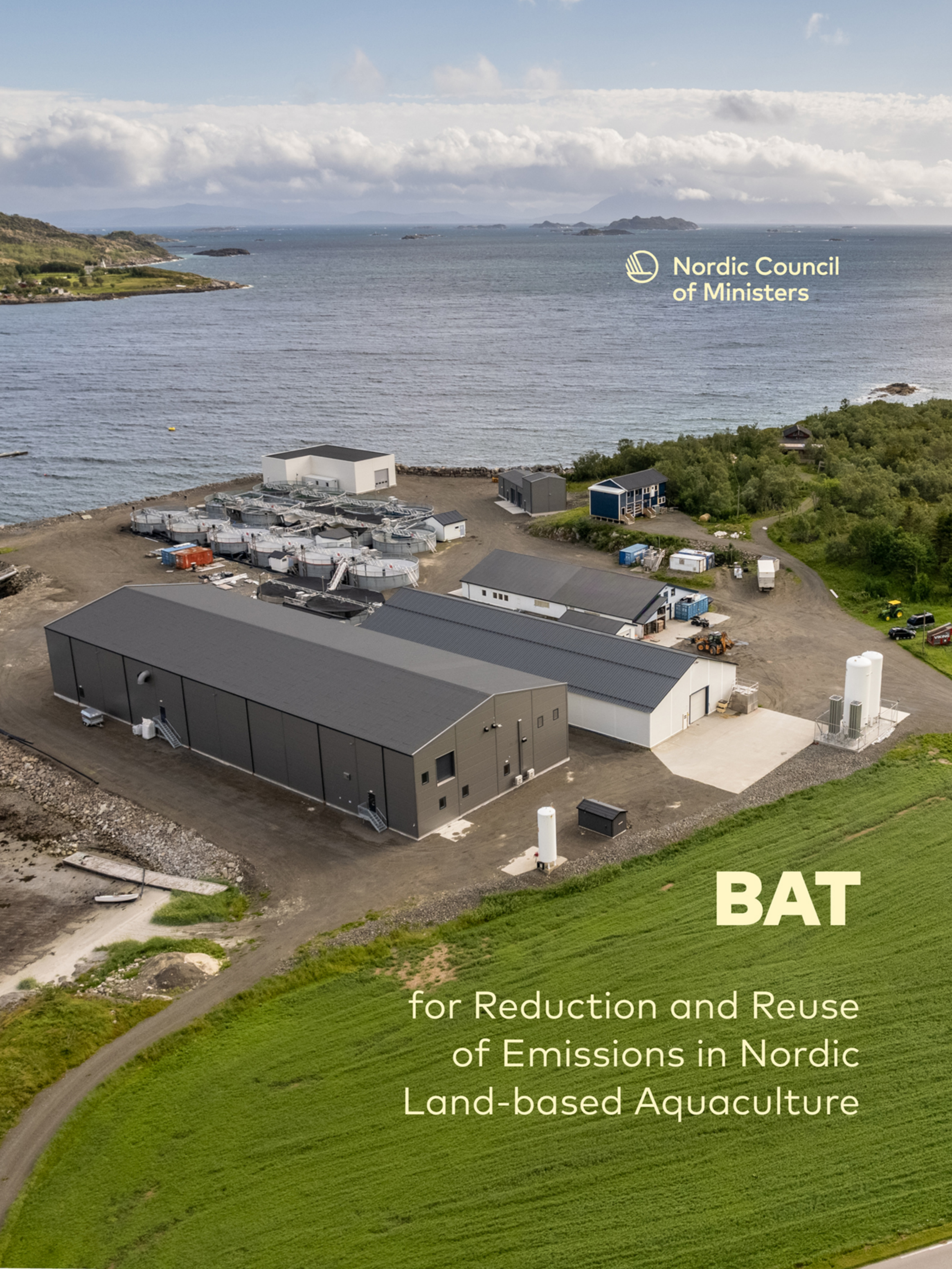

Nordic Council of Ministers

BAT

for Reduction and Reuse of Emissions in Nordic Land-based Aquaculture

Best Available Techniques for Reduction and Reuse of Emissions in Nordic Land-based Aquaculture

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Executive summary

This report describes methods for the reuse and reduction of waste streams from land-based aquaculture systems. It builds on a previous report describing BATs for Nordic aquaculture (Heldbo et al., 2013). Table 1 shows how the state of the art has changed in the intervening decade, highlighting not only technological improvements but also an increase in attention to the reuse of waste, as Nordic countries have become increasingly environmentally conscious. Land-based production is increasingly seen as an opportunity to reduce environmental damage compared to open-water alternatives. Escapes and interactions with wild populations can be avoided and the release of chemical therapeutants, such as antibiotics and anti-parasitics, can be reduced. If water is recirculated, its use can drop dramatically, which may increase energy demand, the environmental impacts of which might be mitigated through renewable sources. Wastes from land-based systems, rather than being discharged into the environment, can be contained and either processed to reduce harm or potentially valorised, turning the wastes into by-products.

The European Union has no dedicated legal framework for the regulation of aquaculture, with relevant legislation being spread across various areas of policy. Environmental legislation such as the Water Framework Directive and the Waste Framework Directive are relevant but only indirectly, and aquaculture does not fall within the scope of the newly revised Industrial Emissions Directive. The Faroe Islands, Norway, and Iceland are not Member States but implement some of EU legislations, particularly those relating to food safety and the use of chemical therapeutants. As the regulation of wastes and emissions from aquaculture is mostly through the legislation of individual nations, it differs across Nordic counties.

The major waste streams (including emissions that may become wastes or by-products) from land-based aquaculture are sludge, discharge water, mortalities, and gaseous emissions. Other potential waste streams common to many industries (e.g., plastics, metals, and wood) are also produced but are less specific to aquaculture and their reuse is covered in a large number of reports.

Sludge consists of faeces and uneaten feed. It can contain a large amount of water, or it can be thickened, dewatered, and dried. Sludge with various levels of moisture can be reused in a variety of manners. Uncontrolled discharge of sludge can cause environmental damage, such as contamination with antibiotics, heavy metals, and solids, and eutrophication due to its nitrogen and phosphorous content. These nutrients allow the sludge to be reused as fertiliser, although care must be taken to ensure that the bioavailability of these nutrients remains and that heavy metals are not in too high a concentration. Drying the sludge before use as a fertiliser reduces transport costs significantly, whilst it is also possible to desalt the sludge. Biogas production in a third-party biogas plant is another option, and drying reduces transport costs and gate fees but increases the capital expenditure (CAPEX) and operating expenditure (OPEX) of farms if conducted onsite. Biogas can be produced onsite and used to supply energy to the farm. Recent advancements in microbial culture selection allow for 100% fish sludge to be used without the addition of exogenous materials. Sludge can also be used to power parts of the farm through pyrolysis. Burning the sludge in the absence of oxygen creates large amounts of heat energy and turns the sludge into biochar, a charcoal-like substance, which, rather than being used as a fuel, can be used as a soil enhancer and filter material. Bio-oil and biogas are other potential products, but biochar is likely the most economically viable by-product. Dried sludge can be incinerated to produce electricity at third-party incineration plants or replace coal during the production of cement. The EU does not allow sludge to be fed to insects, but it is being explored experimentally, and insects could be fed to fish of another species or ruminants. Valorisation of saline sludge poses a larger issue than freshwater sludge Thus, fertilisation of halophyte crops is being explored, with a biogas plant with specially selected microbes is in the pilot stage. Pyrolysis is possible, as is incineration, whilst washing the sludge or using desalting technology allows sludge to be reused in the same manner as freshwater sludge.

Discharge water contains nutrients that can lead to eutrophication but also facilitate its reuse. Fertigation is the watering of crops with a fertiliser solution. It is more efficient than traditional irrigation and fertilisation, wasting less water and causing less nutrient run-off. The nutrients in aquaculture discharge water have proven useful in the cultivation of crops including cucumbers and tomatoes, but this reuse requires fish farms to be in proximity to a relevant agricultural user. Many farms in the Nordics only use fertiliser in certain periods of the year and the same is true for watering. Greenhouse-based agriculture is the most likely candidate for fertigation using aquaculture water. The nutrients in the water can also be used to grow algae. Algae have been used in the treatment of municipal wastewater. Depending on the species grown, algae can be used to produce high-value fatty acids, fertilisers, silicon, or as a bioenergy source. The economics of growing algae in this manner in the Nordics have not been proven. Large surface areas are needed to process discharge water in this manner, and efficient growth in winter typically requires additions of heat and light. Constructed wetlands are often used in Denmark, and if space is available these can present a simple method of discharge water treatment. Discharge water and nutrients can contain heat and physical energy, and capturing this energy can reduce costs on farms.

Almost every farm site we surveyed currently ensiles mortalities, which involves mixing mortalities in an acid solution to prevent bacterial activity. This process can be environmentally and economically expensive and poses a health hazard to workers, although the method is simple and well established. Ensiled mortalities can be processed into protein isolates and fish oils, but the market for these is limited, in part due to EU legislation. The fat content of the mortalities makes bioenergy production a reuse option; the mortalities can be transported to a biogas plant or turned into biodiesel. This option was until recently used in the Åland Islands to power buses in the capital city. The oil content of the mortalities can also be used to replace hydrocarbon oils in the leather industry, and purified fish oil can fetch a high price. Recent advancements in technology present the possibility of drying mortalities. As with sludge, drying decreases the transport costs significantly, sanitises the mortalities, and opens up other valorisation options such as use in cement production. Gate fees at biogas plants are reduced with dried mortalities.

One possible avenue is pet food. This is not currently allowed due to EU regulations, but dried mortalities have proven to be stable, free from bacterial concerns, and nutritionally compatible. Mortalities can be fed to fur animals or animals in a shelter, but pet food regulations are stricter.

Gas emissions from land-based aquaculture are much less regulated or documented than the above-mentioned waste streams. Much of the greenhouse gas (GHG) emissions associated with salmonid aquaculture stem from the agricultural production of crops, and to a lesser extent, wild capture of fish, used to make fish feeds. The generation of electricity used to pump or heat water is a further source of GHG emissions, and increasing efficiency or using green energy sources can reduce this. Carbon dioxide (CO_2) is released by fish respiration, and whilst the amount is not comparable to heavy industry, reducing GHG emissions in any capacity is a noble goal. Two companies have been experimenting with capturing CO_2 from fish farms and using microbes to convert this into protein. This may reduce the reliance on exogenous food sources and associated GHG emissions. Hydrogen is an input into these systems and green energy must be used to produce the hydrogen; otherwise, this capture presents no environmental benefit. Nitrous oxide (N_2O) is another GHG that can be released from a fish farm, and an intermediate product in denitrification, N_2O release from land-based aquaculture is little studied or considered. Advancements in denitrification reactors that favour alternative chemical pathways of denitrification may help reduce this problem, but these reactors are not currently viable for use on a fish farm.

This report focuses on the reuse of waste streams, but it is easier and cheaper to reduce the streams rather than attempt to reuse or recycle them. Simple steps such as appropriate planning, recordkeeping, site selection, equipment choice, and farm practices can reduce the production of all forms of waste, and these should be considered first and foremost.

Table 1. Potential Best Available Techniques as featured in the 2013 and present report.

2013	2022
SLUDGE	**SLUDGE**
Separation of Solids and Water	**Separation of Solids and Water**
Belt Filter	Sedimentation
Disk Filter	Mechanical Filtration (Drum and Disk)
Floatation	Wastewater Outflow
Drum filter	Sludge Water Processing
Band filter	Thickening
Sludge cones	Dewatering
Precipitation/sedimentation	Drying
Drains - eco trap	**Reuse of Sludge**

Geotubes	Fertiliser
Hydrocyclone (drain)	Energy Production
Reuse of Sludge	Pyrolysis
Hydrolysis	Bio-oil and syngas
Biogas	Biochar
Fuel pellets	Incineration
Composting/soil improvement	Insect feed
Vermiculture	Sludge Drying
Insect feed (insect meal production)	Saline Sludge
DISCHARGE WATER	**DISCHARGE WATER**
Biological filtration	**Treatment**
Ultraviolet light	Further Water Quality Improvement
Denitrification	Adsorptive Bubble Separation
	Protein Skimmer
	Dissolved Air Floatation
	Membrane Floatation
	Degassing
	Wetlands
	Reuse of Discharge Water
	Fertigation
	Algae
	Heat/energy Recovery
	CHEMICAL DISCHARGES
	MORTALITIES
	Ensiling
	Protein Isolates and Feed Oil
	Biofuels
	Leather Industry
	Drying
	GAS EMISSIONS
	Carbon Capture
	N_2O Reduction
	Other Forms of Waste
	Reduction Before Reuse

Sammendrag

Denne rapporten beskriver ulike metoder for gjenbruk og reduksjon av avfallsstrømmer fra landbaserte akvakultursystemer. Rapporten bygger på en tidligere rapport som beskriver BAT for nordisk akvakultur (Heldbo et al., 2013). Tabell 1 viser hvordan det vi anser som best, har endret seg i løpet av tiåret som har gått siden den første rapporten. Det har ikke bare vært ved teknologiske forbedringer, det har også vært en økning i oppmerksomheten rundt gjenbruk av avfall etter hvert som de nordiske landene har blitt stadig mer miljøbevisste. Landbasert akvakulturproduksjon blir ansett for å være bedre for miljøet enn produksjon i sjø for enkelte miljøproblemer. Man kan unngå rømming og interaksjon med ville fiskebestander, og utslipp av kjemikalier som f.eks. antibiotika lusemidler og andre legemidler til miljøet kan reduseres. Ved resirkulering av vann vil vannbruken reduseres betydelig, men fordelene nevnt ovenfor kan føre til økt energibehov. Bruk av fornybar energi kan redusere påvirkningen på miljøet. I stedet for å slippe avfall ut i miljøet, kan man fra landbaserte anlegg samle det opp og prosessere det for å redusere effekten på miljøet, eller også bruke avfallet som nyttige produkter eller råstoff. Landbaserte oppdrettsanlegg vil kunne kreve varige fysiske inngrep, og dersom de eksempelvis legges i strandsonen kan det hindre allmennhetens tilgang. Slike anlegg kan også være avhengig av tilgang til ferskvannsressurser og da i noen tilfeller måtte konkurrere med annen vannressursbruk.

I stedet for å ha et eget lovverk for å regulere akvakulturindustrien i EU, er lovverket spredt på lover og regler som regulerer hver sine områder. Ulike typer miljølovgivning som for eksempel Water Framework Directive og Waste Framework Directive (rammedirektiver for henholdsvis vann og avfall) kan være relevante, men kun på en indirekte måte. Akvakultur blir ikke regulert av det nylig reviderte direktivet for industrielle utslipp (Industrial Emissions Directive). Verken Færøyene, Norge eller Island er medlemmer av EU, men noe av EU-lovgivningen, spesielt det som gjelder mattrygghet og bruk av kjemiske legemidler, implementeres også i disse landene. Ettersom utslipp fra akvakulturindustrien for det meste reguleres gjennom lover og regler i de individuelle landene, varierer dette mye mellom de nordiske landene.

De største utslippsstrømmene (inkludert utslipp som blir avfall eller biprodukt) fra landbasert akvakultur, er slam, utløpsvann, dødfisk og gassutslipp. Andre potensielle utslippsstrømmer som er vanlige i andre typer industri (f.eks. plast-, metall-, og treindustri), produseres også, men dette er ikke spesifikt for akvakulturindustrien, og gjenbruk av disse dekkes i et stort antall rapporter.

Slam består av fiskeavføring og fôrpartikler (fôrspill og ufordøyd fôr), det kan inneholde store mengder vann, men det kan også fortykkes, avvannes, og tørkes. Slam med forskjellig mengde vanninnhold kan brukes til ulike ting. Ukontrollert utslipp av slam kan føre til skade på miljøet, som f.eks. forurensing og eutrofiering på grunn av innholdet av nitrogen og fosfor i slammet. På grunn av at slammet inneholder disse næringsstoffene, er det mulig å bruke det som gjødsel, men man må sikre at biotilgjengeligheten til næringsstoffene ikke er forringet, og at slammet ikke inneholder høye konsentrasjoner av tungmetaller. Ved å tørke slammet før det brukes som gjødsel, vil man oppnå en betydelig reduksjon av transportkostnadene. Et annet mulig bruksområde for slammet er i biogassproduksjon. Dette gjøres som regel av en tredjepartsaktør, og tørking vil også her redusere transportkostnadene og avhendingsavgiftene, men øke CAPEX og OPEX til oppdrettsanlegget dersom biogassproduksjonen gjøres på stedet i stedet for hos en annen aktør. Biogass kan også produseres direkte på oppdrettsanlegget og brukes direkte som energi på anlegget. Nyere utvikling innen mikrobiell seleksjon/økologi gjør at man nå kan bruke 100 % fiskeslam i biogassproduksjon, uten at man må tilsette andre materialer. Slam kan også brukes til å drive deler av anlegget ved bruk av pyrolyse. Ved å brenne slam uten oksygen tilstede produseres store mengder varmeenergi som omdanner slammet til biokull – et materiale som minner om vanlig kull, men som i stedet for å bli brukt som en energikilde, kan brukes i jordforbedring og som et filtermateriale. Bioolje og biogass er andre mulige produkter, men biokull er mest sannsynlig det biproduktet som er økonomisk mest levedyktig. Tørket slam kan også brennes i forbrenningsanlegg for å produsere elektrisitet, og det kan dessuten brukes i stedet for kull i produksjon av sement. I EU er det ikke tillatt å bruke slam som fôr til insekter, men dette undersøkes nå videre, og insekter kan brukes som fôr til andre fiskearter eller til drøvtyggere. Marint slam inneholder salt og er mer problematisk enn ferskvannsslam. Gjødsel i produksjon av halofytter (saltelskende planter) blir nå undersøkt, og et biogassanlegg med spesielt utvalgte mikrober er i pilotfasen. Man kan bruke pyrolyse til forbrenning av marint slam. Vasking av slammet eller bruk av teknologi for avsalting av slammet, gjør at slammet kan brukes på samme måte som ferskvannsslam.

