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Utilization of sludge from recirculation aquaculture systems

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Summary:

Norway is an ideal location for salmon farming due to its protected coastline and favorable water temperatures. Historically, salmon smolt production has been under flow-through (FT) systems utilizing the adequate freshwater bodies. Because of this, very few recirculation aquaculture systems (RAS) for Atlantic salmon culture have been implemented in Norway. However, increasing interest in RAS-based production has been shown recently due to increased smolt demand and more limited water resources. We have projected that the installed capacity of RAS in Norway will reach 40 million smolts by the end of 2011. A challenge with RAS production systems is that it will produce rather high levels of sludge. Moreover, if the trends continue with the increased growth rate showed during the last 7 years, around 85 million smolts could be produced in RAS in 2015, with an estimated production of sludge of 1.600 ton/year. Importantly, the composition of the sludge makes it suitable for treatment through anaerobic digestion and composting.

Considering this, we have evaluated the potential of using fish farming sludge produced at recirculation aquaculture systems facilities as an input factor in a commercial context. It was concluded that exploitation of the energy in the sludge by means of anaerobic treatment (Biogas) may be profitable when assuming it can be operated continuously without process failure. It was also concluded that a large number of fish hatcheries would be required to ensure the minimum supply of sludge needed to make an industrial biogas plant economically viable. Still, sludge production from RAS can contribute to supply rough material to any biogas plant and thus generate a value added to the solid waste generated by fish farming. Further, treated sludge may be disposed by land application on agricultural fields. In conclusion, there are two major options for the use of sludge generated at RAS facilities that are technically viable and must be explored further in order to achieve economic efficiencies: sludge as a source for biogas and sludge as a source of fertilizer.

To follow-up this study, the major recommendations are to conduct R+D to analyse in detail the economic potential of a plant for anaerobic digestion at an industrial level, considering the concentration of total sludge production in Norway or in Chile to be processed in one single biogas plant. To involve a significant number of alevin/smolt producers in order to accumulate and then process a bulk of rough material large enough to generate sufficient value-added product (e.g.: fertilizer, biogas or energy). Finally to conduct R+D focused on the design of smaller biogas reactor systems that can be operated on a viable commercial basis and that can be operated in-situ by small amounts of sludge generated at RAS hatcheries.

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1 Main objective

This project aims to estimate future production of sludge in Norwegian and Chilean recirculation aquaculture system facilities and evaluate the potential of using fish farming sludge as an input factor in a commercial context, e.g. biofuel production or feed ingredients.

2 General description of aquaculture activities

Over the last two decades, the aquaculture industry has gone through major changes, growing from small-scale to large-scale and intensive commercial farming, surpassing landings from capture fisheries in many areas of the world. While outputs from capture fisheries have grown at annual average rate of 1.2%, output from aquaculture activities (excluding aquatic plants) have grown at a rate of 9.1% (Gutierrez-Wing and Malone, 2007; NACA/FAO, 2001).

Global population demand for aquatic food products is increasing, the production from capture fisheries has leveled off; approximately, 75% of the world´s fishing grounds are fully exploited, over exploited or severely depleted, and most of the main fishing areas have reached their maximum potential. Sustaining fish supplies from capture fisheries will, therefore, not be able to meet the growing global demand for aquatic food. Aquaculture appears to have the potential to make a significant contribution to this increasing demand for aquatic food in most regions of the world (Fig. 1). However, in order to achieve this, the sector and aquaculture producers will face significant challenges. Key development trends indicate that the sector continues to intensify and diversify and is continuing to use new species and modifying its systems and practices (FAO, 2006).

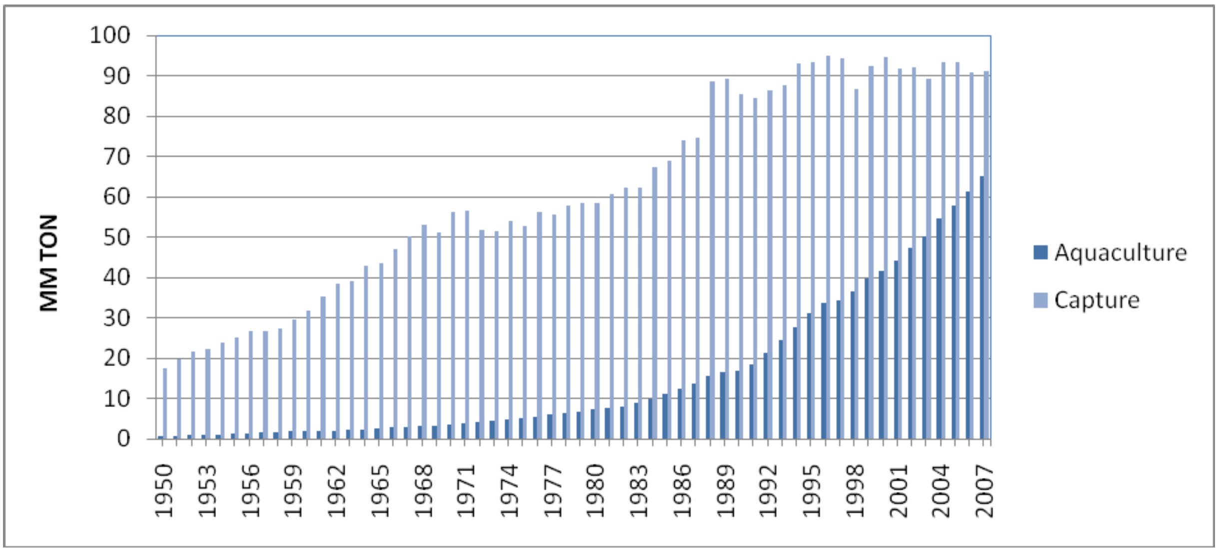

Figure 1 Overall production of aquaculture and capture fisheries between 1950 and 2007 (FAO, 2009)

Within global aquaculture, Atlantic salmon production represents 89% of total volume and is by far the most economically important cultured salmonid (Bostick, *et al.*, 2005). In 2007, approximately 60% of global salmon supply was farmed. The main farming system for the production of Atlantic and Pacific salmon is a first stage production in land-based hatchery and smolt farms, using tanks and raceways, followed by a sea-based on-growing production in floating cages (Bergheim & Åsgård, 1996).

According to the United Nations Food and Agriculture Organization (FAO, 2006), salmonids are farmed in 24 countries. The major producers of salmon are Norway and Chile. Other significant producers include the United Kingdom, Faroe Islands and Canada. The three most common species of cultured salmon are the Atlantic salmon, the trout (Oncorhynchus mykiss), the chinook salmon (Oncorhynchus tshawytscha), and the coho salmon (Oncorhynchus kisutch).

3 Salmon production cycle

The production of salmon (Fig. 2) can be divided into four main phases: hatchery, smoltification, grow-out and processing. The hatchery stage involves the artificial fertilization and hatching of eggs, and rearing of the young salmon until they are ready to start the smoltification process. During the smoltification process, an internal metabolic process enables the fish to adapt from fresh to sea water with a minimum of stress. This process takes place in lakes, estuaries, and in land-based facilities. When the salmon reaches the final stages of smoltification these resulting smolts should be prepared for transfer into sea water for on-growing or harvest depending on the market. In sea-cages salmon smolts will reach market size (ca. 4-5 kg) about three years after hatching and two years after fresh water farms. Then, the fish are processed, exported and distributed to the final markets in a number of product formats.

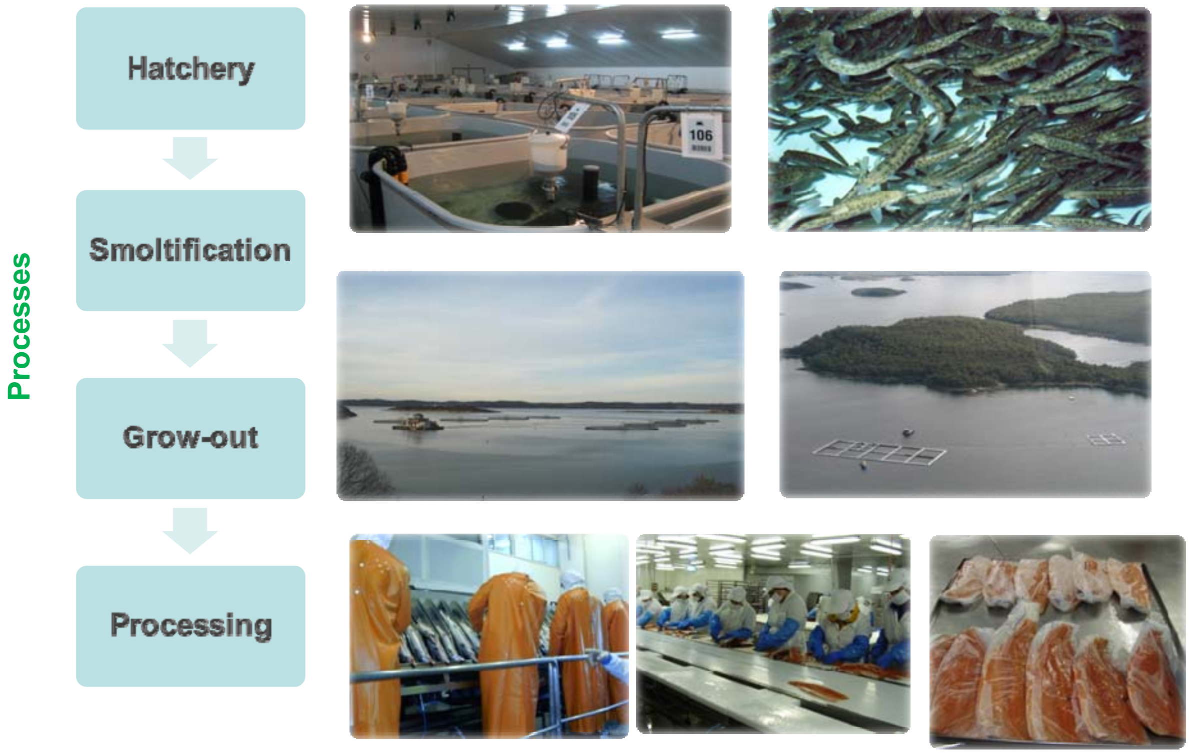

Figure 2 Production cycle of salmon

4 Recirculation Systems-based Production

At present, more than 90% of the hatchery and smolt production stages of salmon takes place in land-based, single-pass flow-through farms, but conversion to recirculation aquaculture systems (RAS) is being considered by many producers (Bergheim et al., 2009). In RAS water flow through the system is mostly recycled and only a small rate of the makeup water is changed daily. Here, environmental parameters of water are monitored and continuously controlled and fish are reared in tanks with constant environmental conditions. The solids waste are filtrated and removed from the system and then discharged in the form of sludge (Chen et al., 1997), oxygen is supplied to maintain adequate level regarding species, size and temperature. Finally, the effluent is treated in a biofilter for the biological conversion of ammonia-nitrogen to nitrate (Timmons et al., 2002), and then the water is recycled back through fish culture tanks.

A number of studies have shown successful examples of commercial-size closed system aquaculture (CSA) operations around the world, where finfish are grown to harvest size. The major fish are Nile tilapia (*Oreochromis niloticus*), trout (*Oncorhynchus mykiss*), Arctic charr (*Salvelinus alpinus*), Atlantic halibut (*Hippoglossus hippoglossus*), turbot (*Scopthalmus maximus*), barramundi (*Lates calcarifer*), sea bream (*Sparus aurata*) and sea bass (*Centropristis striata*) while other species are important in specific locations, such as eel (*Anguilla anguilla*) in Europe and catfish (*Ictalurus punctatus*) in the United States (Suzuki & Georgia Strait Alliance, 2008).

Most of the commercial production of finfish in OECD countries is based on open systems; the precise number is difficult to define as production and trade figures are generally not classified as open - system or recirculation aquaculture system (RAS) (Suzuki & Georgia Strait Alliance, 2008). However, the use of RAS for commercial production of finfish is increasing all around the world. Reliable supply of fingerlings is a bottleneck for the commercial production of marine species, as sea bass, sea bream, yellowtail fish, flat fish and cobia, and this increase in market price will also promote adoption of recirculation technology around the world. An example of the utilization of RAS for farming of marine species is the first juvenile batch production of yellow tail (*Seriola lalandi*) in the northern part of Chile.

CSA systems include those using one time flow-through of water with varying degrees of input and output water treatment methods, to fully recirculation aquaculture systems (RAS) where water is largely reused. Some fish, such as trout, Atlantic salmon and turbot are almost always farmed in CSA. Also, countries such as the Netherlands employ CSA for all farmed fish regardless of species due to legislation and environmental regulations.

Currently, Atlantic salmon smolt is produced within recirculation system in Canada (Couturier et al., 2009; Parker et al. 2000), in the Northeastern Unites States (Wolters et al., 2009), Norway (Terjesen et al., 2008; Bergheim et al., 2009; Kristensen et al., 2009), The Faroe Island (Bergheim et al., 2009) and Chile (Morey, 2009; Emperanza, 2009).

