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Feasibility study on converting fish sludge into fertiliser

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1. INTRODUCTION

This research is a part of the RAScue project which focuses on two studies. First, a study on making the leading nutrient recovery system in Recirculating Aquaculture System (RAS) more cost effective and energy efficeint. Secondly, a feasibility study on producing fertiliser from fish sludge. This report is the findings of the study from the second part of the RAScue project, with the primary goal of minimising eutrophication in the Baltic Sea by finding solutions to reduce the nutrient discharge from the Åland Islands. Thus, it focuses on finding an appropriate method to utilise the nutrient-rich fish sludge produced by land-based RAS named **Fifax Abp** located on Åland. This feasibility study aims to evaluate if the nutrient contents of the fish sludge can be recycled as fertiliser in order to minimise nutrient deposition from artificial fertiliser run-off to the Baltic Sea.

2. RESEARCH OBJECTIVES

The main objective of this research is to analyse different methods of converting fish sludge into organic fertiliser. These methods are assessed in terms of simplicity, application feasibility of fish sludge fertiliser, nutrient retention, nutrient availability to plants, customer demand and profitability. This theoretical approach aims to select the best out of the assessed methods. Furthermore, this research investigates possible applications of organic fertiliser made from fish sludge to the farmlands in the Åland Islands. An additional goal is to find the total replacement of current artificial fertiliser consumption on Åland if the fish sludge from Fifax were used as fertiliser in place of the currently used artificial fertiliser. By doing so, this research also aims to estimate the decrease in nutrient leakage from the Åland area to the Baltic Sea by the replacement of current artificial fertiliser consumption in Åland with the organic solid fertiliser from Fifax's fish sludge. The reduction in nutrient load on the Baltic Sea through the decrease in spillage from importing artificial fertiliser via shipping is also estimated. It is assumed that there would be less shipping of artificial fertiliser as self-reliance on fertiliser increases.

The objectives of this research address the following research questions:

- What is the capacity of fish sludge as fertiliser? Can it work as a mineral NPK fertiliser?
- What are the different methods used for converting fish sludge into fertiliser?
- What is the best method for fertiliser production?
- How much less artificial fertiliser would be required if fertiliser from Fifax's fish sludge is used instead of artificial fertiliser in the Åland islands?
- To what extent would Åland's nutrient leakage into the Baltic Sea decrease if Fifax fish sludge fertiliser is used instead of artificial fertiliser in the farmlands of Åland?
- How much is the decrease in nutrient load on the Baltic Sea through the reduction of spillage by decreasing the shipping of artificial fertiliser?

3. METHODOLOGY

To better understand the composition of fish sludge, a study on the waste characterisation of fish sludge and NPK content in the output of the fish sludge is done. RAS and waste treatment technologies available for RAS are investigated through a literature review. The studied methods of fish sludge treatment included in this report are drying, composting, aerobic, anaerobic, biological aerated filter (BAF) and biochar production. These methods are compared and analysed to find the best possible treatment process.

The work includes a virtual field visit to the Fifax fish farm, gaining practical insights into RAS technology. In addition, semi-structured interviews are conducted with the following stakeholders associated with the RAScue project: the CEO of the waste management company **Svinryggens Deponi Ab**, the CTO of the fish farming company Fifax, crop and fruit growth advisors, agricultural inspectors from the **Government of Åland**, and farmers. These interviews aim to collect opinions and attitudes on the advanced treatment of RAS waste and reuse opportunities in agriculture. The collected data also provides insight into the soil characteristics of Åland, nutrients use and leakage to water areas of Åland, including the Baltic Sea, and the current and future state of waste management of RAS.

The replacement of artificial fertiliser is calculated from utilising fish sludge efficiently as a fertiliser. Further, the calculation on the decrease in nutrient leakage to the Baltic Sea assumes that leakage from the farmlands is decreased by replacing artificial fertiliser with Fifax's fish sludge fertiliser. An assumption is also made that there are no leakages from the Fifax RAS nor the utilisation of Fifax's fish sludge fertiliser. Moreover, the reduction in spillage and overall nutrient load on the Baltic Sea due to less artificial fertiliser shipping is calculated.

3.1. Replacement of artificial fertiliser

The replacement of artificial fertiliser is calculated based on the total recovery of nutrients from Fifax's fish sludge. It has been assumed that the entire nutrient content of Fifax's fish sludge is fully recovered to produce solid organic fertiliser and that the produced fertiliser is completely applied on agricultural land, which replaces the demand for artificial fertiliser to a certain extent. The average sales of artificial Nitrogen, Phosphorus and Potassium (NPK) fertilisers are given in Table 1 (ASUB, 2021). Here, the average sales of artificial fertiliser are considered the actual fertiliser demand on the Åland Islands.

Table 1. Average sales of artificial fertiliser in Åland (ASUB, 2021).

Parameters	N	P	K
Average sales of artificial fertiliser, t*/year	721	48	272

*t: tonnes

The calculation is done using the following formulas:

(1) Replacement of artificial fertiliser (NPK) = (NPK content in Fifax's fish sludge / Average sales of artificial fertiliser (NPK)) * 100 %

(2) Additional need for artificial fertiliser = Average sales of fertiliser (NPK) – NPK content in Fifax's fish sludge

3.2. Decrease in N and P leakage on the Baltic Sea

The nutrient load to the Baltic Sea from different sources varies from year to year. The amount of precipitation has a significant impact on runoff. For example, it rained a lot in 1998-2000, 2008 and 2012; therefore, more nutrients from the land were washed into the waterways (Ålands landskapsregering, 2022).

Among the anthropogenic sources of nutrient load, agricultural activities constitute the major part, of which N accounts for 47 % and P accounts for 36 % of the total load from land (HELCOM, 2018a). This is 293 and 6.5 t/year of N and P, respectively, in the case of Åland. The total N and P loads on the Baltic Sea for the years 2012-2018 were on average of 3 255 t and 91 t, respectively (see Table 2), which includes total load from land, atmospheric deposition, fish farms and water treatment plants (Ålands landskapsregering, 2022).

Table 2. The average total load of nutrients (N and P) on the Baltic Sea from the Åland islands in 2012 – 2018 (Ålands landskapsregering, 2022; HELCOM, 2018a).

Parameters	N	P
Total load from land, t/year	624	18
Total load from agricultural land, t/year	293	6.5
Atmospheric deposition, t/year	2 347	47
Load from fish farms and WTP*, t/year	284	26
Total load on the Baltic Sea, t/year	3 255	91

*WTP = Water treatment plants

When Åland's fertiliser demand from Table 1 is compared to the total load on the Baltic Sea from agricultural land in Table 2, it can be concluded that 41 % (293 t of 721 t) and 14 % (7 t of 48 t) of the N and P fertiliser used, respectively, ends up in the Baltic Sea. Therefore, when the fish sludge fertiliser replaces the use of artificial fertiliser, the agricultural runoff to the Baltic Sea from artificial fertiliser is also decreased.

It has been assumed that there are no leakages from Fifax RAS nor the utilisation of Fifax's fish sludge fertiliser. Fifax's fish sludge fertiliser can replace N and P demand only by a certain percentage. There are still some leakages from the use of artificial fertilisers that are needed in additional amount. Leakages from the additional use of artificial fertilisers are calculated as follows:

(3) Leakage from additional use of N fertiliser (t/year) = 41 % * Additional need for N fertiliser (t/year).

(4) Leakage from additional use of P fertiliser (t/year) = 14 % * Additional need for P fertiliser (t/year).

Then, the decrease in N and P load on the Baltic Sea is calculated by using the following formula:

(5) Decrease in N and P load on the Baltic Sea (t/year) = Total N and P load from agricultural land (t/year) - Leakage from additional use of N and P fertiliser (t/year).

(6) Decrease in N and P load on the Baltic Sea (%) = Decrease in N and P load on the Baltic Sea (t/year) / Total N and P load on the Baltic Sea (t/year) * 100 %.

