varied from 14 °C in May to 19,4 °C in July and 16.4 in September during spiking experiments.

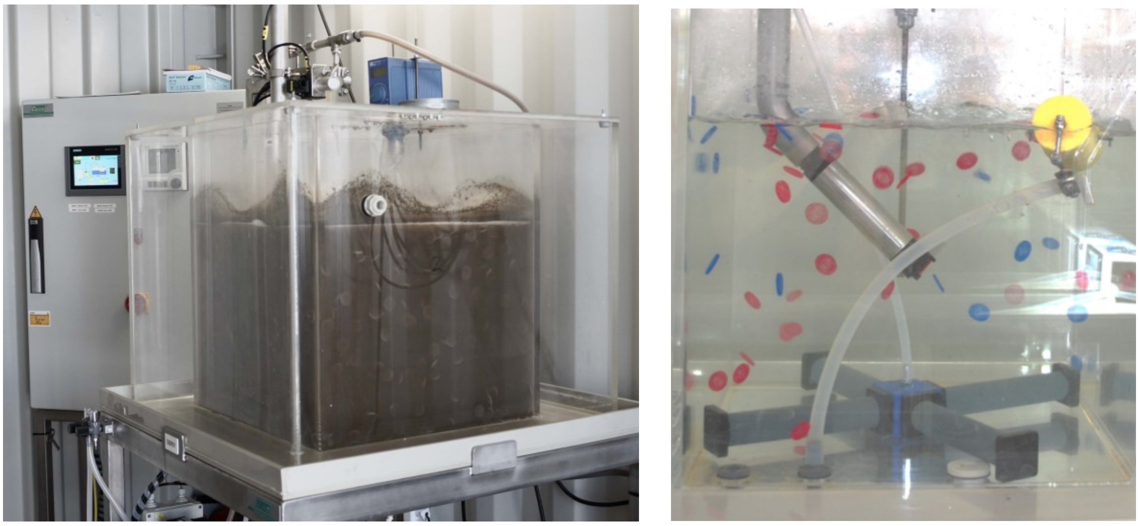

Figure 24:. SBBR setup – with and without wastewater

6.3 Polishing technologies – setup at Samsø

For the polishing technologies ozonation followed by a sand filter was chosen.

6.3.1 Ozonation

The setup for ozonation can be seen in figure 25

Ozonation is a well-known technique for the degradation of organic matter and is used as a polishing step in WWTPs especially in foreign countries as Germany and Switzerland.

The effluent from both MBR and SBBR was pumped to the first of the two ozonation columns in line. The ozonation reactor was designed to prevent short circuiting of inlet to outlet. Ozone was produced from pure oxygen. In general, 15 – 20% of oxygen was converted to ozone in the ozone generator. The first column was to identify the retention time of the water depending on the organic content of the water and ozone dosage. The second column was used for degassing the unused ozone and supersaturated oxygen. The biological treatment plants produced between 120l/h and 200 l/h water with a COD content of approx. 25 - 70 mg/l. The ozone dosage applied was in the range of 17-20 gO_3/Nm^3.

Figure 25 Ozonation columns

6.3.2 Sand filter

The sand filter constructed by Kilian Water was a 40 feet container with 20 cm pea gravel (8 – 16 mm diameter) layer as drainage, 80 cm fine gravel (1-5 mm diameter) as the filtering layer and 20 cm pea gravel on top for spreading the water. The inlet water was spread by tubing with holes distributed homogenously on top of the sand filter layers. The effluent was collected in a well beside the sand filter.

Figure 26: Sand filter under construction

6.4 Results

6.4.1 Common wastewater parameters in biological treatments

The following figures show the common wastewater parameters in the demonstration period on Samsø. Until June 22nd, the plants were operated in winter mode, where nitrification and denitrification was required, as it was decided, that the information for transition time needed between winter and summer scenario was of great value even though it was an extra in relation to the project application. At June 22nd, the sludge age was reduced to 2 days in the SBBR to prevent nitrification and the denitrification tank was disconnected from the MBR.

Figure 27 shows the COD in inlet and outlet of the biological main treatments SBBR and MBR.

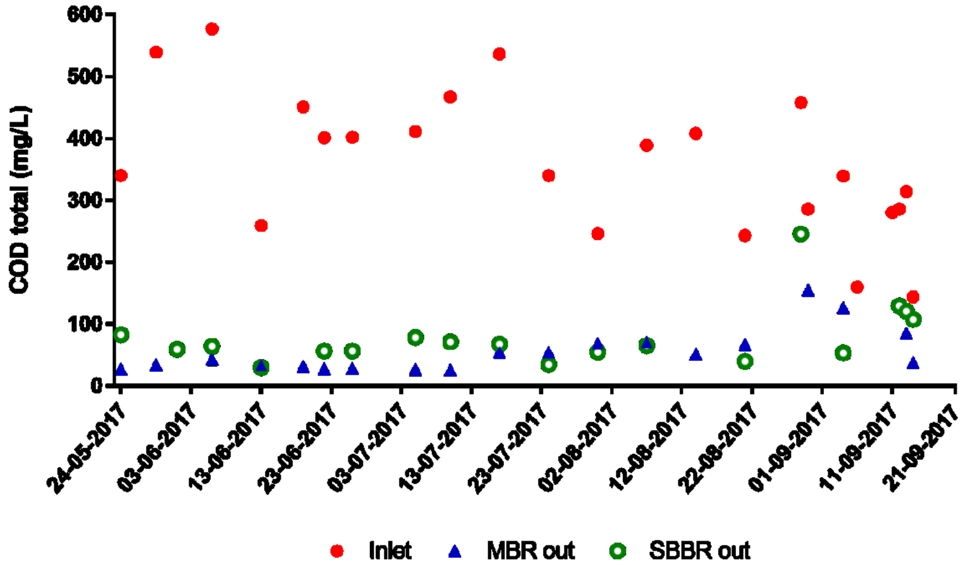

Figure 27. COD content in inlet and outlet samples from the biological main treatment steps

COD concentrations in the effluent of the main biological treatments were generally quite low varying between 50 and 80 mg/l, regardless of operational mode. Operational challenges of heavy rain events resulted in a few elevated effluent samples.

Figure 28 shows the total nitrogen in the inlet and the ammonium in the effluent of the biological treatments on Samsø.

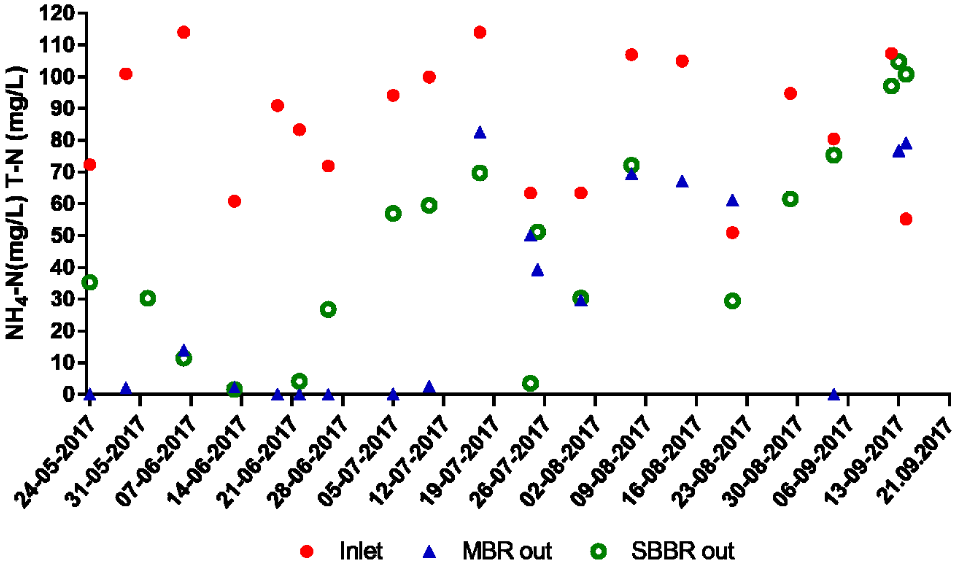

Figure 28. Total nitrogen in the inlet and ammonium in the outlets of the main treatments. The dotted line indicates the shift from winter to summer operation

The biological treatment plants were operated in winter operation mode until June 22nd, where nitrification/denitrification was desired. As evident in Figure 28, the ammonium concentration was very low (longer response time for the SBBR), while nitrate concentration was high (Figure 29).

When the sludge age was adjusted to 2 days in the SBBR and the denitrification tank was disconnecting from the MBR (dotted line in figure 29) the summer operation without nitrification was achieved after two weeks with high ammonium and low nitrate concentrations in both systems, though still challenges in the MBR due to lack of denitrification.

