This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 773330

Deliverable report for

GAIN

Green Aquaculture Intensification

Grant Agreement Number 773330

Deliverable D2.1
Innovative methodologies for reusing aquaculture side streams

Due date of deliverable: 30/04/2019
Actual submission date: 06/05/2019

Lead beneficiary: Salten Havbrukspark AS (SHP)
Authors: Johan Johansen, Christian Bruckner, Hallstein Baarset, Mohamed Soula & Luis Conceição
Task 2.1 – Valorisation of aquaculture side streams

Dissemination Level:		
PU	**Public**	**Y**
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Document log

Version	Date	Comments	Author(s)
Version 1	01/04/2019	First draft	Johansen J. et al.
Version 2	25/04/2019	Second draft	Johansen J. et al.
Version 3	30/04/2019	Final version	Johansen J. et al.

Recommended Citation

Johansen, J., Bruckner C., Baarset, H., Soula M. & Conceição L. 2019. Innovative methodologies for reusing aquaculture side streams. Deliverable 2.1. GAIN - Green Aquaculture Intensification in Europe. EU Horizon 2020 project grant nº. 77330. 18 pp.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 77330

GLOSSARY OF ACRONYMS

Acronym	Definition
BOD	Biochemical oxygen demand (mg l^{-1} oxygen)
COD	Chemical oxygen demand (mg l^{-1} oxygen)
DM	Dry matter content (%)
MPN	Most probable number
MPS	Magnetic particle separation
N	Nitrogen
SS	Suspended solids (%)
P	Phosphorous

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 77330

Table of Contents

1. Introduction 4

1.1. Background 4
1.2. State-of-the-art 5

2. Approach 6

3. Preliminary results and discussion 8

3.1. Characterisation of wastewater from RAS 8
3.2. Technologies for aquaculture waste water treatment 9
3.3 Sludge valorisation 13

4. Concluding remarks and future work 16

5. References and useful links 18

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 77330

1. Introduction

1.1. Background

GAIN is a collaborative project funded by the European Union (EU), designed to support the ecological intensification of aquaculture in the EU and the European Economic Area (EEA), with the dual objectives of increasing production and competitiveness of the industry, while ensuring sustainability and compliance with EU regulations on food safety and environment.
Eco-intensification of European aquaculture is a challenge that requires the integration of scientific and technical innovations, new policies and economic instruments, as well as addressing social considerations, in order to promote the implementation of the principles of circular economy in aquaculture. In short GAIN aims to:

- Add value to cultivation through innovations in side-streams, ensuring improved secondary materials, increased profit and minimisation of the environmental footprint;
- Improve the management of aquaculture farms, in terms of resource efficiency, fish welfare and reduction of wastes;
- Support integrated policies and address current barriers to the implementation of the principles of circular economy in aquatic production.

A key step towards the ecological intensification is the increase of circularity in the aquaculture sector, to be achieved by the implementation of technologies that minimise environmental impact, by capturing aquaculture side streams and valorise them, as far as possible, thus improving resource utilisation.

GAIN focus on both wastewater and mortalities as aquaculture side streams. The former is characterised by very low dry matter content and small particles, making it more challenging to dewater than faeces-based sludge from other sectors (i.e. urban or agriculture). The latter is a well-defined stream in salmon aquaculture, making it relatively easy to valorise for salmon producers throughout EEA, but often less so for other species in open sea fish farming (i.e. bass and bream). This topic will be addressed in a parallel deliverable, D2.2 - Innovative processes for mortality disposal in aquaculture.

GAIN aims at identifying the most promising technologies and demonstrating their functionality and cost-effectiveness, thereby contribute to the scientific basis required to facilitate further development of relevant EU-regulation. Further information will be presented in deliverable D3.1 – Report on legislation, regulation, and certification of aquaculture within the circular economy.

We recognise that there will not be one single technology that will be a universal solution to ensure circularity throughout the European aquaculture industry: technologies will have to be adapted to different aquaculture typologies (land based, open or closed offshore) and regional infrastructures (transportation, logistics etc), as well as to the choice of valorisation end product (e.g. bioenergy, fertiliser). These issues will be taken into account in evaluating the most promising processes and recommending the most suitable ones, in deliverable D2.5 – Eco-efficient solutions for reusing aquaculture side streams.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 77330

1.2. State-of-the-art

Based on measurements carried out in Norway in the framework of GAIN activities, approximately 170 g of dry sludge (mainly waste feed, faeces and excreta) is generated per kg feed used in land-based salmon farming. Extrapolating this value for larger salmon in offshore aquaculture is likely to be a conservative estimation, as feed utilisation efficiency decreases with fish size. For 2018, the Norwegian aquaculture industry alone used 1.75 million tonnes of feed (Barentswatch, 2019), corresponding to a staggering 300 000 tonnes of dried sludge discharged in Norwegian coastal waters. In comparison, global aqua feed usage was 48 million tonnes in 2015 (FAO, 2018). This represents a two-sided challenge: the aquaculture industry should minimise its environmental impact, while global resource efficiency depends on not losing increasingly scarce nutrients to sea.