A decrease in K load on the Baltic Sea is not calculated since scientific data on K load on the Baltic Sea was not found. The new total load on the Baltic Sea after the decrease in leakage of N and P is calculated as:

(7) New total load on the Baltic Sea after a decrease in leakage (t/year) = Total N and P load on the Baltic Sea (t/year) - Decrease in N and P load on the Baltic Sea (t/year)

Additionally, there are nutrient discharge risks caused by fertiliser transportation by ship. A spillage of only 0.5 % is permitted for fertiliser shipments in one cargo. One cargo can contain about 5 000 t of fertiliser. According to estimates, a single ship's spillage of 125 kg of P in the sea is enough to generate 125 t of algae. (John Nurmisen Säätiö, 2020)

Using fish sludge-based fertiliser on Åland can also decrease the import of fertiliser via maritime transport. Hence, the calculation of the decrease in load on the Baltic Sea after the reduction in spillage of N and P from fertiliser transport by ship is also done. It has been assumed that there is 0.5 % of spillage of both N and P on the Baltic Sea during the import of demanded fertiliser. Spillage on the Baltic Sea is calculated by:

(8) Spillage from import of demanded fertiliser (0.5 %) (t/year) = 0.5 % * Demand for artificial fertiliser (t/year)

(9) Spillage from import of additional fertiliser (0.5 %) (t/year) = 0.5 % * Additional need for artificial fertiliser (t/year)

Then, a decrease in spillage is calculated using the following formula:

(10) Decrease in spillage to Baltic Sea (t/year) = Spillage from import of currently demanded fertiliser (0.5 %) (t/year) - Spillage from import of additional fertiliser after partial replacement with fertiliser from sludge (0.5 %) (t/year)

The reduction in load on the Baltic Sea after the decrease in spillage of N and P is calculated by using the following formula:

(11) Decrease in load on the Baltic Sea after decrease in spillage (%) = Decrease in spillage to Baltic Sea (t/year) / Total load on the Baltic Sea (t/year) * 100 %.

Decrease in load on the Baltic Sea after the reduction of leakage and spillage of N and P is calculated by using the following formulae:

(12) Decrease in leakage and spillage (t/year) = Decrease in leakage from farmlands (t/year) + Decrease in spillage from transport (t/year).

(13) Decrease in load on the Baltic Sea after decrease in leakage and spillage (%) = Decrease in leakage and spillage (t/year) / Total load on the Baltic Sea (t/year) * 100 %.

The total load on the Baltic Sea after a decrease in leakage and spillage of N and P is calculated as follows:

(14) New total load on the Baltic Sea after the decrease in leakage and spillage (t/year) = Total load on the Baltic Sea (t/year) - Decrease in leakage and spillage to Baltic Sea (t/year)

4. BACKGROUND

This section provides background information on the following relevant topics for the report: eutrophication in the Baltic Sea, the Åland Islands, agriculture and soil quality on Åland.

4.1. Eutrophication in the Baltic Sea

Eutrophication is induced by an excessive supply of organic matter rich in nitrogen (N) and phosphorus (P) into a water ecosystem, feeding *primary producers* like algae, cyanobacteria and benthic macro vegetation. An increase in primary production reduces water clarity and increases the deposition of organic material, which in turn reduces light conditions in the water and increases oxygen consumption on the seafloor leading to oxygen depletion. Both species composition and food web interactions are affected by these changes. (HELCOM, 2018)

The Baltic Sea ecosystem is changing due to ongoing eutrophication (Asmala and Saikku, 2010). Nutrient loading into the Baltic Sea has been increasing for a long time, peaking between the 1950s and the late 1980s, causing this eutrophication. To address the deteriorating development, actions to reduce nutrient loading were agreed on by the 1988 **HELCOM Ministerial Declaration**. The **Baltic Sea Action Plan** aims to reach a Baltic Sea unaffected by eutrophication. There are improvements in some areas, but the effects of past and current nutrient inputs still predominate the overall status of the Baltic Sea. According to the integrated status assessment, at least 97 % of the Baltic Sea was assessed as eutrophic between 2011–2016. (HELCOM, 2018)

Nutrient emissions from aquaculture are relatively small and responsible for less than 0.5 % of total nutrient emissions affecting the Baltic Sea. This share is a few percent in Finland, but the local environmental impact may be considerable in areas with intense aquaculture. In 2004–2007, the nutrient input into the system in the form of fish feed for rainbow trout aquaculture in Finland was 829 tonnes N and 115 tonnes P per year. About one-fifth of these nutrients were consumed as food for humans. About 70 % of the primary input ended up in the Baltic Sea, directly from aquaculture and indirectly through waste management. (Asmala and Saikku, 2010)

4.2. Aquaculture & RAS

Aquaculture can play a vital role in fulfilling the increasing market demand for aquatic or seafood in the current scenario of decreasing supply of natural aquatic products from oceans, lakes or rivers (Mirzoyan et al., 2010). In most traditional aquacultures, there are direct emissions of nutrients from fish farms to the aquatic environment, raising issues such as algal blooms, oxygen depletion, mass mortalities among aquatic organisms, high turbidities, and increased *total suspended solids* (TSS) loads. (Chen et al., 1997; Monsees et al., 2017) The economic and environmental limitations of traditional aquaculture, fees for waste disposal and nutrient emissions, as well as the dependence on large volumes of water, led to the development of the *recirculating aquaculture system* (RAS). (Mirzoyan et al., 2010) In addition, environmental legislation puts an obligation to improve waste management and reduce nutrient emissions that support the development of sound, environmentally friendly aquaculture production. (Monsees et al., 2017)

RAS is a modern method of aquaculture that has great potential to use water and space efficiently and supports the sustainable development of the fast-growing aquaculture industry. It significantly reduces the volume of water discharged and compensates for an insufficient water supply. (Mirzoyan et al., 2010) RAS recirculates 90 % or more of the water in the system for farming fish or other aquatic species (Pilone, 2021). In the RAS method, water flows from a fish tank or many fish tanks through a series of treatment processes and then back to the same tank(s) (Mirzoyan et al., 2010).

RAS is usually implemented indoors, raising fish in large tanks where the operators can control water quality completely. This method produces large quantities of fish in a relatively small footprint and character the environmental impacts compared to traditional fishing and animal protein production methods. It allows for predictable and regular harvests due to a more controlled system than the seasonal wild-caught fisheries and other conventional culture methods in the natural environment, such as ponds or net-pen. Traditional methods are subject to environmental conditions, such as airborne and waterborne pollutants, which reduce the control and predictability of the system. (Pilone, 2021)

Although RAS is more environmentally sound than traditional aquacultures, it does produce a concentrated waste sludge that can impact the environment adversely if not appropriately managed (Chen et al., 1997). Due to a super-intensive culture, a large amount of sludge is produced in RAS, which must be treated before disposal (Mirzoyan et al., 2010). Typically, RAS consists of wastewater treatment components, including a biofilter for ammonia and organics removal by appropriate bacteria. Furthermore, TSS is separated from the water in a solids separation unit removing the faeces and is discharged from the system as sludge.

Handling of sludge is a crucial issue of large-scale recirculating fish production systems. However, no standard guideline for sludge management considers the strength and amount of waste generated from RAS. To design appropriate sludge treatment systems, the quantity and characterisation of the waste to be treated must be known. TSS produced can be quantified through a mass balance analysis that considers significant TSS fluxes, including fish excretion, uneaten food and microorganism growth during biofiltration (Chen et al., 1997).

4.3. The Åland Islands

Åland is an autonomous Swedish-speaking region of Finland, consisting of 6,757 islands between Sweden and Finland (Nordic Co-operation, 2022), 60 of which are inhabited. The total area of the Åland Islands is 13,300 km^2, while Åland's land area is only 1,553 km^2. There are 16 municipalities (see Figure 1). The population is about 30,000, of which about 40 % live in the capital of Mariehamn. The economy is based on shipping (40 %), trade and tourism. (Prime minister's office, 2022)

Figure 1. Map of Åland (Visit Åland, 2022).

4.4. Soil types on the Åland Islands

Åland soil types vary from fine sand to clay, with generally low carbon (C) content. Most western parts of Åland have sandy soil, and most northern parts have clayey soils. Both are low in C content. The soils are usually high in Phosphorus (P), Calcium (Ca) and low in Potassium (K), Magnesium (Mg) and Manganese (Mn), but other micronutrients are satisfactory. N content in soils depends on organic matter in the soil; about 5 % N is in organic matter, which is not immediately available to the plants. According to farmers on the Åland Islands, low profitability is the main problem in maintaining their farms.

4.5. Agriculture on the Åland Islands

Interviews with the stakeholders associated with the RAScue project are conducted to obtain an overview of the current agriculture practices in the Åland islands. The Chief Executive Officer (CEO) of **Svinryggens Deponi Ab**, the Chief Technology Officer (CTO) of **Fifax**, crop and fruit growth advisors, agricultural inspectors from the **Government of Åland** and farmers are interviewed. The interview findings are summarised below.