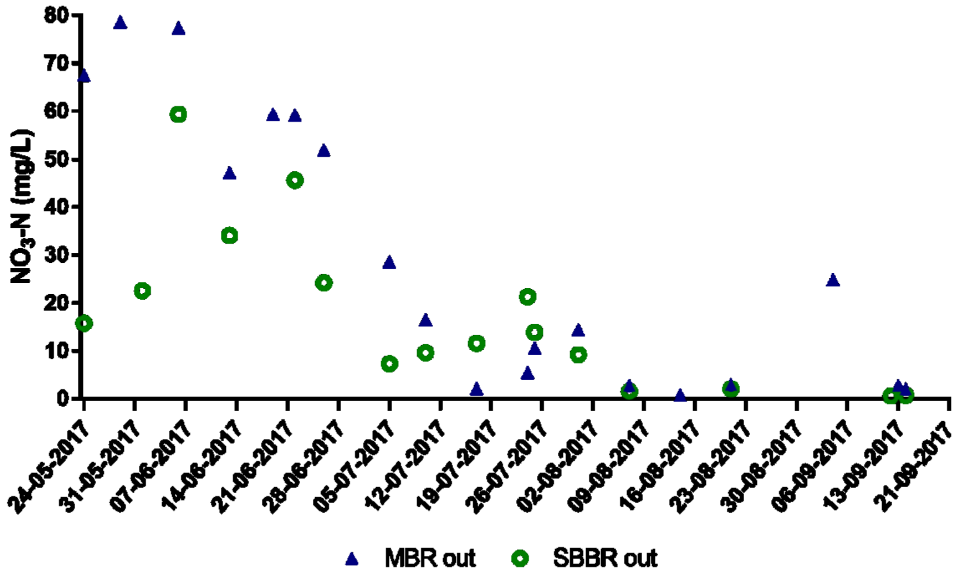

Figure 29: Nitrate concentration at different sludge ages. The dotted line indicates the adjustment of sludge age to 2 days in the SBBR and the disconnecting of the denitrification tank from the MBR.

The phosphorous retention is shown in the following figure 30.

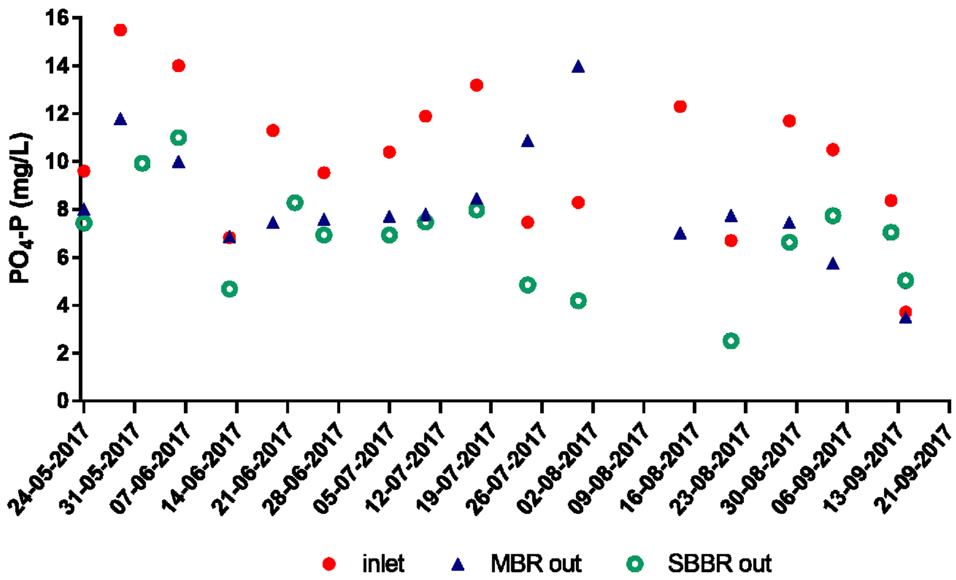

Figure 30: Phosphorous retention in the biological main treatment steps with unfiltered samples for inlet samples and filtered samples from outlet samples (MBR and SBBR)

The inlet values represent total phosphorous analyses from unfiltered samples to show the complete phosphorous load. The outlet values were analyzed from filtered samples to show the amount of dissolved phosphorous available for plant uptake in the outlet water. Therefore, the actual total phosphorous retention might have been higher, as part of the phosphorous is expected to be particle bound. The phosphorous retention was high and in general better in the MBR than the SBBR.

6.4.2 Common wastewater parameters in polishing steps

The outlet water of the main treatments was mixed and lead to the ozonation step, followed by the sand filter. Figure 31 shows the removal of the COD remaining after the main treatments.

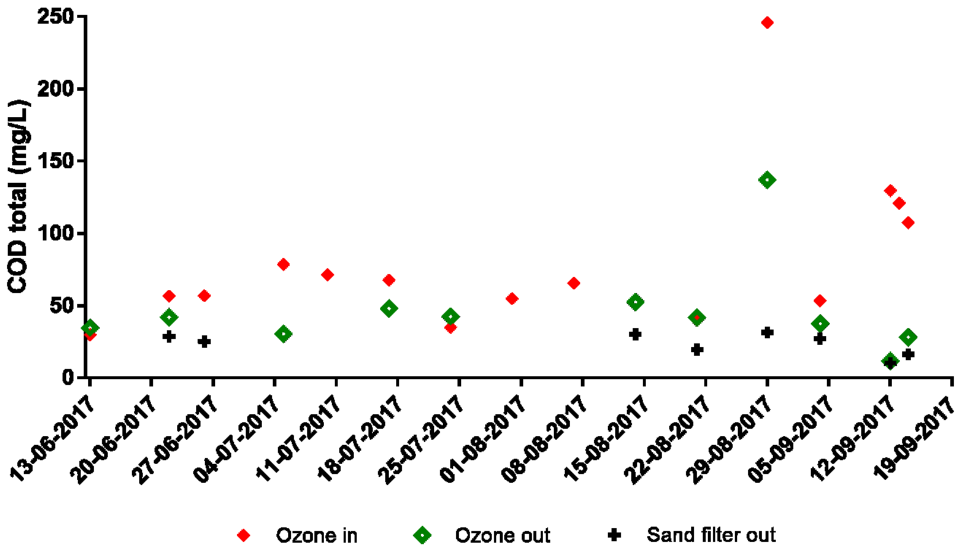

Figure 31. COD removal in the polishing steps. The inlet corresponds to the mixed outlet water from the main treatments

After ozonation step, the residual COD was reduced to a very low level, which was further reduced in the sand filter, resulting in very low COD concentration.

Figure 32 shows the retention of nitrogen in the polishing steps.

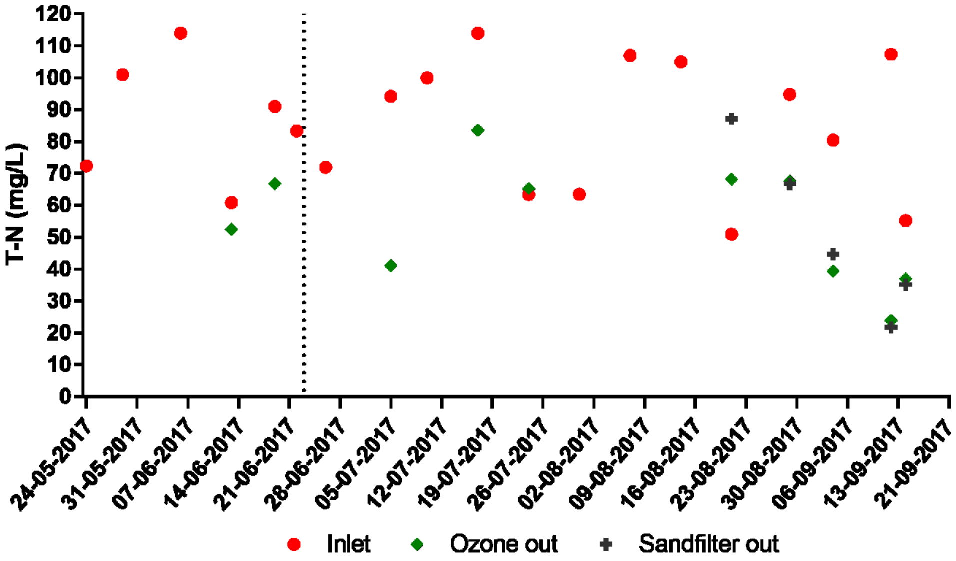

Figure 32. Nitrogen retention in the polishing steps. Inlet was the pooled water from SBBR and MBR outlet.

The inlet water for the polishing step was the pooled outlet water from SBBR and MBR. There was a loss of around 50 % of the nitrogen in the ozonation step as well as in the sand filter.

Figure 33 shows the recovery of phosphorous in the polishing steps.