The release of fish sludge in a recipient is usually regulated through a concession or production license. For Norwegian offshore aquaculture, the production-license is granted on the basis of a maximum allowed biomass, giving an indirect limit to the feed utilisation per site, whereas for land-based aquaculture the production is limited by a certain amount of feed used per annum.

For offshore aquaculture, there is presently no obligation to remove dissolved or particulate matter from the efflux of the cages, but the site is inspected regularly and any sign of detrimental effects of organic loading (accumulation of faeces or feed in the sediments, anoxic conditions, and decreased biodiversity) can lead to a reduction in the allowed production.

For most of the onshore aquaculture the situation is the same, with no removal of dissolved or particulate matter from the aquaculture wastewater. However, recent Norwegian regulation imposes a demand for all new farming licenses awarded for on land-based aquaculture to reduce the particulate matter/suspended solids (SS; defined as particles larger than 0.45 µm) by 50% and the organic content by 20% (measured as chemical or biochemical oxygen demand; COD or BOD; mgO_2l^{-1}). Thus, this new regulation drives an industrial development towards fish farming systems with lower water consumption (i.e. recirculation aquaculture system: RAS), thereby reducing the investments and operational costs for downstream wastewater treatment.

The technologies currently available for treating aquaculture wastewater is generally regarded as too costly and unstable by the industry, indicating that the technology transfer from other sectors of wastewater treatment has been less than successful thus far. This is due to the very low dry matter content (DM) of aquaculture wastewaters rejected from drum filters, often as low as 0.01% DM. Drum filters (commonly with pore-sizes in the range of 20-80µm) are the state-of-the-art technology for initial dewatering and concentration of particulate matter in aquaculture waste water, as they are regarded as the most cost-efficient alternative for the high flow rates in both RAS and non-RAS production.

Dissolved matter passing through fine-meshed filters remains one of the main challenges of water treatment in aquaculture. Other sectors of wastewater treatment have traditionally used coagulants to neutralise charges of dissolved matter and polymers, thus inducing their flocculation, prior to filtration and water clarification. The use of such chemicals represents added complexity and cost, and often renders the final sludge-product impossible to valorise,

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 77330

resulting in a material that is expensive to dispose of. Thus, the whole process must be viewed in a value chain perspective to avoid the risk of initial process steps creating obstacles for valorisation, by understanding how different markets place different demands on the end product, and how this affects the choice of process technology. Pathways for valorisation of the captured sludge considered by the aquaculture industry thus far, can be divided into three categories:

1) feed for insects and marine invertebrates.
2) fertiliser for agriculture.
3) bioenergy as direct incineration, biogas or pyrolysis.

The first has received much attention, as it also addresses the ambitions of circular bioeconomy. However, the EU and Norwegian legislation is very clear on this point: commercially produced animals cannot be fed faeces or excreta from other animals (see deliverable D3.1 - Report on legislation, regulation, and certification of aquaculture within the circular economy). Thus, until legislation change, this route to valorisation remains closed, and the only foreseeable reason for this to change is linked to new evidence that transmission of undesirable components and pathogens can be avoided, which must be considered highly speculative at this point.

As fertiliser, circularity is obvious and research efforts have been directed towards replicable growth studies in small scale (i.e. pots), but no tests were carried out on industrial scale. The ongoing discussion around this emerging source of fertiliser warrants some caution relative to the levels of heavy metals concentration (zinc and cadmium in particular) that are sufficiently high to impose restrictions for the use of fish sludge as fertiliser in commercial agriculture.

As bioenergy, the aquaculture industry generally regards this as a 'less circular' use of sludge compared to feed and fertiliser. However, the end-users in this category often have better developed value-chain logistics for larger volumes of energy substrates. Incineration of dried sludge generally represents the shortest path to valorisation for dried sludge, but for some fish farmers, biogas digestion is preferred as it require less dewatering. Usually, aquaculture sludge represents a small fraction in a mix of substrates required for a successful biogas process, and the undigested rest (biorest) is still a subject for further valorisation. The interest for pyrolysis as a valorisation process for sludge is increasing, but it remains to be demonstrated using aquaculture sludge as substrate. Even so, the resulting biochar is broadly expected to have a commercial value.