The production of Atlantic salmon smolts in Europe is close to 250 million per year with Norway and Scotland as the dominating producers. Moreover, RAS are increasingly applied in Atlantic smolt production and its production may well constitute a substantial part of smolt production in the future (Kristensen et al., 2009).

5 Salmon production using RAS in Norway

Norway is an ideal location for farming salmon, as most of its coastline is protected from storm surges and waves and the water temperatures are favorable. RAS for Atlantic salmon culture in Norway are few due to historically adequate freshwater bodies, and most salmon smolt producers use flow-through (FT) systems. However, increasing interest in RAS-based production has been shown, new plants using recycle principles will be built, and several existing flow-through systems will be converted (Terjesen et al., 2008).

Recently a study of Norwegian's water quality surveys (96 water sources, 1999–2006) shows that smolt production is characterized by utilization of surface waters as inlet-water sources, with lake inlets constituting 88% and river inlets 12%. This results in large seasonal variations in both temperature, and inlet-water quality. The content of total organic carbon and total nitrogen is generally higher in Norway than in Chile, and in low pH waters, concentration of inorganic (labile) aluminium exceeds recommended level (10 mg/L) in 15% of the samples. Also, the measured levels of carbon dioxide (CO2, 11.6 _ 6.2 mg/L) and total ammonia nitrogen (TAN, 499 _ 485 mg N/L) (mean _ SD), exceed current legislative recommendations in 30% and 10.5% of the cases, respectively (Kristensen et al., 2009)

It has been reported that further increases in smolt production in Norway (Fig. 3) beyond 2012 may be hampered without the use of RAS (Kittelsen et al. 2006; Terjesen et al., 2008). Together with expected positive effects of RAS on smolt quality (growth, survival after sea transfer), future water shortage has promoted interest in RAS in Norway (Terjesen et al., 2008).

In 2006, there were a total of 232 licensed hatcheries for smolt production in Norway with an authorised capacity of 242 million smolts per year (Norsk Fiskeoppdrett, 2007) and RAS represented only between 1% and 2% of the total farm sites. The production licence per site ranged from 50,000 to 2.5 million annually, with an average of approximately 1 million per year. However, in March of 2008, there were 9 RAS facilities (Bergheim et al., 2009).

Increased production and limited water resources are the main reasons for finding ways to improve water quality and smolt quality. AquaOptima (largest market share recirculation technology supplier in Norway) affirms that after testing several farming companies have observed increased growth of salmon fingerling followed by better smolt quality and survival rate in the sea by using recirculation (Severinsen, 2009).

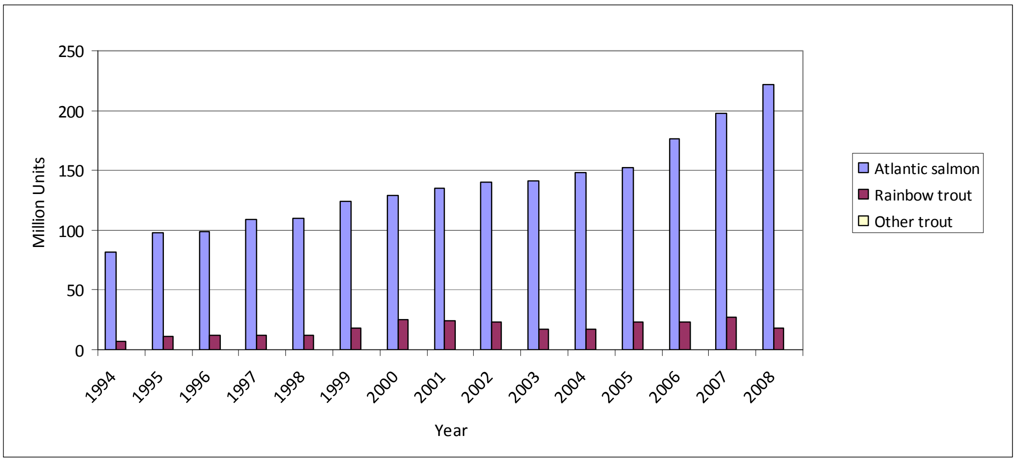

Figure 3 Production of smolts in Norway between 1994 and 2008 (Directorate of Fisheries of Norway, 2009.)

6 Salmon production using RAS in Chile

Chile's extensive coastal areas and close proximity to a large and clean source of fish meal make it a prime location for salmon aquaculture. In the last 25 years, development of Chilean's salmon production has shown a sustained increase of the exports, with an expected growth rate of 10% (Cabezas, 2007). Between 1998 and 2006, the Chilean´s salmon industry exports triplicate its value, from US$ 700 million to US$ 2.207 million (Derosas, 2007). In 2007, salmon and trout exports reached US$ 2.326 million, and increased to US$ 2.475 million in 2008 (Aqua, 2009).

During the last years in Chile, factors as environmental impacts, lacks of good water quality bodies and higher bio-security standards are driving producers to adopt recirculation technology to produce salmonids smolts. The first RAS for salmon fry and for smolt were built in Chile in 2001 and in 2004 respectively. Currently, with a critical sanitary situation, Chilean salmon industry is moving faster to produce more smolt in RAS every year.

Recirculation technology, delivers an increased production of fish, maintaining high culture densities, and environmentally friendly at the same time, for its prevention (Timmons, *et al.,* 2002). Moreover, the benefits of the implementation of this clean technology are not only linked to the reduction and prevention of environmental impacts of production, but is able to perceive a decrease in production costs and achieve greater efficiency in production (Table 1). At the same time, the effects are important aspects of biosecurity that are not obtained in open sites, or in systems without recirculation, and producers can speed up or slow down the growth of fish, and thus adapt to market demands (EcoAmérica, 2004; Timmons, *et al*., 2002). Consequently, the current outlook suggests that all the new Chilean facilities will be based on modern intensive recirculation production systems.

Table 1 Productivity factors with open flow vs. recirculation systems (Águila y Silva, 2008)

Indicators	Open flow system	Recirculation systems
Mortality (%)	48	28
Conversion Factor	1,2	0,8
Grown Index	8	6 to 12
Nº of eggs per *smolt*	3,1 a 3,5	1,2 to 1,5
Batch (Nº/año)	2	5 to 6

7 Description of sludge production process and management in a RAS

As pelleted feeds are introduced into the fish tanks (Fig. 4), they are either consumed or left to decompose within the system. By-products of fish metabolism include carbon dioxide (CO_2), ammonia-nitrogen ($N\text{-}NH_4^+$), and faecal solids. Water constituents in fish tanks effluents include dissolved and particulate organic matter (DOM and POM), TSS, nutrients such as nitrogen (N) and phosphorous, and others specific organic or inorganic compounds (Piedrahita, 2003). If uneaten feeds and metabolic by-products are left within the culture system, they will generate additional carbon dioxide and ammonia-nitrogen, increase oxygen consumption as they undergo bacterial decomposition (Couturier et al., 2009), and have a direct detrimental impact on the health of the cultured product (Losordo et al., 1998).

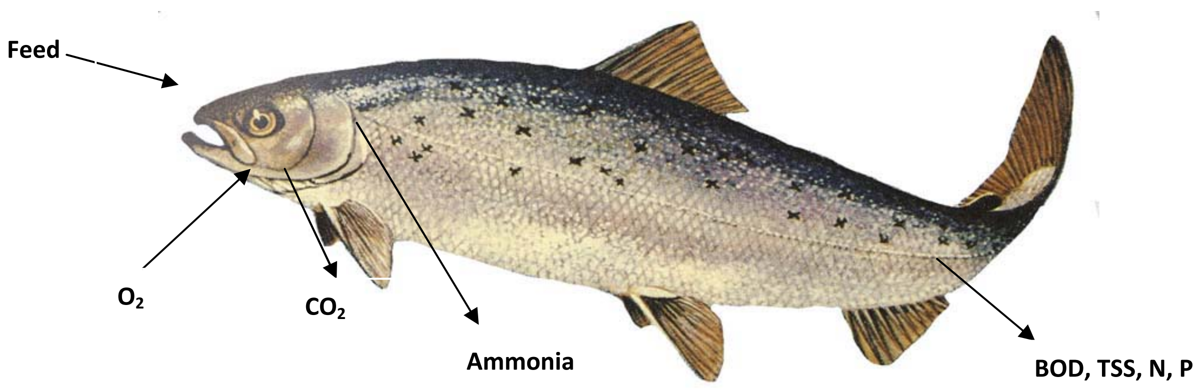

Figure 4 General Mass Balance on a feeding fish (from Chen et al. 1998)

Feed-based waste from intensive aquaculture facilities can degrade the environment and generate conflict with other aquatic resource users. Hence, solids control stages such as feed management, pre-treatment, primary separation; secondary solids handling and disposal may comprise an integrated solids management system (Cripps & Berheim, 2000).

In a RAS, practically all the wastes generated come from the feed. Among these, the major form of waste is particulate matter, which can be measured as Total Suspended Solids (TSS) (APHA, 1999), and be discharged as sludge. A typical RAS is designed with a TSS separation unit that removes the faeces and discharges it from the system as sludge (Chen et al., 1997). Suspended solids adversely impact all aspects of a RAS. Hence, the first objective of any recirculation treatment is the removal of solid waste, and effective control of solids generated is probably the most important task that must be accomplished to ensure long-term successful operation of a RAS (Timmons & Ebeling, 2007).

8 Removal and management of RAS fish farming sludge

As reused of water -within RAS- requires a water purification unit to avoid a self toxification by the metabolites (Schusted & Stelz, 1998), RAS are designed to remove dissolve waste and suspended solids produced by fish (as ammonia, CO2, DBO5, SST, N and P) and return the treated water with a safety level into the fish tank.

Three physical properties that are the most important for solids removal are particle specific gravity, particle size distribution and mechanical stability (Couturier et al., 2009). In traditional tank-based RAS, settleable solids (>100 µm) are generally removed as they accumulate by sedimentation on the tank centre-bottom drain discharge using less than 40% of the effluent water (Couturier et al., 2009). The portion of solids that are kept in suspension (as suspended solids particles) can be removed with a sedimentation tank (clarifier), mechanical filter (granular or screen), or swirl separator (Losordo et al., 1998). These large particles should always be removed first and must be a primary focus, since if they are not removed; they become “smaller” more difficult particles to remove (Timmons & Ebeling, 2007).

In intensive RAS, the majority particles by weight will be 20-35 µm or less in size (Chen., et al., 1993; Chen et al., 2003; Timmons & Ebeling, 2007). Fine and dissolved solids (< 30 µm) increase the oxygen demand of the system and cause gill irritation and damage is finfish RAS. These small solids cannot be removed by sedimentation or mechanical filtration technology. However, foam fraction or ozone treatments are successful in removing these solids from RAS (Timmons & Ebeling, 2007). Figure 5 shows a diagram that describes different particle sizes removed by different solids separation processes in a RAS.

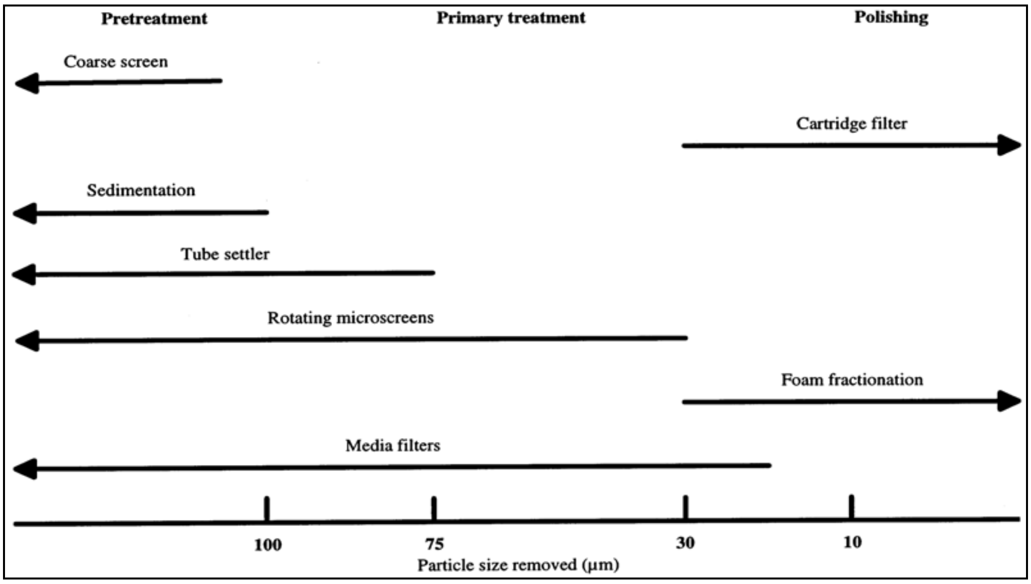

Figure 5 Particle sizes removed by different solids separation processes (Cripps & Bergheim, 2000; Chen et al., 1994)

Although several particle separators, or clarifiers, are commercially available for integration into an intensive aquaculture treatment system and are capable of accepting the pre-concentrated waste from tanks, it is generally more feasible to remove the solids in high flow-low concentration commercial aquaculture wastewaters, than to treat the dissolved fraction using some form of filter bed (Cripps & Bergheim, 2000). Two particle concentrator systems commonly used at the bottom-centre of the tanks in Europe and North America are the Eco-trap® from AquaOptima and the Cornell dual-drain design, respectively. These units can catch commonly above 92% of the TSS produced (Table 2).