Avløpsvann fra oppdrett inneholder også næringsstoffer som kan føre til eutrofiering, men de samme næringsstoffene er det som gjør at gjenbruk er mulig. En mer effektiv måte å vanne og gjødsle avlinger på enn den tradisjonelle måten, er å vanne med en løsning av vann og gjødsel (dette kalles *fertigation*). Dette fører til redusert vannforbruk og redusert avrenning av næringsstoff. Næringsstoffene i avløpsvann fra akvakulturproduksjon har blitt brukt til å dyrke bl.a. agurk og tomat, men denne typen gjenbruk fordrer at oppdrettsanlegget ligger nært planteprodusenten. Mange gårder i de nordiske landene gjødsler og/eller vanner avlingene sine kun i enkelte perioder i løpet av året. Landbruk i drivhus som har produksjon året gjennom, er derfor den mest sannsynlige kandidaten til å bruke denne løsningen. Næringsstoffene i vannet kan også brukes til dyrking av alger. Alger har blitt brukt i behandling av kommunalt avløpsvann. Enkelte arter kan også brukes for produksjon av fettsyrer, de kan brukes som gjødsel, som en kilde til bioenergi, eller de kan produsere silikon som kan brukes industrielt. For å dyrke alger basert på avløpsvann må man ha områder med stort overflateareal, og effektiv dyrking i vintersesongen krever gjerne tilførsel av varme og lys. Denne typen algeproduksjon har ikke blitt bevist økonomisk levedyktig i de nordiske landene. I Danmark brukes ofte våtmarker, noe som kan være en enkel måte å kvitte seg med avløpsvannet på, dersom man har nok tilgjengelig areal. Både avløpsvannet og næringsstoffene kan inneholde varme og fysisk energi, og hvis man fanger denne energien kan man redusere kostnadene på oppdrettsanlegget.

Så å si hvert eneste oppdrettsanlegg ensilerer dødfisken. Det betyr at dødfisken blandes i en syreløsning for å hindre bakteriell aktivitet. Denne prosessen kan være en påkjenning både for økonomien og miljøet, og den utgjør også en helserisiko for de ansatte på anleggene. Metoden er imidlertid enkel og godt etablert i næringen.

Ensilasje kan bli videre prosessert til protein og fiskeolje, men markedet for disse produktene er begrenset, delvis pga. lovgivning i EU. På grunn av høyt fettinnhold kan produksjon av bioenergi fra dødfisk være en mulig gjenbruksmetode. Dødfisken kan transporteres til et biogassanlegg eller gjøres om til biodiesel. Denne metoden brukes på Åland for å drive busser i hovedstaden. Oljeinnholdet i dødfisken kan også brukes i stedet for olje basert på hydrokarboner i lærindustrien, og renset fiskeolje kan selges for en høy pris. Nyere teknologiutvikling har sett på muligheten for å tørke dødfisken. Dette vil redusere transportkostnadene betydelig, det hygieniserer dødfisken og åpner opp for andre gjenbruksmuligheter. Avhendingsavgiftene ved biogassanlegg vil også bli redusert hvis dødfisken er tørket på forhånd, og det kan brukes i sementproduksjon. En annen mulighet er å bruke den som fôr til kjæledyr. Dette er per nå ikke tillatt i EU, men det er påvist at tørket dødfisk er stabil, uten bakterielle problemer, og næringsmessig tilfredsstillende. Dødfisk kan brukes som fôr til pelsdyr eller dyr i dyrehjem, men reguleringen av fôr til kjæledyr er strengere.

Gassutslipp fra landbasert akvakultur er mye mindre regulert eller målt enn andre utslipp. Mye av utslippene av drivhusgasser relatert til produksjon av laksefisk, stammer fra landbruksaktivitet som skjer i forbindelse med produksjon av fiskefôr. Mye mindre kommer fra fangst av villfisk for bruk i fiskefôr. Disse utslippene er like uansett om produksjonen foregår på land eller i sjø. Produksjon av elektrisitet som trengs for å pumpe eller varme vann, er også en kilde til utslipp av drivhusgasser, og dette kan reduseres ved å øke effektiviteten eller gå over til fornybar energi. CO_2 slippes ut som følge av fiskens respirasjon, og til tross for at mengden ikke kan sammenlignes med mengden som produseres i annen industri, er all reduksjon av utslipp av drivhusgasser positiv. To bedrifter har begynt å eksperimentere med CO_2 fra oppdrettsanlegg, og de bruker bakterier for å omdanne gassen til protein, som igjen kan brukes i fiskefôr. Målet er at utslipp av drivhusgasser i forbindelse med ekstern fiskefôrproduksjon da kan reduseres. Men hydrogen er også en innsatsfaktor i denne løsningen, og man må bruke energi for å produsere hydrogenet. Denne karbonfangsten utgjør derfor ingen gevinst for miljøet per i dag. N_2O er en annen drivhusgass som kan slippes ut fra oppdrettsanlegg. Gassen er et mellomprodukt idenitrifikasjonsprosessen, og utslipp av denne gassen er lite studert og hensynstatt når man snakker om utslipp fra landbasert oppdrett. Utvikling av bedre reaktorer for denitrifisering som favoriserer alternative kjemiske spor i denitrifiseringen, kan redusere utslippet av denne gassen, men slike reaktorer er per nå ikke tilgjengelig for bruk i oppdrettsnæringen.

Denne rapporten fokuserer på gjenbruk av avfallsstrømmer, men det er billigere og enklere å redusere avfallsstrømmene enn å forsøke seg på gjenbruk eller resirkulering. Enkle trinn, som f.eks. tilstrekkelig planlegging, rapportering, valg av riktig lokalitet, valg av riktig utstyr og gode driftsrutiner, kan redusere mengden avfall som produseres i et anlegg, og bør vurderes før andre tiltak gjøres.

Table 2. Best available techniques identifisert i 2013 BAT-rapporten og i denne nye rapporten.

2013	2022
SLAM	**SLAM**
Separasjon av fast stoff og vann	**Separasjon av fast stoff og vann**
Beltefilter	Sedimentering
Diskfilter	Mekanisk filtrering (trommel og disk)
Flotasjon	Utløp av avløpsvann
Trommelfilter	Prosessering av vann i slam
Båndfilter	Fortykking
Slamkjegler	Avvanning
Utfelling/sedimentering	Tørking
Avløp - eco trap	**Gjenbruk av slam**
Geotuber	Gjødsel
Hydrosyklon (drain)	Energiproduksjon
Gjenbruk av slam	Pyrolyse
Hydrolyse	Bioolje og gass
Biogass	Biokull
Pellets	Forbrenning
Kompost/jordforbedring	Insekter
Vermiculture	Tørket slam
Insektsfôr (produksjon av insektsmel)	Marint slam
AVLØPSVANN	**AVLØPSVANN**
Biologisk filtrering	**Behandling**
UV	Videre forbedring av vannkvalitet
Denitrifisering	Adsorptive Bubble Separation
	Proteinskummer
	Dissolved Air Flotation
	Membranflotasjon
	Degassing
	Våtmarker
	Gjenbruk av avløpsvann
	Fertigation
	Algeproduksjon
	Varme/energigjenvinning
	KJEMISKE UTSLIPP
	DØDFISK

	Ensilasje
	Protein isolater og matolje
	Biodrivstoff
	Skinn/lærindustri
	Tørking
	GASSUTSLIPP
	Karbonfangst
	N_2O reduksjon
	Andre typer avfall
	Reduksjon før gjenbruk

Glossary

Term	Definition
Anoxic	Depleted of dissolved oxygen
BAT	Best Available Techniques
Biochar	Charcoal-like substance from pyrolysis of sludge
Biofilter / Biofiltration	Filter containing bacteria often attached to floating media, bacteria nitrify and denitrify the water removing toxic compounds
Biogas	Mix of mainly methane and carbon dioxide resulting from microbial digestion of organic material
By-Products	An output of economic production that has an economic value that is lower than that of the primary target of production
CAPEX	Capital expenditure: funds used to acquire, upgrade, and maintain physical assets
Coagulation-flocculation	A process used in water treatment to separate solid and dissolved compounds from water by adding compounds that promote aggregation of particles, which can then be easily removed from the water
Denitrification	Microbial reduction of nitrate to nitrite to gaseous nitrogen
Discharge water	Effluent water from aquaculture facilities
Emission	Substances which having left the aquaculture facility also leave the economic sphere and enter the environmental sphere
Energy Carriers	A substance such as fuel that contains energy and is used to provide power
Ensiling (silage)	Addition of mortalities to acid solution for safe disposal
Eutrophication	Over-enrichment of water with nutrients such as nitrogen and phosphorus, causing oxygen depletion, phytoplankton blooms and ecosystem changes
Finfish	Sometimes called true fish, this group excludes molluscs, crustaceans, and other aquatic life that are sometimes called fish, e.g., shellfish, crayfish, cuttlefish
Flow-through	Semi-enclosed aquaculture system where water flows through the system without being reused. It may flow through more than one pond or tank before exiting into the receiving water source
Static ponds	The term 'static ponds' is used in this report to refer to ponds that are more closed than those operated on a flow-through basis, with water usually being emptied and replenished periodically rather than continuously
Market good	Goods that are traded on markets (international and local), and

	have their value determined by their price
Nitrification	Microbial oxidation of ammonium to nitrate and nitrate
OPEX	Operating expenditure: ongoing cost of running a process or asset
Pyrolysis	The burning of material in the absence of oxygen
Raceway	An artificial water channel in which fish or other aquatic species are reared. Most raceways consist of a concrete basin with an inlet and outlet on each side to create a semi-enclosed flow-through system
RAS	Recirculating aquaculture system
Sludge	Mixture of faeces and uneaten feed, ranging in water content from almost 100% to 5%
Waste	Discharges from an aquaculture facility that, beyond inputs to a waste treatment and final disposal stage, have no further econom-ic intervention
Waste streams	Specific discharges that have the potential to become either waste or by-products, depending on handling

Scientific Names

Common Name	Scientific Name
Arctic charr	*Salvelinus alpinus*
Atlantic cod	*Gadus morhua*
Atlantic salmon	*Salmo salar*
Blue mussel	*Mytilus edulis*
Common carp	*Cyprinus carpio*
European eel	*Anguilla anguilla*
European flat oyster	*Ostrea edulis*
Great European scallop	*Pecten maximus*
Halibut	*Hippoglossus hippoglossus*
Pikeperch	*Sander lucioperca*
Rainbow trout	*Oncorhynchus mykiss*
Senegalese sole	*Solea senegalensis*
Striped bass	*Morone chrysops x Morone saxatilis* hybrid
Yellowtail amberjack	*Seriola lalandi*

1. Introduction

Aquaculture is an important sector in the Nordic region, and recent developments suggest the number and size of land-based aquaculture facilities are likely to increase in the future. Across the Nordics, more than €13 billion worth of fish (including molluscs and shellfish) were produced in 2020 through a combination of fisheries and aquaculture. This production is not evenly spread across the region, with Norway producing more than double the amount of fish than all other Nordic countries combined, whilst Finland and Sweden are net importers of fish and fish products. Despite over 50% of fish produced worldwide being from aquaculture, the Nordic region, except for Norway, relies heavily on capture fisheries. Many Nordic countries have failed to establish an aquaculture industry equivalent to the scale of their marine-based economies. For example, Sweden produces fewer salmonids per year through aquaculture than is possible in a single large land-based facility. There are a multitude of reasons for this failure to meet potential. Environmental conditions give Norway an advantage compared to other countries such as Greenland and Denmark; an abundance of deep, sheltered fjords, and temperatures ideal for Atlantic salmon production allow the country to dominate production of this species. Instead, Denmark has focused on land-based and freshwater production.

The size of nations is relevant when comparing production volumes. The Faroe Islands produce more farmed Atlantic salmon per capita than any other country, despite a significantly lower overall production compared to Norway. Each country has unique factors influencing the growth of its aquaculture industry. Concerns of local stakeholders, including the tourism industry, anglers, and indigenous peoples, the presence or lack of specific legislation, concerns over interactions with wild populations and disease management, the prevalence of private ownership of aquatic spaces, and public suspicion over foreign ownership, all vary between countries. Each of these factors, whilst often valid and based on the wishes of users of shared space, places hurdles preventing the industry from meeting its full potential.

One of the largest and most consistent factors limiting the growth of the aquaculture industry across the Nordics emanates from environmental concern. The present trend in research and policy encourages reductions in environmental emissions from intensive aquaculture and an increased valorisation of waste streams. Nutrient discharge causing eutrophication, impact on benthic ecology, and the historic use of antibiotics have all caused concern. This is one of the appeals of land-based aquaculture systems over sea-based or lake-based cultures. Land-based culture of aquatic organisms, be it contained and tank based or of a more traditional pond or raceway design, gives a level of potential control over the outputs from the system not possible in open, cage-based culture systems. Wastes can be captured and turned into by-products, and control over inputs can reduce mortalities or the need to treat the fish with antibiotics or therapeutants. Whilst control of emissions is possible, land-based systems remain capable of generating large amounts of waste and emissions in various forms (sludge, water, mortalities, gas), and failure to handle waste streams appropriately can result in the emission of pollutants or at very least reduce the environmental benefits of using such a method of production. Landfill and discharge into the ocean or watercourse have been traditionally employed, but many more options are now available and allow for farms to both reuse waste and increase their green credentials.

A previous report highlighted Best Available Technologies (BATs) for waste capture and reuse relevant at the time (2013), but the capacity of land-based systems to capture waste streams and the potential for reusing them are improving through technological innovations. The present report aims to discuss some of the best currently available technologies at the time of writing (2022). It provides a brief overview of aquaculture in the Nordics and of land-based culture. Currently available and emerging opportunities to capture and reuse waste streams are discussed alongside a description of the current legislative requirements and hurdles. It is hoped the report will inform relevant stakeholders with an interest in this field. It will provide an overview of both emerging and established best available techniques for reducing emissions to the environment and for the management of wastes, with a focus on circular economy. Improving waste management might improve the viability of land-based aquaculture, supporting sustainable growth in the sector.

1.1. Aquaculture sectors in the Nordic countries

The Nordic aquaculture industry is dominated by the production of salmonids (Table 3). Atlantic salmon is the most cultivated salmonid species, followed respectively by rainbow trout and Arctic charr. Other than salmonids, blue mussels and halibut are the next most cultured species, but these are not farmed in every country. Small-scale production of other finfish, molluscs, and aquatic plant species occurs across the Nordic region but makes up a small percentage of the total production. Aquaculture production of salmonids occurs in a variety of environments. Cages located in fresh and salt water are often prominent features in discussions about aquaculture, but raceways and flow-through land-based systems have been used for decades. More recently, recirculating aquaculture systems (RAS) have received attention due to the level of control they offer. Shellfish such as blue mussels are typically grown using longlines, from which ropes are suspended vertically in the sea.

Table 3. Aquaculture production statistics for Nordic countries in 2020

Country/ Autonomous Region	Salmonid Production 2020 (Tonnes Live Weight)	Salmonid Production As A Percentage Of Aquaculture Production	Top Three Salmonid Species	Source
Denmark	35.082	81,9%	Rainbow trout, Atlantic salmon, charr	FAO, 2022
Faroe Islands	88.950	99,88%	Atlantic salmon	FAO, 2022
Finland	14.728	97,85%	Rainbow trout	FAO, 2022
Åland Islands	5.571	*	Rainbow trout	The Government of the Åland Is-lands, Office of Fisheries, 2022
Greenland	-	-	-	-
Iceland	40.324	99,33%	Atlantic salmon, Arc-tic charr, rainbow trout	FAO, 2022
Norway	1.485.199	99,65%	Atlantic salmon, rain-bow trout, Arctic charr	FAO, 2022
Sweden	9.700	80,23%	Rainbow trout, Arctic charr	FAO, 2022

*Not within available data

1.1.1. Norway

Norway has one of the largest finfish aquaculture industries in the world, with 1550 production permits being granted in 2021 (Norwegian Directorate of Fisheries, 2021a). This number includes all species and life stages, both on land and at sea. Atlantic salmon is by far the most produced species (93,2% of total production) from around 1,49 million tonnes of finfish harvested in 2020 (FAO, 2022). Commercial production of Atlantic salmon has traditionally been conducted by producing smolt in freshwater in flow-through land-based aquaculture systems, followed by a grow-out phase in open sea cages (Bergheim et al., 2009). However, during the last decade, production regimes have shifted and now include the production of large smolt, post-smolt and even market-size salmon on land. Specifically, RAS facilities have become attractive due to their high efficiency of water re-usage (up to 99%), the high fees for traditional farming licenses, and the possibility to recover and reuse waste streams, contributing to the circular economy. Much of salmonid (including trout) grow-out is still conducted in sea water, with land-based grow-out production making up 5,86% of sites; around 55% of the land-based sites are freshwater and 45% seawater (Norwegian Directorate of Fisheries, 2021b). In 2020, the next largest production after Atlantic salmon was in rainbow trout at 6,45% (FAO, 2022) of total production (96.131 tonnes); blue mussels and halibut followed at 2.033 and 1.896 tonnes, respectively. There is also a small production of cod, oysters, and scallops. In 2021, the aquaculture industry as a whole employed 9.807 people (78,7% men and

21,3% women) (Norwegian Directorate of Fisheries, 2021c). Salmonid production equated to 91,2% of total employment with 92,4% of men and 86,4% of women in the industry employed in salmonid production. Despite making up 21,3% of the total employees, women work 18,2% of total hours, suggesting a higher percentage of part-time or seasonal employment. The license systems for cage and land-based aquaculture differ. A cage-based licence is expensive and highly sought after. A license typically allows a maximum allowable biomass of 780 tonnes, and these licenses ordinarily sell for $15-20 million each (19.000-25.600 per tonne). This figure fell to $10.000 USD per tonne in the latest auction round after a 40% tax was announced. Land-based licenses are not part of the "traffic light system" that regulates how much a farmer can grow in a certain area and are also free of charge. A recent change in technology and an increase in the number of farms using seawater in land-based farms has meant that at the time of writing, the Norwegian government has placed a six-month memorandum on land-based permits to modernise regulations.

1.1.2. Denmark

In 2020, Denmark ranked 48th in global aquaculture production (excluding aquatic plants) (FAO, 2022). Rainbow trout made up 77% of production at 32.821 tonnes (FAO, 2022), and blue mussels contributed 14,82%, followed by Atlantic salmon (4,55%, 1.940 tonnes) and eel (1,47%). A small production of several species including other trout species, pikeperch, yellowtail amberjack, striped bass, and other trout species make up the majority of the remaining production (1,64% combined). In Denmark, a total of 493 people were employed by the aquaculture industry in 2020; men made up 86,2% of the workforce and women 13,8% (OECD, 2020). Statistics Denmark (2022) reports 195 aquaculture farms in Denmark; 53% of the farms are traditional trout farms, 8,7% are Type 1 model trout farms and 8,7% are Type 3 model trout farms (Table 4), which are land-based systems with varying degrees of water recirculation. Fish sea farms make up 9,7% of total farm numbers whilst shellfish farms (11,3%) and "other farms" (mainly containing RAS and eel farms) make up the rest. Due to the high number of land-based trout farms, 84,5% of total Danish aquaculture production is freshwater based, with marine and brackish based production being 4,9% and 0,6% respectively. Pursuant to regulatory changes, the terms Model Pond Farming Type 1 and Type 3 will no longer be used for the statistical reporting of recirculation aquaculture. The order on the reporting of information on Danish aquaculture (No. 2288 of 2021) uses the terms 'low,' 'medium' and 'high' to describe the level of recirculation.