2. Approach

In dialogue with smolt producers that already have, or are obligated to, acquire wastewater treatment technology, we evaluated the available and emerging technologies for capturing dissolved and particulate matter to identify which ones best meet the challenges of the industry. In parallel, the most likely scenarios for valorisation were considered, as they place various demands and/or restrictions on the preceding processes and hence the choice of technology. This iterative evaluation process also considers the analytical data emerging from the characterisation and assessment of wastewater, sludge and end-products.

Other important criteria for prioritising amongst emerging technologies and valorisation

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 77330

pathways was meeting the ambition of circular bioeconomy and increased resource utilisation efficiency, while clarifying the boundaries of current legislation to augment the precision and relevance of these priorities as far as possible.

A uniformly expressed request from the industry was to see the emerging technologies in autonomous operation, on relevant substrate and in relevant scale. Thus, the GAIN ambition to establish an industry scale demonstration unit was well received, and generated interest regarding participation in GAIN task T5.2 – Onsite training courses. Further, a successful demonstration would provide empirical data to support a refinement of the existing regulation on aquaculture wastewater treatment, especially in areas not currently addressed (i.e. sampling protocols and documentation requirements).

The desired criteria to meet for a wastewater technology expressed by the aquaculture stakeholders can be summarised as follows:

- Cost-, energy- and space-efficient, fully automated and reliable.
- Capacity to deal with short term changes in organic loading.
- High removal rates of particulate and dissolved matter to meet the anticipated stricter regulatory demands.
- Removal of dissolved matter without the use of coagulants and polymers.
- Valorisation of the end product in accordance with the principles of circular economy.

Task 2.1, led by SHP, has, thus far, involved GAIN partners: Waister (formerly Multivector; drying of sludge), ANFACO (regulatory overview), SPAROS (feed and faeces composition), WU (fertiliser, aquaponics) and GIFAS (waste streams from offshore aquaculture). In addition, several GAIN end users and other stakeholders have provided valuable contributions, in particular:

- Environmental technology producers:
    - LS Optics AB
    - Mivanor AS
    - Power and Water Ltd
    - Scandienergy AS
- Technology end users:
    - Helgeland smolt AS
    - Salten smolt AS
    - Sundsfjord smolt AS
- Sludge-products end users:
    - Heidelberg group
    - Yara International ASA
    - Protix
    - Renor AS
    - Wapnö gård AB

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 77330

3. Preliminary results and discussion

3.1. Characterisation of wastewater from RAS

As a first step, wastewater from several land-based Atlantic salmon smolt production farms was characterized, in order to provide sufficient background information. All samples taken and subsequent work are based on wastewater discharges from mechanical drum filters (figure 1), also known as reject water (filter mesh-sizes between 40 and 80 µm). The sampling thus far was not systematically carried out to map diurnal and seasonal variations in organic loading, as it will be when the demonstration system is fully operational. However, many samples (volumes between 1 and 25l) were taken to characterize the quality of reject water and to measure the effect of different filtering technologies.

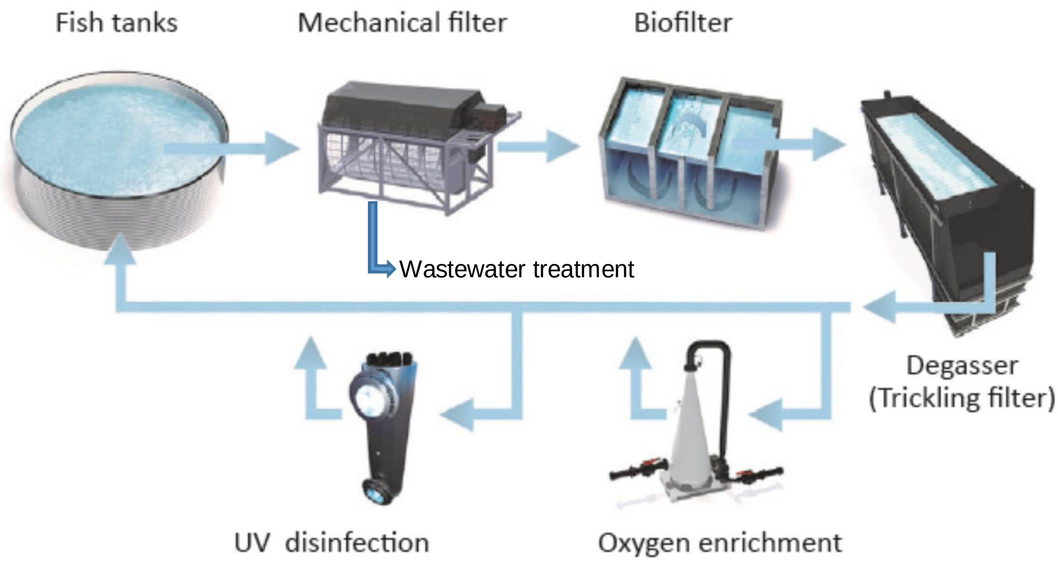

Figure 1. Principle drawing of a recirculation aquaculture system (RAS). The basic water treatment system consists of mechanical filtration, biological treatment and aeration/CO_2-stripping. Oxygenation and UV disinfection can be added as required. Suspended solids are discharged/rejected from the mechanical drum filter and subsequent wastewater treatment includes dewatering and drying (adopted from Bregnballe, 2015).