According to the CEO of Svinryggens Deponi Ab, fish sludge has the potential to produce biogas. Fifax fish sludge must be dewatered before anaerobic digestion (AD) in the biogas plant. Dried fish sludge can be mixed with other municipal wastes for AD. A dewatering machine can dry the sludge up to 70 – 80 %. Depending on the size, a dewatering machine can cost at least 400,000 euros. It can be fruitful for Fifax to establish the dewatering machine in their facility. The CEO sees the potential of the liquid after the dewatering process as it may still contain nutrients that can be utilised as fertiliser. If Fifax is not interested in introducing the dewatering machine in their facility, Svinryggens Deponi Ab has plans to establish a dewatering machine.

Svinryggens Deponi Ab is awaiting permission to establish a biogas plant. It is probable that by spring 2024, the biogas plant will start running. Biogas production depends on customer demand. Svinryggens Deponi Ab also plans to operate a biochar plant by the same time.

Local asphalt and concrete industries are some of the potential customers for this biogas and biochar, as these companies can take unrefined biogas (raw methane gas) directly. Therefore, Svinryggens Deponi Ab does not need to build an extra facility to upgrade biogas into biomethane. Currently, there is no gas grid nearby to connect to, even if biogas is upgraded into biomethane. Solid digestate from the biogas plant can be pyrolysed, and the liquid digestate can be used as fertiliser.

Svinryggens Deponi Ab plans to produce 3000 – 5000 tonnes of biochar per year. To put these numbers into perspective: 5000 tonnes of biochar is less than 1 % of the steel industry's demand. The sprinkler system will be used to activate the biochar.

Svinryggens Deponi Ab plans to earn from sales of biogas and biochar. Currently, they send biowaste to Gasum in Turku for biogas production.

According to the interviewed crop consultants at **Pro Agria of Åland**, apples, potatoes, and onions are the major crops grown in Åland. Commercial mineral *Yara fertilisers* (NPK) in granular form, with a size of about 45 mm, are mainly used on agricultural land on the Åland Islands. The Yara fertilisers are imported from mainland Finland. Furthermore, calcium nitrate is imported from Norway in small quantities. Manure and slurry from domestic animals are also used on farms; the amount depends on the crops grown and the soil type.

Yara fertiliser, with a composition of 11:5:18 (N:P:K), is commonly used for apple, onion and potato farming. The average amount of Yara fertiliser applied per hectare (ha) in apple, onion and potato farms in one season in Åland is shown in Table 3. Other macronutrients (Mg, Mn) are added separately.

Table 3. Existing artificial NPK (Yara) application in apple, onion and potato farms in one season.

Crops	N, kg/ha	P, kg/ha	K, kg/ha
Apple	60 – 80	20 – 30	150 – 200
Onion/Potato	100	5 – 55	120 – 180

Farmers already have the technology to apply granular fertiliser in most agricultural fields in the Åland Islands. The granular form of organic fertiliser may be readily available (soluble) to crops like mineral fertiliser. Most farmers do not have the technology to apply sludge or slurry fertiliser. It is not allowed to use manure or sludge on fields after harvest in October until 15th of March due to the possible risk of leaching. According to the crop consultants, sludge form application seems to be less practical in apple, potato and onion farms.

In the case of apple trees, other macronutrients (Zn, B, Mg) are sprayed on leaves throughout the growing season. Ca is applied only at the end of the harvest. Compost, manure or other fertiliser can be applied before planting new trees to improve soil conditions. For wheat and barley farms, fish sludge (after treatment) can be applied. Still, the application of wet fish sludge is less likely as a large amount is required, which can cause runoff of the nutrients, and farmers usually do not have the technology to apply fish sludge. Moreover, permission is required to use fish sludge.

According to the agricultural inspector from the Government of Åland, fish sludge is not allowed for direct application onto agricultural lands as manure. Neither marketing nor selling is allowed without prior approval. It is possible to retrieve clearance by conducting tests to ensure that the fish sludge is clean of pathogens and contaminants.

An interviewed potato, onion and wheat farmer was interested in buying fish sludge fertiliser under the following conditions:

1. The product should be clean (no pathogens and harmful contaminants like heavy metals).
2. The price should be affordable.
3. The fish sludge should be dried and converted into granular form to apply in the apple, potato and onion farms.

Another interviewed greenhouse farmer, who grows various vegetables such as potatoes, lettuce and cucumber, was not interested in using fish sludge-based organic fertiliser. The farmer was not inclined to part-take in organic farming methods as they have already invested significantly into inorganic farming. The farmer currently uses peat (mixed with mineral fertiliser) to grow potatoes. The peat can be reused (spread in open fields) or it can be decomposed to make compost rich in humus. According to the farmer, the challenges of farming in Åland are:

- Less organic content in soil.
- Fungal disease in potatoes (especially in early produced potatoes in June).
- Problems arising from weeds and insects.

Even though the farmer is not interested in organic farming, they expressed that farmers from the Western and Northern parts of Åland could benefit from fish sludge fertiliser, as these regions are low in carbon and nutrient content. According to the farmer, sand drifting in the Western part of Åland could be minimised by the application of fish sludge fertiliser.

5. WASTE CHARACTERISATION OF FISH SLUDGE

Waste characterisation of sludge can provide valuable information for the disposal and treatment of sludge. It can be challenging to degrade the organic matters present in the sludge since they are in particulate form (Chen et al., 1997) . Waste originating from RAS is usually in the form of sludge composed of stabilised fish excreta, such as faeces and a small percentage of uneaten feed particles, and of bacteria growth. This waste is organic in nature and rich in nutrients (Chen et al., 1997; Monsees et al., 2017). Fish sludge is different from *fish (processing) waste*, which includes materials that result after fish processing, such as dead or damaged fish, fish trimmings, and tissues (e.g., heads, intestines, tails, fins, skins, scales, and bones). (Brod et al., 2021; Ahuja et al., 2020). Fish sludge contains about 50 to 92 % volatile (organic) fraction and is usually characterised by its low *total solid* (TS) content (1.5 – 3 %) compared to other animal production or industrial wastewater. Sludge characteristics may also widely vary according to the fish species. (Mirzoyan et al., 2010)

Total suspended solids control (or TSS control) should be the priority for designing a sludge treatment system. Sludge from RAS can be effectively characterised by the ratio of *five-day biological oxygen demand* (BOD_5) to TSS (BOD_5/TSS) and the ratio of *total kjeldahl nitrogen* (TKN) to TSS (TKN/TSS). The BOD_5/TSS ratio measures the degree of sludge stabilisation. A high BOD_5/TSS ratio means that the sludge will decay rapidly and may cause oxygen depletion and odour problems if not properly managed. BOD_5/TSS ratio in sludge is less than that of the excreted faeces of fish because a biological filter partially decomposes the particulate BOD_5. The BOD_5/TSS ratio should be 10 - 30 % in most aquaculture sludge. (Chen et al., 1997)

TKN/TSS ratio in fish sludge can range from 3.8 to 6.3 %. Fish feeds are the main source of nitrogen (N). Most fish feeds contain between 30 to 55 % of protein depending on the fish species and rearing stage. About 16 % of the protein by weight is N. The total N excretion rate by fish averages about 5 % of the feeding rate with about 20 – 50 % of excreted N contained in particulate matter. *Total phosphorus* (TP)/TSS ratio in fish sludge can range from 0.7 to 2.6 %. (Chen et al., 1997)

5.1. NPK content in the output of RAS

When the suspended solids present in the output processed water from RAS are separated, sludge is produced. Typically, processed water from RAS is treated in two steps. First, suspended solids are concentrated using mechanical filters such as clarifiers or drum filters and discharged either after dewatering or directly with the backwash. Then, in a biofilter, toxic ammonium/ammonia (NH_4^+/NH_3), excreted from the fish gills, is converted to nitrate (NO_3^-) by nitrifying bacteria. (Monsees et al., 2017)

Depending on the fish species, 60 − 90 % of the excreted nitrogen (N) is dissolved in process water. In contrast to classical RAS, aquaponic systems utilise such soluble nutrients derived from the fish unit to grow plants in an integrated hydroponic unit. As a result, additional nitrogen fertilisation is not required in a well-balanced aquaponics system. (Monsees et al., 2017)

Fish sludge can have sound effects as an N fertiliser. N contents in fish sludge can be efficiently recycled as an N fertiliser if applied to agricultural land where the demand for nutrient inputs is high (Brod et al., 2017).