Table 4. Number of traditional and model trout farms in Denmark 2013 – 2020

	Year							
	2013	2014	2015	2016	2017	2018	2019	2020
No. of traditional trout farms	157	145	138	131	127	123	118	104
No. of Type 1 model trout farms	17	17	17	18	17	17	17	17
No. of Type 3 model trout farms	16	15	16	17	16	16	16	16

1.1.3. Faroe Islands

The environmental conditions of the Faroe Islands, which feature relatively stable temperatures and consistent ocean currents, are well suited to salmon aquaculture. Over the past 30 years, the salmonid aquaculture industry in the Faroe Islands has expanded rapidly, and production has increased over 360%, with production growing from 19.098 tonnes in 1992 to 88.950 tonnes in 2020 (FAO, 2022). Almost the entirety (99,88%) of aquaculture is focused on the production of Atlantic salmon, and 100% is marine. The Faroe Islands benefit from a large number of narrow but deep fjords that regularly experience strong currents. This means the fjords can support a large amount of production, coupled with a relative scarcity of freshwater, and there is less incentive for land-based grow-out production than in some other Nordic countries. Land-based facilities still exist but these are focused on smolt production for the Faroese industry or egg production for local and international aquaculture. In 2021, approximately 20.000 tonnes of fish were transferred from land-based facilities to sea for grow-out. The Faroe Islands rank 42nd in the world for total aquaculture production including aquatic plants but 31st for the culture of fish. In 2020, 1.231 people were employed in the Faroese aquaculture industry; women made up the largest proportion of the sector compared to other Nordic countries with 37,8% of the workforce, and men made up 62,2%.

1.1.4. Iceland

The total aquaculture production of Iceland in 2020 was 40.595 tonnes (FAO, 2022), although recent increases will see this figure rise once more recent FAO statistics become available. Of this production, 84,6% (34.341 tonnes) is Atlantic salmon, whilst 13,5% (5.493 tonnes) is Arctic charr, making Iceland the largest producer of Arctic charr in the world. The rest of the production is made up of rainbow trout (1,2%) and a small production of Senegalese sole (0,7%). Of all the salmon production in Iceland in 2020, just over 4% was farmed to harvest in land-based systems, whilst the majority of Arctic charr production occurs on/inland. Land-based aquaculture began in the 1950s and many of the developments since have taken advantage of pathogen-free springs or geothermal waters (Ministry of Food, Agriculture and Fisheries, 2018). Several new land-based facilities are expected to begin the production of Atlantic salmon in the coming years. Each planned facility will significantly increase salmon production in Iceland. If all planned facilities reach their full potential then Atlantic salmon production will more than double. A total of 600 people are currently employed in the industry (OECD, 2020). The majority of production is in marine systems (84,6%), followed by brackish (14,2%), with freshwater making up only a small percentage of production (1,2%) (FAO, 2022).

1.1.5. Finland

In 2020, Finland (including the Åland Islands) was the world's 70th largest aquaculture producer including aquatic plants and 62nd in the production of fish, with a volume of 15.052 tonnes (FAO, 2022). Around 3.000 tonnes were produced inland (National Resources Institute Finland, 2021). Rainbow trout made up 95% of all fish production, with 20% of rainbow trout being farmed inland and the rest at sea (National Resources Institute Finland, 2021). Of the total production, 81% occurred in cages, 12% in tanks and raceways, and the remaining 7% is not specified in the available statistical data. In 2020 1.019 people were employed in the aquaculture sector in Finland; women made up 18,7% of the workforce and men 81,3% (OECD, 2020). Most of the production volume in Finland is marine (78,5%) with the remaining taking place in freshwater systems (21,5%) (FAO, 2022).

1.1.6. Åland Islands

Aquaculture in the Åland Islands represents 40–50% of Finland's overall production. A majority of this is the farming of rainbow trout with a smaller percentage being the production of seatrout. The total production in 2021 was 4.908 tonnes, with 95 people employed in the aquaculture sector (recorded as man years). Most of the land-based rainbow trout production is undertaken in a single high-intensive RAS (Kyrönviita et al., 2021).

Aside from the aquaculture policy objectives governing Finland, the Åland Islands have developed their regional policy objectives under the Autonomy Act. A multiannual regional plan is in place for the aquaculture sector with a focus on research and development, cooperation between government and industry, marketing and information on aquaculture products, cross-border cooperation and improved physical planning.

1.1.7. Sweden

Swedish aquaculture produced an estimated 12.090 tonnes in 2020 (FAO, 2022). Sweden ranks 78th for total aquaculture production including aquatic plants but is the ninth largest importer of aquatic products globally, importing €4,6 billion in 2020 (FAO, 2022). Nearly three-quarters (71,6% or 8.650 tonnes) of production is rainbow trout with another 8.68% made up of Arctic charr, but blue mussels also contribute significantly to the sector, making up 19% (6.317 tonnes). The industry employs 543 workers, half of whom are employed in cage farming; 21% of workers raise fish in tanks, raceways, or recirculated systems (Statistics Sweden, 2021). One-quarter (25,4%) of workers are women and 74,6% are men (OECD, 2020). Like Denmark, most of Sweden's aquaculture production takes place in freshwater systems (71,1%), and marine production makes up the remaining 28,9% (FAO, 2022).

1.1.8. Greenland

At the time of writing, there is no established aquaculture sector in Greenland. This is mostly due to the geography of the country; the landmass is covered by ice, with lakes being frozen most of the year, and pond culture is almost impossible due to the limited available area. Previous attempts to cultivate Arctic charr and blue mussels were unprofitable. There has been some experimental cage mariculture of Atlantic cod, but as this is capture-based it is not considered being aquaculture in national or international statistics as per the FAO (Snyder, 2017).

2. Status of policy, legislation and certification

2.1. EU policy and legislation

Aquaculture is included within Regulation (EU) No. 1380/2013, the 'Common Fisheries Policy' (CFP). However, aquaculture is not directly regulated by the CFP, and it is not an exclusive competence of the EU. Rather, EU legislation applicable to aquaculture is spread across various areas of policy. Aquaculture is especially influenced by environmental legislation, such as Directive 2000/60/EC, the 'Water Framework Directive', and Directive 2008/98/EC, the 'Waste Framework Directive'. These, and other legislation of key relevance, are described in detail in Annex 2. Legislations and regulations relevant to aquaculture and the management of aquaculture waste and by-products are detailed in table 5.

Table 5. European Union policies, legislations, and regulations relevant or of potential relevance to the management of aquaculture wastes, by-products and emissions, and associated BATs

Policy/legislation/regulation	Common Name	Relevance
Regulation (EU) No. 1380/2013 on the Common Fisheries Policy	Common Fisheries Policy	Article 34 calls for the promotion of the sustainable development of the European aquaculture sector through a coordinated strategy, including the production of a multiannual national strategy plan for aquaculture by Member States.
COM/2021/236 Strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030	N/A	European policy for supporting and promoting European aquaculture. Proposes development of detailed, good practice documents, and simplification of administration procedures for granting licences.
Directive 2000/60/EC, establishing a framework for Community action in the field of water policy	Water Framework Directive	Requires Member States to achieve good ecological status in all bodies of ground and surface water.
Directive 2008/105/EC on environmental quality standards in the field of water policy	Environmental Quality Standards Directive	Sets quality standards for substances identified as priority pollu-tants, for use in assessing water status as required by the Water Framework Directive.
Council Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources	Nitrates Directive	Aims to reduce water pollution caused by nitrogen from agricultural sources, through environmental monitoring, designation of 'nitrate vulnerable zones', and establishment of codes of good practices. Although aquaculture is not a direct focus, the legislation is potentially relevant.
Council Directive 91/271/EEC concerning urban wastewater treatment	Urban Wastewater Treatment Directive	Provides rules for the collection, treatment, and subsequent discharge of urban wastewater. Does not apply to aquaculture dis-charge water unless it is treated in an urban wastewater treat-ment plant. However, it does apply to wastewater from fish processing facilities.
Regulation (EU) 2020/741 on minimum requirements for water reuse	Water Reuse Regulation	Provides rules for the reuse of water from urban wastewater (according to Article 12 of Directive 91/271/EEC) for agricultural irrigation. Thus, it only applies to the reuse of water from aquaculture if is treated in an urban wastewater treatment plant.

Directive 2008/98/EC on waste	Waste Framework Directive	Legislative framework for managing wastes according to an order of preference; 'prevention, reuse, recycling, recovery, and dis-posal'.
Commission Decision 2000/532/EC	European List of Waste	Provides the categorisation of aquaculture wastes, according to the provisions in Article 7 of Directive 2008/98/EC.
Regulation (EC) No. 166/2006 concerning the establishment of a European Pollutant Release and Transfer Register	E-PRTR Regulation	Requires operators of facilities to report specified emissions to the environment, for documentation in a publicly accessible register. Applies to aquaculture with production ≥ 1000 tonnes per year.
Regulation (EU) No. 528/2012 concerning the making available on the market and use of biocidal products	Biocidal Products Regulation	Regulatory control of biocidal products that may be harmful to human or environmental health.
Regulation (EC) No. 1069/2009 laying down health rules as regards ani-mal by-products and derived products not intended for human consump-tion	Animal By-product Regulation	Regulations for the management of animal by-products (ABPs). Defines three categories of ABP in order of their risk of transmitting diseases to humans and animals: - Category 1 – highest risk - Category 2 - intermediate risk - Category 3 – lowest riskOptions for reuse or disposal differ for each.
Commission Regulation (EU) No. 142/2011 implementing Regulation (EC) No. 1069/2009 laying down health rules as regards animal by-products and derived products not intended for human consumption and imple-menting Council Directive 97/78/EC as regards certain samples and items exempt from veterinary checks at the border under that Directive	N/A	
Regulation (EU) 2016/429 on transmissible animal diseases	Transmissible Animal Disease Regulation	Regulations for preventing transmission of disease from livestock to animals or humans. Provisions relating to the management reporting of biosecurity measures.
Commission Delegated Regulation (EU) 2020/691 supplementing Regula-tion (EU) 2016/429 as regards rules for aquaculture establishments and transporters of aquatic animals	N/A	Detailed provisions for the management, recording, and reporting of aquaculture biosecurity measures.

2.2. Norway

The Norwegian aquaculture sector has grown considerably, especially since the 1980s, and its regulation has developed over many years. *'The Aquaculture Act'* (Act No. 79 of 2005) provides a legislative framework for the regulation of aquaculture. Pursuant to this act, permits are granted authorising the production of a certain species in one or more defined locations. Permits are issued by the Directorate of Fisheries, which ensures all other permits have been granted if required under the Food Safety Act, Pollution Act, and the Water Courses and Groundwater Act (see table 6). Salmon, trout, and rainbow trout aquaculture are issued according to the provisions of Regulation 22 December 2004 No. 1798. In its original version, the regulation contained no provisions specific to land-based aquaculture. Thus, the granting of permits for land-based facilities was subject to conditions intended for other types of aquaculture activity. In 2016, an amendment of the regulation included the introduction of Chapter 5a., Section 28d., which allows for *'separate'* permits to be granted for hatchery, *'food fish'* production, and breeding facilities *'on land.'* Section 28d. states that 'permission for land-based aquaculture of food fish is limited by the maximum permitted biomass'.

Table 6. Norwegian legislation and regulation relevant to land-based aquaculture

Legislation/regulation	Purpose and relevance
Act No. 79 of 2005 relating to aquaculture	Provisions applicable to aquaculture, including land-based aquaculture. - Requires aquaculture facilities to be granted a permit to operate by the Ministry of Industry and Fisheries. - General provisions for the granting of permits.
Regulation 17 June 2008 No. 822 on the operation of aqua-culture facilities	General provisions relating to operating facilities, fish health and welfare (including water quality, handling, and feeding), mortality management, use and dis-charge of pharmaceuticals and chemicals, environmental monitoring, and biomass limitations.
Regulation 19 June 2017 No. 941 on requirements for tech-nical standards for land-based aquaculture facilities for fish	Requires implementation of Norsk Standard (NS) 3424: 2012 and NS 9416:2013. - Operation, maintenance, inspection, reporting and documentation should meet the minimum requirements of these standards. - Changes to technical equipment should be doc-umented and faculties should install and document technical components for preventing escapees.
Act No. 124 of 2003 relative to food production and food safety (Food Act)	General provisions relating to food safety that are applicable across the food value chains.
Regulation 20 February 1997 No. 192 on disinfection of in-take water for and wastewater from aquaculture - related activ-ities	Provisions for methods and equipment regarding the filtering of intake and discharge water, and for deactivating pathogens. Applies to hatcheries, grow-out, slaughter and secondary processing, and fish transportation. - Intake water for aquaculture facilities must be filtered through a filter/strain device with a pore opening/gap width ≤ 0.3 mm. - Aeromonas salmonicida, infectious pancreatic necrosis (IPN) and infectious salmon anaemia (ISA) virus in intake water and dis-charged water must be inactivated using a recognised method. - Methods and equipment require approval from the Norwegian Food Safety Authority.
Regulation 22 December 2002 No. 1798 on permits for aqua-culture for salmon, trout and rainbow trout	Provisions for the granting of aquaculture permits. Amended by Regulation 1 June 2016 No. 562 to in-clude a requirement for a 'Separate permit for aqua-culture on land'.

Act 13 March 1981 No. 6 on protection against pollution and on waste (Pollution Act)	General provisions for the prevention and reduction of environmental pollution (emissions to land, air, and water), reduction of waste production, and waste management (including discharge water and sludge). - Provides emission limit values. - Provisions for the granting of permits for polluting activities.
Act 24 November 2000 No. 82 on watercourses and groundwater	General provisions for the use and management of waterways and groundwater, including water abstrac-tion and diversion. These activities may require a permit.

2.3. Denmark

Denmark has a comprehensive, well-developed, progressive legislative framework for the regulation of aquaculture. Pursuant to Chapter 5 of The Environmental Protection Act, a list of potentially polluting activities are subject to approval before they can take place. Approval requires that emissions to the environment must not exceed those associated with BATs. Land-based aquaculture is listed in Annex 2 as activity I 201, I 202 and I 202 in Annex 2. Consequently, the regulatory approach to land-based aquaculture is characterised by a strong emphasis on the mitigation and avoidance of environmental impacts through the implementation of BATs (see Case Study 1). Applications for land-based aquaculture permits are submitted to the local municipal council. In addition to being the responsible authority for granting approval, the municipal council performs periodic inspections and assessments.

Table 7. Danish legislation and regulation relevant to land-based aquaculture

Legislation/regulation	Purpose and relevance
Environmental Protection Act (No. 5 of 2023).	Provisions for preventing environmental pollution and reducing waste. - Approval required for land-based aquaculture. - Emissions must not exceed those associated with BATs
Statuary order on the delegation of tasks and powers to the Danish Environmental Protection Agency (No. 1514 of 2021)	Delegates authority to set the conditions for the granting of aquaculture permits to the Danish Environmental Protection Agency
Statuary order on environmental approval and simultaneous case processing of freshwater pond farming (No. 1567 of 2016)	Detailed provisions relating to permit-based regulation of land-based aquaculture environmental impacts - Requirement for approval and periodic assessment (at least every 10 years) - Permits set maximum feed use quota or maximum allowable nutrient emissions in discharge water
Statuary order on approval of listed company (2080/2021)	Covers rules regarding the licensing of aquaculture companies and how this relates to BATs
Water Planning Act (126/2017)	Framework for the protection and management of surface- and ground- water
Decree on action programs for watershed districts (449/2019)	Action plan regarding monitoring and protection of wa-tershed districts.
Statuary order on the determination of environmental targets for streams, lakes, transition waters, coastal waters and groundwater (1625/2017)	Sets out environmental targets and understanding of good ecological and chemical conditions for surface water and groundwater
Act on Environmental Assessment of Plans and	Regulates the requirement for environmental impact assessments during the planning and

Programs and of Specific Projects (1976/2021)	adoption of projects including aquaculture
Executive order on environmental assessment of plans and programs and of concrete projects (1376/2021)	Defines rules for the application and permitting of projects covered by the environmental assessment act (1976/2021)
Decree on waste (2512/2021)	Regulates the handling of wastes, including those specific to aquaculture, such as sludge and animal tissue
Statuary order in the reporting of information on Danish aquaculture (2288/2021)	Provides details that must be reported by aquaculture operators to the Danish Fisheries Agency. Recirculation farms are no longer to be classified as Type 1 and Type 3. The following terms are now to be used: - Plants with low recirculation: Plants located on land that have a water intake of between 5,000 and 25,000 litres per kg of feed - Plants with medium recirculation: Plants located on land that have a water intake of between 1,000 and 5,000 litres per kg of feed - Plants with high recirculation: Plants located on land that have a water intake of less than 1,000 litres per kg feed.

Case Study 1 – Danish Model Trout Farms

The story of how this regulation evolved and determined the trajectory of Denmark's trout farming sector makes an interesting case study. In 1989, The Environmental Act was amended to include provisions for regulating the environmental impacts of freshwater trout farming. The subsequent Decree on Freshwater Pond Farming (BEK 224 of 05/04/1989) introduced new rules for limiting the level of nutrients in water discharged to the environment. A feed quota was introduced, restricting the quantity of feed used per tonne of fish (i.e., FCR), whilst a maximum limit was set for feed nutrient content. The use of feeds other than dry pelleted or extruded diets was prohibited. Additionally, the decree contains provisions that encourage a lower rate of water use, and it became mandatory to use sedimentation methods and sludge traps for reducing the suspended solid content of discharged water. The new rules had a profound impact on Denmark's trout farming sector. Trout farms being typically of a flow-through, raceway-pond design, the mandatory use of sedimentation effectively entailed the construction of large settling ponds. In practice, the production of fish without exceeding the given feed quotas was difficult at best, and for production to increase or even be maintained, methods and strategies for reducing feed use were now needed. Some producers ceased to operate, and sectorial grow stagnated. In 2000, an advisory committee was established by the former Ministry of Food, Agriculture and Fisheries. The committee prompted an investigation of methods and techniques that could be offered a standard model for producing trout that was economically viable and complied with stringent regulatory demands. The resulting 'Model Trout Farms' were a modification of traditional flow-through practices. The most distinct change was the reuse of water, facilitated through the addition of biofilters. Three types of model trout farms where established, each differing principally by the degree at which water is recirculated. Reuse of water reduces the rate at which water is discharged, enabling increased water residence times in sedimentation ponds. Trials undertaken by Danmarks Tekniske Universitet (DTU; Technical University of Denmark) demonstrated reduced emissions of dissolved and solid bound nutrients and all three model type farms (but only Type 1 and Type 2 were cost efficient). The outcome precipitated the most influential legislative shift since the curtailing measures introduced in 1989. Facilities meeting the specifications of a model farm no longer required a feed quota-based permit. Instead, permits could be granted according to maximum allowable nutrient emissions. This removed an upper limit on production to the extent that compliance with emission allowances could be maintained.