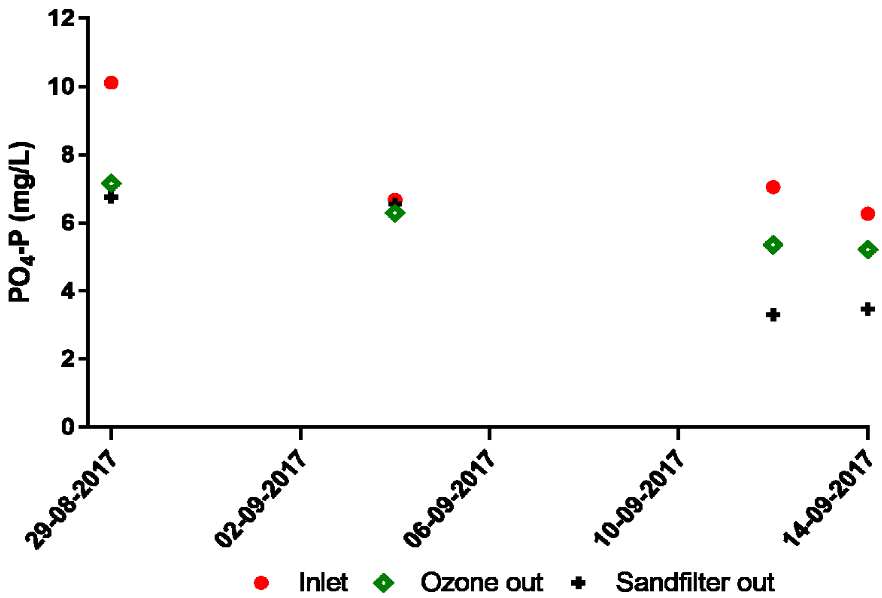

Figure 33. Phosphorous recovery in the polishing steps. Total phosphorous values for inlet values (unfiltered samples) and outlet (filtered samples)

There was detected a minor loss of phosphorous in the polishing steps, varying from approximately 5 to 50 %.

6.4.3 Results of organic micro pollutant removal

The removal of organic organic xenobiotics and heavy metals from wastewater was tested by performing concentration profiles and spiking experiments as described in section 5.1.1.

The concentration of the spiked compounds was ten times higher than the values found in average wastewater for minor wastewater treatment plants in DK. The LAS was not spiked, as a trial in laboratory scale lead to heavy foam formation, which was undesirable in pilot scale. The spiking of the water was performed in two intermediate bulk containers for a calculated period before and while sampling to ensure, that all the water in the plant was exchanged with the experimental water with the desired concentration. While one container was used to feed the MBR and SBBR with spiked water, the other container was filled with inlet water from the WWTP and spiked when filled completely. The spiking experiment was separately performed on the ozonation step to show its removal capacity (see section 6.4.4).

The sand filter was not included in the concentration profile and spiking tests, as the volume and design of the filter did not allow to calculate an exact hydraulic retention time for the water.

Figure 34. Containers for alternating use in the spiking experiments of the biological treatment.

For the biological treatment (MBR and SBBR) two concentration profiles were conducted (26thth of July and 13th of September 2017) to cover different wastewater loads. During summer the population on Samsø is multiplied by a factor 10 due to intensive tourism on the island, while much fewer people are living on the island in the middle of September.

The concentrations of mercury (Hg) and polycyclic aromatic hydrocarbons (PAH) were below detection limit in the inlet samples, and therefore not included in the results. Results for DEHP were very inconsistent and therefore, not included.

The results in Figure 35 show, that the removal of organic xenobiotics was very high. The concentrations were below detection limit for both LAS and NPE in the MBR outlet, the SBBR performed a little less effective, but still the removal was very high. Overall the MBR performed better than SBBR for the removal of heavy metals. Most likely the heavy metals are present in the sludge fraction

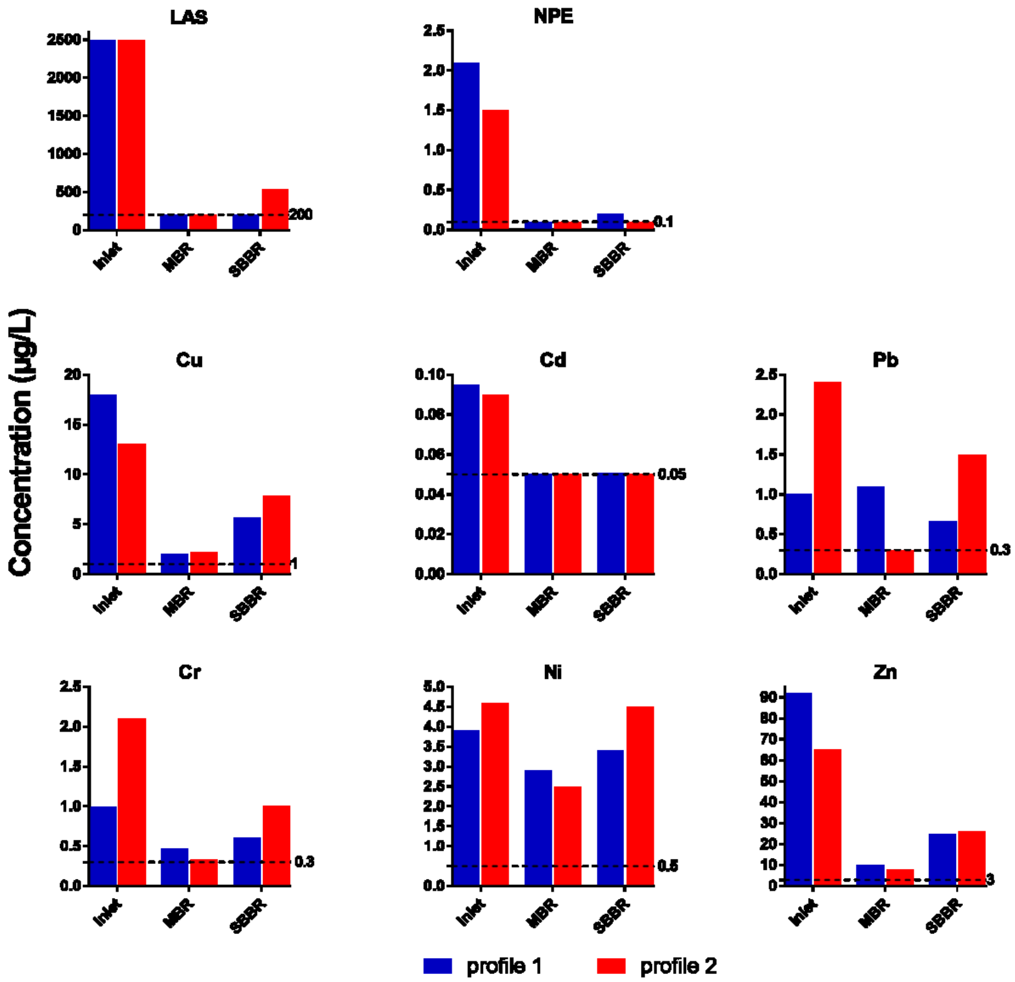

Figure 35. Concentration profiles for 29th of July 2017 (blue) and 13th of September 2017 (red). The profiles show organic mircro pollutants on top and heavy metals in the middle and bottom graphs. Dotted lines correspond to the detection limit for every compound.

Two spiking profiles were conducted to investigate the removal capacity of the biological treatments.

The removal of specific organic xenobiotics is shown in figure 36. The removal capacity of the MBR reactor was better than the one of SBBR, since the concentrations were below detection limit for LAS and close to detection limits for all the other compounds, while it was a little higher for SBBR. Although the organic xenobiotics were removed almost completely in both systems during pilot scale operation. Therefore, the spiking experiments confirmed the high performance of the two treatments.

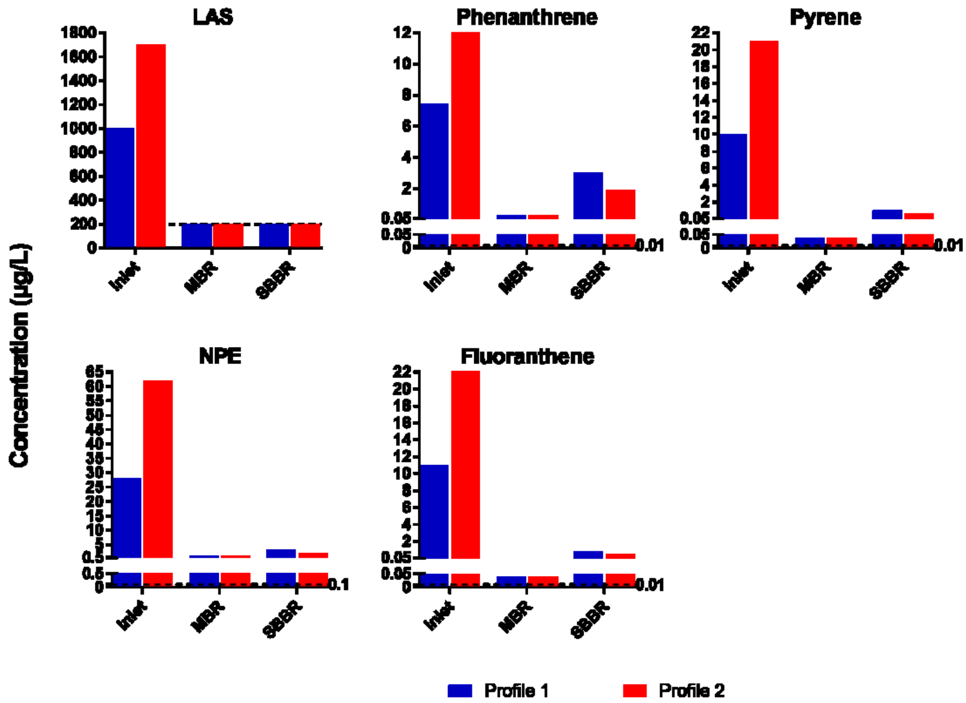

Figure 36. Spiking profiles of organic xenobiotics. The dotted lines correspond to the detection limit for each compound.