The results are summarized in Table 1, revealing very low levels of dry matter (DM), hence we had to use suspended solids (SS) as a proxy for DM, by filtering the water through a filter with 0.45µm pores. This filter mesh size matches the new Norwegian regulatory requirement for minimum 50% reduction of SS larger than 0.45µm before aquaculture wastewater can be released into the recipient. For this reason, it was never an option to consider flow-through based salmon production for the GAIN demonstration site, as flow rates are too high, and SS/DM levels are too low to be measured with any degree of precision. If an established flow-through smolt producer aspired to treat its wastewater, it would most likely use the same type of drum filters that we find in all RAS, and, therefore, we assume that our results are relevant for all land based intensive fish farms.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 77330

Table 1. Observed range of relevance parameters for the characterisation of aquaculture wastewater from Atlantic salmon smolt RAS production. Where more than one sample were analysed ranges are presented (max-min).

Wastewater	Observed values
Suspended solids (>0.45µm)	0.007-0.180 %
Particle size: - Median diameter - Average diameter	 0.097-0.469 mm 0.170-0.569 mm
Organic matter: - biochemical oxygen demand (BOD) - chemical oxygen demand (COD)	 140-180 mg l^{-1} 219-2290 mg l^{-1}
Chloride (Cl^-)	620 mg l^{-1}
Conductivity	47.6-242 mS m^{-1}
Total phosphorous	8.8-9.3 mg l^{-1}
Orto-phosphate	1.5 mg l^{-1}
Total nitrogen	7.3 mg l^{-1}
Ammonium (NH_4)	1.1-6.9 mg l^{-1}
Total fat	5.8-24.2 mg l^{-1}

We have chosen Sundsfjord Smolt AS, a land-based RAS and GAIN end-user in northern Norway, as a pilot demonstration site, where we attempted a mass balance approach to quantify the input and output, in order to estimate the correlation between feed usage and the sludge output. According to our findings about 0.17 kg dry sludge are produced per kg feed used (17%). This value may not be representative for the whole industry, but we believe that its order of magnitude is correct, thus indicating the scale of the faeces and waste feed in salmon aquaculture. Some confusion in literature are due to the various definitions of sludge regarding water content. We believe that this led to some initial failed attempts to transfer technology from agriculture wastewater and sewage treatment, simply because the low dry matter content in aquaculture wastewater was not sufficiently accounted for. Further, as salmon digest complex carbohydrates poorly, their diets and faeces contain very little fibre and starch, structural components found in sewage, manure etc, resulting in more compact and 'sticky' sludge.

3.2. Technologies for aquaculture waste water treatment

Candidate technologies, to be tested at the demonstration site, were shortlisted in collaboration with relevant industry stakeholders. Focus was on filtering and dewatering performance, capacity, cost efficiency and autonomous operation. Further, complexity of the systems and robustness towards fluctuations in organic loading (both in flow and concentration) were evaluated, as these were found to cause more or less frequent stops and release of untreated wastewater into the recipient.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 77330

One common approach to buffer against fluctuations in organic loading is to use polymers to promote the aggregation of organic particles in larger flocs, and exchanging the fine-meshed filter cloths with much coarser sieves that allows for a higher flow. While this has proven to work well in many cases, it adds new challenges: it increases complexity and operational costs, releasing polymers into the recipient, and might restrict the valorisation-potential of the final sludge product. Combining polymers with coagulants that precipitate dissolved matter (such as phosphorous), binding these in flocs, usually results in high removal rates beyond the regulatory demands.

A prime example of chemically assisted wastewater treatment is the new and innovative technology of Magnetic Particle Separation (MPS) patented by a Norwegian company Mivanor AS (www.mivanor.no), originally developed to treat leachate from landfills. By adding small fragments of magnetite together with the coagulants and polymers, they create a floc that can be caught by magnetic discs (figure 2). In this way, they catch particles through a system that cannot clog, and the added advantage of the strong magnetic discs, is that the flocs are dewatered as the magnetic force presses the flocs against the magnetic discs. The resulting sludge us usually above 40 % DM, and the purified water can be returned to the recipient. This system is installed at Salten Smolt AS, and the initial results are very promising: 30%, 95% and 99% removal of N, SS and P, respectively. Dry matter content above 50% has been reached, resulting in a relatively stable fish-sludge that can be shipped for disposal at approved landfills. Thus, MPS meets the new aquaculture wastewater treatment requirements in Norway, but the resulting sludge becomes a waste product that require approved disposal, generating further costs while eliminating the chance of valorisation and circularity.