The portion of solids that are kept in suspension (as suspended solids particles) can be removed with a sedimentation tank (clarifier), mechanical filter (granular or screen), or swirl separator (Losordo et al., 1998). However, the most popular method of mechanical filtration particle separator is by the use of screen. Specifically, rotating microscreens are commonly used at land-based intensive fish-farms in Europe and in South America, often with fine mesh pore sizes from 60 to 200 μm (Cripps & Bergeim, 2000).

Table 2 Reported efficiencies of solids removal units in RAS

Kind of filter	Removal efficiency	Source
Particle separators (Cornell dual-drain)	92% of TSS	Timmons & Ebeling, 2007
Particle separators (Eco-tramp®)	98% of feed waste and 92% of excrements	www.aquaoptima.com
Swirl separator + floating plastic bead bioclarifier + fluidized sand bead	85% of TSS (Overall)	Pfeiffer et al., 2008
Swirl separators + drum filter	88 % of TSS (63 and 22%, respectively)	Couturier et al, 2009
Microscreens (25-100 μm)	71-77%	(Cripps & Bergheim, 2000; Kelly et al., 1997; Cripps, 1995)

Regarding management, sludge produced from recirculation systems needs to be disposed of with or without additional treatment, depending on specific operations. A rational treatment scheme (Figure 6) should be based on sludge characteristics, such as mass, concentration, and the degree of stabilization required. In virtually all applications, treatment and disposal are more economical if a dilute sludge stream is concentrated as much as possible, thus reducing the volume of material to be handled (Metcalf and Eddy, 1995). The concentration process most often used in aquaculture applications is clarification (settling). After clarification, the sludge can be either land applied or further treated by a stabilization process before land application. Any excess water can be used for irrigation or polished for direct discharge. The sludge produced by separation technology can be thickened and stabilised by the addition of lime, to kill pathogens diseases and restrict putrefaction. The resulting sludge has been usually spread on agricultural land (Cripps & Bergheim, 2000). However, the treated sludge can be used as feedstock for composting, earthworm culture (Nieto, 2007) or other biotransformation processes, such as biogas recovery.

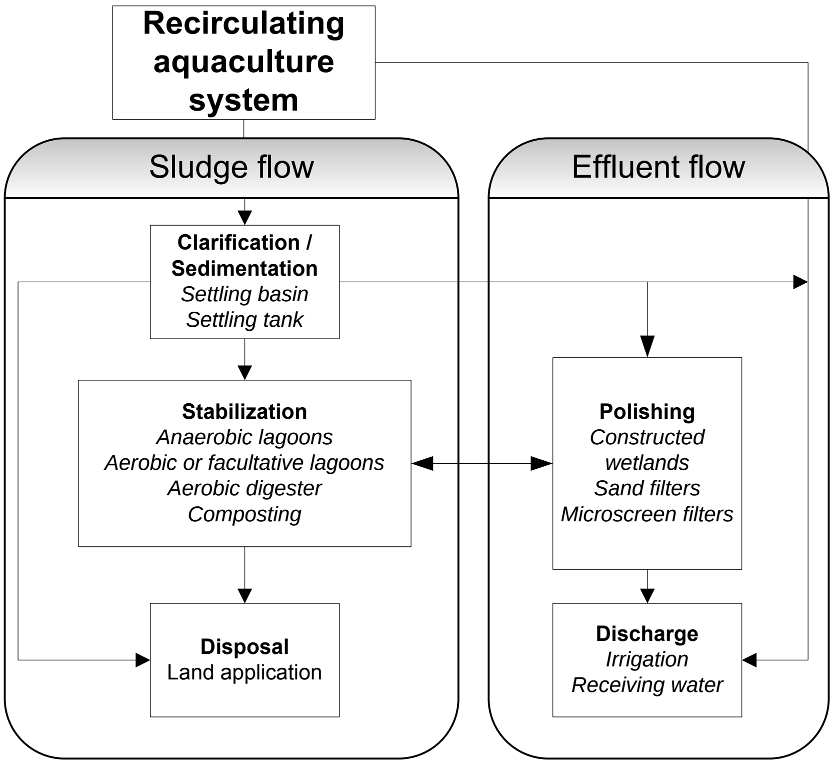

Figure 6 Options for aquaculture sludge treatment (extracted from Chen et al. 1997)

9 Estimation of sludge production in a Recirculation Aquaculture System

Sludge production is commonly measured as the sum of Total Suspended Solids (TSS) captured by all unitary solid removal equipment within the recirculation system, and it is estimated from the amount of feed fed given daily.

Suspended solids are directly generated from faeces, detached bacterial flocks (dead and living bacteria), and uneaten food particles (Couturier et al., 2009; Timmons & Ebeling, 2007; Chen et al., 1997). The TSS production rate (P_{TSS}) from a recirculation system can be quantified through mass balance analysis considering major positive production TSS fluxes (including fish excretion, uneaten feed, microorganism growth during biofiltration) and negative production TSS fluxes (TSS decay and removal) (Chen et al., 1997; Chen et al., 1993).

In general terms, the amount of TSS produced in a RAS can be proportionately related to the fish feeding rate. This generalization is valid, because faecal production goes to cero once feeding activity has ceased. Thus, the P_{TSS} can change with the performance of each system design and configuration. However, since the rate of generation of TSS (P) by each of three sources is proportional to the feeding rate (F), consistently it is possible to define that (Equation 1):

$$\mathbf{P_{TSS} = \mathit{f}_{TSS} \times F} \qquad \textbf{(Eq. 1)}$$

Where,

$f_{TSS,}$ is the mass fraction of wasted solids produced per unit of feed.

F, is the mass of feed fed per unit of time, in dry basis (kg of feed fed/ time)

Cripps and Bergheim (2000) indicate that salmonids typically fed with high-energy diets generate about 0.20 kg of faecal matter per kg of feed ingested. Vinci et al. (2004) used a TSS production rate (f_{TSS}) of 0.35. Overall, the literature gives variable values ranging from 20% to 40% of feed fed on dry basis (Timmons et al., 2002). However, Timmons and Ebeling (2007) recommend the use of 0.25 of the amount of feed fed to project the produced quantity of TSS (in dry matter basis) in RAS. Accordingly, Equation 1 can be expressed as:

$$\mathbf{P_{TSS} = 25\% \times F}$$

The amount of feed given annually (F) in a recirculation system can be estimated multiplying the annual biomass production to be farmed by the Feed Conversion Ratio (FCR) commonly expected for commercial farms. The annual biomass production of a RAS is defined by its installed capacity. This biomass is the number of fish multiplied by the range of fish weight reared annually (Equation 2).

$$F = FCR \times \text{Annual biomass production} \quad \textbf{(Eq. 2)}$$

Where,

FCR is the Feed Conversion Ratio, in kg of feed/ kg of biomass.
Annual Biomass production is the quantity to be farmed annually (Tons/ year)

In order to project the amount of feed given annually (F) by a common RAS that produce fry and smolts, an FCR value of 0.8 and 0.9 was selected, respectively. Table 3 shows the FCRs change according to fish weight.

Table 3 Expected FCR (Feed Conversion Rate) of Atlantic salmon by range of weight, based on feeds and feeding advice for farms (Ewos, Norway).

Range of size (g)	**FCR (kg feed/ kg biomass)**
0.1 -1.0	0.70
1.0 – 5.0	0.70
5.0 – 15.0	0.75
15.0 – 30.0	0.80
30.0 – 50.0	0.90
50.0 – 100.0	0.95

In addition to this, to predict the sludge production rate from a RAS (P sludge) it is necessary to include the average fraction of the total waste solids that is captured by all the solids removal equipments within a RAS, which is consolidated in a efficiency factor "**η**" (Couturier et al., 2009), as shown in Equation 3:

$$P_{SLUDGE} = P_{TSS} * \eta \quad \textbf{(Eq. 3)}$$

Where,

η, is the efficiency factor which represent the performance of all the removal devices

Studies have shown that an overall solid removal efficiency (η) in a RAS ranges between 85% and 95% (Couturier et al., 2009, Pfeiffer et al., 2009; Davidson & Summerfelt, 2005; Vinci et al., 2004; Timmons et al. 2002, 2007). Differences are related to food quality, cultured species, recirculation system configurations, removal equipments and water exchange rate (Vinci et al., 2004; Davidson & Summerfelt, 2005; Pfeiffer et al., 2008; Couturier et al., 2009). On this report, a **solid removal efficiency (η)** of **87.5%** was used to estimate the sludge production.

10 Projection of sludge production from RAS in Norway and Chile

A projection of the sludge production in RAS both in Norway and Chile was made, based on a prediction of the installed capacity in a period of ten years for fry and smolts. The annual increase in the biomass production capacity in commercial RAS in Norway an Chile, was used to estimate the trends of growth, which was projected until 2015 in order to make the sludge production estimations from the total biomass of fry and smolts salmonids produced in RAS in Norway and Chile.

Integrating the equation 1 and 2, we can express $\mathbf{P_{SLUDGE}}$ as:

$$\mathbf{P_{SLUDGE} = \mathit{f}_{TSS} \times FCR \times Annual\ biomass\ production \times \eta}$$

In Norway as well as in Chile the salmon production in RAS is planned in cycles from 3 to 5, even 6, ensuring a year-round production. Only as a reference an average production of 500,000.00 fish was used as a minimum and stable unit of fish on a monthly base, to determine biomass and sludge production in a typical production cycle in a single hatchery. In a yearly base, three production levels were used to estimate the associated sludge production (500,000 1,000,000 and 5,000,000 fish).

A regular smolt production can be split arbitrarily, as reference, in four stages (Table 4); using the respective FCR referred in Table 3, the sludge production can be calculated.

Table 4 Estimation of dry sludge production (in tons) in a given yearly fish production

Fish weight (g)			Biomass yearly base by given number of fish (tons)			FCR	Dry sludge produced (tons)		
Initial	Final	Gain	500,000 fish	1,000,000 fish	5,000,000 fish				
0	20	20	10	20	100	0.8	2.2	4.4	21.9
20	50	30	15	30	150	0.9	3.3	6.6	32.8
50	100	50	25	50	250	0.9	5.5	10.9	54.7
100	200	100	50	100	500	0.95	10.9	21.9	109.4
		Total	100	200	1,000		21.9	43.8	218.8

10.1 Estimated annual sludge production in Norway

The Norwegian available capacity in RAS has revealed an increasing growth rate during the last years (Figure 7). One of the first RAS in Norway was converted from a FT system in 2002, and had a license to produce around 1 million smolts per year, as reported by Bergheim et al. (2009). However, there is a recirculation farm under construction at Sundsfjord that has projected a production of 8 to 10 million smolt per year, being one of the largest and modern facilities in Norway (Severinsen, 2009).

Current production licences per recirculation farm ranges between 200.000 to 5.000.000 fish per year (according public data from Fiskeridirectoratet 2010). At the end of this year (2010), it was estimated that near 10 Norwegian RAS farm will have an installed capacity of 27 million 90g smolts.

With a few RAS under construction, installed capacity in RAS in Norway will reach 40 million smolts by the end of 2011. Moreover, if the trends continue with the increased growth rate showed during the last 7 years, around 85 million smolts could be produced in RAS in 2015, as is shown in Table 5. (Detailed information of Norwegian recirculation system installed capacity per year is provided in Appendix 1).

Table 5 Sludge production estimation based on the available RAS capacity in Norway in the period 2002 – 2015

Year	**New Available RAS Capacity (smolts/ year)**	**Accumulated RAS Capacity (smolts/ year)**	**Total Biomass Capacity (tons/ year)**	**Projected Sludge Production (tons/ year)**
2002	850,000	850,000	77	15
2003	0	850,000	77	15
2004	50,000	900,000	81	16
2005	2,500,000	3,400,000	290	57
2006	3,050,000	6,450,000	564	111
2007	5,000,000	11,450,000	1,014	200
2008	0	11,450,000	1,014	200
2009	4,750,000	16,200,000	1,442	284
2010	11,000,000	27,200,000	2,472	487
2011	12,500,000	39,700,000	3,777	744
2012	7,315,833	47,015,833	4,436	873
2013	11,429,545	58,445,379	5,545	1,092
2014	12,688,258	71,133,636	6,779	1,335
2015	13,946,970	85,080,606	8,138	1,602

As is shown in figure 7, available smolt production capacity in RAS will achieve 85 million smolts in 2015, which is three times over the available capacity reported to reach within 2010.