The removal of specific heavy metals is shown in figure 37, indicating that also here the removal was very high. Very low concentrations of heavy metals were present in the outlet of MBR. The removal capacity of MBR reactor was slightly better than the one of SBBR, since the concentrations were below the detection limit for Cd, Hg, and close to detection limit for the other compounds except nickel, which was reduced with 60 – 70 %. A possible explanation to this can be a low presence of sulphide in the raw wastewater. If it were present the nickel would have formed nickel sulphide, which would be captured in the sludge.

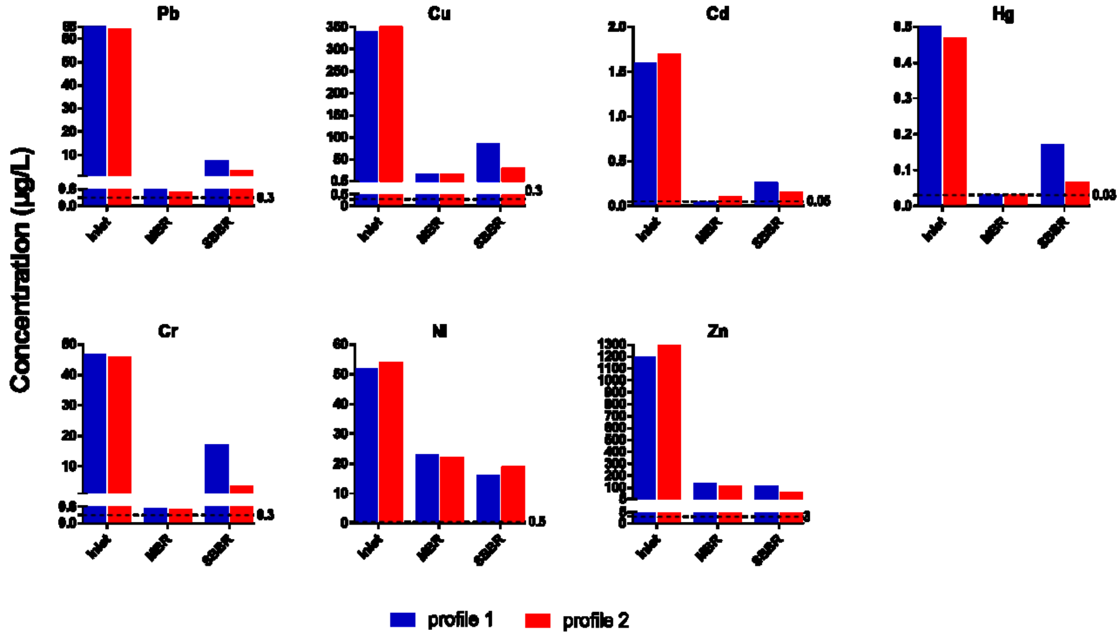

Figure 37. Spiking profiles of heavy metals. The dotted lines correspond to the detection limit for each compound.

6.4.4 Treatment with ozonation

The spiking profile for the ozonation was conducted separately with the same concentrations as the biological treatment plants, to show the ozonation capacity at high concentrations (as ozonation is a polishing step it normally would receive the outlet water from MBR and SBBR with the low concentrations of spiking compounds). As ozone does not affect heavy metals, only organic xenobiotics were analyzed after the ozone stage. The DEHP showed again very fluctuating unlogical results, why it was eliminated from the results. Two profiles were conducted with a difference of 1 hour.

The results are shown in figure 38. After the ozone treatment, the concentration of LAS was below detection limit. For the rest of the compounds, the concentrations were very low, corresponding to removal rates of > 96 %.

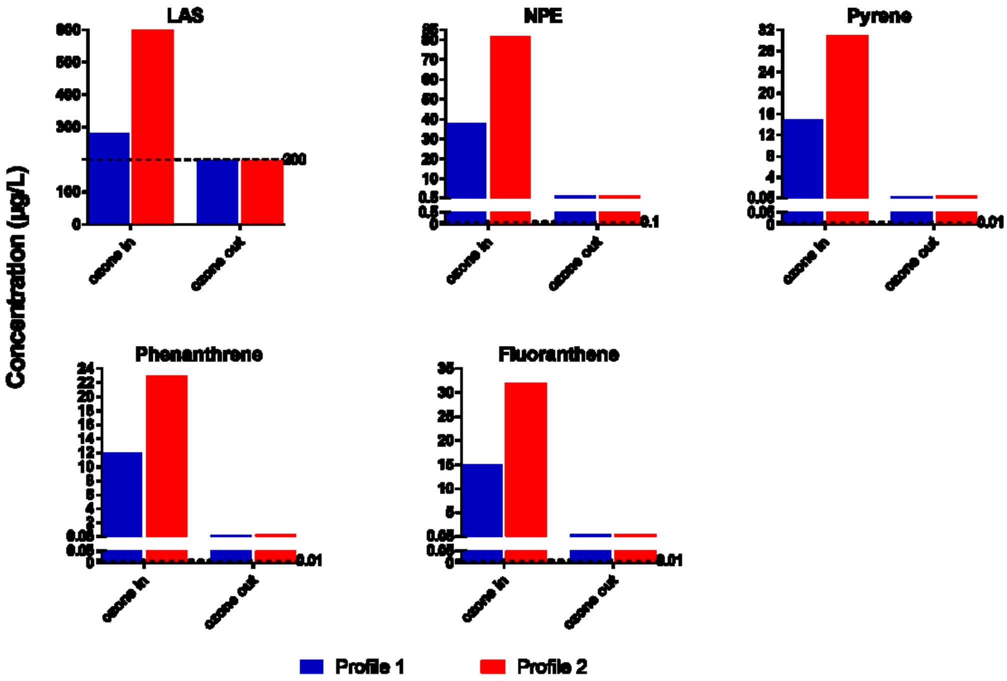

Figure 38. Spiking profile with organic xenobiotics in the ozone treatment. The two profiles were conducted with one hour interval. The dotted lines correspond to the detection limit for every compound

Overall, all the selected xenobiotics were removed to low concentrations using biological treatment and any residual concentrations were removed by ozonation.

6.5 Microbial data

The abundance of viable bacteria was estimated at relevant points in the water treatment stream to evaluate the potential of reducing the microbial abundance by the membrane in the MBR (microfiltration) and ozonation, respectively. The SBBR outlet was led to the ozonation step and was evaluated in the ozonation results, as SBBR does not remove bacteria.
The same method as described in section 5.2.4 was used for estimation of the abundance of viable bacteria in the influent to the belt filter and the effluent from microfiltration and ultrafiltration. Samples from ozonation influent and effluent were analyzed by Compact Dry™ TC (Hardy Diagnostics), following the manufacturer's instructions. Duplicate dilutions were prepared for each sample, and the respective dilutions were plated in triplicates.
At the inlet to the belt filter viable bacteria were numerous (10^6 colony forming units/mL). The reduction of live bacteria by microfiltration, ultrafiltration and ozonation was 95%, 68% and 96%, respectively. Potentially, the treatment was more effective, since microbial growth in tubes might have contaminated the water. Pathogenic bacteria, growing at 37°C (10^5 CFU/mL), were removed completely by ozonation.'

6.6 Toxicity test for heavy metals

A toxicity test for heavy metals was applied to freshwater aquatic plants of the genus *Lemna* (duckweed) based on the OECD guidelines for the testing of chemicals. Plants of the genus *Lemna* were grown as monocultures in different concentrations of the test substance over a period of seven days. The objective of the test was to quantify substance-related effects on vegetative growth over this period based on assessments of frond number and biomass (total frond area, dry weight or fresh weight). To quantify substance-related effects, growth in the test solutions was compared with that of the controls. The concentration responsible for x % inhibition of growth (e.g. 50 %) was determined and expressed as the EC_x (e.g. EC_{50})[23].
During the test, all different samples were prepared in duplicates and diluted to 100%, 50%, 25%, 12.5% and 6.25% in clean 100 ml glassware (figure 39). The pH was adjusted between pH 5 and pH 5.5, and 11-13 duckweed leaves were added to each sample.