Figure 2. Magnetic particle separation (MPS) developed by Mivanor AS, and commercialised as MivaMag™. Photo with permission from Mivanor, showing water samples from the inlet and outlet of the MPS.

The efficacy of the coagulants (commonly aluminium-, iron- or magnesium-salts) lies in the fact that they are cheap and establish strong bonds with dissolved phosphorous, a process which is costly to reverse. As an example, phosphorous coagulated using metal salts are

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 77330

regarded by Yara International ASA, one of the world leading producers of artificial fertilisers, as unusable as it renders the phosphorous unavailable for uptake by plants.

To meet the aim of circularity, and the ambition of valorisation, SHP have searched for technologies that can remove dissolved matter without the use of such coagulants. The only emerging candidate technology meeting all criteria is Sono-electro flocculation, originally developed to capture heavy metals in process water from the mining industry by the Welsh company Power and Water Ltd (figure 3; www.powerandwater.com). In this patented system, the wastewater flows through a strong electric field that manipulates the charges of dissolved and particulate matter causing aggregation of flocs. Ultrasonic generators directed towards the non-sacrificial electrode helps break up particles and cells to improve efficiency further, while keeping the electrode surface clean of redox-products and the efflux sanitised.

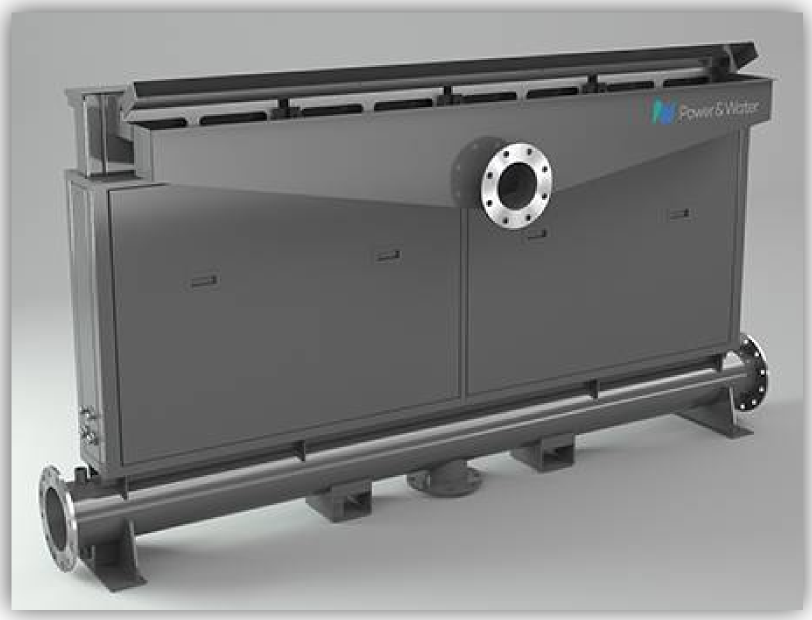

Figure 3. Sono-electro flocculation developed by Power and Water Ltd., and marketed as Soneco™ DB reactor (www.powerandwater.com).

After the flocculation unit, the flocs are still in suspension and needs to be separated from the wastewater, either through skimming or sedimentation (aided by added micro-ballast). This result in a sludge in the range of 1-5% DM, and conventional dewatering and drying equipment are then applied to achieve the desired level of DM.

A first installation of this technology in a land-based aquaculture facility (ERKO Seafood, Norway) has indicated excellent performance: over 95% removal of phosphorous, SS and COD, while over 80% of ammonia was removed. The sludge is subsequently dried, and as no chemicals have been added, it can be marketed as organic fertiliser. However, the complexity of the total system makes the footprint large, and the operational costs high, compared to

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 77330

competing technologies.

Another patented technology called filter-dryer developed by a Swedish company, LS Optics AB (www.lsosweden.com), was identified as the most promising technology to separate the flocs generated by sono-electro flocculation out of suspension with a fine filter (mesh size 7 µm). Under current Norwegian regulation, this filter system meets the obligatory demand for wastewater purification as a standalone unit, without the use of polymers. By using vacuum to draw wastewater through the filter material, high flow rates can be achieved, in spite of the fine filter mesh size. Further, the filter material has exceptional heat transferability properties, with heat energy recovery rates around 95% (without considering the energy in the condensate), making this a significantly more energy-efficient technology than anything on the market. For these qualities, this emerging technology was selected for our demonstration facility. Figure 4 indicates the span in dry matter content where the selected GAIN technologies are cost-efficient, from reject water (0.01% DM) to dry sludge (90% DM).