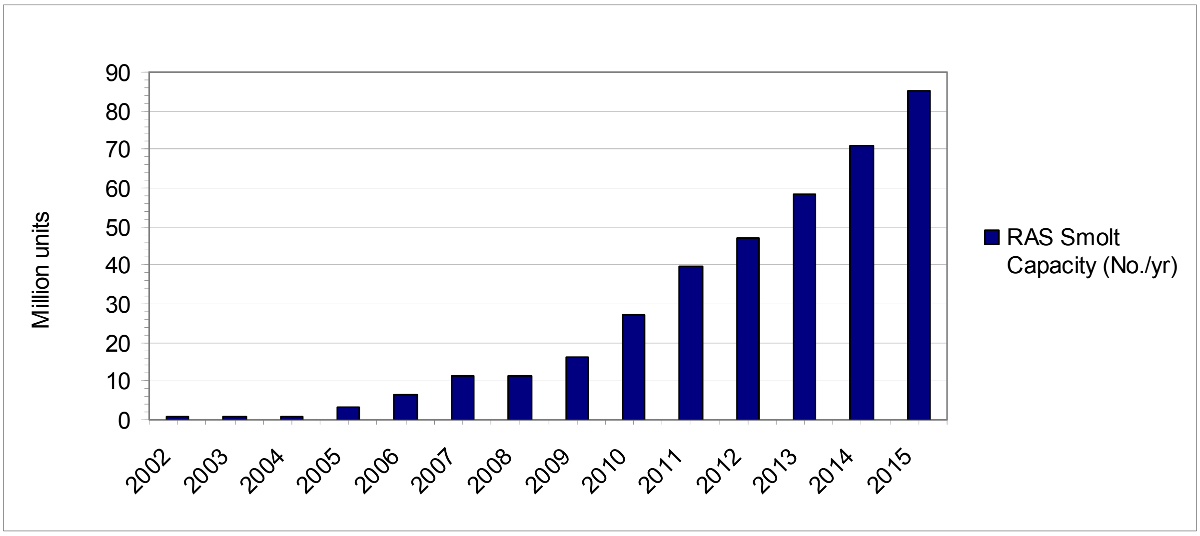

Figure 7 Estimated installed capacity in RAS for salmonid smolt production in Norway

Most of the freshwater based farms, describe integrated production from eggs incubation to smolt ready to be delivered to the sea based sites. Consequently, the sludge production can be expressed as the smolt sludge production as shown in figure 8.

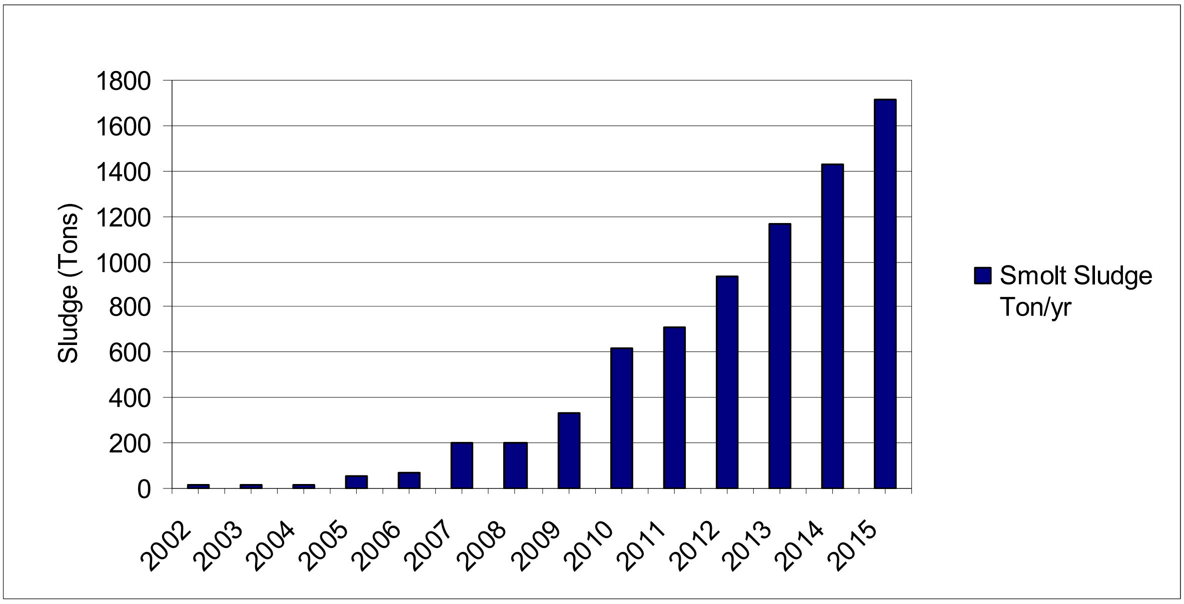

Figure 8 Estimated annual sludge production from RAS in Norway between 2002 and 2015

However, according to the experience of The Norwegian Food Safety Authority (pers. comm. Skrudland, 2010) most of the RAS are located close to the sea, so they are allowed to discharge its effluents directly to the open sea. This fact was also described by the general manager of Flø RAS facility (pers. comm., 2010).

10.2 Estimated annual sludge production in Chile

The Chilean freshwater-salmon recirculation production is in most of the cases divided in fry and smolt unitary facilities. As is shown in figure 9, at the beginning production was dominated by use of recirculation system only for fry production from start feeding to vaccination varying the final size from 10 to 40 grams. However, from 2004 the trend has changed and most of the new facilities that have been built are for smolt production. In 2009, Chile had an installed capacity to produce more than 128 million fry and 93 million smolts in RAS, with an average size of 18 and 79 grams, respectively. Currently, 3 new recirculation plants are under construction. Two of those are projected to start its smolt production this year (2010) and one during 2011, rising up the installed capacity to above 111 and 117 million, respectively. Moreover, a projection of the available capacity until 2015 within RAS would be close to 189 million smolt (Detailed information of Chilean recirculation system installed capacity per year is provided in Appendix 2).

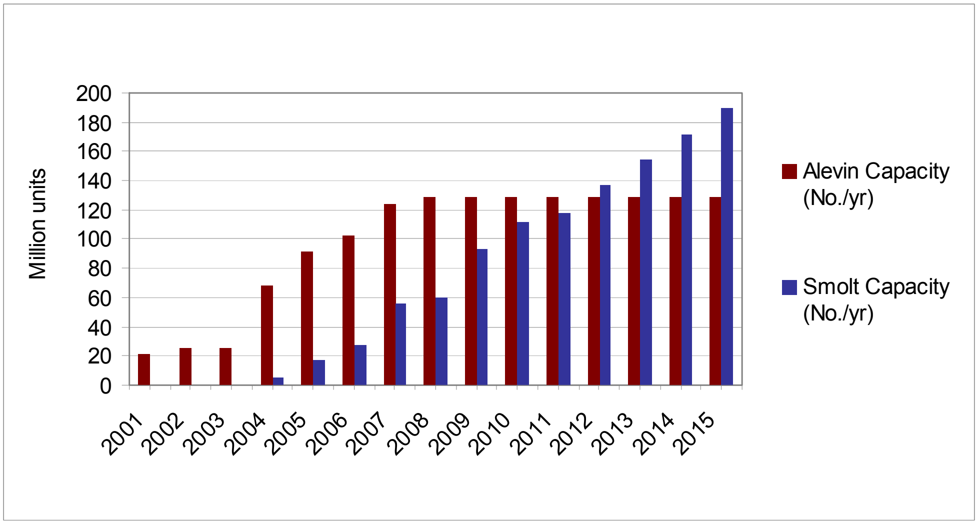

Figure 9 Estimated installed capacity in RAS for salmonid alevin and smolt production in Chile

Figure 9 shows the separate fry and smolt production and how smolt production is increasing to more than 180 million smolts produced using RAS. Consequently, figure 10 shows a high increase in sludge production projecting near to 3.000 tons in 2015 of dry sludge.

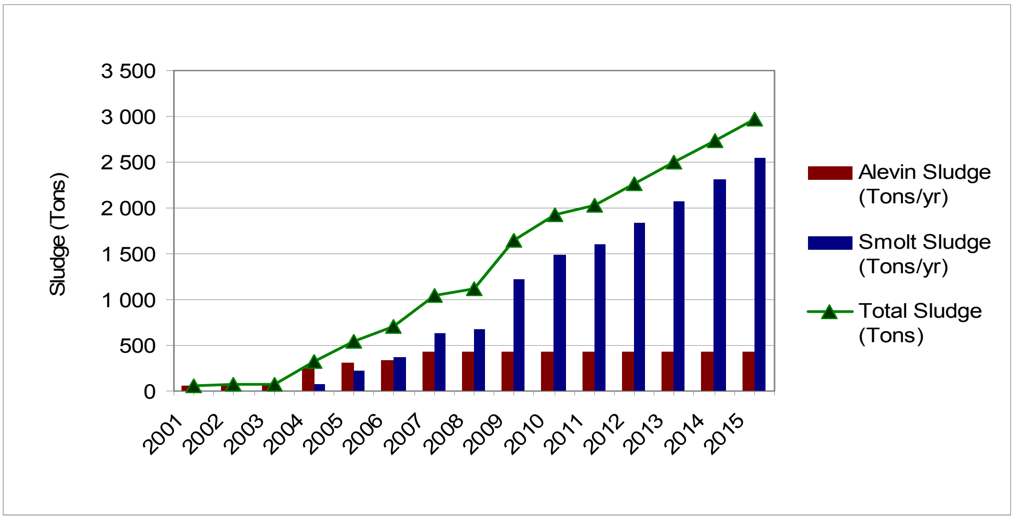

Figure 10 Estimated annual sludge production in Chile between 2001 and 2015

11 Physical and biochemical characteristics of sludge produced from fish farming

Farmed fish are fed pelleted feed to provide a balanced diet for optimum growth rates. Feeds contain nutrients such as nitrogen (N) and phosphorus (P) as well as trace elements. Approximately 70% of the P and 15% of the N fed to fish may be lost through faeces. Since fish typically utilise only 30% of the ingested N and P, the remainder is voided (Table 6). Most of the voided N is dissolved, whereas for P, the majority is associated with the solid material (Chadwick and Salazar, 2007).

Table 6 Waste Production Characteristics of Aquaculture Sludge (Chen et al., 1993)

Parameter	Range	Mean	St Dev
Total Solids (%)	1.4-2.6	1.8	0.35
TVS (% of TS)	74.6-86.6	82.2	4.1
BOD5 (mg/L)	1590-3870	2760	210
TAN (mg/L)	6.8-25.6	18.3	6.1
TP (% of TS)	0.6-2.6	1.3	0.7
Alkalinity	284-415	334	71
BOD20 (mg/L)			

Sludge composition data for a number of fish and culture systems is shown in table 7. In general, sludge from flow through system settling basins tends to have higher total solids (TS) concentrations and lower N and P concentrations. In part, this is due to the long time these solids remain in contact with the water, allowing for decomposition of some of the organic matter and release of some of the nutrients originally in the solids. The high constituent concentrations in sludge (Table 7) make them suitable for treatment through anaerobic digestion and composting. Treated sludge from freshwater operations may be disposed by land application on agricultural fields (Chen et al., 2002).

Table 7 Characteristics of various aquacultural sludge. Data includes total solids (TS), volatile solids (VS), total nitrogen (TN), total Kjeldhal nitrogen (TKN), total phosphorus (TP), chemical oxygen demand (COD), and five day biochemical oxygen demand (BOD_5) (source: Piedrahita (2003))

Sludge source	Composition (g/l)						
	TS	VS	TN	TKN	TP	COD	BOD_5
Trout tank clarifier[a]	22	17	0.2				
Bead filter in a catfish recirculation system[b]	1.0			0.039	0.007	1.0	0.2
Clarifier (no details given) in a recirculation striped bass system[c]	40–60	3.5–5.5	2.5–3.5			75–95	
Trout raceway settling basin[d]	50–120	25–90	0.7–6		0.8–4		
Bead filter in a tilapia recirculation system[e]	14–26	10–23	0.5–1.2		0.08–0.7		1.6–3.9
Trout raceway settling basin, solids accumulate less than 8 days[f]	36–84	27–62		2.1–3.7	0.7–2.4	78–113	

[a] Lanari and Franci (1998).
[b] Chen et al. (1997).
[c] Kugelman and Van Gorder (1991).
[d] Mudrak (1981).
[e] Ning (1996).
[f] Westerman et al. (1993).

12 Analysis of alternative uses of sludge produced from RAS

The following analysis is primarily focused on the potential for utilization of sludge as a source for biofuel, i.e.: as biogas by anaerobic digestion. In addition to this, a brief description of other potential uses of sludge, including information on its application as agricultural fertilizer, input factor in microalgae production, source for combustion and ingredient for fish feed.