The opportunity for increased production was a key driver behind the development and adoption of best technologies and techniques. Increased production required higher expenditure (CAPEX and OPEX), encouraging greater efficiency through economies of scale. Smaller farms merged, and the sector's production grew without a concomitant increase in the number of farms. Regulatory changes no longer classify farms as Type 1 or Type 3, but the importance of the model trout farm to the regulatory development of Danish aquaculture has been significant.

Below: Transition of a traditional flow-through trout farm to a Type 1 model farm, near Ringkøbing, Jutland, Denmark. Google Earth images show how the physical landscape of the farm has changed with the addition of technology, sedimentation lagoons, and the size and number of raceways.

July 2005

September 2011

April 2015

June 2018

2.4. Faroe Islands

Aquaculture in the Faroe Islands is subject to a well-developed legislative framework under the jurisdiction of the Ministry of Foreign Affairs, Industry and Trade. The Faroese Food and Veterinary Authority is responsible for administrating the granting of aquaculture licences as required by the Act on Fish Farming (see table 8). Approval for aquaculture is also required from the Faroese Environmental Agency according to the provisions of the Environmental Act (No.134/1998).

Table 8. Faroese legislation and regulation relevant to land-based aquaculture

Legislation/regulation	Purpose and relevance
Parliamentary Act No. 83, 25th May 2009, on Fish Farming and Other Provisions	Legislative framework for aquaculture in water and on land, including provisions for regulation through the granting of licences.
Executive Order No. 82, 14th June 2019 on Allocation of Aquaculture Licenses	Provisions for the allocation of licenses for aquaculture, including land-based, to be administrated by the Food and Veterinary Authority.
Parliamentary Act No. 16, 23rd February 2001 on Animal Disease (On the prevention and slaughter of sick animals and market control of animals and animal extractions)	Legislative framework for regulating animal disease management, including aquaculture animals. General provi-sions for use of animal manure, and animal waste including mortality, feed, and medicines.
Announcement No. 72, 26th July 2002, on Disinfection of Wastewater from Aquaculture Farms and Aquaculture Facilities, etc.	Provisions for disinfection and treatment of water discharged from land-based aquaculture: - inactivation of Aeromonas salmonicida, IPN and ISA virus - equipment and method require evidence-based approval.
Parliamentary Act No. 49, 30th April 2018 on Animal Welfare (An-imal Welfare Act)	General provisions for the promotion of animal welfare.
Executive Order No. 80, 14th June 2019, on the establishment of and disease-prevention in aquaculture facilities	Detailed provisions for establishment and operation of aquaculture activities, relative to health, disease and biosecurity. Provisions for landbased: - Approval and assessments required to ensure compliance - Set minimum distances between farms according to type and based on water inlet and discharge points - Require treatment of intake water to inactivate pathogens -System design must enable complete system draining and disinfection - Different year classes allowed if in separate production units - Minimum of one week fallow between production cycles - Set minimum number of health inspections according to type and production quantity - Requires detailed operation plan and recording of specific parametres relating to stock data, health and water quality.

2.5. Finland

Aquaculture in Finland is regulated through legislation related to environmental protection and animal welfare. Despite the absence of a dedicated legislative framework, Finnish regulation of aquaculture is well developed and comprehensive. Land-based aquaculture requires an environmental permit and a permit for water abstraction. Applications are processed by the Regional State Administration Authority. Approval of biosecurity measures for disease control is also required, as is a permit for building on land.

Table 9. Finnish legislation and regulation relevant to land-based aquaculture

Legislation/regulation	Purpose and relevance
Animal Protection Act (247/1996)	General provisions for the protection of animal welfare.
Government Decree on the Pro-tection of Farmed Fish (812/2010)	Provisions for protecting the welfare of farmed fish. Au-tomatic and mechanical equipment that affects welfare must be checked daily and must be an alarm to signal malfunction. Recirculation systems must have a low oxy-gen alarm.
Animal Disease Act (2021/76)	Implements EU Directives and regulations relating to an-imal diseases. Pursuant to Section 43, aquaculture facility disease control measures must be approved by Food Agency.
Decree of the Ministry of Agricul-ture and Forestry for Combating Animal Diseases in Fish, Crusta-ceans and Molluscs (1009/2013)	Provisions for prevention, control and prevention of the spread of animal diseases in fish, crustaceans and molluscs. - Includes provisions specific to aquaculture activities and for controlling specific diseases - Details that must be self-reported for approval of disease control measures.
Environmental Protection Act (527/2014)	Provisions for preventing environmental damage. - Requires use of BATs for reducing emissions as a basis for environmental permit regulation. - Section 53 provides criteria for selecting BATs. - Permit required for 'fish breeding or fish farming facility where at least 2,000 kg of dry feed is used per year or an amount of other feed equivalent in nutritional value, or where the additional growth of fish is at least 2,000 kg per year, or a natural pond or group of ponds with a size of at least 20 ha'.
Government Decree on Environ-mental Protection (713/2014)	Details relating to the state environmental permit au-thority, which has the responsibility to resolve case-specific matters relating to the environmental permits for fish farms.
Water Act (587/2011)	General provisions for the protection of water bodies other than those provisions in the Environmental Protec-tion Act.Permit required to abstract water from surface and groundwater.
Government Decree on Water Management (1560/2011)	Detailed provisions relating to the issuing of permits re-quired pursuant to the Water Act. - Stipulates details to be provided when applying for a permit.

2.6. Sweden

Aquaculture in Sweden is regulated through fisheries, environmental, animal health and welfare, and food-related legislation. The Swedish Board of Agriculture is responsible for policies relating to care, disease, trade, and registration. Other ministries such as the Ministry for the Environment and the Ministry of Enterprise and Innovation also have jurisdiction and contain relevant agencies such as the Environmental Protection Agency and the Agency for Marine and Water Management. Large facilities may require an environmental impact assessment, and permitting is the responsibility of the county administrative board. Smaller facilities are granted permits at the municipal level.

Table 10. Swedish legislation and regulation relevant to land-based aquaculture

Policy/legislation/regulation	Purpose and relevance
Fisheries Act (1993:787)	Legislative provisions for regulating fisheries and aqua-culture, including permit-based regulation of aquacul-ture by a competent authority.
Regulation (1994:1716) on Fish-ing, Aquaculture and the Fishing Industry	Implements Fisheries Act (1993:787). Basic provisions for aquaculture permits issued by the Country Adminis-trative Body; issuing of regulations by the Swedish Board for Agriculture; regulation of aquaculture prod-ucts and financial support for the industry.
Environmental Code (1998:808)	General provisions for the protection of the natural environment and human health, and environmental assessment of activities including intensive aquaculture. Stipulates (Ch.3 §5) land and water important for aqua-culture are to be protected against interventions of significant hindrance. Aquaculture facilities are exempt from requiring a permit for extracting water (Ch.11).
Environmental Examination Reg-ulation (2013:251)	Implements Environmental Code provisions on envi-ronmental permits. Aquaculture >40 tonne feed/year requires a permit from the County Administrative Board and is subject to environmental assessment. Aquacul-ture >1.5 tonnes up to 40 tonnes must notify municipal authorities.
Animal Protection Act (2018:1192)	Legislative provisions for protecting the welfare of ani-mals kept by humans.
Animal Protection Regulation (2019:66)	Implements Animal Protection Act. Aquaculture facili-ties require examination for suitability by County Ad-ministrative Board (Ch. 6 §1). New technology used for animal husbandry must also be approved (Ch. 6 §5).
Regulation on registration, ap-proval, traceability, movement, import, and export, concerning animal health (SJVFS 2021:13)	Detailed provisions relating to the permitting of aqua-culture, including land-based facilities, concerning ani-mal health and disease control.

2.7. Iceland

The Act on Aquaculture sets the main legislative framework for the regulations of aquaculture in Iceland. However, various other legislative acts are of relevance. Fish farming requires a permit from the Environmental Agency of Iceland based on the Act on Hygiene and Pollution Prevention. An operational licence is also required, based on the Act on Aquaculture. This is obtained from the Icelandic Food and Veterinary Authority, conditional to food safety, animal welfare, and biosecurity-related criteria. Other licences such as for water abstraction and building on land are also of relevance to land-based aquaculture.

Table 11. Icelandic legislation and regulation relevant to land-based aquaculture

Legislation/regulation	Purpose and relevance
Act on Aquaculture (No. 71/2008)	Legislative provisions for the regulation of aquaculture - Administration of act delegated to Food and Veterinary Agency - Permit-based regulation of aquaculture - Aquaculture farming requires a license from the Environmental Agency and Food and Veterinary Agency.
Regulation on Aquaculture (No. 540/2020)	Covers in detail the provisions outlined in legislation No. 71/2008 including carrying capacity, genetic mixing, appli-cations, operations, and controls.
Regulation on the registration obligation of parties in aquacul-ture (No. 1133/2021)	Provisions specifically for the requirement of land-based aquaculture to register with the Food and Veterinary Agen-cy - If the maximum biomass in food fish farming and research farming is up to 20 tonnes at any one time and the maxi-mum biomass in fry farming is up to 1,000 kg or 10,000 fry at any one time - Is not 'subject to an environmental impact assessment according to the Act on environmental assessment of projects and plans' - General provisions relating to the use of equipment, reporting and inspection.
Animal Welfare Act (No. 55/2013)	General provisions for the promotion of animal welfare.
Act on protection against fish diseases (No. 60/ 2006)	General provisions for the prevention of fish diseases and parasites. Requires the development of regulations for the control of aquaculture diseases and parasites.
Regulation on the Welfare of Farm Animals, Prevention of Diseases and Health Control of Farms (No. 300/2018)	Implements provisions in Act No. 60 regarding the regulation of aquaculture disease and parasite control.
Act on Hygiene and Pollution Prevention (No. 7/ 1998)	General provisions for prevention of reduction of emissions to air, soil, and water, and to prevent waste. - Provisions for licence-based regulation of activities, including aquaculture. - Licence is granted according to sets emissions limit values. - Requires implementation of BATs.
Regulation on Industrial Emission and Integrated Pollution Prevention and Control No. 550/2018	Covers in detail the provisions outlined in legislation No. 7/1998 on the prevention and reduction of emissions to the atmosphere, water, and soil. Including preventing the generation of waste.
Act on environmental assessment of projects and plans (No. 111/2021)	Provisions for administration and requirements of environmental impact assessments. - May require an environmental impact assessment if the maximum biomass is 200 tonnes or more and effluent goes to sea or 20 tonnes with effluent going to freshwater.
Act on research and utilisation of resources in	Abstraction of groundwater beyond a rate of 70 li-tres/second requires a permit from the

the ground (No. 57/1998)	National Energy Authority.
The Planning Act No. 123/2010	Regulates the permits required for the construction of an aquaculture facility.
Act No. 160/2010 on Structures	Regulates the construction of structures including those required for aquaculture facilities.
Act No. 36/2011 on Water Man-agement	The act aims to protect water and ecosystems and the sus-tainable use of water.
Regulation on wastewater treatment No. 798/ 1999	Covers the discharge of wastewater and sludge and the maximum allowable discharge of certain pollutants.
Act No. 33/2004 on the Prevention of Marine and Coastal Pollution	Covers pollution of coastal areas and insurance that land-based farmers must buy when discharging into these envi-ronments. Also covers contingency plans.

2.8. Certification schemes

Several organisations have developed certification schemes for aquaculture. They may require extensive documentation and auditing to prove that the requirements for certification have been met. Criteria for food safety, social accountability, animal health and welfare, traceability, and of relevance in the context of this report, environmental responsibility, are variably included within their scope. The requirements for qualification may be more stringent than governmental regulation. Some schemes set specific limits for discharges and prescribe defined methods, whilst others are more general in scope.

Table 12. Main certification schemes of relevance to land-based aquaculture

Standard	Application
Global Seafood Alliance, Best Aqua-culture Practices Farm Standard	Finfish production in flow-through, partial exchange, RAS, cages/ net-pens, closed-containment (not in-cluding broodstock, hatcheries, or salmonids reared in marine-based cages).
Global Seafood Alliance, Best Aqua-culture Practices Hatchery Standard	Broodstock, hatchery, and nursery facilities.
Aquaculture Stewardship Council RAS Module	Recently developed standards especially for RAS.
Aquaculture Stewardship Council Freshwater Trout Standard	Standards for the production of rainbow trout, in-cluding on-land production.
Aquaculture Stewardship Council Salmon Standard	Standards for the production of salmon, including inland production of smolts.
Global G.A.P. Standard of Integrated Farm Assurance for Aquaculture	Covers all species of finfish and other aquaculture species. This applies to all system types, broodstock, grow-out, harvesting and transportation.

3. Land-based systems

Aquaculture systems are often categorised according to production intensity and the degree of their dependence on the exogenous supply of inputs, especially feed. Aquaculture methods that exclusively use manufactured feed, such as pelleted and compound diets, are described as being intensive. Intensive feeding and the supply of other inputs are often associated with higher fish stocking densities and production volumes. Contrastingly, extensive methods rely almost entirely on natural production to supply nutrition to the cultivated species. The only exogenous inputs of economic consideration are fertilisers to support primary productivity. Mussel farming is a good example of extensive aquaculture. Mussels are often grown attached to ropes, and they feed by extracting seston from the surrounding seawater. Sometimes extensive farming methods are combined with the use of manufactured or hand-made diets. Such practices are referred to as semi-intensive or semi-extensive. This approach can be seen in some pond systems where herbivorous fish feed on naturally present aquatic plants but are also fed human-produced feed to increase the growth rate and/or stocking density. Intensive feeding may enable (and, indeed, the term is sometimes used to imply or denote) greater volumes of fish and stocking densities, and, thus, is often associated with a dependence on other inputs, such as oxygen and energy (e.g., electricity for operating equipment).

Production systems may also be categorised by their level of connectivity with natural water bodies. Open systems present few barriers to the exchange of water from and to the natural environment. They rely on the surrounding ecosystem to supply water of a temperature and oxygen content suitable for cultivation and to remove and assimilate waste nutrients. Cage and net-pen farming in seas and freshwater lakes, cultivation of bivalves on drop-ropes and lantern nets, and seaweed production on rafts and longlines are examples of open systems. There are fewer examples of what can be considered a *true*, closed system, in which there is no exchange of water with the environment. Oxygen levels, temperature, and other water quality parameters are to be controlled within a closed system with minimal reliance on the provisions offered by the natural environment[1]. Recirculation aquaculture systems are often described as closed systems. However, frequent water changes are often required to prevent the accumulation of nitrate. In semi-open (or semi-closed) systems, there is an exchange of water with the surrounding environment, but they also offer a degree of containment. Raceway flow-through systems are an example of land-based, semi-closed aquaculture. Water from a proximal natural source flows through the raceways before (usually) entering the same watercourse, albeit further downstream. Ponds are also frequently described as semi-enclosed. Water is let into the pond and discharged at the time of harvest.

There is sometimes debate about the categorisation of aquaculture systems, especially regarding the relative extent to which they can be considered open or closed. However, it is important to understand that these are useful but somewhat loosely applied terms, and they are not intended to be absolute.

1. I.e., their provision occurs within the economic sphere, which requires economic activity.

3.1. Flow-through

Land-based flow-through systems are dependent on a continuous supply of suitable water from a natural source. Fish are reared in constructed ponds or tanks through which abstracted water makes a single pass before its subsequent release. They can be defined as semi-enclosed because, although water flows somewhat freely between the environment and the system, there is some, albeit limited, containment. The use of flow-through systems for cultivating freshwater trout proliferated in the 20th century and the practice is still in use today. Trout grow-out farms are often located next to streams or rivers, from which water is abstracted and fed via gravity through elongated, rectangular ponds called raceways before being discharged into the same watercourse. Freshwater trout hatcheries consisting of much smaller raceway tanks and nurseries with circular or square tanks were also of a flow-through design. Raceways or tanks may be arranged in parallel or in series. The latter enables abstracted water to pass through two or more cultivation units before it exits the system, potentially lowering the volume of water required per unit of fish produced. Depending on characteristics such as the size and shape of raceways and the rate at which water flows, the proportion of nutrient-containing solids remaining within flow-through systems may be significant. This reduces the need for mechanical filtration, and water is sometimes discharged directly into the surrounding watercourse without prior treatment. As such, appropriate site selection is important to ensure that dissolved nutrient discharges do not exceed the assimilative capacity of the receiving environment. Phosphorous and nitrogenous nutrients can also be removed from outlet water using settling ponds and constructed wetlands.

Compared to traditional, relatively simple raceway designs, the operation of more modern flow-through systems incorporates greater use of technology. Typical examples can be found among salmon smolt production facilities. They consist of large, usually circular tanks that allow the fish to swim in shoals, which in turn enables higher fish densities. It is common to oxygenate the water to compensate for high biomasses and to lower water consumption. Water flow may be maintained via gravity alone or assisted by mechanical pumping. The intake water often gets filtered and treated with ultraviolet (UV) radiation before it comes into contact with the fish, as the system is vulnerable to diseases and the loss can be severe if pathogens get established in the plant. Other interventions may include degassing of carbon dioxide (CO_2) and the addition of minerals such as sodium chloride (NaCl) and lime (containing $CaCO_3$). Large biomasses entail large amounts of faeces and possible feed residues, so water might be subject to mechanical filtration before being discharged, perhaps as a condition for regulatory compliance. Captured solids may then be subject to thickening, flocculation, and dewatering, resulting in a condensed sludge (see Section 5.1.).

3.2. Recirculating aquaculture systems

Recirculation Aquaculture Systems (RAS) are similar to many other land-based systems in that the farmed species are cultivated in tanks, ponds, or raceways, through which water flows. However, unlike flow-through designs, water is recirculated throughout the cultivation system rather than being completely discharged after making a single pass. Instead, in RAS the percentage of water exchange typically varies from 5 to 20% according to various species-related parameters and according to production targets, water availability and budgets. Zero-water exchange systems have emerged in recent years and, rather than discharging water and exchanging it with freshwater, they replace only the water that is removed via evaporation or sludge removal. This results in around 2.5% replacement of system water per day. Owing to the degree of containment this 'reuse' of water can help maintain, RAS are often characterised as closed. They are also intensive, with feed and, most often, various other economic inputs and interventions being required to provide the suitable conditions for cultivation. Thus, RAS are frequently more dependent on technological processes than other types of aquaculture systems. Mechanical and biological water filtration technology is required to remove suspended solids and to prevent the accumulation of nutrients in their most toxic form. Oxygen must be added to replace oxygen consumed via fish respiration and other processes, and heating and cooling methods may also be required. The unit processes likely to be found in a basic RAS are:

- **Mechanical filtration** – Organic solids such as fish faeces and uneaten feed need to be removed to maintain appropriate water quality and enhance the efficiency of biological filtration. They are removed via a mechanical filter, the most common method being drum filtration. Cultivation water passes across the cylindrical screen (drum) which collects the solids. The solids are then removed from the screen via rotating the drum and backwashing and concentrated into an organic sludge.