Phosphorus (P) in RAS process water is not as abundant as N. Still, P is essential for plant growth. Plants can only assimilate P as dissolved inorganic phosphate ($PO4^{3-}$), which is also called soluble reactive phosphorus (SRP). Dietary P is not retained in fish in a high percentage, but rather excreted. Since the dissolved P strongly adsorbs onto particles, feed leftovers and fish faeces are the primary sources of P, either in organic form or inorganic form as $PO4^{3-}$. Thus, the mechanical removal of suspended solids removes a significant part of P, which can only be recovered if recycled as fertiliser. Substitution of fishmeal with modern plant-based diets increases the deposition of plant-derived organic phosphorus in the sludge but reduces SRP. (Monsees et al., 2017)

P in fish sludge is present as slowly soluble calcium phosphates resulting in low immediate availability of P to plants. Therefore, additional efforts are needed to optimise the P effects if fish sludge is transformed from waste into valuable fertiliser. For example, P is mainly soluble in the hydrogen chloride (HCl) fraction and thus addition of HCl can enhance P solubility. The solubility of calcium phosphates also depends on soil pH, with lower pH enhancing the solubilisation of calcium phosphates and higher pH retarding solubilisation. (Brod et al., 2021)

The presence of potassium (K) is often limited in the process water of RAS, which is not adequate for the plants. Therefore, in aquaponics systems, synthetic chemical fertilisers - mainly nitrogen, phosphate and potassium (NPK-fertiliser) - are supplied to formulate aquaponic media if specific nutrient profiles are not met. Unlike P, K is not a scarce resource. Current legislation and fees do not consider K concentrations in aquaculture emissions. (Monsees et al., 2017)

5.2. Pre-treatment of fish sludge

Effective collection of fish sludge is essential for the recovery of nutrients. The solid removal methods adopted by RAS are sedimentation, sieve separation, medium filtration, and foam separation (Monsees et al., 2017). Different treatments are needed to remove different particle sizes, as shown in Figure 2. The most common solid-removal units used for aquaculture are: a) settling basins that use gravity for separation; b) hydro cyclones or swirl separators that use centrifugal sedimentation, which allows for more rapid separation of the particles from the liquid; c) micro screen filters that screen particles that are larger than the screen's mesh size; and d) granular/porous media filters that use the passage of water through a medium on which the solids are deposited/strained. A backwash is done to clean these filters. Typically, the more sophisticated the technology, the more costly it is. (Mirzoyan et al., 2010)

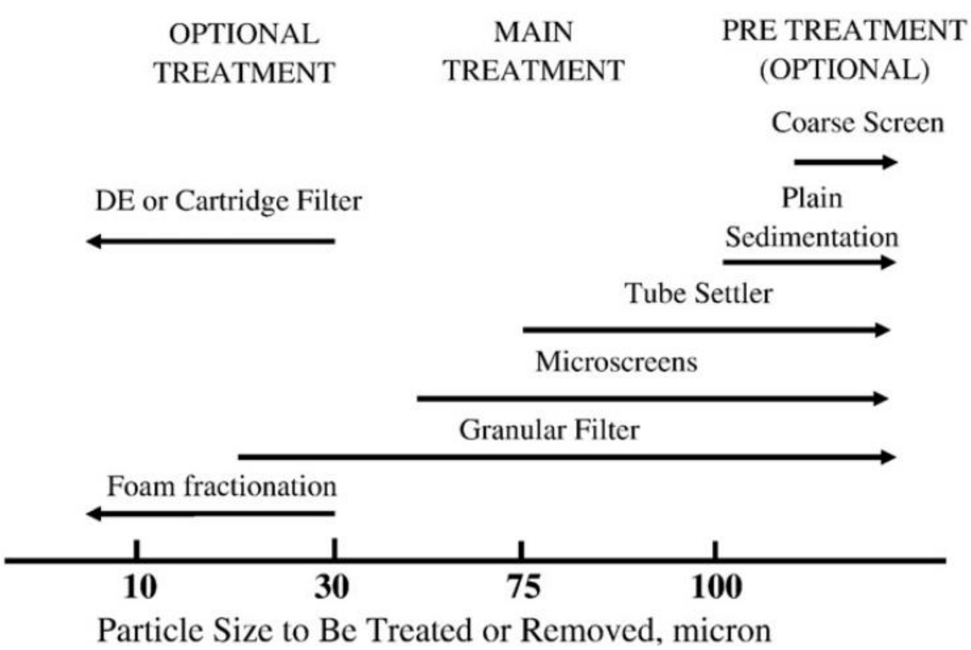

Figure 2. Solid-removal processes for the removal of different particle sizes in microns (Mirzoyan et al., 2010).

In most cases, the concentrated solids, after removal, are discharged from the RAS either into receiving water bodies or the local sewer system or into a decentralised treatment unit, such as *waste-stabilisation ponds* (WSPs). Aquaculture sludge is usually in high volumes with high organic matter content and salts that might interfere with municipal sludge treatment. Thus, their disposal into wastewater-treatment systems is often prohibited. (Mirzoyan et al., 2010).

6. CASE STUDY: FIFAX RECIRCULATING AQUACULTURE SYSTEM

Fifax is the only land-based RAS on Åland and facing the challenge of managing fish sludge efficiently. While it is possible to collect fish sludge from the land-based RAS, it is not possible in sea-based fish farms. The RAS method implemented by Fifax is designed to significantly reduce environmental impact compared to traditional fish farming and conventional RAS methods. Fifax has an entire production facility with a nearly closed-loop water recirculation system, where the fish live indoors in large land-based tanks, with limited effect from external factors such as the weather, climate, environmental factors and water disturbances all year round. As a result, Fifax is able to offer an antibiotic-free product. The RAS method offers more possibilities to optimise the growth environment of the fish through a fine-tuned, largely automated system-operated process. Further, the fish grow in a relatively steady and stable manner, and year-round production yields more predictability compared to more traditional fish farming methods. (Fifax 2022)

Water for the production facility is pumped from the Baltic Sea, which is filtered and treated before it enters the system, and it is continuously purified and recycled in the RAS. Water discharge to the sea is almost entirely free from waste and harmful substances. Their operations cover the whole production chain for farmed rainbow trout. Fish are hatched, cultivated, purged and slaughtered under one roof, and the end product is fish ready for customer deliveries. (Fifax 2022)

By achieving total production capacity, it would be possible for Fifax to produce approximately 3,200 tonnes of whole fish to be slaughtered in a year. The output of the fish sludge is about 20 tonnes per day with TSS of 15 – 20 %.

Pre-treatment of fish sludge is done at Fifax in two steps. First, fish sludge is passed through a *dissolved air flotation* (DAF) system to remove suspended materials such as solids, oil, etcetera. After DAF treatment, the TSS content of the sludge is about 1-2%. Then, the sludge is pressed with a lamellar screw press resulting in TSS of about 15 – 20 %. This sludge is still wet in thick slurry form, as shown in Figure 3.

Figure 3. Picture of wet fish sludge with TSS of about 20 %, produced from Fifax RAS.

After the screw press, the pre-treated sludge is transferred to the container using a screw conveyor without dewatering, which is transported by truck to the composting facility. At the moment, Fifax is paying a waste handling company to remove the wet fish sludge with a TSS of 15 – 20 %.

Composted sludge is not currently utilised in agricultural fields and is not allowed to be sold nor applied in agricultural fields without getting approval from the Government of Åland. There can be nutrient leakage to the nearest water bodies during composting and from the compost area. There is also a possibility that nutrients can be leaked during the transportation of wet sludge. Further, transportation of wet sludge is expensive since large volumes of sludge need to be transported. At the moment, drying the fish sludge is the main challenge for Fifax since it is energy intensive and expensive.

6.1. NPK composition in Fifax's fish sludge

When total production is achieved, the fish sludge produced by Fifax is about 20 tonnes/day with a TSS of 15 – 20 %. The company aims to reach 80 – 90 % TSS in their sludge.

The nutrient composition (NPK) per tonne (t) of fish sludge is known from laboratory analysis. Total nutrients (NPK) produced in a day is calculated by using the following formula:

(10) NPK produced per day (kg/day) = NPK content in sludge (kg/t of sludge) * Sludge produced in a day (t/day).

Nutrients produced in a year are calculated by using the following formula:

(11) NPK produced in a year (kg/year) = NPK produced per day (kg/day) * 365 days.

The NPK composition of Fifax's fish sludge with TSS of 15 – 20 % and their estimated production in a day and in a year are listed in Table 4.

Table 4. NPK composition in Fifax's fish sludge with 15 – 20 % TSS.

Parameter	N	P	K
kg/t sludge	62	19	3.2
% of nutrients/t sludge	6	2	0.32
kg/day	1,240	380	64
kg/year	452,600	138,700	23,360
t /year	453	139	23

If fish sludge is produced 365 days a year, then the amount of N, P and K that can be retained from it are 453 t, 139 t and 23 t, respectively.