12.1 Source for biofuel (biogas by anaerobic digestion)

12.1.1 What is anaerobic digestion?

Anaerobic digestion (AD) is the degradation and stabilisation of organic materials brought about by the action of anaerobic bacteria with the production of biogas, also known as bio-methanisation (Figure 11). AD is carried out in an oxygen-free environment (known as anaerobic conditions) to allow the presence of bacteria adjusted to these conditions which then multiply and grow, and by so doing achieve the process aims of:

- sanitisation of the feed material and of any liquid discharged
- net positive surplus generation of energy as a biofuel to allow power production from methane gas (biogas) produced by the organisms.

12.1.2 What is the rough material for anaerobic digestion?

The main source materials for Anaerobic Digestion (Temperate Climates) are among others:

- Catering waste from private households
- Food residues
- Restaurant and canteen residues
- Farm manure (e.g. liquid manure, dung)
- Vegetable residues from commerce and trade
- Waste water from food production
- Grease trap fat
- Fish farm sludge

12.1.3 Which are the products of anaerobic digestion?

- A gas, so called biogas: Methane – or biofuel.
- A solid fibrous material; which is spread without further treatment, or after post composting (maturation), to provide organic matter for improvement of soil quality and fertility (improves soil structure and reduces summer irrigation demand).

12.1.4 What is a Biofuel?

A biofuel, also called biogas is a mixture of gases, predominantly methane and carbon dioxide, produced by anaerobic digestion (http://www.anaerobic-digestion.com). A biofuel is made from recently dead biological material, most commonly plants. Typical biofuel feed stocks include plants, seeds, wood waste, wood liquors, peat, wood sludge, spent sulfite liquors, agricultural waste, straw, tires, fish oils, tall oil, sludge waste, waste alcohol, municipal solid waste, and even landfill gases (http://www.flbiofuels.org). The production of biofuels to replace petroleum-based oil and natural gas is in active development. The carbon in biofuels was recently extracted from atmospheric carbon dioxide by growing plants, so burning it does not result in a net increase of carbon dioxide in the Earth's atmosphere (see: Atmospheric Carbon-dioxide). As a result, biofuels are seen by many as a way to reduce the amount of carbon dioxide released into the atmosphere by using them to replace non-renewable sources of energy (http://www.bdpedia.com/).

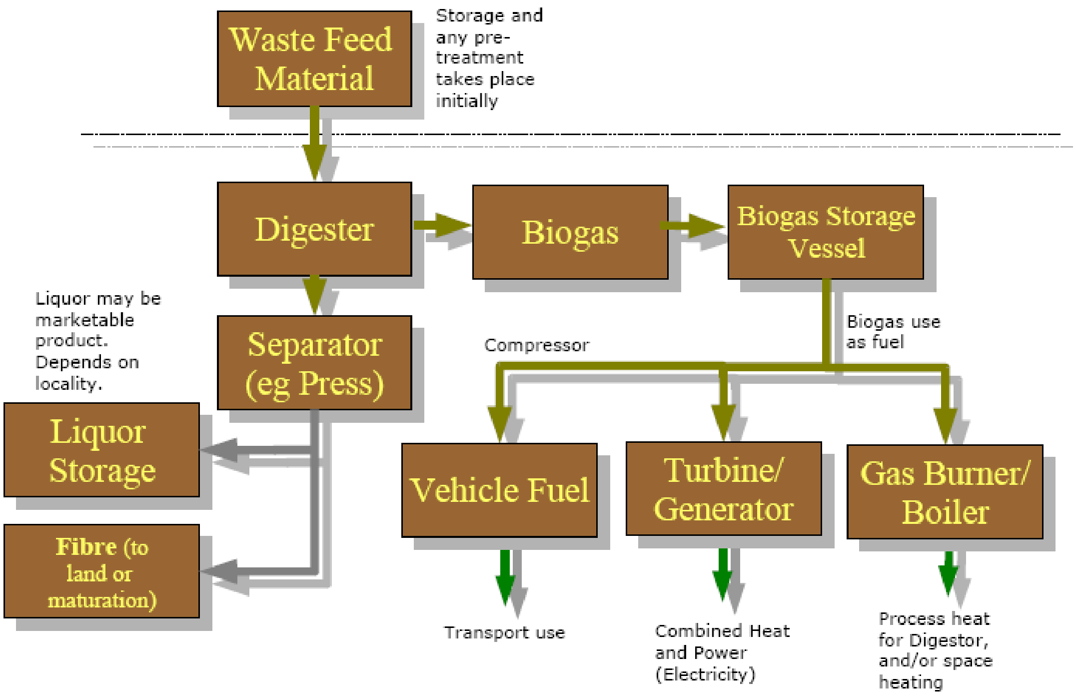

Figure 11 Anaerobic digestion flow chart (Source: http://www.anaerobic-digestion.com/html/anaerobic_flow_diagram.html)

12.1.5 Industrial process

The industrial process of anaerobic digestion is carried out in a reactor that is constructed to effect the degradation of organic matter by anaerobic bacteria. In such Anaerobic Digestion Plant, refuse collection vehicles (RCVs) deliver the collected waste to the plant and the degree of sorting then applied varies. Source separated garden and food waste often can go straight into the process, but mixed residual ('black bag') waste needs sophisticated sorting mechanically to remove the non-biodegradable contaminants. The plant in which this sorting is done is called a Materials Recycling Facility (MRF).

Sorting may involve screens, rotating drums for segregation, air classifiers, and powerful magnets. The organic waste fraction is then shredded and usually mixed with water. The waste and water slurry is then pumped into a sealed vessel where it is heated and stirred where it stays for up to about 3 weeks. This is known as the digestion or fermentation stage. During this period the bacteria digest the waste and create a gas comprising of about sixty percent methane with the remainder being mostly carbon dioxide. This can be used as the source of the heat energy to warm the digestor(s), and there is usually sufficient methane left over to power an electricity generation set.

The process is normally continuous and filling and removal of the treated material takes place simultaneously. The output takes two forms. There is a solid digested material (digestate) which is often pressed to reduce the water content. The solid digestate is fibrous and can be used as a soil improver once it has been further matured usually by being placed in piles to aerobically compost, further reducing its weight, for about two weeks. The digestate is very similar to compost once it has stood in the air for this period.

Unfortunately, even for most source segregated wastes there will be foreign matter, especially plastics etc, in the matured digestate. So, additional sorting is usually required to remove contaminates before it can be used, and the most common is the use of a small mesh size screen.

The liquid fraction can be re-circulated back into the process, but in almost all process designs some excess water is generated. And depending on the removal of, or avoidance of, the presence of possible infectious agents from the feedstock, this can be used as a fertiliser. If the waste source was classed as contaminated (eg food waste) and the waste is not then pasteurised within, or after, the digestion stage the resulting liquid product cannot be used on the land and has to be disposed of to sewer.

The following figures show a typical layout of a biogas plant, designed for anaerobic digestion of liquid and solid organic waste. Whereas figure 12 and 13 gives an overview of the layout of a biogas plant for anaerobic treatment, figure 14 shows a biogas plant from organic Waste, located in Borås, Sweden.

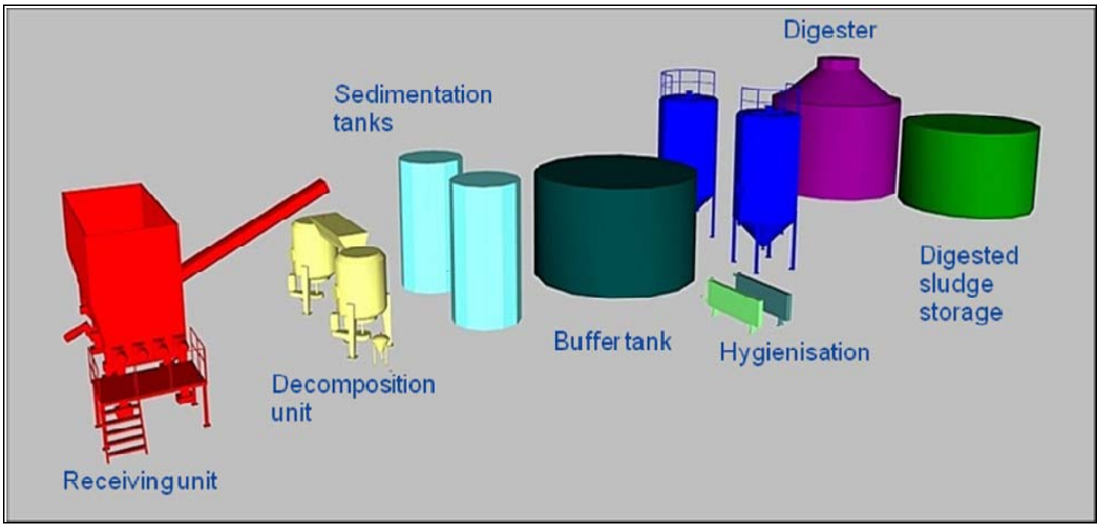

Figure 12 Typical layout of a biogas plant, designed for AD of liquid and solid organic waste

Figure 13 Design of a biogas plant for anaerobic treatment (Ultuna Biogas - Purac, 2010)

Figure 14 Biogas plant from Organic Waste – Borås, Sweden (Ultuna Biogas - Purac, 2010)

12.1.6 Analysis of the potential for commercial use of the sludge as biogas

Anaerobic treatment of sludge from trout or salmon farming in freshwater has been investigated by Kugelman and Van Gorder (1991), Lanari and Franci (1998) and McDermott et al. (2001). Kugelman and Van Gorder (1991) studied the treatment of concentrated sludge (4–6 wt% TS, 2.5– 3.5 g/l Tot-N) and diluted sludge (2–3 wt% total solids (TS), 1.3–1.8 g/l Tot-N), respectively, in continuously stirred tank reactor (CSTRs) at mesophilic temperature, 35°C. Lanari and Franci (1998) investigated the treatment of less concentrated sludge (1.3–2.4 wt%, <250 Tot-NH4-N) in an anaerobic filter at 24–25°C. McDermott et al. (2001) treated a sludge with 0.4 wt% TS <350 mg/l Tot-NH4-N) in a semi-continuous stirred tank digester at 18–20°C. Kugelman and Van Gorder (1991) found strong inhibition of the process with concentrated sludge with Volatile Fatty Acids (VFA) -concentrations of up to 7.8 g/l in the reactor, and measured methane yields corresponding to only 35.7– 46.9 % of the theoretical maximum yields.

Gebauer and Eikebrokk (1996) studied the anaerobic treatment of a concentrated type of sludge (10–12 wt% TS), collected by means of particle traps and completing hydro-cyclones from tanks of an experimental Atlantic salmon smolt hatchery. This was investigated in semi-continuous stirred tank reactors at mesophilic temperature (35°C). The concentrated sludge was chosen to minimise the energy demand for heating the sludge suspension to process temperature. The authors concluded that an anaerobic treatment plant for fish farming sludge could be operated continuously (under given operating conditions) returning a net energy production from burning of the biogas from a full-scale smolt hatchery, with a yearly production of 1 million smolts, would be between 43 and 47 MW h/year. In addition to this, that amount could account for 2–4 % of the energy demand in flow-through hatcheries, and at least twice as much in recirculation hatcheries. In the same line, the net energy production from the biogas achieved by Lanari and Franci (1998) would be 53–65 MW h/year, corresponding to 4– 6% of the energy demand in flow-through hatcheries.

Gebauer and Eikebrokk (1996) made an economic assessment which indicated that exploitation of the energy in the sludge by means of anaerobic treatment—assuming it can be operated continuously without process failure may be profitable, assuming usual Norwegian values for the payback time and interest for anaerobic digesters of 20 years and 7–12 %, respectively (Norwegian Pollution Control Authority, 1993). In the same context, the same authors concluded that the treated sludge might not be suitable as a fertilizer, due to high VFA content (18–28 g/l). In particular, exploitation of the energy generated by anaerobic treatment of a concentrated type of sludge (10–12 wt% TS) would require a reactor volume of 33 m3. With typical digester costs of €500–1000 per cubic meter, this would cost approximately €25,000. In addition, there would be minor costs for foundation, pumps, gas-burner, pipelines and operation of the process. Given energy prices of approximately 0.50 NOK/kW h (0.063 €/kW h) the gain from use of the biogas would be €2700–3000 per year.

On the other hand, industrial suppliers of biogas plants have defined a minimum volume of mixed substrates from industries and/or from household (estimated at 50,000 tonnes per year) in order to make an operation economically viable (Purac, 2010). Therefore, a major question is: could it be possible (and economically feasible) to operate a biogas production plant, being this exclusively supplied by sludge generated at RAS hatcheries? Or in other words: which would be the minimum amount of hatcheries (producing 2 million fish per year) required to operate an industrial biogas plant?