- **Biofiltration** – Dissolved ammonia is released into the water as a product of fish metabolism and bacterial degradation of organic matter. Biofiltration reduces ammonia, which in specific concentrations and forms, especially the unionised form, can be toxic to fish. There are various forms of biofilters, although in general, they usually contain a form of media such as plastic beads, providing a large surface area upon which biofilm can be established. Nitrifying bacteria grow in the biofilm. These nitrifying bacteria convert ammonia in an aerobic two-step process, first to nitrite and then to nitrate. Nitrate is less toxic for fish than other forms. Nitrates are usually reduced by regular water exchange. In RAS facilities with a very high degree of recirculation, the removal of nitrate may also be necessary. This can be achieved with an anaerobic biofilter in which nitrate is converted to nitrogen gas (N_2) through a multi-step process facilitated by bacteria. The nitrogen gas can then be removed.

- **Oxygenation** – Oxygenation is required to maintain an appropriate level of dissolved oxygen in the water. This can be achieved via aeration, which is the mixing of air with water, for which a variety of methods exist, such as the use of air stones that send a stream of air bubbles through the water to its surface. Alternatively, pure oxygen can be used, supplied either by oxygen gas or liquid oxygen injection techniques. The use of pure oxygen is a highly effective and efficient technique. Oxygen can be dissolved into the water via a saturation cone or a venturi injection. Oxygen can also be produced onsite by a pressure swing adsorption generator.

- **Degassing** – At high stocking densities or low water exchange, carbon dioxide (CO_2), released via fish and bacterial respiration can reach toxic levels. To prevent this, excess CO_2 is stripped from the water. This can be achieved by passing water over a medium that diffuses the water, increasing its surface area, so that CO_2 transfers passively into the surrounding air. However, degassing units are not always required, as the aeration systems can be sufficient to strip CO_2 from the water, especially at lower stocking densities.

- **Ozonation and UV disinfection** – Ozonation is an effective method of destroying bacteria and viruses and is achieved by the mixing of ozone and cultivation water in a separate unit. Too high levels of ozone can be fatal to fish, with larvae being particularly sensitive. For this reason, ozone is not used in all RAS. UV treatment maybe be used alone or in conjunction with ozone. It is an effective method of water sterilisation and relies on exposing water to UV light. UV radiation ranges between 0 and 400 nm wavelength. However, 250-260 nm wavelength has the highest disinfection potential. UV-C radiation inactivates bacteria by creating thymine-thymine dimers inside the DNA. Effective UV sterilisation requires relatively clear water; a high level of organic content provides places for pathogens to hide. The most common type of UV lamp used in RAS is the low-pressure high-intensity mercury iridium amalgam vapour lamp.

- **Monitoring** – Maintaining appropriate water chemistry and quality with RAS requires a high level of monitoring. Probes and sensors are employed for continual monitoring of key variables such as oxygen level, temperature, salinity, pH and total dissolved gas pressure (TGP). In modern recirculating systems, these probes can automatically regulate O_2 dosing and pH level via programmable regulators and solenoid valves. Water chemistry, such as levels of ammonia, nitrite, and alkalinity, is tested daily using chemical test kits. More frequent testing is common during shifts in stocking intensity or when first starting up a RAS.

Recirculation systems are usually housed within a constructed shelter (e.g., insulated buildings and 'polytunnel' greenhouses), although there are examples of RAS being located outdoors (e.g., Type 3 model trout farms). Roofs, walls, and floors protect electrical and mechanical equipment and other infrastructure from damage through exposure to local environmental conditions. A suitably designed and constructed building can also support the maintenance of biosecurity by presenting a barrier to, e.g., birds and by facilitating measures for excluding other vectors of pathogens.

Over the past two decades, RAS have come to be seen as an emerging technological approach to fish farming that offers various advantages and opportunities. Certainly, Europe has witnessed a general increase in RAS, both in terms of the number of RAS facilities and the number of RAS proportional to other types of land-based systems. Technology is constantly improving, allowing for increased control, stocking densities, and water reuse. These advancements increase the viability of RAS but also the complexity. Various start-ups and small aquaculture businesses have chosen RAS for growing salmonids, pikeperch, carp species, African catfish, and other types of fish, mainly for local and niche-product markets. However, these endeavours have experienced limited commercial success, and the increase in the number of RAS facilities has come from the already established salmonid aquaculture sector, mainly to produce rainbow trout and Atlantic salmon smolts (previous to growing them in sea cages or net-pens) and some Arctic charr. During the last decade, the production of fish, e.g., Atlantic salmon, to slaughter size in RAS facilities has increased.

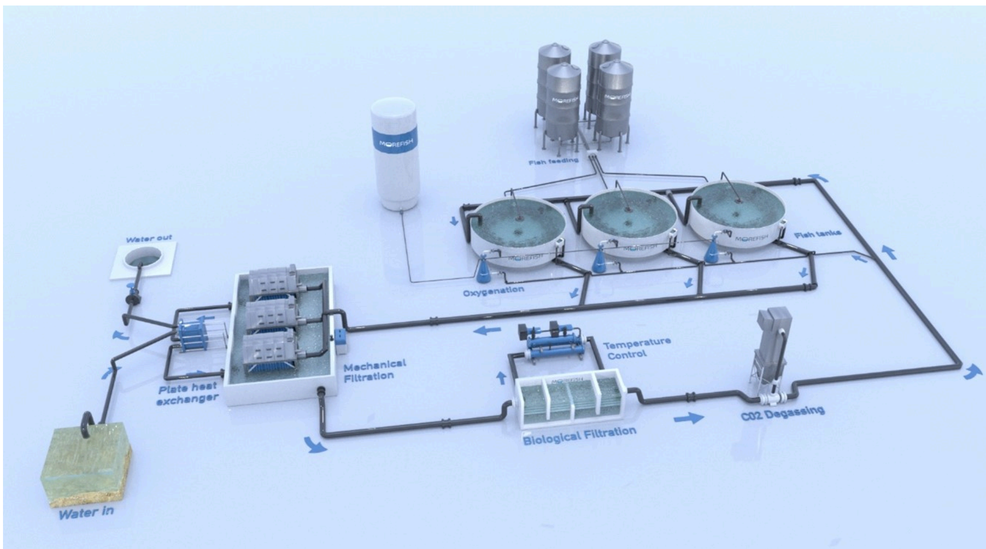


Figure 1. Schematic of a recirculating aquaculture system

3.3. Static ponds

Ponds are dug into the ground, sometimes with raised banks, and may be earthen, with a lining of clay or other material to prevent water seepage. Water from a natural source, such as a river, is introduced to the pond via an inlet. Although the water is contained for the duration of the production cycle, in reality, there may be a frequent or even constant, although small, outflow of water. This water must be replaced by new water. Although intensive cultivation involves the addition of nutrients in the form of feeds, the nutrient concentrations of discharged water are not always elevated beyond those of the inlet water. Ponds may act as a nutrient sink due to their semi-enclosed nature and the processes occurring within. Nutrients are often used up by algae or aquatic plants, which in turn may be consumed by the omnivorous fish enclosed. The decomposition of the plants creates sediment also consisting of faeces and any uneaten feed. At the end of this cycle, the removal of nutrient-containing sediment may be required. There may be economic pathways for the valorisation of these nutrients, although any use of chemotherapeutants and herbicidal compounds are potential bottlenecks (EUMOFA, 2021).

Approximately 33% of freshwater finfish produced in the EU, Norway and Iceland were produced in static ponds (EUMOFA, 2021). In Europe, ponds are mostly used for the farming of cyprinid fish. As salmonids prefer flowing, well-oxygenated water, static ponds are generally considered to be less suitable for their cultivation compared to flow-through systems and RAS.

3.4. Aquaponics

The theory behind integrated aquaculture is that two or more organisms can be grown together in a symbiotic relationship. In aquaponics, aquaculture (usually finfish farming) is combined with hydroponics – raising plants in water rather than soil. The rationale is that the aquaculture section produces waste streams containing nutrients, dissolved and undissolved excretions, that can be used by plants in the hydroponics section. By reusing the nutrients from aquaculture, the net waste is reduced. Moreover, the process offers the potential to share resources such as water, energy, and space.

Although combined plant and fish culture has been practised in rudimentary forms for thousands of years, modern aquaponics was first conceptualised in the 1970s and now almost exclusively uses RAS. To optimise the balance between fish and plants, the management of waste streams is a key feature of aquaponics, both qualitatively and quantitatively. Fish primarily produce nitrogenous waste, but other macronutrient requirements of plants (particularly potassium), and bioavailable nitrogen are often not sufficiently introduced through fish waste and must therefore be augmented using water exchanges and/or chemical additions.

Whilst offering great possibilities, realising the potential of aquaponics is proving a challenge both commercially and academically. In some cases, for example, if the use of pesticides is necessary, fish and plant cultures are typically incompatible, necessitating a paradigm shift in intense agricultural production methods if the two crops are to be integrated. This, combined with the challenging need to optimise nutrient balances, has led to conclusions that the two food production methods are best perfected separately. In any case, it is widely agreed that more research is needed.

4. Emissions, wastes and by-products from land-based aquaculture

The main emissions, wastes and by-products from land-based aquaculture in the scope of this study are (in no order of preference):

- Sludge (fish faeces and uneaten food)
- Discharge water
- Mortalities
- Gaseous emissions (mainly N_2O and CO^2)

Further environmental impact is related to the production of fish feed (agriculture and fishing), the production of electricity to power land-based facilities, the construction of facilities, the transportation of fish to market, and standard industrial waste such as metals, plastics, and wood. These environmental impacts do not differ significantly from other industries and are covered in more detail in other reports.

4.1. Definition of emissions, wastes, and by-products

Commonly accepted concepts and definitions provide a framework for discussing techniques and approaches for reducing the wastes and unwanted environmental effects of economic activity. The production of a market good takes place as part of a chain of activities connected by the flow of materials. These activities (processes) are grouped into stages, and the material outputs of one stage are the inputs to another. Production stages transform material inputs into one or more outputs, which in turn become the inputs to other stages. Material flows may be considered as either products or wastes. A product is a material flow with an economic value. This value may be as an input to the manufacture of another good or as a food item for human consumption. Frequently, more than one of the outputs of a production stage has an economic value. The 'primary product' or 'target product' is the intended output of production. If there is more than one primary product of equivalent value, they are collectively referred to as 'coproducts.' Although distinct, coproducts are often confused with 'by-products', which are defined as outputs that are not the primary product but likewise have, albeit a lower, economic value. In contrast to both coproducts and by-products, 'wastes' have no positive economic value for the producer[2]. Wastes are inputs to a waste treatment and final disposal stage, beyond which there is no further economic intervention. Thus, when solutions are implemented that valorise waste flows, the waste becomes a by-product.

2. The management of wastes is likely to incur a cost to the producer, whilst being a source of revenue for the waste management process.

Products, coproducts, by-products, and wastes are material flows that exist within the sphere of human economic activity. Substances that are emitted into the natural sphere are referred to as 'emissions.' In general, the emissions are either to land, air, or water. Common emissions to air include gaseous emissions such as carbon dioxide (CO_2) and other greenhouse gases. Discharge water from land-based aquaculture remains a waste if it is subject to further treatment, but once discharged to natural waterbodies, substances it contains, such as nitrogenous and phosphoric compounds, become emissions to water. The use of sludge to fertilise crops presents an interesting situation worthy of consideration. Sludge used in this way is a by-product. The nutrient compounds in the sludge that leach into the soil are still considered to be a material flow existing within the economic sphere, as an agricultural field is a managed economic production activity. These nutrients have an economic value as fertilising substances, the principal reason for the application of sludge. Any nutrients that exit the field system to the natural environment are emissions to either water or land and (usually) if emitted as a gas, the air. Emissions occur across all stages of a product value chain and may potentially contribute to a variety of environmental impacts. 'Environmental problem shifting' is a term used to describe when a reduction in an emission from one stage of production is achieved at the expense of additional emission elsewhere. Likewise, efforts to reduce the contribution of production to a specific environmental impact may increase contributions to another area of environmental concern. This is an issue of particular relevance to the development of BATs, but one which is often overlooked.

4.2. Discharge water

Waters discharged from land-based aquaculture vary in terms of their quantity and their chemical and physical characteristics. They typically contain dissolved and solid-bound organic and inorganic nutrients, which result from the feeding of cultivated fish (Figure 2). Nitrogenous and phosphoric compounds are the principal nutrients emitted from aquaculture when water is discharged. The form and quantity of these emissions depend on various factors, such as water discharge rate, the biomass of farmed fish, the type of aquafeed, and the presence of water reuse and treatment technology. The retention of nitrogen (N) and phosphorous (P) has been calculated at between 36,5–47% and 20,4–38,6% respectively, depending on feeding rate and frequency (Sun et al., 2016). Faeces contain 26,4–28,9% of the nitrogen in feed and 52,9–70,9% of the phosphorous, whilst 25,9–35,6% of the nitrogen and 7,41–8,9% of the phosphorus is dissolved in system water that is later discharged (Sun et al., 2016). Although nitrogen and phosphorus can lead to local and wider-scale environmental impacts, the fate of nutrients emitted from aquaculture and their associated effects depend on the characteristics of the environment into which they are discharged. Appropriate site selection and production management should ensure that nutrient emissions are well within the assimilative capacity of the receiving environment. When farms are poorly located, dissolved nitrogen and phosphorous may contribute to the occurrence of nutrient enrichment of natural water bodies. In severe cases, nutrient enrichment can promote high rates of primary production (e.g., algal blooms), with the microbial decomposition of phytoplankton consuming dissolved oxygen and creating an anoxic (absent in oxygen) environment. Localised depletion of dissolved oxygen may also occur due to the degradation of organic matter (such as that with suspended solids). In addition to the concentration of dissolved nutrients, biological oxygen demand (a measure of oxygen consumed by the respiration of microorganisms) is a key characteristic of discharge waters and their potential environmental impacts.

Water discharged from aquaculture may also contain levels of chemical substances, such as therapeutants. The use of chemotherapeutants is regulated in European Member States, although there are still some concerns regarding their potential impacts on the natural environment (e.g., Tello et al., 2010).

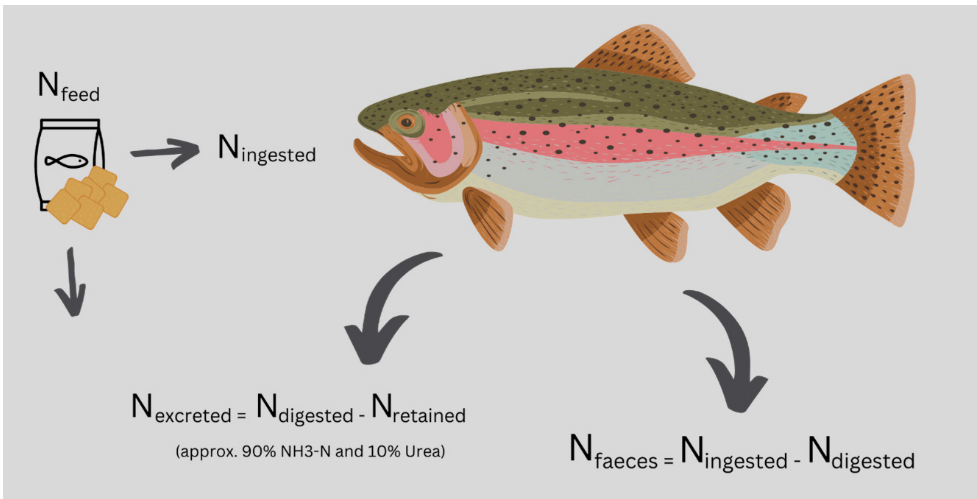


Figure 2. Model of nitrogen assimilation and excretion

4.3. Sludge

Cultivation water commonly contains suspended solids in the form of faeces and uneaten feed. High levels may negatively affect fish welfare and lower the performance of equipment, such as pumps. When discharged directly from the farm, sludge can result in undesirable environmental impacts similar to those mentioned in the above section and fouling and contamination of water bodies are also possible. Typically, they contain organic and inorganic nutrients (the majority of the phosphorous unretained by the fish is excreted in faeces), with smaller levels of heavy metals. Various methods may be employed to separate suspended solids from cultivation water to maintain conditions suitable for cultivation, and from the effluent before it is discharged into the environment. Mechanical filtration is frequently employed for these purposes. Drum filters separate suspended solids from water by passing them through a permeable filter screen or sieve. Accumulated solids are backwashed from the screen, producing wastewater containing suspended solids. This wastewater may be subject to another separation process, producing a partially dewatered sludge, which itself may undergo further separation and processing steps. Biological filtration is a common feature of RAS. Depending on the type of filter, this segment of the loop can be a source of sludge. The term 'sludge' may seem to have a rather vague meaning, as it is often applied loosely to describe everything from solids that have been partially separated to concentrated solids with a low humidity content (e.g., 10%). 'Biosolids' has emerged as a term to describe processed sludge with economic use, such as an agricultural fertiliser.

4.4. Mortalities

Within the framework of EU legislation, aquaculture mortality is classified as an animal by-product (ABP). ABPs fall into three main categories as stipulated by EC Regulation No. 1069/2009. These categories are defined by health rules concerning ABPs that are not intended for human consumption.

Category 1 material includes that which consists of by-products suspected of being infected by transmissible spongiform encephalopathy (TSE) or other specific diseases transmissible to animals or humans or that may pose serious health risks. These by-products must for the most part be disposed of by incineration in an incineration plant and therefore any further use is negated.

Category 2 ABPs include any product that may contain residues of veterinary drugs and contaminants, animals that have died in a way not related to slaughter for human consumption, i.e., being killed to eradicate a disease, and any ABPs that do not fall into Category 1 or 3. In most cases, finfish mortalities can be expected to be classified in this category. Use of Category 2 waste is restricted to disposal through incineration or co-incineration, disposal in a landfill site post-pressure sterilisation, transformation to a fertiliser or soil improver post-pressure sterilisation, ensiling, composting or conversion to biogas, and use as a fuel for combustion.