7. METHODS FOR CONVERTING FISH SLUDGE INTO FERTILISER

Different methods can be used to efficiently manage fish sludge and convert it into valuable products such as fertiliser and biochar. This section introduces the following methods: Drying, composting, aerobic treatment, anaerobic digestion (AD) and biochar production.

7.1. Drying

In the pre-treatment process, fish sludge can be partially dried up to 20 %. Then, it can be further dried by using an air dryer or a dewatering machine that works as a bailing machine (a hydraulic press that compacts materials into a dense package of a specific size). Drying in a dewatering machine seems more cost and energy friendly than an air dryer, which requires intensive energy. Therefore, as energy prices keep rising, drying in an air dryer can become even more expensive.

The US company *Sebright Technologies* manufactures solutions-based waste handling and recycling equipment, including *Belt Filter Press Sludge Dewatering* machines. Different kinds of *Belt Filter Press* machines are available in different size dimensions. The performance of the *Belt Filter Press* depends on the sludge types. For example, mineral slurries can be dried to cake solids with a 50 – 70 % TSS. (Sebright Product Inc., 2022).

Mechanical filtering before the application of drying techniques can also increase fish sludge's dry matter (DM) to up to 90 %. Pellets can be produced as recycling fertilisers from dried fish sludge, which can be spread on agricultural land with conventional fertiliser spreaders. (Brod et al., 2017)

The bioassay, the incubation and the field experiments performed by Brod et al. (2017) indicated that organic N in dried fish sludge mineralises rapidly and quickly becomes available to plants (barley, ryegrass and spring cereals). The effect of dried fish sludge applied as N fertiliser to ryegrass or spring cereals in pot experiments with nutrient-deficient soils has shown to be as high as 50 – 90 % of the effect of mineral fertiliser. In the same experiment, the effect of dried fish sludge as P fertiliser on ryegrass or barley is comparable to that of dairy manure. (Brod et al., 2017)

In addition to the positive effects on fertilisation, dried fish sludge will be more cost- and energy-efficient to transport than wet sludge or the nutrients in anaerobic digestate based on fish sludge (Brod et al., 2017). Drying fish sludge can be expensive as it requires an initial investment in the dewatering machine. However, after a few years, it should be profitable when the sales of dried solid fertiliser return the investment cost. The simple logistics analysis of a representative smolt hatchery showed that transporting fish sludge to central biogas plants was one of the main cost drivers for the fish sludge digestate treatment alternative (Brod et al., 2017).

7.2. Composting

During composting, organic material in sludge is biologically degraded to a stable end product. This process can reduce waste volume by 50 – 85 %, and properly composted sludge should be pasteurised, nuisance-free, humus-like material. The final product of compost can be used as a soil conditioner. However, due to the high water content in aquacultural sludge, it must be dried first to reduce the water content from above 90 %. Otherwise, it may limit the composting of aquacultural sludge. Co-composting with other solid waste is one solution to solve this issue. (Chen et al., 1997)

Until now, no study has been done on the nutrient (NPK) recovery in composted fish sludge. Future research is recommended to evaluate the potentiality of fish sludge compost for growing different plants.

7.3. Aerobic treatment

Aerobic digestion is used primarily in smaller commercial and public wastewater treatment operations. The major advantages of aerobic digestion are simple operation, lower capital costs, lower effluent biological oxygen demand (BOD) concentrations and production of a biologically stable sludge. (Chen et al., 1997) Some of the disadvantages of aerobic treatment are the cost of aeration, lack of a usable by-product like methane gas, and that the growth rate of microorganisms is much faster than in anaerobic conditions, producing a considerable amount of new biomass accumulated in the reactor, which hinders the reduction of solids (Delaide et al., 2018).

The design criteria for an aerobic digester can be determined from the *hydraulic retention time* (HRT) and *volatile suspended solids* (VSS). Usually, HRT for sludge at 20 ^{o}C is 15 days, and solids loading is 1.6 – 4.8 kg VSS/m^3 per day. Aquaculture can produce sludge from 0.88 to 2.63 m^3 per 20 kg feed input (or 1,000 kilograms of catfish). About 20 – 40 m^3 of air per 1,000 m^3 digester volume per min is required to aerate a digestor tank. Aerobic treatment can be suitable for use in urban areas where land availability is limited, and odour control is important. (Chen et al., 1997)

A study by Monsees et al. (2017) revealed that aerobic treatment of water-sludge mixture from aquaculture has a high potential for significant improvements in nutrient recycling in aquaponics. The study showed that nutrient mobilisation under aerobic treatment resulted in a 3.2-fold increase in mean soluble reactive phosphorus (SRP) from 9.4 to 29.7 mg/l, owing to a decrease in pH. However, in the anaerobic treatment, SRP remained unchanged between 9.4 and 9.3 mg/l. Both treatments increased K concentrations from 28.1 to 36.8 mg/l in aerobic treatment and 32.2 mg/l in anaerobic treatment. Aerobic treatment has the best mobilisation of P and K without major losses of nitrate (NO_3^-) nitrogen. The nitrate concentration in the aerobic reactors was reduced by 16 % compared to 97 % in the unaerated treatment. (Monsees et al., 2017)

Sludge after the aerobic treatment may not be thoroughly dried. A study done by Radaideh et al. (2010) showed about 50 to 60 % average reduction in volatile solids (VS) by aerobic treatment of sludge produced from a wastewater treatment plant. The particle size of the sludge is the most critical parameter affecting the sludge's dewaterability. When the particle size increases, the filtration rate of sludge improves, and the cake moisture content is reduced (Radaideh et al., 2010). Since aerobically treated sludge may still be wet, it might not be possible to make dry solid fertiliser by aerobic fish sludge treatment. It may be possible to make liquid fertiliser by collecting the dewatered liquid during the aerobic process. Further research should be done to evaluate it.

7.4. Anaerobic Digestion (AD)

Anaerobic digestion (AD) is a biochemical process which involves a large variety of microorganisms in which organic molecules undergo biodegradation to produce biogas (methane and carbon dioxide) and digestates (Bücker et al., 2020). Anaerobic digestion (AD) is widely used for treating municipal wastes (Mirzoyan et al., 2010); however, it is a new approach for treating fish sludge or fish waste since few experiments have been conducted on AD of aquaculture waste (Chen et al., 1997). AD of fish sludge, with or without co-digestion of manure, has gained attention, as the organic carbon (C) present in it is transformed into biogas, and the nutrients remain in the liquid digestate, which has low dry matter (DM) content.

Digestate can be applied to agricultural land by equipment designed for cattle or pig slurry application. (Brod et al., 2017) There is a possibility to make liquid fertiliser from the digestate.

The significant advantages of anaerobic treatment are the generation of methane (CH_4) gas and the reduction of pathogens. However, the cost and the complexity may be the limiting factor for applying anaerobic digesters in aquacultural systems. Two central problems are identified: the long retention time and the free ammonia inhibition of the anaerobic bacteria. Due to long retention times, there is a need for larger digester volumes, and ammonia inhibition sludge should be diluted, which requires an even larger digester volume (Chen et al., 1997).

The bioassay study by Brod et al. (2017) of seven different fish sludge-based recycling fertilisers - five liquid products (untreated fish sludge, four different anaerobic digestates based on co-digestion of fish sludge and dairy manure) and two dry products (pellets and granules) - revealed that the N content in one of the digestates was the highest at 220 g N/kg DM and the lowest in fish sludge granules at 71 g N/kg DM. The P content in one of the digestates was highest at 31 g P/kg DM and lowest in fish sludge granules at 14 g N/kg DM. The K content in one of the digestates was highest at 200 g K/kg DM and lowest in fish sludge granules at 0.27 g K/kg DM. Similarly, other nutrients such as Sulphur (S), Calcium (Ca), and Magnesium (Mg) are present at a higher degree in digestates compared to fish sludge granules (Brod et al., 2017). Thus, this study indicates that nutrient retention in anaerobic digestates based on co-digestion of fish sludge and dairy manure is much higher than in fish sludge granules.