In order to attempt an answer to those issues and using relevant parameters from Gebauer and Eikebrokk (2005) and the calculation base developed on section 11, an estimation of the sludge production for an increasing amount of hatcheries (producing 2 million fish per year) was carried out, followed by a projection of its potential on biogas production, energy production and potential incomes by energy sold. As a result, table 8 shows that a large number (around 300) of hatcheries are required to ensure the minimum supply of sludge needed to make an industrial plant economically viable (green band). In addition to this, considering the projected amount of RAS hatcheries for Norway (blue band) in 2015, only around 1,600 ton/year of sludge would be produced, being this a supply well below the minimum supply of sludge required to make an industrial plant economically viable.

Table 8 Simulation of sludge production, biogas generation, energy production and projected incomes for an increasing number of 2 million fish RAS hatcheries

Number of Hatcheries	Smolts (number/ year)	Biomass (tons/year)	Sludge production (tons/ year)	Biogass production (m3 methane)	Energy production (MWh/ year)	Energy production (KWh)	Income by Energy Sold (NOK)	Income by Energy Sold (NOK/year)
1	2.000.000	180	35	284	104	12	5,3	46.800
5	10.000.000	900	177	1.418	520	59	26,7	234.000
10	20.000.000	1.800	354	2.835	1.040	119	53,4	468.000
50	100.000.000	9.000	1.772	14.175	5.200	594	267,1	2.340.000
100	200.000.000	18.000	3.544	28.350	10.400	1.187	534,2	4.680.000
150	300.000.000	27.000	5.316	42.525	15.600	1.781	801,4	7.020.000
200	400.000.000	36.000	7.088	56.700	20.800	2.374	1068,5	9.360.000
250	500.000.000	45.000	8.859	70.875	26.000	2.968	1335,6	11.700.000
300	600.000.000	54.000	10.631	85.050	31.200	3.562	1602,7	14.040.000
350	700.000.000	63.000	12.403	99.225	36.400	4.155	1869,9	16.380.000
400	800.000.000	72.000	14.175	113.400	41.600	4.749	2137,0	18.720.000

Although this represents a preliminary assessment, these figures clearly show that sludge generated from RAS-based production must be analysed as a complement source of rough material to supply an industrial-scale biogas plant.

In accordance to this, the planned production of biogas in Norway (Table 9) (Nedland and Ohr, 2010), shows a minor contribution (around 2.4%) of slaughter waste category 2 (11,000 tonnes/year) in the overall supply for biogas production. In particular, commonly sludge from RAS in Norway are classified within this category 2, which include manure and digestive tract content and all animal materials collected from treating waste water, including sludge and materials removed from drains. Thus, the ammount projected may consider a small contribution of sludge from flow-through operated aquaculture facilities and RAS hatcheries.

Table 9 Planned sludge and food waste biogas plant in Norway

Waste Fraction	Tonnes waste / year	% Solids	Tonnes TS	% of TS
Sewage sludge	98.500	25	24.600	28
Source Ordered food waste	61.000	30	18.000	21
Food waste from shops	10.200	26	2.600	3
Bio substrate	25.000	10	2.500	3
Food waste from hotels and rest.	12.300	25	3.100	4
Manure	207.000	10	20.700	24
Slaughter waste category 2	**11.000**	**19**	**2.100**	**2**
Fish waste category 3	4.000	30	1.200	1
Grease from grease trap	1.600	50	800	1
Other industrial waste	36.200	30	10.900	13
Total	**466.800**	**19**	**86.500**	**100**

12.2 Other uses

12.2.1 Agricultural fertilizers

The simplest and most common use of sludge produced from fish farms is as fertilizer for direct land application. Fish sludge contains macro and micro nutrients, especially high levels of nitrogen and phosphorus, which potentially can be returned to the land to fertilize crops and provide much needed organic material to certain soils. Although nitrogen is not directly available for plants and must be decomposed by microorganisms in a stable organic product by composting to be incorporate to the soil, this represent a low cost disposal option.

In general terms, there is scarce information regarding commercial application as agricultural fertilizer. The Chilean Institute of Agriculture research -INIA (Teuber, 2006) made a treatment in a potato farm were three salmon sludge rates (50, 100, 200 ton/ha), a control (no fertilizer) and a commercial inorganic fertilizer treatment were incorporated into the soil. As result of the harvest the inorganic fertilizer was 64.3 ton/ha, significantly superior to the results with the salmon sludge rates, and no differences among the sludge (45.6 – 47.5 ton/ha) and the control (39.4 ton/ha) treatment were found. After the potato harvest an annual ryegrass was seeded with significantly difference in yield among treatments and control (Teuber, 2006).

The use of RAS sludge as fertilizer is recommended depending on the biochemical composition of it. In particular, it is essential to know the nutrient content and availability as well as the content of heavy metals, Na and viable pathogens. Further R+D efforts must be placed on the commercial application as agricultural fertilizer. Being a low cost disposal option, the use of sludge as fertilizer is most likely to be a predominant option for the sludge production projected from RAS facilities.

12.2.2 Input factor in microalgae production

Microalgae are a source of high-value products as polyunsaturated fatty acids (PUFAs) (Belarbi et al., 2000), natural colorants (Zhang et al., 2009), biopolymers, and therapeutics (Sanchez et al., 2002; Borowitzka, 1999). Microalgae are essential feed for shellfish and fish juvenile aquaculture. Commercial monoculture of microalgae biomass is usually carried out in outdoors in closed bioreactors (Sanchez et al., 2002), or in open ponds (Zhang et al., 2009).

Under certain environmental conditions, P and N can be released from nutrient rich sludge and may stimulate algal growth. Fish farm effluents containing P and N have been reported to have caused eutrophication of receiving waters. Sludge must be also removed from below lake and sea cages to prevent the production of anoxic gases that may be toxic for the fish and to reduce the growth of micro organisms that can remove oxygen from the water (dissolved oxygen also is low under fish cages).

Sludge from intensive fish farm effluents has been used as the culture medium for microalgae cultures and the algal meal produced used as an ingredient in fish feeds. However, it was found that the critical limiting nutrient was carbon dioxide (Dikson, 2008). Algal meals produced were low in protein (20–35% crude protein) because of high levels of silt contamination. Algal meals could not compete with other readily available feed materials because of high costs and low quality.

Wong et al. (1996) investigated the feasibility of using sewage sludge to culture microalgae (Chlorella-HKBU) and their subsequent usage as feeds for rearing different organisms. They also evaluated results of applying the sludge-grown algae to feed *Oreochromis mossambicus* (fish), *Macrobrachium hainenese* (shrimp), and *Moina macrocopa* (cladocera). In general, the yields of the cultivated organisms were unsatisfactory when they were fed the sludge-grown algae directly.

Based on the results of studies, the use of sludge from intensive fish farms as input factor in microalgae production would not be recommended. This must be analysed further, considering the assessment of different sludge compositions generated from RAS as media in commercial microalgae production systems.

12.2.3 Source for combustion

The company Keppel Seghers has developed fluidised beds able to perform combustion of: mechanically dewatered sludge from wastewater treatment plants, dried sludge and sludge pellets. This process is not designed specifically for sludge generated from fish farms, but may be applicable under given specific operating conditions.

The fluidised bed combustion technology consists of a turbulent fluidized bed furnace with heat recovery. The proprietary air distribution system combined with a shallow bed ensures homogeneous, stable fluidisation at a wide range of operating conditions. The use of a shallow bed avoids formation of hot and cold spots, and prevents the occurrence of dead zones. The ZEROFUEL® fluidized bed features an internal energy recovery system, allowing for auto-thermal combustion of low-calorific sludge, i.e. the combustion air is pre-heated up to 650°C by internal heat recovery, resulting in a reduction of the consumption of auxiliary fuel. In addition, the size of the furnace is significantly smaller than in conventional fluidised bed systems, and an innovative feed system distributes the sludge in small particles evenly across the entire surface of the bed (http://www.keppelseghers.com/sludgecombustion).

12.2.4 Ingredient for fish feed

Studies and literature related to the use of sludge ad ingredient for feeds is very scarce. Here, the Institute of Oceanography and Fisheries in Cairo has conducted research on the development of a process for converting sewage sludge to feed suitable for fish and poultry. Digestibility studies on various feed ingredients were also carried out (FAO, 1979). Here, in cage culture trials at the El-Serow station, researchers assessed growth and feed conversion rates, cage size, supplementary feed, and stocking densities for various Tilapia species. Five fish pellet formulations incorporating by-products such as tomato seeds, poultry manure, fish meal, sewage sludge, and pea pods were developed as feed, and growth studies were conducted. An experimental pellet mill was installed at the Barrage Fisheries Station to initiate pellet production using agricultural and food by-products (National Institute of Oceanography and Fisheries, 1984).

The use of sludge from RAS as ingredient for fish feed is not recommended until further research is carried out to determine its nutritional value, digestibility, anti-nutritional factors, and/or any other potential negative effects (e.g.: microbiological risk and/or disease transmission) on the fish to be fed. In addition to this, the market perception regarding the use of fish or other animal waste on feeds is an issue to be carefully taken into account.

13 Potential partners for collaborative applied R+D and/or commercialization projects

13.1 Norway

13.1.1 Equipment suppliers

Company	Web site
AquaOptima	http://www.aquaoptima.com
Aqua Tech Solutions	http://www.aquatec-solutions.com
Hobas Ltd.	http://www.hobas.no
AKVA group	http://www.akvagroup.com
Inter Aqua Advance	http://www.interaqua.dk
KRÜGER KALDNES	http://www.krugerkaldnes.no
Sterner AquaTech	http://www.sterner.no

13.1.2 Smolt producers in Norway

Company	Farm Location
Marine Harvest	Flø
Aakvik Settefisk AS	Halsa
Smøla Klek.& Settef. AS	Smøla
Sørsmolt AS	Sannidal, Kragerø
Marine Harvest	Salsbruket
Ertvaag Settefisk AS	Aure
Aakvik Settefisk AS	Halsa
Hardingsmolt AS	Tørvikbygd, Kvam
Lerøy Midnor AS	Lensvik
Fjordsmolt As**	Skånland
Aakvik Settefisk AS*	Halsa
Sørsmolt AS*	Sannidal, Kragerø

13.2 Chile

13.2.1 Equipment suppliers

Company	Web site
Billund Aquaculture Chile S.A.	http://www.basalmon.com
Hesy	http://www.hesy.com
Inacui	http://www.inacui.cl
PRAqua	http://www.praqua.com
Aquatec Solutions - Chile	http://www.aquatec-solutions.com
Hydrogest	http://www.hydrogest.cl
AKVA Group Chile	http://www.akvasmart.cl
Atlantech Chile Ltda.	http://www.atlantech.ca/public/chile.html

Keppel Seghers (http://www.keppelseghers.com/home)

This company has developed fluidized beds able to perform combustion of: mechanically dewatered sludge from wastewater treatment plants, dried sludge and sludge pellets.

13.2.2 Companies related to aquaculture solids treatments

Company	Web site
Empresa de Tratamiento de Residuos Copiulemu	http://www.copiulemu.cl
Ambar S.A.	http://www.ambar.cl
AZ Ingeniería y Máquinas Ltda.	http://www.azing.cl
Bioaqua	http://www.bioaqua.cl
Dorin / Resiter	http://www.dorin.cl
Ecovann Chile Ltda.	http://www.ecovann.cl
Eratech Chile Ltda.	http://www.eratech.cl
Geobarra - Exins	http://www.geobarra.cl
Hidronor Chile S.A.	http://www.hidronor.cl
Minimet S.A.	http://www.minimet.cl
Rexin	http://www.rexin.cl
Tresol Ltda.	http://www.tresol.cl

13.2.3 Fry and smolt producers

Alevin		Smolt	
Company	Farm	Company	Farm
Camanchaca	Petrohué	Yaldrán	Río Chico
Skysal	Mina Marta	Pesquera Los Fiordos	Mano Negra
Marine Harvest	Río Blanco	Marine Harvest	Rauco
Nalcahue	Chesque	Camanchaca	Petrohué
Marine Harvest	Pichichanlelfu	Salmones Humboldt	Santa Juana
Tornagaleones	Los Chilcos	Invertec	Lago Verde
Ecofish	Correntoso	Camanchaca	Petrohue
Multiexport	Puerto Fonk	Sealand Aquac SA	Chayahué
Patagonia	Puyahuapi	Novofish	Colaco
Salmones Humbolt	Santa Juana	Pesca Chile S.A	Pto Chacabuco
Multiexport	Molco	Itata	Huenquilahue
Mainstream	Río Pescado	Sealand Aquac SA	Chayahué
Invertec	Lago Verde	-	-

13.2.4 Biogas plants in Norway

Location	Municipalities / Companies	Type of facility - Technology	Type of waste treated	Capacity * (tons / year)
Lillehammer	Mjøsanlegget (Glør, GLT og HIAS)	Biogass - Cambi	Food waste	14,000
Jevnaker	HRA AS	Biogass - Biotek	Food waste	10,000
Elverum	Hera Vekst (SØIR/GIR/Norsk Jordforbedring)	Biogas / composting - AIKAN	Food waste	25,000
Treungen/Telemark	IATA IKS	Biogass - Biotek	Food waste	11,000
Verdal	Ecopro	Biogass - Cambi	Food waste + sewage sludge	35,000
Drammen/Lillehammer/Lofoten/Gjøvik	Lindum/GLØR/LAS/GLT	Biocells	Biodegradable waste	10,000
Halden	Halden Resirkulering	Biowaz	Manure (+ food waste)	5,000
Fredrikstad	FREVAR KF	Treatment plant with biogas	Sewage sludge + pumpable waste	
Oslo-Bekkelaget	Bekkelaget Vann AS	Treatment plant with biogas	Sewage sludge + pumpable waste	
Stavanger-Randaberg/SNJ	IVAR	Treatment plant with biogas	Sewage sludge + pumpable waste	5,000
* Data Updated at 3.11.2009				115,000

Source: http://www.biogassforum.no/

13.2.5 Biogas plants in Sweden

Company	Rough material
Kalmar Biogas	sludge, manure, abattoir waste
Helsingborg	industrial organic waste
Ultuna Biogas	farms, food industry, abattoir waste
Karlstad	sludge
Lövsta	agricultural
Nynäs	agricultural
Bodens Biogas	sludge, organic household waste
Älmhults Biogas	sludge, organic household waste
Falköpings Biogas	sludge, organic household waste
Borås Biogas	household waste
Plönninge	agricultural
Ecoferm	household waste
Skellefteå	abattoir waste, organic household waste

13.2.6 Extensive microalgae producers

Atacama Bionatural Products S.A. (http://www.atacamabionatural.com/)

Biotechnological company dedicated to the cultivation of *Haematococcus pluvialis* from where carotenoid astaxanthine is obtained which is used for making Natural Asta Oil products and Supreme Asta Oil.