Category 3 material consists of by-products that are fit for human consumption but not intended for human consumption for commercial reasons, parts of slaughtered animals rejected as unfit for human consumption but not affected by disease, defined components of slaughtered animals post antemortem inspection, and fresh by-products from fish from manufacturing plants producing fish products for human consumption. This category applies to fish waste from secondary processing plants, or fish culled due to small size or premature maturation. Materials that fall under Category 3 can be processed in a multitude of ways and have various applications such as biogas, pet food, or being processed into organic packing materials.

4.5. Gas emissions

Fish respiration, microbial activity, and some methods of aeration introduce carbon dioxide (CO_2) into the cultivation water. The solubility of CO_2 in water is a function of temperature, salinity, and its presence in atmospheric air. Although CO_2 is not usually present in water at concentrations likely to be toxic to fish, if stocking densities, water residence times, or recirculation rates are high, it can accumulate to problematic levels. Recirculation systems often feature 'degassing' devices that facilitate the transfer of CO_2 from water to air. Degassing of CO_2 can also occur at biofiltration units and cultivation tanks when aeration is added. Nitrogen gas may be produced through microbial denitrification, which requires anaerobic conditions (absence of oxygen) but can be deliberately induced to prevent the accumulation of nitrate in systems with a high rate of recirculation (see Section 5.3.1.6). Other sources of on-farm emissions of CO_2 and nitrogen gases (e.g., nitrogen dioxide) and other gases (e.g., methane) include fossil-fuel-powered generators and oxygen generators, and sludge depending on the method of disposal. Mortalities are unlikely to be a direct source of greenhouse gas emissions if handled according to existing requirements. Their disposal is, however, a source through transportation, processing, and potentially incineration. If handled incorrectly or landfilled, moralities could be a source of GHG emissions.

Emissions of greenhouse gases and other pollutants also occur from across the value chain of land-based aquaculture farms. Increased use of energy dependant equipment such as electricity-powered water pumps is associated with CO_2 and other greenhouse gas emissions from electricity-producing power plants. Recirculation systems using a high amount of technology or machinery may achieve improved production performance and reduced water discharge rates at the cost of an increased contribution to climate change. It is also noteworthy that when emissions from across the value chain are taken into account, the majority of emissions to land, air, and water, and not from the cultivation of fish, but rather fishing and the agricultural production of crops for use as feed ingredients.

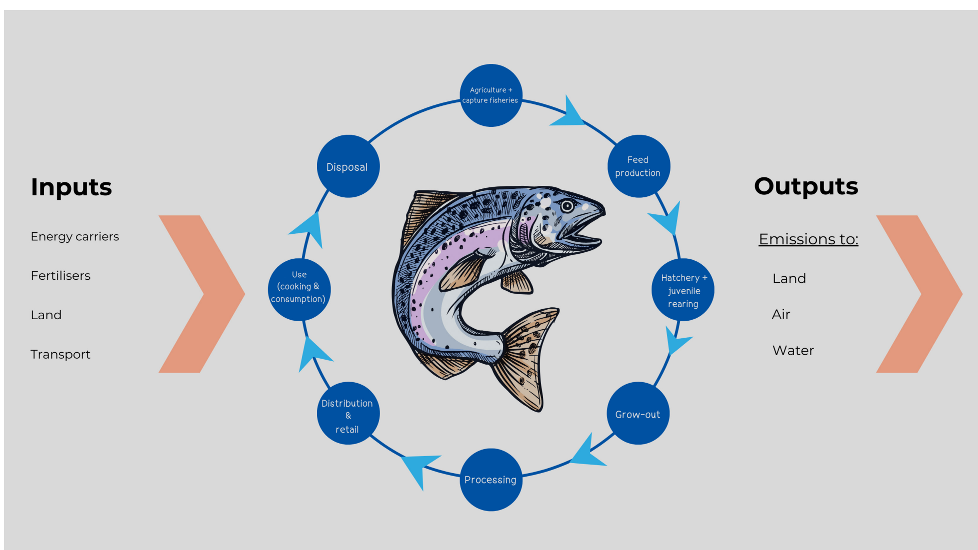


Figure 3. Basic diagram showing the major production stages of an aquaculture value chain (blue circles) and some of the inputs that these stages require (such as energy and transport). All stages are associated with emissions to land, air, and water, as is the production and provision of inputs such as electricity.

4.6. Sources of waste streams from RAS

The section below describes the various waste streams produced in land-based aquaculture. Not all waste streams are produced at every point of a land-based system. Figure 4 gives an example of a basic recirculating aquaculture system and shows where in the system waste streams are generated. In pond or raceway systems that also employ mechanical or biological filtration, the same waste streams will be generated at these points. Without these filtration steps or degassing, the waste products will remain in the discharge water rather than become distinct waste streams.

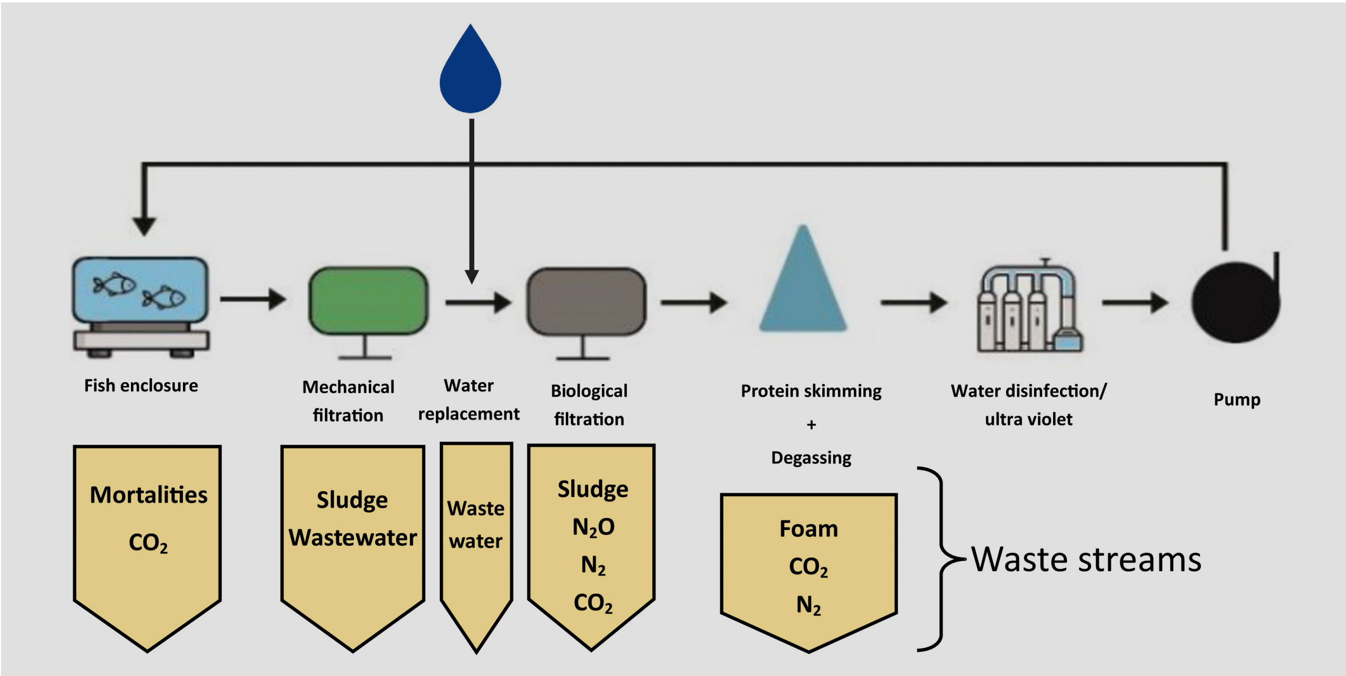


Figure 4. Diagram of a simple RAS loop and the points at which waste is generated

5. Techniques for management of waste and reduction of emissions

5.1. Separation of solids and water

As outlined above, sludge and wastewater are two major waste streams from land-based aquaculture systems. In the tank, pond, or raceway, faeces and uneaten feed are suspended in the body of system water. These must be separated from the water to process them and to keep water quality high (system water in RAS, and discharge water in flow-through).

5.1.1. Sedimentation

Sedimentation is the simplest form of solids removal. When hydraulic conditions are correct, solids suspended in the water body will sink and conglomerate into a sediment mass. In semi-intensive pond aquaculture, this approach can be as simple as ensuring slow water flow and removing sludge from the bottom of the pond at the end of the production cycle. In more intensive systems, grids and sludge cones can be used to sediment sludge, which is then regularly removed. This approach is often used in raceway systems, but sedimentation is also employed in some minimal-discharge RAS facilities.

5.1.2. Mechanical filtration

Another common approach in particle removal is mechanical filtration. Mechanical filtration is employed in the vast majority of RAS, some raceways and, in rare cases, even flow-through systems when the quality of discharge water must be managed. Some RAS facilities employ the use of tanks with dual drains. In these tanks, 5–20% of the water will exit from the low-flow bottom drain, whilst the rest is removed by the side drain. The water exiting the centre drain will contain a much larger percentage of the total solids compared to the side drain. The bottom drain water will be directed to mechanical filters to separate the solids, whilst the side drain water will undergo simpler cleaning before being returned. Swirl separators are sometimes employed to further concentrate the level of solids before mechanical filtration.

5.1.2.1. Drum filter

Drum filters are the most common type of mechanical filter in RAS. They use self-cleaning microscreen filters that remove particles typically down to 30 µm (i.e., µm pore size). Water enters the machine housing a drum covered in a cloth filter, the water flows through the unit and particles clinging to the filter are removed from the water (see Figure 5 below). Various mesh sizes are available, ranging between 20 and 200 µm. However, it is not recommended to use smaller than 20 µm because it compromises the water flow. Moreover, drum filter outlet water should not be filtered completely; a certain amount of organic solids is helpful for the nitrifying bacteria in the biofilter. Particles are removed from the filter using a backwash spray bar. This backwash water, which contains the accumulated particles, is removed for further processing. In fish farms, it is common for a drum filter to rinse every three to five minutes. Some fish farms also rinse continuously. This is due to the heavy loads of solids that are accumulated when producing large amounts of fish.

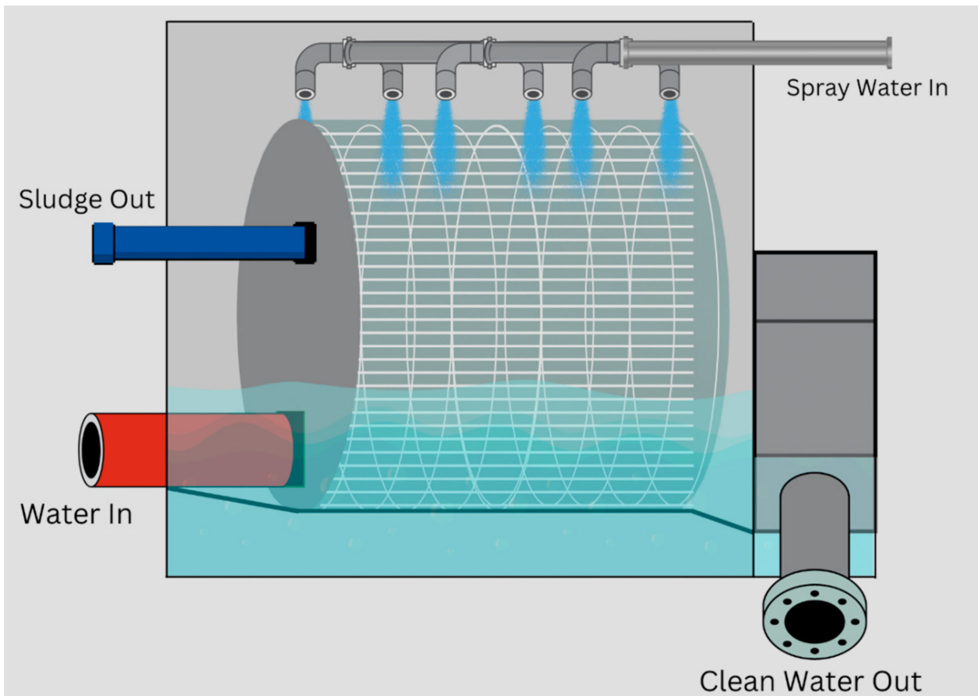


Figure 5. Diagram of a drum filter

5.1.2.2. Disc filter

Just like drum filters, disc filters are self-cleaning microscreen filters. The water flows through the unit and is passively filtered using cloth filters. An advantage of the disc filter is the use of several sequential filter cassettes, which increases the surface area of the unit, providing either more efficient filtration or a small unit footprint. A backwash system cleans the filters and the wastewater containing the concentrated suspended solids is removed for further processing. Finer filter meshes can be used in a disc filter than in a drum, and backwash frequency is reduced, resulting in backwash containing larger percentages of solids.

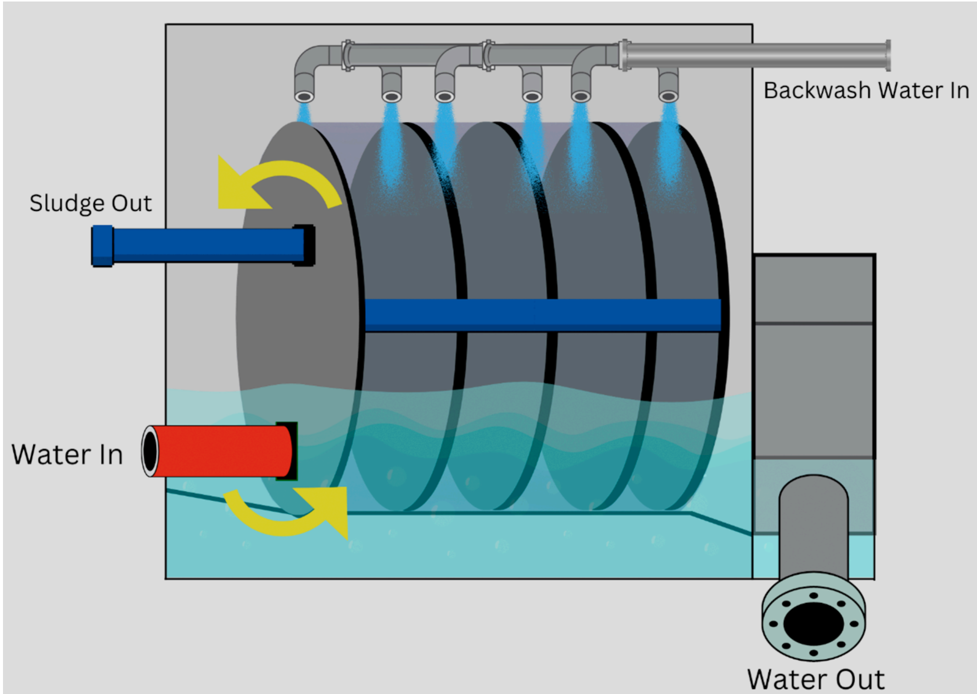


Figure 6. Diagram of a disc filter

5.1.3. Wastewater outflow

After mechanical filtration, water is often discharged. In recirculating systems, this is done to remove nitrate, whilst in "zero-water exchange" RAS, denitrification is used in the place of water discharge, with water replacement occurring to offset the water removed during solids removal and evaporation. Water replacement is the major source of wastewater from land-based aquaculture systems. Another source is water that has been removed during the sludge thickening, dewatering, and drying process. This water is not always discharged, and once solids have been removed the water can be "polished" and returned to the system water. Options to process and valorise wastewater are described in the wastewater section of this publication.

5.1.4. Sludge water processing

Backwash from mechanical filtration can contain total solids (TS) as low as 0,05%. This sludge water must be processed to concentrate and separate the suspended solids from the water, resulting in wastewater and sludge. Sludge water can also originate from biological/sand filter backwash. Some companies employ an additional separation step to increase the level of solids in the water. This step typically employs gravity separation such as a lamella or gravimetric separator, which can result in sludge water with 3–4% TS before the main processing steps. Sludge at this stage can be transported off site for disposal or reuse, but further processing is common. Not every farm fully dries its sludge, and sludge at every level of moisture can, and is, used by certain companies. The uses for sludge and the level of moisture required are described further on.

Thickening. The first stage of sludge water processing is thickening. Suspended solids are coagulated/flocculated, and these accumulations are removed using a mechanical filter. Coagulation involves the addition of ions with the opposite (normally positive) charge to neutralise the charge of the suspended particles. The neutralised particles, rather than repelling each other, now begin to form microflocs. In the water treatment industry, inorganic metal (iron or aluminium) salts are commonly used. These coagulants are easier to use than organic coagulants, such as those based on amines, or activated starch, but they also react with phosphorus to form stable metal-phosphates, which can limit the viability of certain downstream uses for the dewatered solids, e.g., fertiliser (Kirchmann et al., 2017). Microflocs cannot be seen by the naked eye and flocculants must be added to further conglomerate the particles into large flocs. These flocs can be seen in the water body and can be actively removed. A range of polymers can be used. Synthetic polymers are most commonly used with the most common being polyacrylamides, whilst some companies chose to use natural polymers. Natural polymers can be animal-, plant-, or microorganism-based, and depending on the downstream uses for the solids, these can present a more attractive option (Kurniawan et al., 2020). Choosing the correct polymer for the water conditions (pH, salinity, temperature) can improve flocculation efficiency. An alternative to chemical coagulation/ flocculation is electrocoagulation. These systems combine electrolysis and ultrasound to flocculate solids without the use of chemicals. These systems present a promising alternative to traditional chemical coagulation and flocculation, but they can be difficult to optimise on an industrial scale. Once particles have been flocculated, they are removed from the body of water. This is usually achieved using a belt or band filter (Figure 7). The water content of the removed solids is still high with 3–10% TS. Belt filters operate similarly to drum or disk filters in that they use a filter mesh to separate solids from surrounding water and employ a backwash to clean the filter. The flow through the filter can be improved using a vacuum (not pictured).