Previous studies have shown that fish sludge has a considerable biogas potential. However, when the fish sludge is the only substrate in AD, accumulation of ammonia, long-chain fatty acids and volatile fatty acids can inhibit the biogas process (Gebauer and Eikebrokk, 2006). In a co-digestion process, AD becomes more stable when several substrates are used. A study shows increased biogas yield when the co-digestion of fish ensilage and manure (85:15) is done compared to the mono-digestion of fish ensilage. (Bücker et al., 2020)

The higher the fraction of fish sludge in the AD process, the higher the fraction of mineral N in the digestate. The bioassay and the incubation study indicated that the organic N in digestates based on fish sludge and manure does not mineralise fast enough to supply crops with sufficient N. During AD of organic matter, easily degradable carbon is transformed more quickly into biogas than recalcitrant organic compounds. (Brod et al., 2017)

The anaerobic degradation of organic solids can produce less residual sludge than aerobic processes. Still, the conversion period is usually more extended, and the residual sludge has a low C:N ratio (Zhang et al., 2020). Therefore, the organic N remaining in the digestate will probably be present in stable, recalcitrant compounds and will not result in the desirable net mineralisation. Higher mineralisation rates can be obtained if the agricultural soil has high microbial activity. (Brod et al., 2017)

7.5. Modified biological aerated filter (BAF)

A *biological aerated filter* (BAF) is developed based on a flexible and efficient European bioreactor. BAF is filled with granular or porous media to trap solids from water passing through and has a large specific surface area of filter media that enables the growth of nitrifying and heterotrophic bacteria, which helps in removing ammonium and in degrading organic compounds in the water. It has been used for treating industrial and municipal wastewater for years (Zhang et al., 2021).

Since BAF integrates mechanical filtration with biofiltration, it may also perform well in recovering nutrients from aquaculture sludge after proper modification. The modified BAF should be capable of capturing a large amount of fish sludge quickly and then efficiently converting the sludge into nutrients by aerobic nutrient mineralisation without backwashing in one device. It can reduce nutrient loss at maximum and improve operating efficiency with a compact footprint (Zhang et al., 2021).

The reactor contains two columns connected by the flange (See Figure 4). The transparent upper side column is used for observing the water level, and the lower side column with filter materials inside is for the interception of sludge. The effluent from the upper side column is pumped into the BAF and then flows downward through the lower side column. The lower side column contains three layers of a perforated aerator, named high-level aerator, middle-level aerator and low-level aerator, controlled by valves. First, the upper filter media is blocked by the fish sludge, which results in the rise of the water level in the upper side column. It opens a high-level aerator, alleviating the upper filter media's resistance. For the time being, the middle filter media obstructs fish sludge. The middle-level aerator opens when the water level in the upper column is observed again. The low-level aerator opens for nutrient conversion until the water level in the upper side column rises again, and the valve of the effluent of BAF is then closed (Zhang et al., 2021).

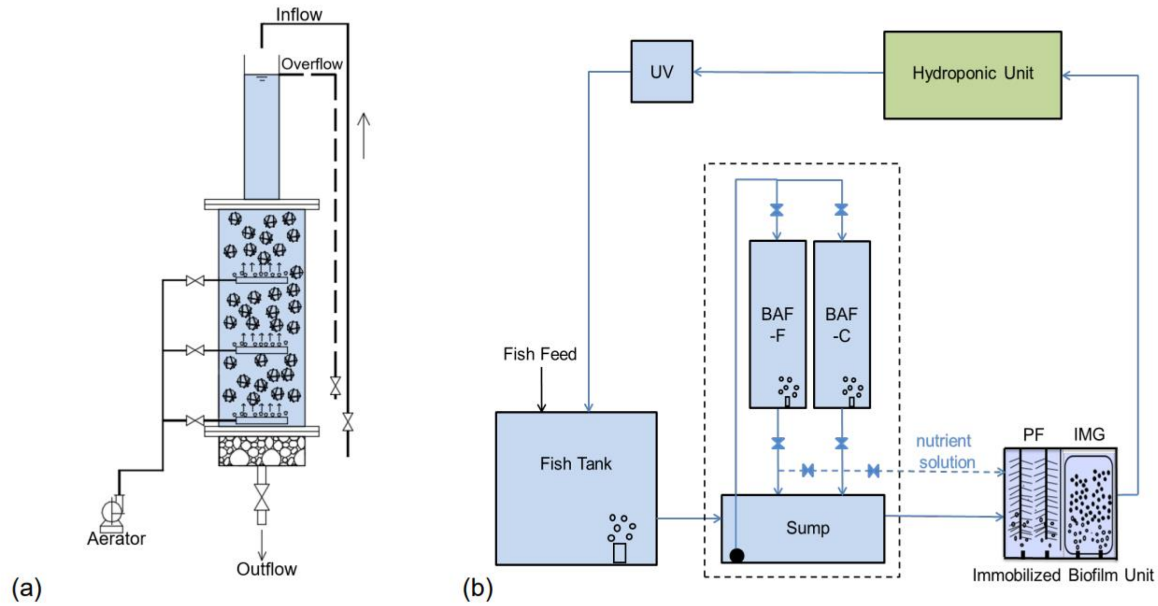

Figure 4. Schematic diagram of (a) the modified BAF and (b) aquaponics with modified BAFs (Zhang et al., 2021).

The modified BAF for the aquaponic system is shown in Figure 1b, which includes the fish tank, the sump with two BAFs, the immobilised biofilm unit with *polypropylene fibres* (PF) and *immobilised microbial granules* (IMG) in separate compartments, the hydroponic unit, and the ultraviolet (UV) disinfection tank. The unit with PF is for the sludge's interception, and IMG is for converting ammonia nitrogen into nitrate. At least two BAFs are required to perform continuous operation: one is for fish sludge collection (BAF-F), and another is for nutrient conversion (BAF-C). The flow rate of circulating water of the BAF is important. When the circulating rate is faster, the efficiency of interception of fish sludge increases, benefiting nutrient recovery, but more energy is consumed in the process. After the nutrient conversion period ends in a BAF, the liquid solution flows from the BAF into the hydroponic system, where the hydroponic plants get all the required nutrients. (Zhang et al., 2021)

The selection of filter media in BAF plays an important role. Zhang et al. (2020) tested ceramsite with different lignocellulosic materials (corn straw, wheat straw, and sawdust) as filter media of BAFs and BAF with ceramsite plus sawdust achieved the highest mineralisation capacity based on nitrification and dissolved total phosphorus.

7.6. Biochar production

Biochar is a solid product resulting from the thermochemical decomposition of biomass at moderate temperatures (350–700°C) under oxygen-limiting conditions, also known as the slow pyrolysis process. Biochar is used as a soil amendment to increase water retention, permeability, water infiltration, aeration, etcetera in agricultural soils due to its high carbon (C) content, high pH, high stability, high porosity, and high surface area. Biochar improves soil quality and, at the same time, stores stable C in soils and reduces climate gas emissions to the atmosphere. However, each biochar is unique and has different chemical and physical properties due to differences in biomass feedstock and operating parameters. Therefore, not all biochar can provide the same benefits as mentioned above. There are also many challenges to using biochar as a soil amendment since the regulations often consider it a waste or a hazardous product, even if it is clean. It can be challenging to produce biochar large-scale with low costs. (Brassard et al., 2019)

P-rich substrates are usually unsuited for biochar production due to the formation of complex and slowly soluble P compounds. Biochars based on fish sludge have low concentrations of soluble P and low P fertilisation effects. Therefore, treatment processes other than pyrolysis should be chosen for effectively closing global P cycles. P-solubility in biochar could be higher if fish sludge and manure were pyrolysed at lower process temperatures. However, one study has clearly illustrated decreased immediate P availability even in biochar produced at 300 ◦C (Brod and Øgaard, 2021). Thus, biochar from fish sludge can be appropriate for soil amendment, but not as a fertiliser in terms of P availability.

N in biochar that is produced from manures and wastes at low temperature (≤ 400 °C) serves as an important source of plant nutrients. P, K and other nutrient contents are higher in manure or waste biochars than those in crop residues and woody biochars. The nutrient contents and pH of biochar are positively correlated with pyrolysis temperature, except for N content. (Hossain et al., 2020)

As of now, there have been no studies done on the N and K fertilisation effects of biochar produced from fish sludge. Future studies should be done on this topic to know the fertilisation effects of biochar from fish sludge.

8. RESULTS

In this section, the following are presented: (1) evaluation of the best method of fertiliser production from fish sludge, (2) potential applications of fish sludge-based fertiliser on the Åland Islands, (3) calculation of theoretical replacement (%) of artificial fertiliser by the utilisation of Fifax's fish sludge-based fertiliser and the resulting decrease in nutrient leakage to the Baltic Sea.

8.1. Evaluation of best methods

The advantages and disadvantages of different methods that are analysed in the earlier section for converting fish sludge into fertiliser are presented in Table 5.

Table 5. Advantages and disadvantages of different methods for converting fish sludge into fertilisers.