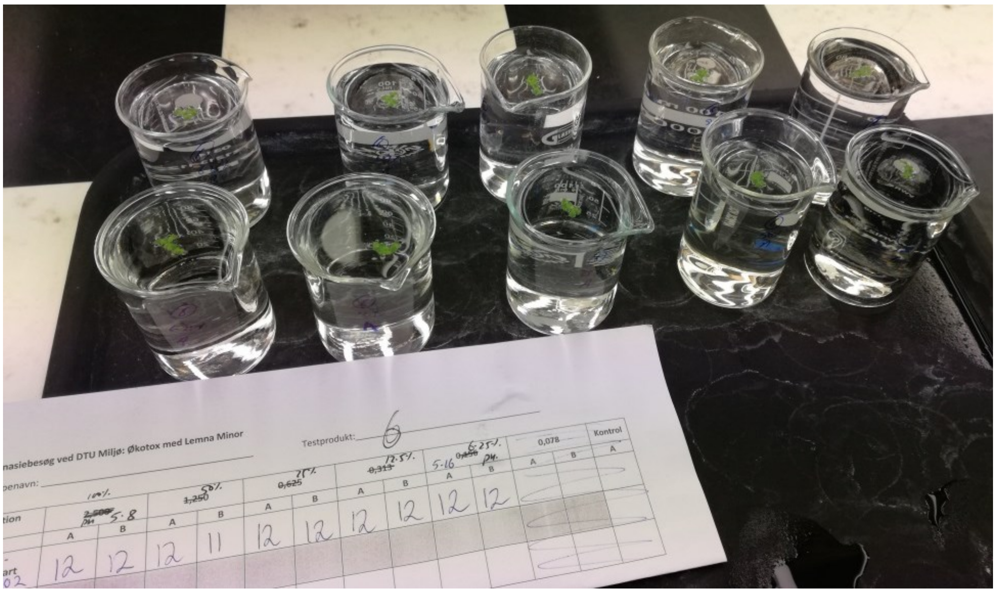

Figure 39: Duplicates of samples and dilutions with addition of *Lemna* leaves, incubating period: 7 days under artificial light.

Table 11 shows the results from the toxicity test. There was inhibition in the undiluted inlet samples but no inhibition in any of the outlet samples, showing that the wastewater treatments were effective producing non-toxic water for the growth of the model organism.

Samples	pH	Inhibition %
Inlet 14/09 kl 13.00	7.9	1.37
Inlet 14/09 kl 17.00	8.2	24.1
SBBR out 14/09 kl 17.00	8.37	Negative
MBR out 14/09 kl 17.00	8.03	Negative
Sand filter out 14/09 kl 17.00	7.74	Negative
Ozone out 14/09 kl 17.00	7.86	Negative

Table 11. Inhibition % for six different samples taken from different steps in the plant.

6.7 Evaluation of irrigation suitability

From the above evaluation of the analysis results from the pilot demonstration, it is possible to produce nutrient rich water with extreme low concentrations of contaminating substances if any. As described in section 4.1.1, since the water has an agricultural value, it is the ministerial act nicknamed the ‘Sludge Act’ that regulates the use of it for irrigation purposes. To evaluate if it is possible to bring ‘The Irrigation Symbiosis Water’ onto the fields in Denmark, it will have to be compared to the threshold values stated in this act.

However it is not possible to make this comparison directly, since the values are given in relation to the dry matter content of sludge. To make the comparison is has to be done on a common parameter. One such is kg. applied phosphorous, but that is only possible for a few of the heavy metals. Another approach is to use the maximum amount of sludge (measured in dry matter) it is allowed to apply per hectare land as reference, and compare that with the maximum amount of water it is possible to apply to a grass field in Denmark during the growth season and then back cast the threshold values for water.

In the matrixes below these calculations are shown for heavy metals and organic xenobiotics respectively (< indicates the measure was below detection limit).

Threshold values Sludge Act	unit	Cd	Hg	Pb	Ni	Cr	Zn	Cu
- with dry matter reference	mg/kg	0,8	0,8	120	30	100	4000	1000
- with phosphorus reference	mg/kg	100	200	10000	2500			
max. applicable sludge per ha	kg/ha/Y	7000	7000	7000	7000	7000	7000	7000
- threshold value pr. ha	mg/ha/Y	5600	5600	840000	210000	700000	28 mill.	7 mill.
Conversion to water reference								
-max irrigation grass field - m3	m3/ha/Y	1800	1800	1800	1800	1800	1800	1800
-max irrigation grass field - liter	l/ha/Y	1.8 mill	1.8 mill	1.8 mill	1.8 mill	1.8 mill	1.8 mill	1.8 mill
Threshold value water - mg/l	mg/l	0,0031	0,0031	0,4667	0,1167	0,3889	15,5556	3,8889
Threshold value water - µg/l	µg/l	3,1	3,1	466,7	116,7	388,9	15555,6	3888,9
Actual detected content								
Normal concentration combined	µg/l	< 0,05	< 0,03	< 0,3	2,9	0,43	12	4
Spiking 14/9-2017								
MBR out	µg/l	< 0,05	< 0,03	0,63	23	0,54	130	17
SBBR out	µg/l	0,26	0,17	7,7	16	17	110	85
Factor below threshold								
Normal concentration combined		62	104	1556	40	904	1296	972
Spiking 14/9-2017								
MBR out		62	104	741	5	720	120	229
SBBR out		12	18	61	7	23	141	46

Table 12: Threshold calculation for heavy metals

Threshold values Sludge Act	unit	LAS	PAH	NPE	DEHP
-with drymater reference	mg/kg	1300	3	10	50
- with phosphous reference	mg/kg				
max. applicable sludge	kg/ha/Y	7000	7000	7000	7000
- threshold value pr. ha	mg/ha/Y	9100000	21000	70000	350000
Conversion to water reference					
-max irrigation grass field - m3	m3/ha/Y	1800	1800	1800	1800
-max irrigation grass field - liter	l/ha/Y	1800000	1800000	1800000	1800000
Threshold value water - mg/l	mg/l	5,0556	0,0117	0,0389	0,1944
Threshold value water - µg/l	µg/l	5055,6	11,7	38,9	194,4
Actual detected content					
Normal concentration	µg/l	< 200	< 0,04	< 0,1	0,2
Spiking 14/9-2017		* not spiked			
MBR out	µg/l		0,23	1,1	
SBBR out	µg/l		2,04	3	
Ozone out	µg/l		1,39	0,1	
Factor below threshold					
Normal concentration,		25	292	389	972
Spiking 14/9-2017					
MBR out			51	35	
SBBR out			6	13	
Ozone out			8,4	389	

Table 13: Threshold calculation for organic xenobiotics.

The two matrixes show that the potential content of remaining problematic substances in the water is far below the threshold values stated in the Sludge Act. For heavy metals it is between a factor 10 and 700 below the threshold in the spiking situation, which means, that it is up to 10 times below the mentioned values in the normal operation conditions with 10 times lower inlet concentrations.

Nikkel is the only exception, which is explained above in section 6.4.3. For organic xenobiotics you also see a factor between 10-1.000 below threshold - in most cases even in spiking condition. It also shows that the MBR are the best performing technology on most parameters, and that ozonation does not seem to be necessary after a MBR treatment as the organic xenobiotics are removed. Only an UV treatment might be necessary for hygienisation of the water.

Hence - evaluated against to The Sludge Act, it can be concluded that the water produced by the Irrigation Symbiosis method is suitable for irrigation, and the irrigation can be carried out without risk to the environment.

Being The Sluge Act regulating the reuse of water for agricultural purposes, currently creates unnecessary restrictions for the use, since several food companies like eg. Arla, do not accept sludge being spread on the fields of their supplying farmers. This is understandable as there can be a risk of contamination applying sludge to the field. But the treated wastewater will be rejected on the same grounds even though the risk profile is almost as different from sludge as it can be, as the comparison above shows.

This and the complexity of the above calculations and difficulties of making this comparison shows, that the sludge act is inappropriate to apply on reuse of treated wastewater for irrigation. In conclusion there is need for a new legislative framework for regulating this - in Denmark - new praxis. A framework with clear quality criteria for the water, defining what it can be used for and how.

6.8 Irrigation test

To get an impression of the effect of irrigating with the nutrient rich water, an irrigation test was carried out on a grass field near the pilot plant in Nordby. Before the test was initiated, the project applied for and was granted permission to spread the treated water on the field. But the process of getting the permission was in itself a demonstration of the lack of an adequate legislative framework for reuse of treated wastewater for irrigation. The responsible municipality had to evaluate the request within several legislative areas and on a range of periphery parameters, before permission could be granted. This delayed the upstart of the test irrigation, and it was only carried out from mid August till end of September 2017.