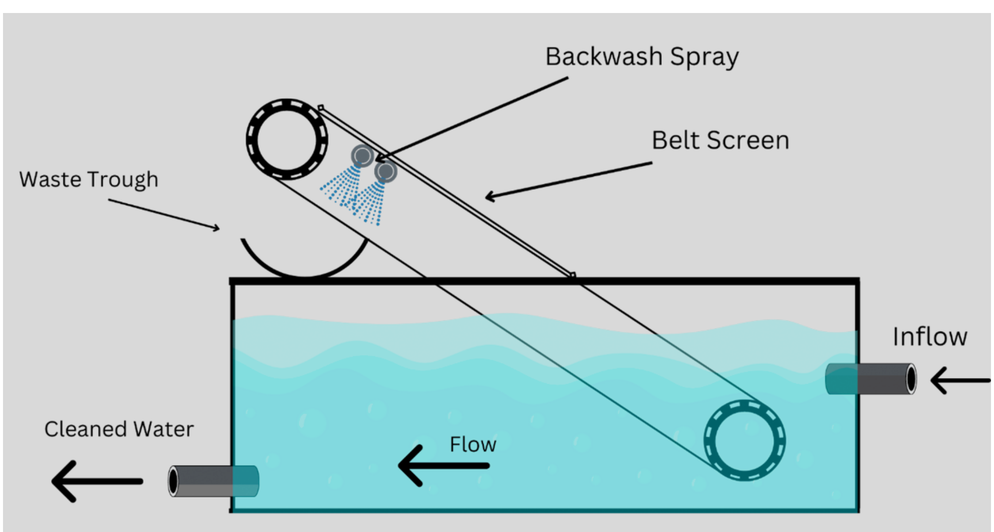


Figure 7. Diagram of a belt screen filter

Dewatering. Many reuse options require sludge to be further concentrated, which is achieved through dewatering. Decanter centrifuges, screw presses (Figure 8) and to a lesser extent filter presses are used to produce sludge with 20–30% TS. A screw press uses an Archimedes screw to move sludge along a permeable chamber. This chamber is normally inclined to assist with water drainage. The filter is typically wedge-wire or perforated metal, and this is less susceptible to clogging than cloth filters. A decanter centrifuge uses centrifugal forces to push solids towards the walls of the chamber, which are then moved along using a screw, the lighter water component flows freely towards the other end of the chamber. These systems must treat the sludge carefully as the lack of fibre makes it more delicate compared to municipal wastewater sludge. Dewatering beyond 30% TS is possible but the sludge is difficult to pump, and the benefits of such a practice are outweighed by the logistical and actual costs.

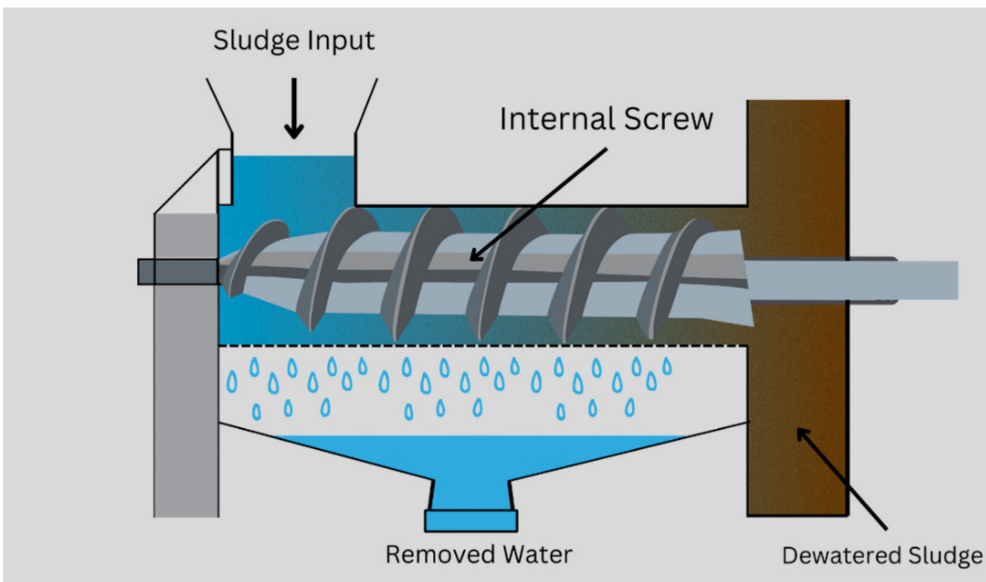


Figure 8. Diagram of a screw press used for sludge dewatering

Drying. Drying is the final stage that may be employed in aquaculture sludge processing. The TS of the sludge can be over 90% and this process can produce a hygienised and stable sludge that can be stored for extended periods and used in a larger number of reuse options compared to wetter sludge (see Section 5.2.4). Drying the sludge can be achieved through various methods including thermally, but this is a costly approach. The most cost-effective is the use of superheated steam, heat pumps, or thermo-mechanical drying. Drying is the most energy-intensive stage of sludge processing. It takes around 0,75kWh to evaporate 1kg of water (this decreases as starting temperatures increase), but many companies report values of more than 50% lower, thanks to efficient reuse of energy.

5.2. Possible reuse of sludge

5.2.1. Fertiliser

The following sludge reuse options are focused on freshwater sludge. Saline sludge poses additional challenges in its reuse due to its salt content and will be discussed separately (see Section 5.2.5). Sludge may be landfilled depending on local legislation; however, not only is it environmentally unsound, but it is also expensive for farmers, who must pay to dispose of their sludge. One alternative is to use it as fertiliser. In Atlantic salmon raised in RAS, a large percentage of the nitrogen and phosphorous is excreted in faeces, 26,4–28,9% and 52,9–70,9% respectively. This results in large quantities of nutrients vital for plant growth being expelled from aquaculture systems in sludge. Using resources such as these is a key facet of the circular economy.

The use of aquaculture sludge as an organic fertiliser, whilst previously permitted in the EU, has recently been restricted. EU regulation bans the use of animal by-products, derived products, and waste (other than manure or guano) on crops both intended for direct human consumption and indirectly, after consumption via livestock. This legislation does not stop the use of fertiliser in the country of origin (assuming local rules allow) but does prevent the export to other EU countries. Based on stakeholder responses, turning sludge into fertiliser remains fairly common, with the use of this technique reported by stakeholders in Norway, Sweden, Denmark, Iceland, and the Åland islands.

Once the solids in the water have been collected and thickened, the resulting sludge can be used directly as a fertiliser in local agriculture. This method is simple to implement, but the market for such fertilisers is limited and aquaculture producers must pay significant transport fees due to the liquid nature of the sludge. This sludge cannot be stored and the risk of emissions from nutrient run-off is high.

One way to mitigate these issues is to dewater and dry the sludge, as described in Sections 5.1.4 and 5.2.4. Several companies offer technologies for this process, based on concepts including but not limited to centrifuges, heat pumps, infrared evaporation, and superheated steam. Production of sludge with TS of >90% is possible, which hygienises the sludge, increases the storage potential, and reduces transport costs. The dried sludge can be transported to a fertiliser producer, where it will undergo further processing and likely be mixed with other organic nutrient sources to produce organic fertiliser. The dried sludge can also be used immediately, either as a ground powder or formed into pellets. The technology behind creating organic fertilisers is well established and large volumes of sludge can be handled by processors, making this viable for farms both large and small. A fish farmer who turns sludge into fertiliser should not, however, expect large profits. Farmers can either choose to have their wet sludge collected or can dry it on their farms. Sludge processors charge farms to process the sludge but are responsible for sludge handling, processing, and transportation, releasing farms from the need to invest in the technology. These systems can handle over 100m3 of wet sludge every hour, but the modular nature means that they can handle even larger volumes should they be required. The cost of organic fertiliser is low and whilst sludge processors get paid by the tonne for dry sludge by the fertiliser manufacturer, one supplier said this only covers the cost of the bag that holds the sludge. Drying the sludge on farm increases the complexity of farming operations, but the dried sludge may be collected free of charge by the fertiliser manufacturer.

Restrictions on the exportation of the fertiliser can limit the valorisation of the sludge as much of the sludge is produced in countries that are not nutrient poor but cannot be exported to other EU countries that require inputs of fertiliser. The Norwegian coast, for example, is a potential source of a large amount of fish sludge from both land and cage-based aquaculture, but due to inputs from animal manure and inorganic fertilisers, much of the soil already holds excess amounts of phosphorous (Bechmann, 2014). Further additions of phosphorous are not only wasteful but also harmful, with run-off decreasing surface water quality and increasing the likelihood of eutrophication (Maguire et al., 2005). Nordic countries also have a surplus of nitrogen in the soil (Table 6), with inputs (atmospheric, biological fixation, manure, and synthetic) outweighing outputs heavily. The extent of the surplus is such that policies are in place to mitigate agricultural nitrogen losses (Hellsten et al., 2019). In addition to the possibility of emissions of nutrients into surface waters, microbes in the soil turn the nitrogen present in fertiliser into nitrous oxide, a potent greenhouse gas. That being said, the process is not unique to organic or aquaculture sludge fertilisers and this is thought to be a greater issue when using inorganic fertilisers. The risk of emissions means that it is not recommended that fish sludge fertiliser be added in addition to established sources of nutrients. Instead, it can provide an alternative to inorganic fertilisers. Produced more locally and without inputs such as natural gas, this replacement fits the requirements of the circular economy. Some companies currently ship fertilisers made from aquaculture sludge to markets with less stringent regulations and high demand, namely the Asia-Pacific region, which makes up around 50% of the global fertiliser market (Allied Market Research, 2022).

Table 13. Nitrogen inputs, outputs, and surplus in five Nordic countries in 2018 (FAO, 2021)

Country	Inputs (kg/Ha)				Outputs (kg/Ha)	Nitrogen Surplus (kg/Ha)
	Atmospheric Deposition	Biological Fixation	Manure Applied	Synthetic Fertilisers	Crop Removal	
Norway	7,2	0,2	60,1	127	20,3	174,2
Sweden	11,7	1,9	25,1	72,1	29,8	81
Finland	7,2	0,4	19,8	61,6	28,1	60,9
Denmark	14,3	0,4	69,4	79,3	65,9	97,5
Iceland	9,6	-	34,5	97	0,9	140,2

The level of nutrients in the sludge can vary depending on how the sludge is collected. Using inorganic coagulants to collect solids from discharge water results in sludge with approximately 10% of the total phosphorous being bioavailable and the other 90% being strongly bound to iron (Fe) or (Al) aluminium and therefore in a form with lower bioavailability (Kirchmann et al., 2017). Organic coagulants can be used, which reduces this issue, but the cost of these coagulants is around four to five times that of inorganic coagulants (Heiderscheidt et al., 2020). In dried sludge, the immediate bioavailability of the nitrogen is low, but it quickly undergoes mineralisation, allowing uptake by the plant. Dried fish sludge pellets can replace between 50 and 80% of the nitrogen in mineral fertilisers (Brod et al., 2017).

Further processing such as anaerobic digestion alongside dairy manure can increase the fertilisation effect (Brod et al., 2017), but this increases the resources involved in processing. The bioavailability of phosphorus from fish sludge is notably lower than manure, replacing 47±24% of phosphorus in mineral fertilisers (Brod and Øgaard, 2021). Although fish sludge fails to be as effective a fertiliser as the same mass of mineral fertilisers, it can provide a cheap and local source of nutrients for agriculture.

A variety of factors can influence heavy metal concentrations in sludge, including feed makeup and origin of raw materials, the chemistry of influx water, and the level of recirculation in the system. There are a limited number of studies into the concentration of heavy metals in sludge from RAS systems, but what evidence does exist suggests that the values allow for use as fertiliser, with restrictions on the use. A study by Nofima (Ytrestøyl et al., 2016) looked at the levels of heavy metals in the sludge from three commercial hatcheries. The levels of cadmium would allow use as either Class 0 or Class 1 fertilisers under Norwegian regulations, whilst the zinc levels required categorisation as a Class 1 fertiliser. Class 1 fertilisers can only be used up to four tonnes of dry matter per hectare per ten years and can be used on agricultural land, private gardens, and parks (Norwegian Regulations on Organic Fertilizers, 2003). Similar values were reported in the sludge from land-based salmon aquaculture in Chile (Class 1 in Norway) with higher values of cadmium reported in the sludge recovered from underneath lake cages (Celis and Sandoval, 2010). Communication with a sludge processor revealed that all aquaculture sludge they process is over the Class 0 requirements regarding zinc (Zn) and cadmium (Cd). Using too much fertiliser over Class 0 risks farmers not being able to add more fertiliser to plots of land for many years and therefore preventing effective use of that land. Heavy metals are not routinely removed during the drying process, but the aquaculture sludge can be used as an ingredient in Class 0 fertiliser so long as other compounds are low in the same heavy metals. Some companies offer heavy metal removal as part of sludge processing based on the sorption of heavy metals to a specialist filter. The use of this technology on a production scale has not been shown, and the cost of removal is likely to be prohibitive when sludge fertiliser can be mixed to decrease its class.

5.2.2. Energy production

Biogas can be produced using aquaculture sludge as substrate. Given the correct processing, the sludge can be converted to biogas, either on farm or at third-party plants, with the gas being used for the generation of electricity. Biogas is a mixture of mostly methane (CH_4) and carbon dioxide, making up between 50–70 and 30–50% v/v, respectively (Angelidaki et al., 2011). The process of creating biogas is the action of three main groups of microorganisms, primary fermenting bacteria, anaerobic oxidising bacteria, and methanogenic archaea (Angelidaki et al., 2011). The use of this process to create methane gas in bioreactors can be traced as far back as 1890s Bombay, but its use in land-based aquaculture systems is much more recent and it has yet to be fully used by the industry.

Of the survey respondents that treated their sludge, over 50% were using some form of biogas production. However, a large number did not treat their sludge at all. Both wet and dried sludge can be transported to third-party biogas plants, but economic analysis conducted under a GAIN project (Tirano et al., 2021) concluded that drying the sludge using either of the two drying techniques presented increased short- and medium- or long-term profit compared to transporting wet sludge. The cost of transporting wet sludge is the major reason behind this difference, followed by reduced gate fees at biogas plants. A life cycle assessment conducted by Cristiano et al. (2022) claimed that all drying options also created significantly less environmental impact than offsite wet sludge biogas production. The study did not look at the impact of onsite biogas production. Emissions of greenhouse gases are a downside of biogas production, but biogas energy has a lower carbon footprint than fossil fuels. In addition, should the sludge be landfilled, microbial digestion and release of methane can still occur, but this release is often uncontrolled and unused.

Using third-party biogas plants removes both increased complexity and capital costs from a farming operation. However, it also limits valorisation, with farms being charged significant gate fees to dispose of their sludge in this manner. It is not uncommon for Norwegian farms to transport sludge hundreds of kilometres to Danish biogas plants where gate fees are lower. This is an environmentally unsound practice, and some larger farms are moving to onsite biogas production. Using sludge onsite has benefits such as reducing reliance on fossil fuels and lower transport fees. Following biogas generation, the volume of the sludge is reduced by up to 80%, thereby reducing the cost of subsequent handling and disposal without the need for drying (Letelier-Gordo et al., 2020). Aquaculture sludge is not the perfect feedstock for biogas production with the carbon/nitrogen ratio typically requiring the addition of a carbon source such as plant material or pig slurry. However, 100% fish sludge biogas production is possible. Ammonia accumulation in the digester is also a concern, and if this builds too high it can wipe out microbial communities entirely. Biogas reactors can occupy large amounts of land and require large inputs of biomass to be viable. It is therefore not a recommended solution for a farm with either limited expansion potential or a low production volume.

For the onsite production of biogas, various companies offer bioreactors. Different reactor types are available, depending on space, cost, and efficiency required, but all operate according to the same principle: anaerobic degradation of organic material to biogas.

Continuously Stirred Tank Reactors (Figure 9) are simple in design and operate by mixing sludge using an impeller. A settling tank is often attached with treated water being extracted and solids returning to the reactor. Most systems of this design operate with high efficiency in sludges consisting of 5–10% TS content. The downside of such reactors is that operation can be expensive, with long retention durations and higher energy and labour costs than some other designs.

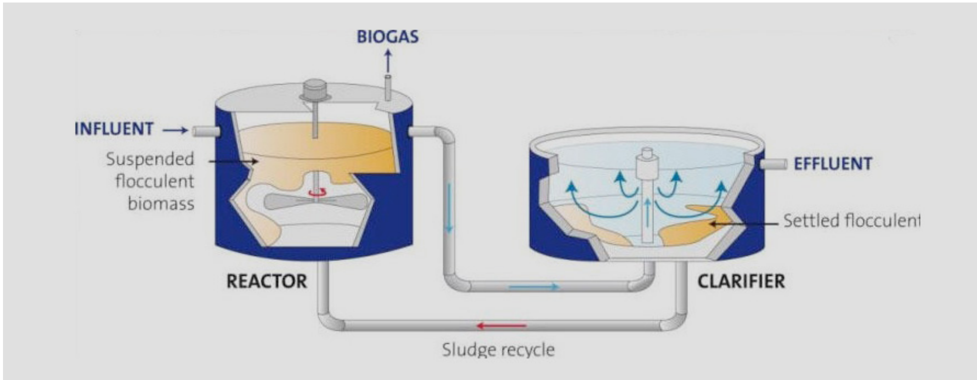


Figure 9. Continuously Stirred Tank Reactor – taken from Banerjee et al., 2022

Up-flow Anaerobic Sludge Blanket Reactors (Figure 10) allow for lower operational costs whilst allowing for higher solid-removal efficiency from discharge water with a TS content of 3–4%. These systems use a suspended blanket of granular sludge through which discharge water flows upward, being processed by microorganisms along the way. The long retention times should be considered when choosing this system.

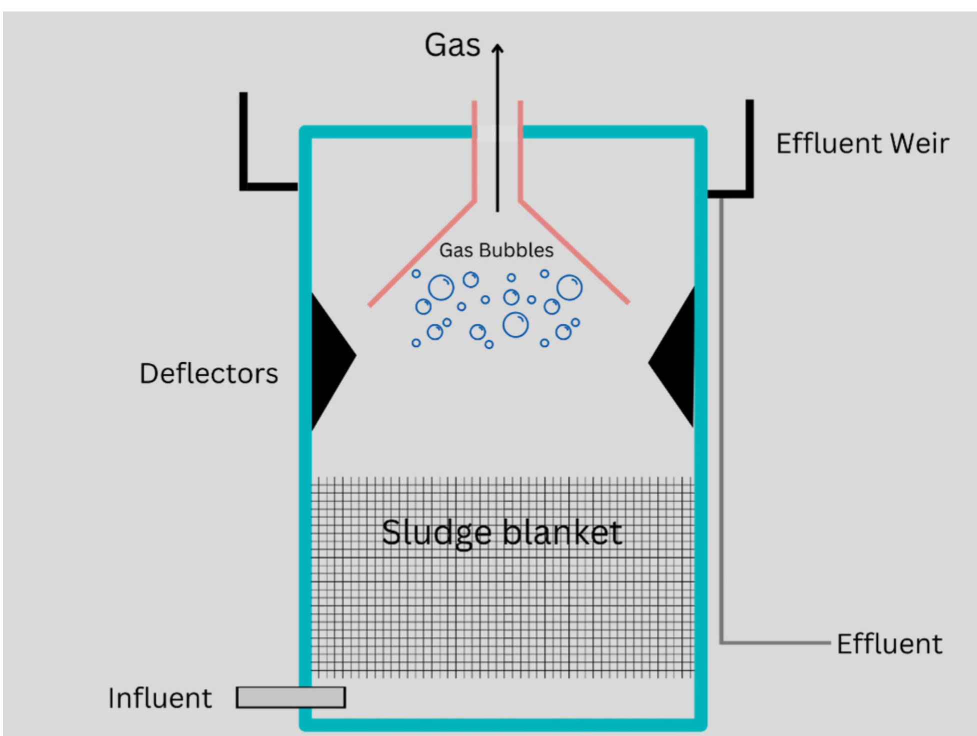


Figure 10. Up-flow Anaerobic Sludge Blanket Reactor.