Algatech, Israel (http://www.algatech.com/)

Company that develops and commercializes Astaxanthin and other microalgae-derived products for the nutraceuticals and cosmeceuticals industry.

14 Preliminary patent search

To analyse the potential for patenting processes related to sludge treatment a web-based search of related patents was carried out. To determine the definite patentability, the results summarised below would have to contrast against the specification of the new processes to be developed, in order to conclude its distinction or improvement with regards to the state of the art and its industrial application degree. Despite the search done is only based on public-access sources, it clearly reflects a large number of processes related to sludge treatment, regardless of the industrial sector of application.

Among the patents that have been granted in the area of sludge treatment for converting sludge into soil amendment and electricity are the following U.S. patents:

- U.S. Pat. No. 3,981,800 is concerned with the production of high quality of methane gas. In this process, dry manure is blended with water and seed sludge to the desired consistency and then the mixture is subjected to anaerobic digestion for a period of days in a digester. The mixture then passes into a second digester where it again is subjected to anaerobic digestion for several more days. Methane gas is recovered from each digester while some sludge is recirculated from the second digester to the first digester. Remaining sludge is thickened, partially recirculated to the blender and partially dewatered. The dewatered sludge is dried, using methane as the heat source, to form a dry marketable product, which is presumably a fertilizer.

- U.S. Pat. No. 4,040,953 is directed to a process for conversion of organic material to methane gas and a residue suitable for use as a soil conditioner, organic fertilizer, or protein-rich animal feed supplement. An organic slurry, from which grit, inorganic solids and carbon dioxide have been stripped, is passed through a multi-stage anaerobic digestion for the production of methane gas. After removal of methane, the sludge is partially recycled to the carbon dioxide stripping step. The remainder of the sludge is thickened and dewatered to form a solid residue.

- U.S. Pat. No. 4,267,049 converts treated sludge from raw municipal waste waters or raw agricultural wastes into organic feedstock or fertilizer. The treated sludge is passed through a hydrolytic enzyme conditioning and then tissue and cells are mechanically disintegrated. Heavy metals are removed, and the sludge is subjected to autolysis by an infusion of fresh endocellular enzymes. The autolysate product is dewatered, and the resultant solid may be used as an organic feedstock or as high quality fertilizer.

- U.S. Pat. No. 4,369,194 defines a process in which manure is finely ground and then mixed with water to produce a mixture having at most 4 % solids. Filaments and vegetable fibers are removed in a separator, and the liquid is fed to a bioreactor for the production of methane. After a suitable time in the digester, e.g., four days, and removal of methane, the resultant suspension is fed into a separator for removal of al solid substances. The solid substances are then dried, using methane produced in the digester as a heat source.

- U.S. Pat. No. 4,388,186 concentrates waste water from a solids content of about 1% of solids contents of about 6 % to about 10 % in a centrifugal condensing machine. This concentrate is then treated in an anaerobic digestion tank. The digested sludge is then dewatered and dried. Methane, which was produced in the digester, provides heat to the drier.

- U.S. Pat. No. 4,632,758 utilizes a honeycombed reactor to generate methane and sludge from waste water as derived from a food processing plant. The waste water is first freed of debris such as cans, boards, and large vegetable scraps. It is then heated prior to introduction into the reactor, in which organic matter is converted into methane and sludge in an anaerobic process. Methane thus produced is used to heat the waste water prior to its introduction into the reactor; excess methane is burned off. Some sludge is recirculated to different parts of the system and the rest is withdrawn from agricultural utilization without further treatment.

- U.S. Pat. No. 4,818,405 involves a process where municipal sludge is converted from an environmental problem into soil amendment and electricity. Methane, produced in an anaerobic digester (2), is used partially to generate electricity and partially to dry the concentrated sludge in a rotary dryer (7). Excess heat from the dryer is used to maintain the temperature in the digester at approximately 105° to 130° F. Heavy metals are removed so that the dried sludge can be safely used as a soil amendment.

Other patents that have been granted within the area of sludge treatment, in relation to fish farming are the following:

1. **United States Patent 4,985,149**
   Ohshima , et al. January 15, 1991

Anaerobic digestion method

Sewage sludge or an agricultural or fish waste material is subjected to pre-treatment in the form of wet mill treatment and then is subjected to anaerobic digestion.

2. **United States Patent 5,081,954**
   Monus January 21, 1992

Method of raising fish

Water from a fish growth tank is pumped through multiple filter tanks containing a filter media and injected with ammonia fixing bacteria. Metabolic wastes from the fish growth tank are absorbed by hydroponic or sand growth beds. Oxygen content and temperature of the water is constantly monitored by sensors and air blowers and heaters are activated when oxygen level or temperature respectively falls below the prescribed conditions for growth of the fish. All backwash water from a sludge digestion area is recirculated to the fish growth tank to conserve water in the system.

3. **United States Patent 7,462,284**
   Schreier , et al. December 9, 2008

Dissimilatory sulfate reduction as a process to promote denitrification in marine recirculation aquaculture systems

The present invention relates to a novel approach for nitrate removal from a marine recirculation system (10) wherein high concentrations of sulfate found in seawater is used in combination with sludge (20) collected from fish growing tanks (12) to promote dissimilatory sulfate reduction to hydrogen sulfide. The sulfide is used as an electron source to promote autotrophic denitrification in an up-flow fix bed bioreactor (16), followed by nitrification in a nitrification unit (14). By utilizing the symbiotic relationship between the sulfate-reducing and sulfide-oxidizing bacterial community, nitrate accumulation is controlled in the recirculation water of the system thereby reducing water exchange in the marine recirculation system.

4. United States Patent 7,553,410

Chennault June 30, 2009

Septage treatment system

The present invention generally includes a septage treatment system comprising: (a) a primary treatment process system comprising: (1) a receiving station to pump the septage from a vehicle; (2) equalization tank(s) to receive septage from the receiving station; and (3) two or more mixing and odor control tanks to generate waste activated sludge; (b) a primary settling tank to generate waste activated sludge; (c) a secondary treatment process system comprising: (1) aeration tank(s) to receive waste activated sludge from the primary treatment process system and to generate water effluent; and (d) a tertiary treatment process system comprising: (1) wetland ditch(es) to receive water effluent from the aeration tank and to generate filtered water effluent; (2) wetland pond(s) to receive filtered water effluent from the wetland ditch(es) and to generate filtered water effluent; and (3) an aquaculture hydroponics and sand bed greenhouse to generate filtered water effluent.

5. United States Patent 5,736,047

Ngo April 7, 1998

Hybrid biological nutrient removal system

A hybrid system and related process for the removal of biological nutrients from wastewater. The system provides an activated sludge system, including both a single-sludge reactor and clarification unit, flowably connected with a final aquaculture pond for final polishing of BOD from the clarified mixed liquor supernatant.

6. United States Patent 7,422,680

Sheets, Sr. September 9, 2008

Animal waste effluent treatment system

Animal waste such as fecal material from swine, chicken, turkey, and cattle is converted into useful forms such as fertilizer, other types of soil builders, and even nutrient feed additives. Devices, systems, and methods are provided that allow economical conversion and in many instances, alleviate the production and release of undesirable gases such as sulfide and ammonia. In one embodiment, undesirable anaerobic and facultative anaerobic bacteria are killed at a greater rate than desirable soil compatible aerobic bacteria. The use of low temperature killing diminishes off gassing commonly associated with other techniques, and the use of gas trapping additives such as zeolites provides enhanced soil building qualities such as slow release of nitrogen and slow release of moisture to soil. The methods allow convenient adjustment of composition, allowing conversion of waste into tailored designer fertilizer suited for particular soils. Other embodiments provide other soil building qualities as well as nutrient qualities for feedstock used in animal husbandry such as aquaculture.

7. United States Patent 7,258,790
Brune, et al. August 21, 2007

Controlled eutrophication system and process

A controlled eutrophication system and process are disclosed. The system includes the combination of a partitioned aquaculture system in conjunction with an anaerobic digester. Wastewater containing pollutants, such as nitrogen and phosphorus, are fed to the partitioned aquaculture system. Algae within the system converts the pollutants into algal biomass. Fish populations, in turn, control the algal populations. The fish populations may then be periodically harvested for human or animal consumption. A polishing chamber is contained in the system in which aquatic organisms remove substantial amounts of the algae from batch fed additions of water. The water is then discharged to an external water source containing virtually no pollutants. In one embodiment, the biomass excreted by the aquatic organisms in the system are collected and fed to a digester. In the digester, the biomass is converted to a hydrocarbon gas and collected for its fuel value, while the liquid fraction is collected for its fertilizer value.

8. United States Patent 6,863,826
Sheets March 8, 2005

Animal waste effluent treatment

Animal waste such as fecal material from swine, chicken, turkey, and cattle is converted into useful forms such as fertilizer, other types of soil builders, and even nutrient feed additives. Devices, systems, and methods are provided that allow economical conversion and in many instances, alleviate the production and release of undesirable gases such as sulfide and ammonia. In one embodiment, undesirable anaerobic and facultative anaerobic bacteria are killed at a greater rate than desirable soil compatible aerobic bacteria. The use of low temperature killing diminishes off gassing commonly associated with other techniques, and the use of gas trapping additives such as zeolites provides enhanced soil building qualities such as slow release of nitrogen and slow release of moisture to soil. The methods allow convenient adjustment of composition, allowing conversion of waste into tailored designer fertilizer suited for particular soils. Other embodiments provide other soil building qualities as well as nutrient qualities for feedstock used in animal husbandry such as aquaculture.

9. United States Patent 4,995,981
Gott February 26, 1991

Process for anaerobically degrading highly loaded process waste waters

The invention relates to a process for anaerobically degrading highly concentrated process waste waters as obtained particularly in the chemical industry, in paper mills and cellulose plants, fish-processing plants, and in the production and elimination of alcohol or the like, whereby the CSB-content may be up to 10.sup.6 mg/l or more. This process comprises a putrefactive process which is induced in at least one decomposition tank at about 34.degree. C. by circulating normal sewage sludge, whereby upon start-up of the putrefactive process, a change to chemical process waste waters is carried out without adding communal sewage sludge. Subsequently, the sludge is withdrawn from the decomposition tank, flocculated, and returned to the external circulation for circulating the putrefactive sludge in the decomposition tank.

15 Potential environmental impacts of sludge

Depending on the use of sludge or its by-products, the potential environmental impact will vary. In particular, sludge could contain harmful substances, such as heavy metals and pathogens which would limit their suitability for fertilising crops. Under certain environmental conditions, P and N can be released from nutrient rich sludge and may stimulate algal growth. Also sludge derived from salt water fish farms could also contain significant quantities of sodium (Na) which may impact on soil structure. Fish farm effluents containing P and N have been reported to have caused eutrophication of receiving waters (Salazar and Saldana, 2006).

With regards to pathogens, sludge produced from fish farming may contain fish pathogens that may reach rivers with overflow water from fertilized areas and thus infect wild fish populations. On the other hand, fish sludge contains nutrients and organic matter, which can be returned to the land to fertilise crops and provide much needed organic material to certain soils, having therefore a potential positive environmental impact.