The test field measured 0,1 hectar and was irrigated 4 times with a 10 m^3 slurry spreader with 12 m boom with hoses. As such the test field was applied 40 mm. of nutrient rich water.

Figure 40: Irrigation with produced nutrient rich water.

With an average nutrient concentration of 60 mg/l for N and 7 mg/l for P, the 0.1 hectare of land was applied 2.4 kg N (26 kg/ha) and 280g P (1.8 kg/ha). As the test was carried out late in the growth season, which in addition had been very rainy, the effect of the irrigation was not measurable in content of protein formations and N uptake in the plants. Though the effect of applying ammonium with the water was visually clear, by the greener nuance of the grass at the irrigated strip of the field, as seen in the figure 42 below.

‘

Fiure 41: Visual effect of applying nutrients to the grass – right side is irrigated.

7. Full scale concept

As elaborated above, both lab trials and pilot tests proved that the Irrigation Symbiosis approach to water treatment is possible. Next step was to estimate how it can be scaled up and turned in to full-scale operation. Below this is done, with the Nordby WWTP as model – and based on the experiences running the pilot plant.

7.1 Conceptual design basis for a full scale plant in Nordby

The Nordby WWTP has a capacity of 3500PE (based on BOD load) and a hydraulic load of 130.000 m^3/year. As described in section 4.2 the composition of the wastewater received at the treatment plant in Nordby is generally comparable to the average indicators of wastewater received by small Danish WWTPs < 5.000 PE. However, the content of nitrogen appears to be higher (thick waste water), whereas the amounts of organic environmentally harmful substances were low in all of the four samples analyzed. Furthermore, the levels of heavy metals were also very low but corresponded to average levels found in small WWTPs.

During the pilot plant demonstration phase at Nordby WWTP the winter operation mode with full nitrification/denitrification as well as the summer operation mode, where nitrogen was kept in the water, was successfully demonstrated. Furthermore, the pilot test demonstrated the ability of the technology setup to remove unwanted substances resulting in an effluent quality that complied with the requirements. Based on these results, the pilot plant configurations are assumed to be scalable, hence it will provide the design basis for the conceptual design.

As described in section 6.1 the pilot plant setups comprised a pretreatment step using a band filter, followed by two separate main treatments; MBR and SBBR, respectively, and a two-step polishing process consisting of ozonation and a traditional sand filter. See figure 42 below.

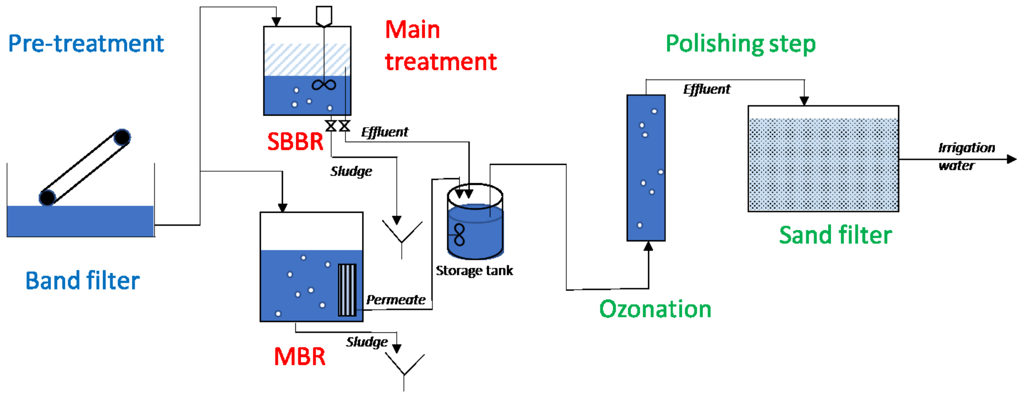

Figure 42. Pilot plant technology setup.

In the conceptual design the sand filter will not be included, as the individual effect of this polishing step was not documented in this project. Furthermore, the reed bed, which was initially included in the treatment train, is omitted from the conceptual design, as this technology was not included in the pilot scale setup. As the new Nordby WWTP (commissioned in 2017) is already based on SRB technology it is considered to be relatively easy to convert the plant to SBBR operation. Therefore, the SBBR technology is not included in the conceptual design of a green field WWTP. But to use it as a reference, the CAPEX for this plant was 12.3 mill. DKK and the estimated OPEX is 313.000 DKK a year.

7.2 Full scale treatment setup and cost specification

In the following a conceptual design of a full-scale treatment plant based on band filter, MBR and ozonation is presented in terms of associated costs and operation requirements. The conceptual design is based on upscaling and optimization of the pilot plant configurations and operation conditions both in terms of the capacity (hydraulic and chemical load) as well as the consumables (electricity, CIP chemicals etc.).

The pilot plant setup was designed to obtain an effluent quality equivalent to the requirement for direct discharge from municipal WWTP in Denmark. However, as described previously, the water is to be used for irrigation and fertilizer purposes, therefore different plant operation modes and effluent requirements concerning phosphorus and nitrogen apply in summer and winter, respectively: The phosphorus is to be removed in winter and maintained in the water phase during summer operation. However, as no specific biological or chemical phosphorous removal step was included in the setup this is not comprised in this conceptual design. The lack of operational data for phosphorous removal is not considered of concern as chemical precipitation of phosphorous in municipal wastewater is well known and related cost can easily be estimated. Biological nitrogen removal is to be fully implemented in the winter period, whereas the operation mode in summer should allow for the nitrogen to stay in the effluent water. The change in operation parameters i.e. lager oxygen consumption for the MBR process in winter time is taking into account in the operational costs and consumables.

In full scale the band filter is designed for a max. hydraulic load of 100 m3/h with a filter belt size of 150µm. The band filter is operated based on level controlled start/stop activation. During peak periods i.e. in tourist season and heavy rain fall, the belt filter will run more continuously hence require more electricity than during dry weather and low season. The band is cleaned using a combined scraper and spray system. The conceptual design and associated cost of a full-scale band filter is further described in table 14.

For the main MBR process, the necessity to run in different operation modes in winter and summer, respectively, requires more operational flexibility in a full-scale plant than it was possible to demonstrate in the pilot plant setup. In example, the flux in summer operation will be lower due to a higher fouling rate. Figure 43 illustrates a conceptual way to look at the flexibility of the MBR process. The cost and consumables associated with the full-scale implementation of the MBR technology is specified in table 14, 15 and 16.

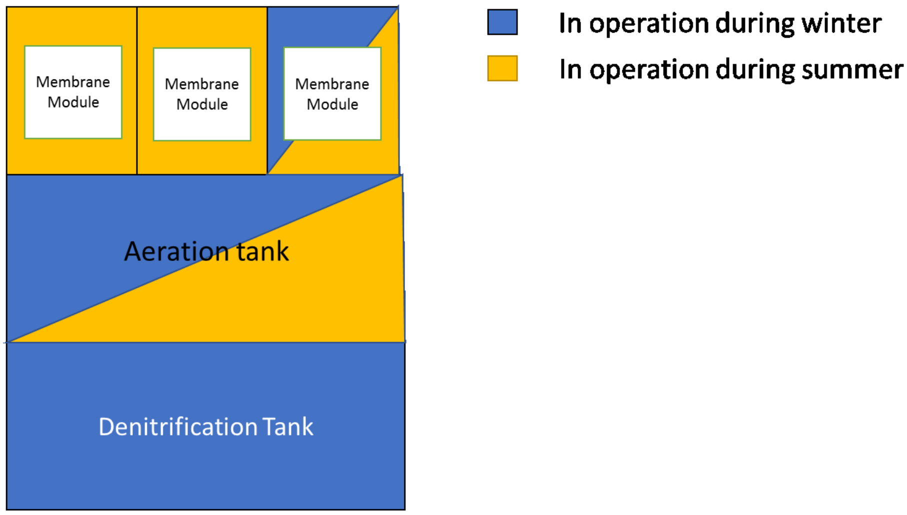

Figure 43: Conceptual setup for MBR operation in summer and winter mode.

Based on experience data and the results obtained in the pilot setup, the consumables associated with a full-scale plant for ozonation of the wastewater in Nordby (average flow of 15m^3/day) has been estimated. It is assumed that an ozone (O_3) dosage of 6-10mgO^3/m^3 is sufficient to obtain the required water quality after this polishing step. This means, that approximately 2-3,6kWh is consumed for the production of ozone (based on oxygen) to be applied per day (see table 14).

Table 14. Costs specifications concerning the conceptual design of a full scale setup. The cost for electricity is based on a KWh price of 2.25 DKK/KWh on Samsø (March 2018).