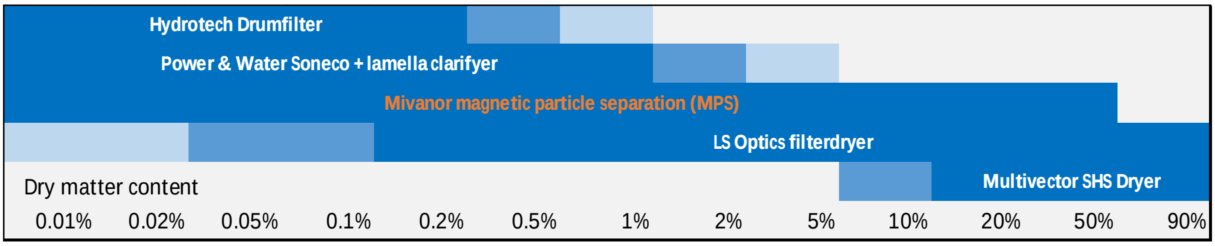

Figure 4. Illustration of the optimum areas (dark blue) and thresholds (light blue) regarding dry matter content, within which the GAIN technologies will be cost-efficient. The degree of overlap between two technologies indicate the robustness of such a combination. Orange indicate system using coagulants and polymers, the white operate without any consumables.

In cooperation with the GAIN industry end user, Sundsfjord smolt AS, we set up a buffer tank (figure 5) collecting all wastewater from the entire RAS smolt production. Three outlets allow us to run different technologies in parallel for comparative studies.

Figure 5. Buffer tank, 3x2m.

The GAIN aquaculture wastewater treatment demonstration technology, referred to as model S3, is now installed at Sundsfjord smolt, and different filter cloths are being tested (figure 6), the overall process is being optimised to reach the target flowrate of 20 l/s while upholding high removal rates. As the work progresses, information is compiled into a user manual available online (Svenningsson & Anglade, 2018), which will be completed within the GAIN project period.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 77330

Figure 6. S3 demonstration unit as produced by LS Optics AB. Right frame show the details of the filter during change of filter cloth. Photo by Salten Havbrukspark AS.

As soon as the filter cloth was in place, the first wastewater samples were drawn before and after filtration to establish a baseline value. This indicated 96-97% reduction of suspended solids (SS), whereas the reduction in organic content measured as chemical oxygen demand (COD) fell under detection level, so we can only say it's at least 86% removal. This is a very promising starting point, because many factors were not optimal, foremost the fact that there was no 'filter cake' established on the filter cloth, which would have increased the filtration efficiency.

3.3 Sludge valorisation

The fish sludge (figure 7) investigated for valorisation potential has been dried by the superheated steam dryer produced by GAIN-partner Waister AS (previously Multivector AS; www.waister.eu) and installed at Helgeland smolt AS, a Norwegian RAS smolt producer, which will be presented in a parallel GAIN Deliverable: D2.2 - Innovative processes for mortality disposal in aquaculture.

Figure 7. Dried, stable and sanitised fish sludge. Photo from Waister AS.

Analysis of the dried sludge indicated a DM content between 90 and 96%, and thermo-tolerant coliform bacteria were below detection level (<20 MPN g^{-1}). This agrees with previous reports on the ability for superheated steam dryers to sanitise sludge (Nygaard & Hostmark, 2008). Furthermore, the dried powdered sludge was odourless, and surprisingly anhygroscopic as there were no indication of increased water content even after many weeks

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 77330

of storage in woven big bags under humid conditions. The density of the sludge appears to be around 0.7 kg l^{-1}, so a full 2 m^3 big bag (1x1x2m) weighs ca 1 400 kg. This seems as very good results, as air-dried fish sludge has been reported to have very low densities (<0.3 kg l^{-1}) with appearance like LECA (Light Expanded Clay Aggregate), making the big bags too unstable to stack, and shipment inefficient and costly.

A seemingly obvious choice for maximum circularity and resource utilisation is to feed the sludge to insects and invertebrates which have shown to eat similar materials in nature, thereby transforming undigested remains into potentially high-value animal protein. However, as will be reported by in GAIN deliverable D3.1 – Report on legislation, regulation, and certification of aquaculture within the circular economy, current EU regulation prohibits the use of animal excreta such as faeces or urine as animal feed ingredient for any commercial animal production. Thus, regulatory adaptations are necessary for this to be a viable alternative for reuse of fish sludge, so together with WUR, a project was initiated for growth and safety assessment aquaculture sludge as a feed source for black soldier fly larvae. Protix, a renowned Dutch producer of insect meal (www.protix.eu) carried out these experiments.