Methods	Advantages	Disadvantages
Drying	Profitable in the long run if drying is done close to RAS, thus reducing transportation of wet sludge. High availability of soluble nutrients (NPK)	Initial capital investment can be expensive. NPK present is lower than in digestates from AD.
Composting	Useful end products.	No information on nutrient availability. Low concentrations of soluble nutrients. Risk of leakage.
Aerobic treatment	High retention of nutrients. Yields stable sludge. Suitable in urban areas where odour minimisation is necessary.	High energy consumption. Costly for aerations. High accumulation of biomass in the reactor due to fast growth-rate of microorganisms. Lack of usable by-product, such as methane gas. Maybe only suitable for aquaponics.
Anaerobic digestion (AD)	High retention of nutrients in digestates. Nutrients are in soluble form.	Complex process. Higher maintenance costs.

	Has CH_4 generation for bioenergy.	Mono-digestion of fish sludge can be unstable, therefore co-digestion with other waste, such as manure, may be necessary.
Biological aerated filter (BAF)	Reduces nutrient loss. Suitable for aquaponics.	Higher risks from being a new technology for combination with RAS, more research is required. Produces only liquid fertiliser. A hydroponics unit may be required for the immediate use of liquid fertiliser.
Biochar production	Enhances soil quality. Improves the nutrient capacity of the soil.	Immediate availability of P is reduced. The N and K fertilisation effects of biochar from fish sludge are not known.

Besides considering advantages and disadvantages, the suitability of the methods also depends on the location of the RAS, the demand for the organic fertiliser in the local area, the interest of the farmers to use fish sludge fertilisers, regulations regarding the sales of fertilisers produced from fish sludge and price of such fertiliser.

At the moment, Fifax is paying to get rid of the composted fish sludge. It might be challenging to make compost in the proximity of the RAS facility to minimise the transportation cost since a large amount of sludge is produced every day (about 20 t per day in Fifax aquaculture), which requires a large area. Moreover, Fifax may not get customers for compost as most farmers are interested in using fertilisers that are readily available to plants. Since the nutrients from compost are released slowly (may take about a year), the compost is unsuitable when farmers need to complement the nutrient deficiency immediately. In addition, composting causes problems such as release of odour and a high risk of nutrient leakage to the nearest water sources. Considering these challenges, composting may not be a suitable option for Fifax to convert fish sludge into fertiliser.

Fifax can employ circular economy concepts from the fish sludge by making fertiliser and selling them to the farmers since the fish sludge has a good composition of nutrients suitable for significant crops (onion, potato, apple, wheat, barley) grown in Åland. In the case of Fifax, drying the fish sludge by implementing a dewatering machine, such as a *Belt Filter Press,* could be the best possible method for converting the fish sludge into a solid fertiliser. The drying method is quite simple compared to others mentioned, such as aerobic treatment, AD, BAF, or biochar production. In terms of cost, it may not be costlier than these methods. However, the exact cost of strategies is not evaluated in this research.

According to the conducted interviews, if the sludge is dried and made into a granular form fertiliser, similar to the Yara mineral fertiliser, and sold at a competitive price, the farmers would be willing to buy the sludge-based fertiliser. There is existing technology available to produce fertiliser in a granular form. For example, Biolan Oy from Finland is already producing organic fertiliser in a granular form. Most farmers already have the technology or equipment to apply granular fertiliser in the agricultural field. Therefore, applying solid, dried granular organic fish sludge fertiliser with the existing equipment would be feasible. On the other hand, most of the farmers lack the technology to use fertilisers that are wet or in slurry form.

The drying method also has a good amount of nutrient retention, and nutrients in organic granular form may also be readily available to plants as mineral fertiliser. However, further experiments should be done to evaluate the bioavailability of dried granular fertiliser based on fish sludge. Overall, the drying method fulfils the condition of method simplicity, application feasibility, customer demand, nutrient retention, bio-availability and profitability better than other methods. Moreover, there will be less chance of nutrient leakage since there will be no transportation of wet sludge. In addition, the liquid after dewatering the sludge may still be rich in nutrients, and could be utilised as liquid fertiliser. Further investigation should be done to evaluate the nutrients in the remaining liquid.

In Åland, AD could also be another alternative, but it would need to be transported by truck (about a 24 km distance) to the biogas plant, which is yet to be constructed. Therefore, this business case would need to be further evaluated.

8.2. Application of fish sludge on Åland

The significant plants grown in Åland are apples, potatoes, and onions. These crops are exported to mainland Finland. Other crops such as wheat, barley, strawberries, lettuce and seasonal vegetables are grown in small amounts. So far, there are no studies on applying fish sludge-based fertiliser in the significant plants mentioned above except for barley. A study done by Brod et al. (2017) in Norway indicated that organic N in dried fish sludge mineralises rapidly and quickly becomes available to barley. Like barley, fish sludge fertiliser can also be effective for wheat crops. Further study should be conducted.

Nevertheless, several studies have been conducted on sewage sludge and manure application to different plants. Sewage sludge (SS) is generated as a by-product of wastewater treatment. SS can be used to improve soil fertility due to its nitrogen and phosphorus contents (Ceccanti et al., 2022). Sewage sludge may be an appealing option in regions where soils have high pH and lime content and lower plant uptake of heavy metals (Bozkurt et al., 2010). Soil treated with sewage sludge compost revealed lowered pH and increased levels of organic matter, primary nutrients, soluble salts and heavy metals (Bevacqua and Mellano,1993).

The data from a four year-long study on the application of SS at rates of 0, 10, 20, 40 and 60 kg per apple tree and manure to the soil at a rate of 25 kilograms per apple tree revealed that cumulative application of SS to apple trees significantly increased fruit yield, trunk cross-sectional area, shoot growth and leaf N, Mg, Fe, Mn, Zn and Cu contents at the end of the study. The repeated SS application to apple trees did not cause toxicity in leaves and fruits. However, long-term SS application may increase Zn, Cu and Ni contents in the soil and apple plants (Bozkurt et al., 2010). Higher yields of onion *(Allium cepa* cv. Spanish Sweet Utah) and lettuce *(Lactuca sativa* cv. Black Seeded Simpson) were noticed by the application of SS compost (Bevacqua and Mellano, 1993). A study by N'Dayegamiye et al. (2013) showed that application of paper mill sludge significantly increased N uptake and potato yields with a higher value of N use efficiency.

A study of SS amendment (used at 10 and 20 % of the weight of soil) on the leaf photosynthesis of pot-grown lettuce (Lactuca sativa) and strawberry (Fragaria x ananassa) showed improvement in the leaf CO_2 assimilation rate of both plants, which resulted in the higher biomass production compared to control plants. Trace metals (Cu, Zn and Hg in lettuce and Zn and Hg in strawberry) were accumulated in higher levels in the edible organs of both plant species compared to the relative controls. But the detected amounts were lower than the Reg. CE 1881/2006 and FAO/WHO threshold values, except for Cu content in lettuce leaves, amended with SS-20 % at the second cut. (Ceccanti et al., 2022)

Some other studies have also shown that SS compost and integrated application of effective microorganisms, vermicompost with organic and inorganic nutrients has resulted in significant growth of strawberry plants, increased strawberry yield and enhanced fruit quality (Ceccanti et al., 2022; Datta and Barooah, 2020; Kumar et al., 2015; Wang and Lin, 2002)

Similarly, like SS, fish sludge fertiliser may be effective for the growth of apple, onion, potato, lettuce, and strawberry plants. Future study is recommended for this.

8.3. Replacement of artificial fertiliser

The calculated result of the replacement of artificial fertiliser is presented in Table 6, where average sales of artificial fertiliser (NPK) to the agricultural lands in Åland from 2008 to 2019 and NPK contents in Fifax's fish sludge are also given. In the last row of the table, a plus (+) sign represents the additional need for artificial fertiliser, while a minus (-) sign denotes the surplus amount of organic fertiliser produced after fulfilling the demand using fish sludge-based fertiliser.

Table 6. Replacement of artificial fertiliser by organic fish sludge fertiliser in Åland.

Parameters	**N**	**P**	**K**
Demand for artificial fertiliser, t/year	721	48	272
NPK in Fifax's fish sludge, t/year	453	139	23
Replacement of artificial fertiliser, %	63	289	9
Additional need for artificial fertiliser, t/year	+268	-91	+249

From the result, it has been found that the utilisation of fish sludge to full potential with complete recovery of nutrients from Fifax's fish sludge can replace the demand for artificial N, P and K fertilisers by 63 %, 289 % and 9 %, respectively. About 91 t/year of P fertiliser is produced in a surplus amount from Fifax's fish sludge compared to the actual demand in Åland. It proves that efficient recovery of nutrients from the fish sludge can make the Åland Islands self-sufficient in P fertiliser and can increase self-reliance on N fertiliser by more than 60 %. In contrast, the demand for K can only be partially fulfilled.