Technology (Treatment step)	CAPEX	OPEX			
	Plant installations costs including total equipment, engineering, installation, commissioning	Electricity	Chemicals for operation incl. CIP (type/amount/cost)	Manpower for operation and maintenance	Other costs associated with operation, maintenance, sludge/ waste handling
Band filter, AL-2 (Pretreatment)	300,000DKK*	0.68-2.03 kWh depending on the hydraulic load (1,53-4,57 DKK per hour of operation)	Not specified	2-3 hour/ week for operation control, cleaning and maintenance 10-12 hours/year for standard service	5-15,000 DKK for spare parts/year.
MBR, Alfa Laval (Main treatment)	~3,500,000-4,000,000 DKK**	~1 kWh/m^3 for normal MBR operation (2,25 DKK/m^3) ~1,2 kWh/m3 low sludge age MBR (2,70 DKK/m3)	Specified in table 15 and 16	1 full time employee	Not specified
Ozonation Air Liquide (Polishing)	Not specified	16 kWh/kgO3 (0.32-0.54 DKK/m3 when assuming an ozone consumption of 6-10gO^3/m^3)	Oxygen for the production of ozone	Not specified	Not specified

*) Price including Al-2 Band filter 3,6 M, control box, PE Tank for the band filter, rotary scraper, cleaning/spray pump, sludge pump, sludge tray, 20 ft. container (isolated).

**) Full scale plant designed for both low sludge age and normal MBR operation (because one has more membrane, the other larger plant)

Table 15. Consumables for CIP of membranes during standard MBR operation/ winter operation (approximately 8 months per year)

Product type	Product concentration (% mass)	Volume per CIP of one module (l)	Volume per CIP of the whole plant (l)	Number of CIP/ soakings per season	Seasonal consumption (l)
Citric acid	40	62.5	187.5	1	187.5
HCl*	37	6.7	20	1	20
NaOCl	15	25	75	2	150
NaOH*	35	3.3	10	2	20

*) Estimated based on alkalinity and pH value

Table 16. Consumables CIP of membranes during low sludge age MBR operation/ summer operation (approximately 4 months per year)

Product type	Product concentration (% mass)	Volume per CIP of one module (l)	Volume per CIP of the whole plant (l)	Number of CIP/ soak-ings per season	Seasonal consumption (l)
Citric acid	40	69.44	278	1	278
HCl*	37	7.41	30	1	30
NaOCl	15	41.67	167	12	2000
NaOH*	35	5.56	22.22	12	267

*) Estimated based on alkalinity and pH value

7.3 Feasibility of full scale plant

The results from the pilot test and the above estimations for a full-scale plant indicate that it is technically and economically feasible to establish and run the Irrigation Symbiosis concept at small plants in agricultural areas, like in Nordby at Samsø. It can be expected also to be the case for medium sized WWTPs with a capacity of 10-20.000 PE. For larger plants specific tests and calculations will have to be done.

As mentioned above the newly established WWTP in Nordby is based on SBR technology, which fairly easy can be altered to SBBR and operated in Irrigation Symbiosis mode. By doing so, Samsø Spildevand can turn the Nordby WWTP into a producer of up to 130.000 m3 nutrient rich irrigation water a year.

The other WWTP at Samsø located in Ballen is relatively old and requires renewal within the coming years. An adjacent solution could be to build a new plant based on MBR technology thereby enabling production of fertilizing water here as well. With both plants operating in Irrigation Symbioses mode Samsø Spildevand will be able to replace the amount of groundwater that the farmers at Samsø today use for irrigation – and in addition supply them with a considerable amount of the nutrients needed for growing their crops. Though it will only be done on non-food crops, until proper legislation for reuse of water for irrigation is in place and there is full documentation for the food safety.

8. Conclusion

The Irrigation Symbiosis project has proven, that by running existing treatment technologies without nitrification and with short retention time, it is possible produce safe nutrient rich irrigation water. It lays the foundation for establishing new symbioses between wastewater treatment and agricultural production.

8.1 Summary of results

The Water symbiosis approach to wastewater treatment was developed and tested through lab trials with simulated wastewater and then in pilot scale with real wastewater at Nordby at Samsø.

The lab trials proved that is possible to run existing technologies for main biological treatment without nitrification and with short retention time to keep the majority of the nutrients in the water, and still remove both heavy metals and organic xenobiotics. The SBBR (Sequencing batch bio reactor) and MBR (membrane bio reactor) proved to be the best performing technologies in this regard. It also showed that a reed bed and a sand filter modified absorbed N and P respectively and hence are not suitable as polishing steps when producing nutrient rich irrigation water.

The pilot scale test confirmed the performance of the SBBR and MBR technologies, but also pointed out the MBR as most efficient in term of removing pollutants. It also proved that it is possible to shift the operation of the technologies between a summer mode without nitrification and a winter mode with nitrification and removal of phosphorous.

A comprehensive analysis programme during the test period including a spiking campaign, showed cleansing levels below detection values, when using normal wastewater in Nordby, and on some parameters even when using spiked wastewater with 10 times higher concentration. The heavy metals are presumable withheld in the sludge. The low doses organic xenobiotics that eventually pass though to the water fraction can easily be removed via the ozonation, which was added as polishing step in the pilot test set up. But with the detected low concentrations it might not be necessary to add this relatively costly process. An UV treatment might be sufficient. For the same reason the sand filter, which also was added during the pilot test, is superfluous.

An initial analysis of the relevant legislative lead to the conclusion, that there is no legislations in Denmark nor EU that prohibit use of treated wastewater for irrigation purposes, but when it has an agricultural value, as is the case when it contains nutrients, it is the act nicknamed 'The Sludge Act' that regulates this. It is difficult to apply on nutrient rich irrigation water though since the threshold values for concentrations of heavy metals and organic xenobiotics in this act are stated in relation to dry matter content of the sludge and not water. A comparison on the maximum amount of water that can be applied to a grass field per year, shows that the amount of pollutants that possibly can be brought to the field are between 10 and 1000 times below the threshold values for applying maximum allowed amount of sludge – which in praxis makes 'The Sludge Act' inadequate for regulating use of treated wastewater for agricultural purposes.

8.2 Main conclusion

This evaluation of the produced water within the relevant legislative framework shows, that **it is possible to produce safe nutrient rich irrigation water by the method proposed, developed and tested in The Irrigation Symbiosis project.** And the developed full scale concept demonstrates, that with a few modifications and improvement this method can be applied in full-scale, which can lead to the formation of symbiosis collaborations between farmers and wastewater companies in urban areas surrounded by farmland. On the Island of Samsø alone, Samsø Spildevand would be able to supply water equal to what is pumped up from the underground for irrigation pr. year - between 200-300.000 m3. Several hindrances have to be overcome for it to become a widespread praxis in Denmark though – like unclear and inappropriate legislative framework and mental barriers. A new legislative framework on national and EU level, with clear quality criteria for the water, defining what it can be used for and how, can ease the way towards implementing the method and help making it an acceptable praxis.

8.3 Value creation - occupation

The economical value created by the Irrigation Symbiosis approach to wastewater treatment can be estimated on 2 parameters:

1) Improved economy in WWTPs
2) Increased sale of technologies

1) Samsø Spildevand's plants in Ballen and Nordby , can be used as an example for estimating the value created by implementing the Irrigation Symbiosis solution in a WWTP. It will realistically neutralize the cost for energy consumption and potentially generate revenue from sale of irrigation water. Furthermore environmental taxes for discarding treated wastewater to recipient can be avoided.
For the two plant the figures are:
Capacity: 15.000 person equivalents (PE)
Savings energy consumption: 100.000 dkk
Environmental taxes: 150.000 dkk
Total annually savings: **250.000 dkk**.
Irrigation water: 380.000 m3 + 15T N + 2,2T P, can irrigate and fertilize approx. 400 ha
Estimated income: 5 dkk. per m3 water = **1.9 mill dkk**.

In places abroad where it would be relevant to install the Irrigation Symbiosis solution, it would typically be in plants of 100.000 PE or more and in areas with water shortage and hence a much higher price on irrigation water. This will make the business case very favourable.

2) The export potential for the Irrigation Symbiosis solution is foreseen to be substantial. For Alfa Laval and the other technology providers this will result in a significant value creation both in terms of revenue and employment. Below the potential is estimated with Alfa Laval as example.
A sale of membranes to a 100,000 PE capacity per year will mean additional earnings of 30 mill. dkk. and employment of approx. 8 extra employees of which 75% might come in their plant in Nakskov, which is characterized by declining business activity and low employment.
If a capacity of 1 mio. PE was sold, further 300 mio. dkk. in revenue is generated and estimated another 20 employees will be needed.

In addition to this direct value creation there will be an indirect local in terms of new bio economical business opportunities. Since the solution is based on proven technologies and primarily consists of new ways of running them will be no options of taking out a patent on the Irrigation Symbiosis solution.