Early results indicated that the drying was too harsh on the amino acids, yielding lower growth than control diets, therefore the experiment was repeated with slightly more gentle drying, lowering the dried sludge DM from 95 to 90% to evaluate if that improved the larval growth. Preliminary results indicate that larval growth and survival were better for 90% DM sludge, but performance was still poorer than for other feed streams. More importantly, some of the heavy metals present in the sludge were bioaccumulative in the fly larvae; cadmium, mercury, manganese and potassium. Taken together, it suggests that the sludge must be diluted in a larval feed mix to ensure growth and safety. The results are being prepared for publication, and will be made available within the project period.

Another pathway of valorisation of sludge is bioenergy, which can be further divided into three different sub-paths; biogas, direct incineration and pyrolysis. Regarding biogas, there are reports of successful use of aquaculture sludge, but only as a minor component mixed with other substrates (Cabell et al., 2018), due to the relatively high levels of protein and fat which results in accumulation of ammonium and volatile fatty acids, respectively. These rest products inhibit the anaerobe digestion, making it difficult for one-chamber digesters to handle high inclusion levels of fish sludge or fish mortalities. SHP are in contact with groups and projects developing multi-chamber digesters allowing them to have different microbes targeting different components of the sludge, and will provide sludge for testing when possible.

Seemingly, the shortest and most mature route to valorisation as bioenergy is the direct incineration for heat production. We have provided dried sludge to the HeidelbergCement group, through their representatives in Norway; Norcem AS and Renor AS. These end users

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 77330

are very competitive and actively position themselves to ensure access and logistics of emerging bioenergy sources. The feedback was very good, with an average calorimetric energy capacity for the dry sludge (96% DM) of 4810 kcal kg^{-1} or 20.2 MJ kg^{-1}. In a comparison with sludge from other landbased fish farms that were producing dry sludge, the sludge dried by the GAIN-partner Waister AS (formerly Multivector) and the only one dried with superheated steam, was considered the best quality. Compared to hot air-dried sludge (as used by the other fish farms – who remain anonymous to us), our sludge was homogenous, containing no 'moist' patches (associated with mould, foul smell) and had higher density and energy concentration. Prior to this test, the cement industry expressed concern about the chloride content, which could hinder the use of the sludge for this application, but the content, 0.65% (dry weight basis), appears to have been within acceptable limits.

Pyrolysis represents a very interesting technology, which has not been investigated for fish sludge as yet. This represents a technical approach to harvest energy as syngas: therefore, it can represent an alternative route to biogas production, which relies on microbial action. However, burning of the resulting gases can represent a source of pollution to the atmosphere, which is currently regulated more strictly then wastewater from aquaculture. Another difference to biogas, is the final product (biochar/black carbon, vs. biorest) which is more easily utilisable and valuable. Although we have not yet had opportunity to investigate this, we are in contact with companies developing such technologies offering to evaluate our sludge within the GAIN project period. An interesting observation is that, while capacity is always a limiting factor for filtering and dewatering technologies, when it comes to pyrolysis, even the pilot plants have higher capacity and could treat the sludge produced by large land-based fish farms.

The last valorisation pathway is as fertiliser. We have provided 80 tonnes of dried sludge to Wapnö Gård, a large Swedish agricultural company (www.wapno.se) and we are awaiting their evaluation from commercial scale conditions. One of the most common issues with the use of fish sludge as fertiliser in commercial agriculture is the high concentrations of some heavy metals, typically zinc and cadmium, where analysis of our sludge resulted in values in the range 330-360 mg kg^{-1} for zinc and 0.45-1.5 mg kg^{-1} for cadmium. These concentrations correlate to the inclusion levels of inorganic minerals in the fish feed, and the fact that these minerals generally have low bioavailability. When uptake and retention is low, most of the minerals added as micronutrients in the feed will end up unutilised in the sludge.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 77330

Table 2. Maximum concentration of heavy metals (mg kg^{-1} dry weight) in organic fertilisers of different quality grades, and their maximum commercial usage (Lovdata, 2019). Numbers in red indicate problem areas reported for fish sludge, leading to quality downgrading.

Quality grade	**0**	**1**	**2**	**3**
Annual usage	**As required**	**0.4 kg/m^2**	**0.2 kg/m^2**	**none**
Cadmium (Cd)	0.4	0.8	2	5
Lead (Pb)	40	60	80	200
Mercury (Hg)	0.2	0.6	3	5
Nickel (Ni)	20	30	50	80
Zinc (Zn)	150	400	800	1500
Copper (Cu)	50	150	650	1000
Chrome (Cr)	50	60	100	150

Maximum concentration of heavy metals in organic fertilisers and their allowed usage for agriculture are listed in table 2 (Lovdata, 2019). As the levels increase, the quality grade goes down and the allowed usage drops. This is of course reflected in decreasing value, and while quality grade 0 can be sold, the lower grades commonly has to be deposited at landfills at a gate fee. Accordingly, it is an economic incentive to make sure the heavy metal contents are sufficiently low to ensure valorisation potential. One way this can be done, is to exchange the inorganic minerals added to fish feed with organic metal species, usually incorporated in beer yeast or in chelated forms, similar to what have been used in agriculture for many years. This issue is addressed by specific activities, aimed at increasing zinc bioavailability in feed, which are being carried out in GAIN Task 1.1 and 1.2.