In order to optimise the use of fish sludge on land and minimise their environmental impact, it is essential to know the nutrient content and availability as well as the content of heavy metals, Na and viable pathogens (Salazar and Saldana, 2006).

In particular, salmon manure has low nutrients and heavy metal contents and a potential use in agricultural soils, which could reduce the risks of water pollution on water from fish farming (Salazar and Saldana, 2006).

16 Description of current regulations

16.1 Norwegian regulation

In order to be permitted for use as a fertilizer in Norway, the treated sludge has to fulfill the Norwegian regulations for fertilizers of organic origin (Norwegian Ministry of Agriculture, 2003). These regulations prohibit substances that may be harmful for the environment or for humans, animals or plants, and make demands on the content of heavy metals and organic contaminants and on hygienisation and stabilization. According to Gebauer and Eikebrokk (1996), the concentrations of heavy metals in the untreated fish farming sludge would not be critical for reuse of the sludge as a fertilizer. Although the concentrations in the treated sludge will be about double those in the untreated sludge. Also, the concentrations of organic contaminants in the sludge will be low because of very low concentrations of organic contaminants in fish feed (Julshamn et al., 2004).

Concerning the hygienic quality, the regulations will generally protect against the transmission of diseases and explicitly prohibit the content of *Salmonella sp*. and restrict the content of thermo-tolerant *coli* forms in organic fertilizers. Both *Salmonella* and *coli* are associated with warm-blooded animals and will thus normally not occur in fish farming sludge. But fish farming sludge may contain fish pathogens that may reach rivers with overflow water from fertilized areas and thus infect wild fish populations. Therefore, any treatment of sludge from fish farm will have to ensure that the fish pathogens will be inactivated in the process. In the same context, Gebauer and Eikebrokk (1996) found that treated fish farming sludge in an anaerobic digestor would not be sufficiently stabilized to avoid nuisance from odour, as demanded by the regulations, because at least half of the organic matter still exists as easily degradable soluble compounds.

In order to use sludge from RAS as a by-product in biogas plants or composting plants, this sludge must fulfill the Regulations of the European Parliament concerning animal by-products not intended for human consumption (EC/1774/2002).This regulation laid down the collection, transport, storage, handling, processing and use or disposal of animal by-products, to prevent the products from presenting a risk to animal or public health.

This regulation classifies the animals by-products in three categories:

Category 1 materials shall comprise animal by-products, or any material containing such by-products:

a) all body parts, including hides and skins, of:
   - animals infected by all transmissible spongiform encephalopathies (TSEs), or killed as TSE eradication measures,
   - animals other than farmed animals (bred by humans and used for the production of food) and wild animals, including pet, zoo and circus animals
   - animals used for experimental and other scientific purposes, and
   - wild animals, infected with diseases communicable to humans

b) specified risk material;

c) products derived from animals to which substances prohibited have been administered and products of animal origin containing residues of environmental contaminants.

d) All animal material collected when treating waste water in which specified risk material is removed.
e) Catering waste from means of transport operating internationally
f) Mixtures of category 1 with either category 2 or 3 material.

Category 2 material shall comprise animal by-products, or any material containing such by-products of:
a) manure and digestive tract content;
b) all animal materials collected when treating waste water from slaughterhouses
c) products of animal origin containing residues of veterinary drugs and contaminants
d) products of animal origin, other than Category 1 material, that are imported from non-member countries or fail to comply with the veterinary requirements for their importation into the Community
e) animals and parts of animals, other than those Category 1, that die other than by being slaughtered for human consumption, including animals killed to eradicate an epizootic disease;
f) mixtures of Category 2 material with Category 3 material; and
g) animal by-products other than Category 1 material or Category 3 material.

Category 3 material shall comprise animal by-products, or any material containing such by-products, of:
a) parts of slaughtered animals, which are fit for human consumption but are not intended for human consumption for commercial reasons;
b) parts of slaughtered animals, which are rejected as unfit for human consumption but are not affected by any signs of diseases communicable to humans or animals and derive from carcases that are fit for human consumption
c) hides and skins, hooves and horns, pig bristles and feathers originating from animals that are slaughtered in a slaughterhouse, after undergoing ante-mortem inspection, and were fit, as for slaughter for human consumption
d) blood obtained from animals other than ruminants that are slaughtered in a slaughterhouse, after undergoing ante-mortem inspection, and were fit for human consumption
e) animal by-products derived from the production of products intended for human consumption, including degreased bones and greaves;
f) former foodstuffs of animal origin, which are no longer intended for human consumption and do not present any risk to humans or animals;
g) raw milk originating from animals that do not show clinical signs of any disease communicable to humans or animals;
h) fish or other sea animals, except sea mammals, caught in the open sea for the purposes of fishmeal production;
i) fresh by-products from fish from plants manufacturing fish products for human consumption;
j) shells, hatchery by-products and cracked egg by-products originating from animals which did not show clinical signs of any disease communicable to humans or animals;
k) blood, hides and skins, hooves, feathers, wool, horns, hair and fur originating from animals that did not show clinical signs of any disease communicable through that product to humans or animals

Commonly sludge from RAS in Norway are classified as category 2, which include manure and digestive tract content and all animal materials collected from treating waste water, including sludge and materials removed from drains. In general terms, this category 2 is permitted to be used in biogas plants or in composting plants that are subjected to approval by the competent authority and a long list of requirements of this regulation (mentioned in

Annex VI, Chapter II) regarding equipments and units needs, hygiene requirements and processing standards that must be met (EC/1774/2002).

16.2 Chilean regulation

There is no specific regulation for sludge from aquaculture activity, and currently this compost is not recognized as fertilizer. Nowadays, most of the hatcheries have a solid control of the effluent by filtration in drum filters to achieve the committed level of TSS, generating wet sludge as their main product. This sludge often is dried, stored and delivered to authorized companies for its disposal. In general terms, every aquaculture and fishery activity is regulated under the law "*Decreto* Nº 340. *Ley General de Pesca y Acuicultura*" of Ministry of Economy launched on January, 1992. Article Nº 87 established a necessity to regulate measurements to protect the environment of water sources.

The environmental regulation for aquaculture was published on December of 2001 under the law Nº320 "*Reglamento Ambiental Para la Acuicultura*" – RAMA, that in its article 4th established that every aquaculture location must comply with the national environmental regulation under the law Nº 19.300 "*Bases Generales de Medioambiente*". This article states that every industrial discharge must be managed following the specific regulation according to the specific procedures established by the related agency.

Article 8 established that every land based fish farm must comply with the regulation of emission in line with the article 40^{th} of the law Nº19.300 defining that every specific emission is regulated by the specific norm applied to the source of water and kind of emission. Emission to a source of water is regulated by the ordinance law Nº90 that establish the regulation associated to pollution from emission to continental or marine source of water, Decreto Ley Nº90.

Some special requirements might be asked in land-based fish farm, like flow rate of the discharge, if the discharge is above 300 m3/day will be required a chamber and flow meter with daily record, and pH and oxygen monitoring.

17 Follow-up actions

1. Looking at decreasing scales on economies, we recommend to conduct R+D to analyse in detail the economic potential of a plant for anaerobic digestion at an industrial level, considering the concentration of total sludge production in Norway or in Chile to be processed in one single biogas plant. Assessment of operations and logistics related to this chain should be also taken into account.

2. Within alternative uses of sludge, production of compost using humid fish farm sludge must be studied as an option of protein production recognised by governmental agencies. Nowadays, this process is only utilised for treatment of sludge on-site without commercial purposes. This involves getting the approval of concerned regulating agencies, in Chile and in Norway.

3. To make fish farm sludge suitable as fertilizer, the sludge must include and additional source of carbon and other traces (such as potassium). An option to be studied could be the use and inclusion of other by products from processing plants and/or agriculture disposals in the production process (value added) of sludge.

4. In order to develop an R+D project involving optimization of biogas production from anaerobic digestion of fish farm sludge a consortium with different Norwegian Institutes should be established.

5. To carry out any project looking at commercial applications for sludge from fish farming, we strongly recommend involving a significant number of smolt producers in Norway and/or in Chile jointly. In general terms, is recommended that industrial production of sludge to be accumulated and then processed in order to achieve a bulk of rough material large enough to generate sufficient value-added product (e.g.: fertilizer, biogas or energy).

6. Further R+D must be focused on the design of smaller biogas reactor systems that can be operated on a viable commercial basis and that can be operated in-situ by small amounts of sludge generated at RAS hatcheries.

7. Specific R+D must be developed looking at the energy outputs from different types and qualities of sludge from RAS, mainly focused on its concentration and chemical composition (e.g. depending on the treatments done at the hatcheries such as use of salt and other chemicals for the fish production).

18 Conclusions

- Sludge production from RAS can contribute to supply rough material to any biogas plant and thus generate a value added to the solid waste generated by fish farming.

- A large number of fish hatcheries would be required to ensure the minimum supply of sludge required to make an industrial biogas plant economically viable.

- Sludge generated from RAS-based production must be analysed as a complement source of rough material to supply an industrial-scale biogas plant.

- When sludge is processed on an anaerobic digester, a stabilised mud may be obtained for its use as fertilizer, because its quality can be better that the one generated by composting processes.

- The use of sludge from RAS as ingredient for fish feed is not recommended until further research is carried out to determine its nutritional value, digestibility, anti-nutritional factors, and/or any other potential negative effects (e.g.: microbiological risk and/or disease transmission) on the fish to be fed. In addition to this, the market perception regarding the use of fish or other animal waste on feeds is an issue to be carefully taken into account.

- The use of sludge from intensive fish farms as input factor in microalgae production would not be recommended. This must be analysed further, considering the assessment of different sludge compositions generated from RAS as media in commercial microalgae production systems.

- There are two major options for the use of sludge generated at RAS facilities that are technically viable and must be explored further in order to achieve economic efficiencies: sludge as a source for biogas and sludge as a source of fertilizer.

- To implement a commercial-scale operation for processing sludge from fish farming in Norway or in Chile, a significant number of fry/smolt producers must be involved in order to accumulate and then process a bulk of rough material large enough to generate sufficient value-added product (e.g.: fertilizer, biogas or energy).

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Appendix 1 Norwegian RAS installed capacity and sludge production estimations

Year	Smolt Capacity (No./yr)	Accumulated Capacity (No./yr)	RAS Biomass Capacity (Tons)	RAS Sludge (Tons/yr)
2002	850 000	850 000	77	15
2003	0	850 000	77	15
2004	50 000	900 000	81	16
2005	2 500 000	3 400 000	290	57
2006	3 050 000	6 450 000	564	111
2007	5 000 000	11 450 000	1 014	200
2008	0	11 450 000	1 014	200
2009	4 750 000	16 200 000	1 442	284
2010	11 000 000	27 200 000	2 472	487
2011	12 500 000	39 700 000	3 777	744
2012	7 315 833	47 015 833	4 436	873
2013	11 429 545	58 445 379	5 545	1092
2014	12 688 258	71 133 636	6 779	1335
2015	13 946 970	85 080 606	8 138	1602

Appendix 2 Chilean RAS installed capacity and sludge production estimations

Year	Alevin Capacity (No./yr)	Smolt Capacity (No./yr)	Total units (No./yr)	Alevin Biomass (Tons/yr)	Smolt Biomass (Tons/yr)	Total Biomass (Tons/yr)	Alevin Sludge (Tons/yr)	Smolt Sludge (Tons/yr)	Total Sludge (Tons)
2001	21 000 000	0	21 000 000	315	0	315	55	0	55
2002	25 000 000	0	25 000 000	395	0	395	69	0	69
2003	25 000 000	0	25 000 000	395	0	395	69	0	69
2004	67 600 000	4 800 000	72 400 000	1 421	347	1 768	249	68	317
2005	91 350 000	17 250 000	108 600 000	1 784	1 156	2 940	312	228	540
2006	102 850 000	27 650 000	130 500 000	1 968	1 832	3 800	344	361	705
2007	123 850 000	56 250 000	180 100 000	2 418	3 186	5 604	423	627	1 050
2008	128 550 000	60 250 000	188 800 000	2 465	3 466	5 931	431	682	1 114
2009	128 550 000	93 261 700	221 811 700	2 465	6 163	8 628	431	1 213	1 645
2010	128 550 000	111 761 700	240 311 700	2 465	7 579	10 044	431	1 492	1 924
2011	128 550 000	117 761 700	246 311 700	2 465	8 118	10 583	431	1 598	2 030
2012	128 550 000	137 031 304	265 581 304	2 465	9 326	11 791	431	1 836	2 268
2013	128 550 000	154 479 226	283 029 226	2 465	10 514	12 979	431	2 070	2 501
2014	128 550 000	171 927 149	300 477 149	2 465	11 702	14 167	431	2 304	2 735
2015	128 550 000	189 375 071	317 925 071	2 465	12 890	15 355	431	2 538	2 969

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