8.4 Perspectives – export potential

Due to the current barriers in a Danish context, the potential for the developed solution on short term primarily lies in countries with more severe water challenges and hence a longer tradition of using treated wastewater for irrigation. Today this is often done without proper treatment and safety precautions. The Irrigation Symbiosis approach can offer an environmentally safe alternative to this praxis in an economically feasible way, which makes it interesting to apply many places in the world – also in lesser affluent regions, lacking basis water treatment infrastructure. Furthermore the business case for providing nutrient rich irrigation water will be even better in climatic conditions, where it can be used for cultivation all year round. Hence the Irrigation Symbiosis concept can be foreseen to have a substantial export potential.

8.5 Outreach

These perspectives have evoked a great interest in the project from professional stakeholders in Denmark and abroad and from the public at both Samsø and in Denmark. During the coarse of the project a number of seminars have been held with participants from both authorities, business organizations and research institutions – latest at the closing seminar held at the newly build innovation center for water, Aquaglobe in Skanderborg in February 2018. While the pilot plant was running at Samsø during the summer 2017, several delegations from wastewater companies and other interested stakeholders visited the test site at Nordby to learn about the Irrigation Symbiosis concept - among them a delegation from the Turkish Ministry of Water and Environment. Also the Samsø islanders showed great interest. At a function at the Nordby plant in June 2017, up to 100 people, primarily from Samsø showed up and had an introduction to the Irrigation Symbiosis concept and the perspectives in this new approach. In conjunction to this event, the project was presented in a news feature on the regional radio channel, and was mentioned in local newspapers.

Finally the project has been represented at national and international conferences on water with papers/posters and presentations. The Danish Water conference in spring 2017, The Nordic NORDIWA conference held in Aarhus October 2017 and not the least at the International Water Association conference in May/June 2017 held in Florianopolis, Brazil and it will be presented in Tokyo 2018. Here it was presented under the main theme, Resource Recovery. Apart from obvious environmental benefits from reusing the resources in the water and the water itself, the discussions under this theme focused on the new business models it allows for, which can make it affordable to bring wastewater treatment to the billions of people who currently lack access to clean water and proper sanitation facilities, and at the same time give access to key resources for a local agricultural production. This development perspective underlines the relevance of applying the Irrigation Symbioses approach worldwide.

Appendix 1. Relevant Legislation

The review of all aspects in four legislative acts that are relevant for field irrigation with treated wastewater. Please find conclusions in the main report in Section 4.1.3

Consolidated Environmental Protection Act (LBK No. 966 of 23/06/2017)[21]
Water Directive has been implemented in the Danish Environmental legislation (consolidated environmental protection act). The main aim of the environmental protection act has been summarized in Section 1: “The purpose of this Act is to contribute to safeguarding nature and environment, thus enabling a sustainable social development in respect for human conditions of life and for the conservation of flora and fauna.” Treated wastewater for usage as field irrigation water will become a product subjected to the environmental act, because according to section 2 the act also includes “products or goods likely to cause pollution in connection with manufacture, storage, use, transport or disposal.” Article 3 includes several sections on protection of soil and groundwater relevant when using wastewater for field irrigation.

The following aspects are especially relevant in relation to the usage of treated wastewater for field irrigation:

- Section 19: “Substances, products and materials likely to pollute groundwater, soil and subsoil shall not without a license be... 2) discharged to or placed on the ground... Licenses are issued by the regional council unless otherwise decided by the Minister for Environment and Food in Denmark (Subsection 4).

- Section 20: “A license under section 19 above may be modified or revoked at any time and without compensation, when advisable because of: 1) risks of pollution of water supply plants, 2) implementation of another method of sewage discharge in accordance with a plan under section 32 below, or 3) other considerations for the environment.”

Ministerial act on water quality and control of water supply plants (Bekendtgørelse om vandkvalitet og tilsyn med vandforsyningsanlæg (BEK no. 1147 of 24/10/2017)[22]
According to Article 1, this ministerial act determines the quality requirements to be achieved regarding water for all water supply plants, which deliver water for food product companies, medicine companies, institutions, restaurants, hospitals etc. and households. In Appendix 1, the threshold values for drinking water have been specified. However, the ministerial act does not specify the threshold values for other water types.

Ministerial act on wastewater permits etc. according to Article 3 and 4 in Consolidated Environmental Protection Act (Bekendtgørelse om spildevandstilladelser m.v. efter miljøbeskyttelseslovens kapitel 3 og 4 (BEK nr. 726 af 01/06/2016[23])
Ministerial act applies to all wastewater plants, and furthermore regarding the addition of substances to groundwater (Article 1). Article 9 includes several sections that specify requirements regarding discharge of wastewater into waterways, lakes or sea.
The following aspects are particularly relevant regarding the usage of treated wastewater for field irrigation:

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[21] https://www.retsinformation.dk/forms/r0710.aspx?id=192058

[22] https://www.retsinformation.dk/Forms/R0710.aspx?id=194227

[23] https://www.retsinformation.dk/forms/r0710.aspx?id=180360

- The ministerial act does not include permit for discharge and disposal of wastewater etc. with agricultural value on ground surface (Section 3).

- It is prohibited to add certain substances directly into groundwater with no ground passage (section 12 and appendix 2).

- The local authority issues license according to Article 19, subsection 1 on discharge and disposal of wastewater without agricultural value on ground surface. Subsection 2 upon issue of license according to subsection 1, it must be ensured that discharge or disposal does not risks of or results in:
  1. groundwater pollution,
  2. surface water pollution,
  3. health threat for people or animals,
  4. nuisance to neighboring inhabitants or
  5. surface runoff.

- Subsection 3. In case of doubt whether there is a risk of health threat to humans, the local authority may require for a statement from the Danish Health and Medicines Authority (Sundhedsstyrelsen), before making a decision.

- According to Article 46, the Danish Nature Agency (Naturstyrelsen) determines whether wastewater, which is to be discharged or disposed of on ground surface has an agricultural value.

<u>Ministerial act regarding the usage of waste for agricultural purposes (Bekendtgørelse om anvendelse af affald til jordbrugsformål (BEK no. 1650 of 13/12/2006))</u>

The scope of this ministerial act is specified in Section 2: "This ministerial act applies to waste from households, institution and companies, including biologically treated waste, industrial process wastewater and wastewater sludge, to the extent that the waste will be used for agricultural purposes".

The following aspects are specifically relevant according to usage of wastewater for field irrigation:

Section 6. Usage of waste, not included in Appendix 1, for agricultural purposes requires a license according to Section 19 in Consolidated Environmental Protection Act.

Sub-section 2. After acquisition of license according to Section 19 in Consolidated Environmental Protection Act, which is not included in the list in Appendix 1, for agricultural purposes, the local authority must establish terms and conditions regarding the fact that requirements in Part 5-10 are valid. The local authority may increase the terms and conditions after the requirements in part 5-10 or establish additional requirements and thus decide that the usage must not take place on specified areas.

Sub-section 3. The local authority must receive a statement from the Danish Health and Medicines Authority and the chief veterinary officer in food product region before the decision is made.

Section 7. Waste, which is to be used for agricultural purposes or added to animal manure based biogas or pre-treatment plants, must comply with threshold values in appendix 2 and must not contain large amounts of other organic micropollutants.

Section 21. Use of waste must not cause pollution of groundwater.

Section 23. Liquid waste must be spread max. in volumes of 3,000 m3 pr. ha pr. planning horizon. In the period from February 1 to April 1, only 1,000 m3 pr. ha can be spread.

Section 24. Usage of waste must take place according to the declaration in Section 13.

Section 25. The hygienic restrictions for usage must be followed, according to Appendix 3.

Section 26. The user shall no later than March 31 every year send field maps and maps indicating the spreading areas to the local authority in the user's municipality. The information requirements are valid only if the user receives waste in volumes exceeding 10 tons of dry matter per year.

Section 27. No more than 7 tons of dry matter pr. ha per year must be added to earth as a result of waste, calculated as average over a period of 10 years. In parks and forests, where no consumable crops are grown, 15 tons of dry matter pr. ha pr. year may be added, calculated as an average over a period for 10 years.

Section 28. Areas, where waste is added, may not contain more heavy metals than indicated in Appendix 4.

Section 29. The local authority monitors whether the requirements stated in this ministerial act are complied with.

Section 30. The supervising authority may issue a request for corrective measures if the usage or storage is or may cause essential harm or pollution.

Sub-section 2. The supervising authority may prohibit the usage of waste for agricultural purposes if the usage directly causes pollution or risk for pollution, or that the general requirements in Sections 7-8 are not met.

- Section 31. In certain cases, the Danish Environmental Protection Agency may grant an exemption from requirements upon a specific application.

Irrigation Symbiosis

The purpose of the project "Irrigation symbiosis – local reuse of water for field irrigation" was to investigate whether it is possible to treat municipal waste water in such a way, that the valuable nutrients are kept in the water, while the problematic substances are removed by running existing treatment technologies differently and hence produce safe fertilizing irrigation water. The conclusion of the project is that it is possible to produce safe nutrient rich irrigation water from wastewater with existing treatment technologies. In the project both trails in laboratory tests and test runs at Samsø in pilot scale have been conducted.

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