8.4. Decrease in N and P leakage on the Baltic Sea

The calculated results of the decrease in leakage to the Baltic Sea after replacing artificial fertiliser with fish sludge fertiliser are presented in Table 7. It is assumed that there is no leakage by using fish sludge fertiliser on the agricultural land. The table shows the new total load on the Baltic Sea after decreased leakage.

Table 7. Decrease in N and P leakage to the Baltic Sea by the replacement of artificial fertiliser with Fifax's fish sludge fertiliser.

Parameters	**N**	**P**
Current total load on the Baltic Sea, t/year	3 255	91
Current leakage from the agricultural land, t/year	293	6.5
Percent leakage of the artificial fertiliser that is applied to the agricultural land, %	41	14
Leakage from artificial fertiliser still required after partial replacement by fish sludge fertiliser, t/year	109	0
Decrease in leakage on the Baltic Sea, t/year	184	6.5
Decrease in leakage on the Baltic Sea, %	6	7
The new total load on the Baltic Sea after a decrease in leakage, t/year	3 070.6	84.7

The decrease in leakage on the Baltic Sea would be about 184 t of N and 6.5 t of P by the replacement of artificial fertiliser with the fertiliser from Fifax's fish sludge for use on the agricultural land in Åland. Since Fifax's fish sludge is able to replace the demand of artificial P fertiliser by 100 %, leakage of P from the agricultural land would be completely eliminated. The total decrease in N and P load on the Baltic Sea is about 6 % and 7 %, respectively, if the fish sludge fertiliser is efficiently utilised in the agricultural land without any leakages.

The calculated results on the decrease in nutrient load on the Baltic Sea after the reduction of the spillage of N and P from transport via ship are presented in Table 8.

Table 8. Decreased load on the Baltic Sea after a decrease in spillage of N and P.

Parameters	**N**	**P**
Current demand for artificial fertiliser, t/year	721	48
Additional need for artificial fertiliser after partial replacement by fish sludge fertiliser, t/year	268	-91
Spillage from import of currently demanded artificial fertiliser (0.5%), t/year	3.60	0.24

Spillage from import of additional artificial fertiliser (0,5%), t/year	1.34	0
Decrease in spillage on the Baltic Sea, t/year	2.26	0.24
Decrease in load on the Baltic Sea after decrease in spillage, %	0.07	0.26
New total load on the Baltic Sea after decrease in spillage, t/year	3 252	91

By producing organic fertiliser from Fifax's fish sludge, self-reliance on fertiliser increases, and thus the import demand of artificial fertiliser decreases, which may result in less spillage during transport. From the calculation, it has been found that spillage of about 2.26 t of N and 0.24 t of P per year on the Baltic Sea can be decreased, assuming 0.5 % of spillage via ship by importing additional artificial fertiliser in Åland. The decrease in load on the Baltic Sea after the reduction in spillage is slight. However, this slight reduction can still have large impacts. For example, a decrease in 0.24 t of P is substantial as it can generate 240 t of algae (John Nurmisen Säätiö, 2020).

The net decreased load on the Baltic Sea after summing the decrease in leakage by the replacement of artificial fertiliser with Fifax's fish sludge fertiliser and the reduction in spillage during shipping is presented in Table 9.

Table 9. Decrease in load on the Baltic Sea after reduction in leakage and spillage.

Decrease in leakage and spillage, t/year	186.2	6.8
Decrease in load on the Baltic Sea after decrease in leakage and spillage, %	6	7
The new total load on the Baltic Sea, after a decrease in leakage and spillage, t	3 068.3	84.5

Total decrease in load on the Baltic Sea after reduction in leakage and spillage is about 186 .2 t of N and 6.8 t of P. In terms of percentage decrease in N and P load on the Baltic Sea after reduction in leakage and spillage is similar to that of decrease in N and P load after only decrease in leakage from the replacement of artificial fertilisers in agricultural land which is about 6 % and 7 % respectively.

9. DISCUSSION AND CONCLUSION

From the findings, it can be concluded that fish sludge from Fifax is rich in nutrients, primarily N and P. Besides N and P, it is also rich in other macro-nutrients such as Calcium, Magnesium and Sulphur. Such nutrient-rich fish sludge has the potential to be used as fertiliser for growing significant crops such as potatoes, onions, and apples on the Åland Islands.

Drying could be the best method to convert fish sludge into fertiliser in terms of method simplicity, the applicability of dried fertiliser, nutrient retention, the release of nutrients to plants, customer demand and profitability. Most of the farmers in Åland are currently using mineral fertiliser from Yara, which is in solid granular form, and they have the technology to apply this kind of fertiliser. If the fertilisers are wet or in slurry form, most farmers might not have the technology to use them in the field. Therefore, dried fish sludge in granular form can be applied with the existing technology. Further, dried fish sludge fertiliser is readily available to the plants. Moreover, there is less chance of leakage compared to wet or liquid fertiliser.

Åland soil varies from fine sand to clay, usually low in carbon content. The soils are generally high in P and Ca and deficient in K, Mg, and Mn. Still, other micronutrients are at a satisfactory level. Future study is recommended to determine if applying the fish sludge fertiliser can increase the carbon content in the soil.

The NPK composition of Fifax's fish sludge fertiliser is appropriate for the major crops on the Åland Islands. It can also be suitable for wheat, barley and strawberry plants. However, further research is recommended. The N and K composition in Fifax's fish sludge is insufficient to meet the Åland Islands' entire demand. The additional need can be complemented by the supply of artificial mineral N and K fertilisers. When making fertiliser from fish sludge, NPK composition in the fertiliser can also be prepared according to the standard NPK formula, such as with the composition of 11:5:18. For example, if K content in the fish sludge is not sufficient to make such standard composition, then mineral fertiliser can be added to make the suitable composition.

The total recovery of nutrients as solid organic fertiliser from Fifax's fish sludge has the potential to replace the demand for artificial N, P and K fertilisers by 63 %, 289 % and 9 %, respectively. Thus, Åland can become self-sufficient in P fertiliser; moreover, its self-reliance in N fertiliser increases by more than 60 %. Simultaneously, there will be less fertiliser import, resulting in less spillage to the Baltic Sea through shipping. Spillage of about 2.26 t of N and 0.24 t of P can be prevented by importing less fertiliser in Åland by producing and utilising

Fifax's fish sludge. In terms of percentage, the decrease in spillage is not significant; Nevertheless, its impacts on the Baltic Sea can be substantial. For example, the reduction of 0.24 t of P can reduce algae in the Baltic Sea by 240 t. It has been found that there can be a decrease of about 6 % N and 7 % P leakage on the Baltic Sea by the replacement of artificial fertiliser with the Fifax’s fish sludge fertiliser with the assumption that there is no leakage from Fifax RAS nor the utilisation of Fifax's fish sludge fertiliser in the agricultural land.

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APPENDIX

Legislation on organic fertiliser production and use

Fish sludge is not considered as an animal by-product by the current legislation in Åland (Regulation of ÅLR 2020/1897). Therefore, direct use of fish sludge is not allowed on land in agriculture or in landscaping. It must be either composted or further processed, for example, through the anaerobic digestion process to make biogas. Approval is required before using composted or processed fish sludge on land. Fertilisers that are not approved are not allowed to be used on land in agriculture and to some degree also in landscaping, except for manure.

One must notify the Åland regional government before starting the business of a fertiliser that includes the manufacture or marketing of a fertiliser product. A description of how the business is organised, product declarations and a written self-inspection plan must be attached to the notification. Anyone who manufactures, markets, or sells fertiliser products must keep records so that the products can be safely traced. They must prepare an annual report once a year with the necessary information about manufactured or marketed fertiliser products and notify the provincial government.

Anyone operating in the fertiliser product sector must have a self-monitoring system which ensures that the fertiliser product and its handling meet the requirements set out in the legislation. Anyone who manufactures or technically processes organic fertiliser products or raw materials for these must be approved by the provincial government. A facility that manufactures or technically processes animal by-products must be approved by the environmental agency of the provincial government. Each production facility is approved specifically. (Ålands landskapsregering, 2022)

The buyer and user of a fertiliser product must always receive a goods declaration in association with the sale or transfer. The goods declaration for a fertiliser product must include information about the fertiliser product's type designation and trade name, properties, composition, use, manufacturer and importer. The goods declaration must be attached to the fertiliser product's packaging. (Ålands landskapsregering, 2022)