4. Concluding remarks and future work

Work progress as planned, with no deviation in the timeline for the deliverables. Focus will be on developing the demonstration unit, while following up the initiatives relative to valorisation pathways, and the results will be distributed throughout the tasks in WP4. GAIN have identified the following technologies to best meet the industrial requirements for aquaculture wastewater treatment:

- For particulate matter: S3 filter-dryer by LS Optics AB
- For dissolved matter: Soneco DB reactor by Power and Water Ltd
- For sanitising and stabilising the sludge: SHS dryer by Waister AS (formerly MultiVector)

The challenge of low concentration of suspended solids in the reject water, has proven a

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 77330

formidable one, especially as we aim to bring the fish sludge from 0.01% to 90% DM in one process without any additives. To our knowledge, there is no other technology on the market that offer this functionality. Thus, if we succeed, it will be a game changer for wastewater treatment, across industry sectors, and so it represents a truly disruptive technology.

In the time ahead, task T2.1 will continue optimising filtration performance in our demonstration unit, and then focus will be shifted towards drying the resulting sludge, so that we can produce dry, stabile and sanitary sludge ideal for valorisation. In parallel, the aim is to see how wastewater treatment efficacy increase by pre-conditioning wastewater with sono-electro flocculation. As much as possible of this will be incorporated in the on-site training courses (task T5.2) during year 3 of the GAIN project.

Macroalgae aquaponics will be evaluated as an alternative to sono-electro flocculation for the capture of dissolved matter from RAS aquaculture wastewater. While foreseen to require large footprint to be effective, low operational costs and high value of the 'crop' might make a good case for biologic water purification rather than a technological one. Macroalgae are interesting candidates due to their absorptive capacities, and promising species will be investigated to reveal their growth and bioremediation efficiencies in aquaculture wastewater. In contrast to integrated multi-trophic aquaculture (IMTA) where nutrients in the watershed from offshore farms quickly dilutes and disperse, aquaponics contains the nutrients in the production system, allowing for much higher absorption.

It is foreseen by the Norwegian aquaculture industry that the regulatory requirements regarding capture of dissolved and particulate matter will become stricter as technology develops, and although widely assumed that this will eventually encompass offshore farms as well, this seems to be very difficult and challenging enough in closed/semi-closed offshore cage farms, and virtually impossible for flow-through cages. In the latter case, the best approach is to design diets with high nutrient bioavailability, leaving as little as possible to be released into the recipient.

Given time, the validated GAIN feed concepts (task T1.2) becomes available for use in land-based aquaculture, using zinc supplementations of superior bioavailability, thereby ensuring good fish health with lower dietary inclusion levels, and lowering zinc levels in sludge below 150 mg kg^{-1} and qualify for the top fertiliser grade (quality grade 0; see table 2), maximising valorisation and lifting restrictions on commercial usage. A successful demonstration of improved biologic and economic performance through improved resource efficiency will effectively illustrate all aspirations of aquaculture ecointensification.

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 77330

5. References and useful links

Barentswatch (2019) https://www.barentswatch.no/en/havbruk/

Bregnballe J. (2015) *Recirculation Aquaculture. An introduction to the new environmentally friendly and highly productive closed fish farming systems*. www.fao.org/3/a-i4626e.pdf

Cabell J.F., Gebauer R., Solli L., Kittelsen H. & Briseid T. (2018) *Biogass fra marint fiskeslam sambehandlet med husdyrgjødsel og myse.* NIBIO Rapport 4(112). http://hdl.handle.net/11250/2567506.

FAO (2018) *The State of World Fisheries and Aquaculture*. http://www.fao.org/3/I9540EN/i9540en.pdf

Lovdata (2019) *Forskrift om gjødselvarer mv. av organisk opphav.* https://lovdata.no/dokument/SF/forskrift/2003-07-04-951

Nygaard H. & Hostmark O. (2008) *Microbial Inactivation during Superheated Steam Drying of Fish Meal.* Drying Technology, 26:2, 222-230, DOI: 10.1080/07373930701831648.

Svenningsson L. & Anglade C. (2018) *S3 – technical manual*. http://lsosweden.com/onewebmedia/S3%200%20Technical%20Manual.pdf

The project has received funding from the European Union's Horizon 2020 Framework Research and Innovation Programme under GA n. 77330