Membrane Bioreactors (Figure 11) provide high effluent quality and high conversion of influent. They also come with high operational costs and the risk of biofouling. These systems use a submerged membrane to filter particulate waste from the major liquor solution, operating like a traditional activated sludge system.

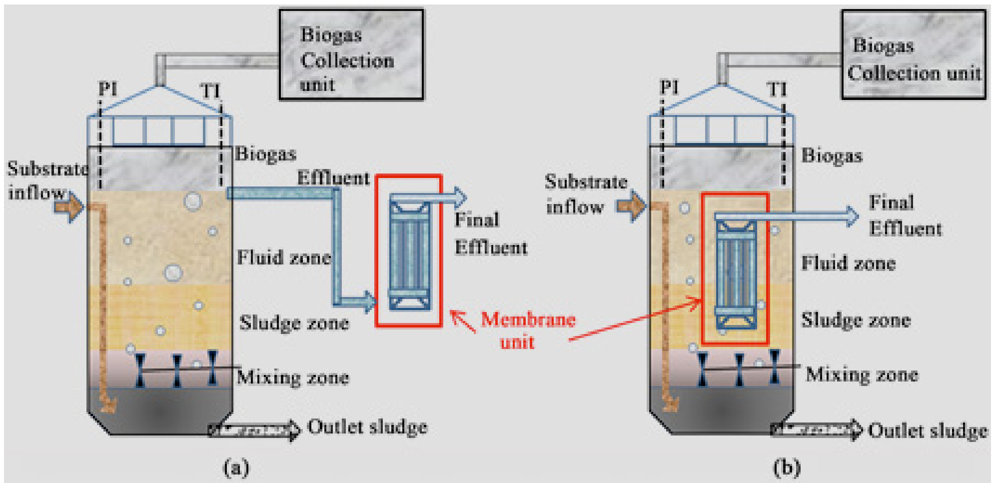


Figure 11. Membrane Bioreactors – (a) Side-stream configuration; (b) Submerged or immersed membrane configuration. Taken from Jain et al., 2018.

Anaerobic Baffled Reactors are widely used in discharge water treatment and can treat water with high solid content. These reactors resemble modified septic tanks with a series of baffles along the length of the tank (Figure 12). As the influent travels across the tank, the sediment settles, therefore separating the solids retention time from the hydraulic retention time. These systems are robust against hydraulic and organic shock and are simple to build and operate. Technology of this type has been used to generate around 500.000 kWh/year from 260 tonnes of sludge (weight as dry matter) at a Norwegian hatchery (see Case Study 2). The heat and electricity generated by the biogas can be used to fuel the sludge dewatering, biogas production, and drying of the remaining sludge. These processes do not use all of the energy in the biogas, and over 50% of the heat and electrical energy is available for usage in additional farming operations.

Whilst dilute discharge water can be used in bioreactors, the efficacy of the process is reduced significantly compared to using dewatered and thickened sludge. A commercially active bioreactor on a salmon farm in Norway was reported to use sludge thickened to less than 5% TS before input into the bioreactor (Case Study 2). This system used microbes selected for high nitrogen tolerance and was able to operate on 100% fish sludge without inputs of an exogenous carbon source. Biogas production does not use the entire volume of the sludge and the remaining residue can be used as a fertiliser.

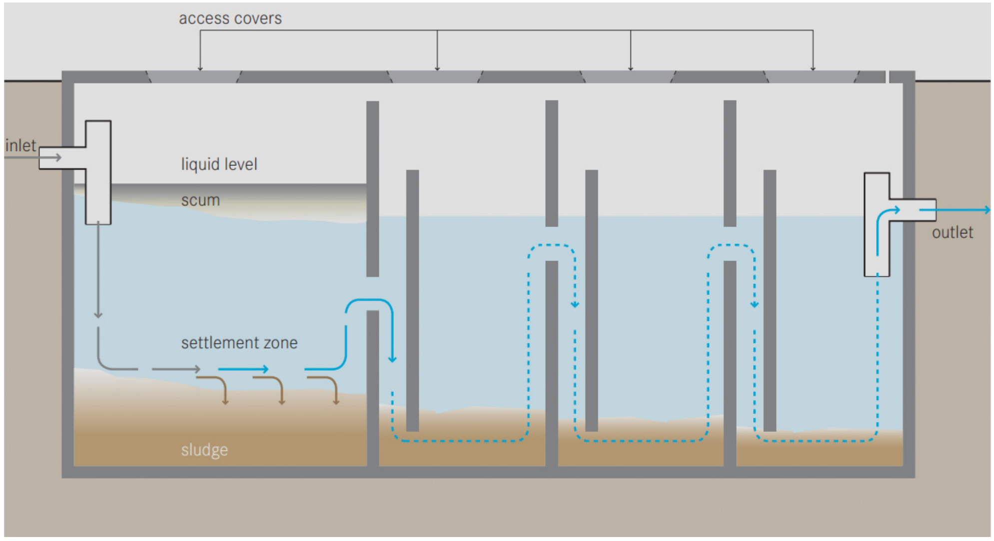


Figure 12. Anaerobic Baffled Reactor – Biogas extraction can occur from vent – Taken from Tilley, 2014.

Case Study 2 – Sterner

Sterner AS is a Norwegian-based company that has been offering water treatment solutions since the early 1990s. They offer two main solutions for aquaculture sludge treatment: sludge drying and on-site biogas production. Sterner's approach to sludge dewatering and drying is mechanical, using sludge thickeners, dewatering screws, and belt dryers to create a sludge up to 90% TS that can be used as fertiliser or sent to an external biogas plant. Drying in this manner can use as little as 0,3 kW per litre of water removed.

Biogas production takes place inside an anaerobic baffled reactor. Sludge thickened to 3-4%TS enters the reactors and the water remains for around six days. Solids settle out and are removed with a screw. This digestate can be mechanically dewatered and used as fertiliser. Inside the reactor, bacteria that have been specially selected for tolerance of a low carbon/nitrogen ratio can turn 100% fish sludge into biogas (CH_4 and CO_2). Sludge from marine aquaculture can also be used following novel dewatering techniques. A Sterner biogas plant of this type has been running for almost four years with a good production of biogas, which can be used to power parts of the farm. More than 50% of the electricity produced from the biogas is available for use on the farm, with the rest being used to power the sludge treatment process itself. The heat energy from the process can also be used to heat system water. Onsite biogas production is not applicable to every situation; farms below 5.000 tonnes may find that drying the sludge is more economical, depending on factors such as the remoteness of the farm and electricity costs.

Photo of a Sterner Biogas reactor on a fish farm

Pyrolysis is also an option for the valorisation of sludge. Put simply, pyrolysis is the heating of organic material in the absence of oxygen. In general, pyrolysis uses sludge that has been dewatered and partially dried, although systems that can process sludge with <15% TS are available. These often use microwave heating and can incorporate drying, pyrolysis, and gasification into one process (Lin et al., 2017). Despite pyrolysis use dating back to ancient Egyptian times (Mohan et al., 2006), it was not until the 1980s that the pyrolysis of sewage sludge began to be investigated (Fonts et al., 2012), and only recently has this technology been used as a method of processing aquaculture sludge.

The three major products of pyrolysis are biochar, bio-oil, and syngas. Pyrolysis of biosolids typically occurs between 300 and 900 °C, with the temperature and duration of the process determining the amount of each product. Slow pyrolysis increases the production of biochar to the detriment of biogas and bio-oil production. Fast pyrolysis increases bio-oil production, whilst flash pyrolysis increases bio-oil production even further (Elkhalifa et al., 2022). Some emissions of H, CO, CO_2, and CH_4 occur during sludge pyrolysis and commercial units often include gas cleaning and purification systems to remove NO_x, CO_x, particulates, and sulphur. Pyrolysis equipment can be purchased from aquaculture suppliers, including the option to handle all processing such as sludge drying and dewatering (see Case Study 3).

Bio-oil and synthetic gas (syngas) are two of the three main products of pyrolysis. The energy content of syngas is considerably lower than that of natural gas (~6 MJ/kg^{-1} and ~54 MJ/kg^{-1} respectively) (Laird et al., 2009). This energy can, however, be used to power the pyrolyzer itself, reducing the costs associated with this process. This option is already being offered in some aquaculture pyrolysis ovens.

The heating value of bio-oil varies depending on the nature of the feedstock, but aquaculture sludge will likely produce heating values around half that of No. 2 fuel oil (Laird et al., 2009). Bio-oil cannot be used as a direct replacement for diesel or petrol and must first be refined increasing the cost and complexity of using bio-oil as a fuel source (Gupta et al., 2021), although it can be burned in industrial boilers (Laird et al., 2009). The use of aquaculture sludge in this manner will not only reduce the sludge emissions of a farm but also decrease reliance on fossil fuels. There has also been recent interest in the chemical composition of bio-oil with the possibility to extract a wide range of value-added products from the oil, which can have economic value and industrial applications (Brodie et al., 2018), but the low quantity of these compounds makes the use of these resources from aquaculture sludge a challenge. Burning syngas and bio-oil emits greenhouse gases and toxic compounds, including CO, CO_2, NO_x, SO_2, and in the case of bio-oil, particulate matter (PM<2,5). Despite these emissions, because the carbon in these fuels is sequestered from the environment, they are considered by some to be carbon neutral.

Biochar production results in much of the carbon content of sludge being captured in solid form. Compared to incineration, pyrolysis emits considerably less carbon into the atmosphere, and the carbon can remain stored for hundreds of years. Biochar can be used as a soil enhancer, increasing the nutrient uptake efficiency of plants by trapping nutrients in the soil for longer and decreasing run-off (Carey et al., 2015; Figueiredo et al., 2021). Biochar can also be used to neutralise the soil, with acidic or alkaline biochar being produced from the same urban discharge water sludge depending on the temperature of the pyrolysis (Hossain et al., 2011). Biochar may also be used as a fertiliser, but without the addition of chemicals such as potassium acetate (Buss et al., 2020) or calcium oxide (Liu et al., 2019), the bioavailability of the phosphorous will be low. The temperature of pyrolysis can alter the concentration and bioavailability of nutrients. In municipal discharge water sludge, the total nitrogen content decreases with rising temperatures, as does the bioavailability of the remaining nitrogen (Hossain et al., 2011). Conversely, total and plant-available phosphorous increased with pyrolysis temperature as did the concentration of assessed micronutrients (Ca, Fe, Mg, S, Cu, and Zn) (Hossain et al., 2011). The heavy metal content of the biochar also increased with pyrolysis temperature. However, the availability of these to plants (DTPA-extractable concentration) decreased with temperature (Hossain et al., 2011).

The use of biochar has also been suggested in water treatment systems, with the highly porous nature of biochar, particularly biosolid biochar (Elkhalifa et al., 2022) allowing the removal of chemical, biological, and physical contaminants (Gwenzi et al., 2017). Removal of H_2S and NO_x from gas streams is another use, as is the sorption of metals, phenols, and dyes (Paz-Ferreiro et al., 2018). Due to its porosity, biochar is a good catalyst during biodiesel production, or for the removal of tar from bio-oil and syngas (Lee et al., 2017). Activated carbon is a further valorisation option. This requires additional processing, but prices can range from €670–2000/tonne (Alibaba, Dec 2022). One company offering pyrolysis to aquaculture (see Case Study 3) reported tuning their system to only produce biochar due to the larger market and increased usage of the product. Pyrolysis occurs at high temperatures, and much of this heat can be recaptured and fed back into the system or used to heat system water. It can also be used to generate electricity to power farming operations. Using this heat decreases the costs associated with pyrolysis. Compared to bioreactors, pyrolysis units are smaller and can process sludge much more quickly. Purchasing and the initial start-up process of a pyrolysis unit can have significant costs and a large amount of sludge is needed to make the operation economically viable. For large farms (10.000 to 15.000 tonnes/year), they can present a viable solution for sludge management.

Case Study 3 – Blue Ocean Technology

One supplier offering pyrolysis-based solutions for aquaculture sludge is Blue Ocean Technology. Started in 2012, Blue Ocean Technology offers a systems approach to sludge management capable of handling all facets of sludge thickening, dewatering, and drying, and offers pyrolysis systems for further valorisation. Specially designed belt filters and screw presses handle the sludge more delicately than those designed for municipal wastewater sludge. These systems require little maintenance and few worker hours, with only ten minutes twice a day being needed. These containerised solutions can be placed anywhere onsite, increasing flexibility and reducing wasted space.

The company can capture sludge from beneath sea cages and boasts the ability to remove 60-70% of the salt, allowing saline sludge from marine or land-based facilities to be used as fertiliser or for biogas production. Blue Ocean Technology states that biogas production onsite generally becomes viable once production is above 10.000 to 15.000 tonnes/year. An alternative for both larger and smaller farms is pyrolysis.

Blue Ocean Technology calculates that on larger farms the total cost of processing the sludge including pyrolysis was reported as 200-400NOK/tonne of fish produced. The pyrolysis system requires heating to 400 °C before the heat from the process itself increases temperatures to 700–900 °C. Too small a volume of sludge makes this process less cost-effective. The pyrolysis system is tuned to produce biochar, which can be used as a soil enhancer, or for other applications such as air or water filtration. The pyrolysis unit produces up to 1300 kWh of heat constantly, based on approximately 4000 tonnes of sludge with 15 MJ energy content. If the sludge possesses a larger energy content (20 MJ) then it is possible to produce 1750 kW of heat or 525 kW of electricity constantly. This makes the system more than self-sufficient as the unit needs only 65 kW to operate. The remaining energy can be delivered to the farm. At 150 m2 to 200 m2 , the pyrolysis unit is smaller than many biogas reactors in general.

A technician works on a Blue Ocean Technology screw press

Burning – biofuel for the cement industry

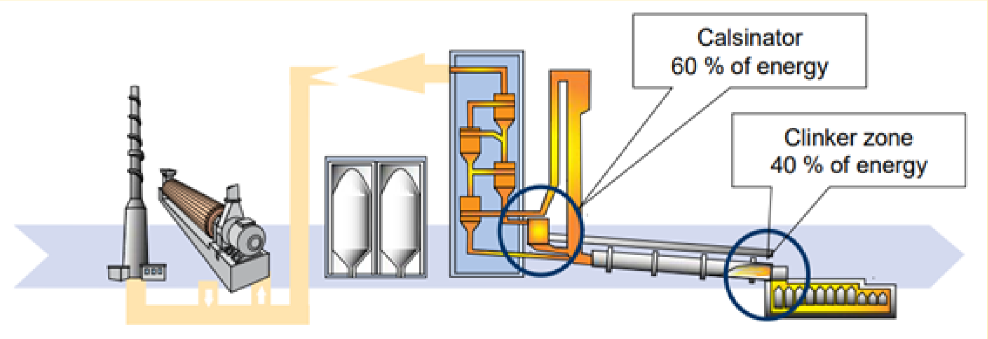
In addition to biogas and pyrolysis, the energy in the sludge can also be harnessed through incineration. Dried sludge can be transported to plants which incinerate the sludge alongside waste products from other industries and municipal sources. The burning of sludge compared to microbial digestion prevents the emission of methane but emits large volumes of CO_2 into the atmosphere. Cleaning (scrubbing) of the air is common, but carbon capture is not, with only one known carbon capture and utilisation system operational on a European incinerator. Compared to energy produced from renewable sources, e.g., wind or hydroelectric, burning of waste is less efficient and produces much higher emissions of CO_2, but when incineration of biomass replaces a hydrocarbon source of fuel, CO_2 emissions can be reduced overall. The cement industry uses large amounts of coal every year and emits huge amounts of CO_2. The coal is used to burn limestone ($CaCO_3$) to calcium oxide (CaO). Both the combustion of coal and $CaCO_3$ release CO_2, but renewable sources of energy cannot currently be used during the combustion process. Replacing coal with biomass is an option however and is an option being explored by a cement manufacturer in Norway (see Case Study 4).

Case Study 4 – Norcem AS

Norcem is one of the world's largest manufacturers of building materials, including cement. Norcem is a good example of a company considering circularity as part of its core business. Cement is a notoriously "dirty" industry, burning large amounts of coal and emitting large amounts of CO_2. Since 1996, Norcem has reduced the percentage of coal used to power Kjøpsvik cement plant from over 95% to just over 50% in 2022. Located in Norway, Kjøpsvik is the northernmost cement plant in the world, and this presents unique challenges including high transport costs for fuels. The plant is located in a region rich in aquaculture farms and routinely uses aquaculture sludge as a fuel source for cement production. During the calcination stage, the dried sludge is used alongside coal and other alternative fuels including used tires, municipal waste, and spoiled fish feed. The plant routinely receives sludge from a number of different farms and is upgrading onsite facilities to accommodate tankers of sludge rather than the current supply in big bags. Sludge and animal meal combined make up 2.000 tonnes of fuel used in the plant each year, and it is hoped this can be increased to 10.000 tonnes of fish sludge in the future.

Sludge is not the perfect fuel source for cement production, and whilst it could replace large volumes of coal, running a plant entirely on fish sludge is unlikely, even if a sufficient supply could be guaranteed. The phosphorus content of the sludge can result in high levels of phosphorus pentoxide (P2O5) and high nitrogen levels can increase NOx emissions that may require additional processing, whilst the chlorine content, especially in marine sludge, can present an issue. Removing phosphorous and nitrogen from the sludge can reduce the issue and allow for larger percentages to be used. Despite these issues, the plant hopes to use large amounts of sludge in the future and sees both environmental and economic benefits in reducing coal usage and replacing it with locally sourced fuel. Should the 10.000-tonne target be met, this would remove the need to burn around 5.000 tonnes of coal. The carbon present in fish sludge was sequestered from the atmosphere and it is therefore a carbon-neutral fuel. Coal (fly) ashes are often added to cement to increase the strength and durability of concrete and the ashes from the burning of the fish sludge can also be used for this purpose.

Norcem AS Kjøpsvik cement plant



Overview of cement burning process – Sludge can be used in the calcinator

5.2.3. Insects

There is growing interest in the use of insect meal as a feed ingredient in agriculture and as a replacement for fish meal in aquaculture. However, despite investment, by 2019 only 6.000 tonnes of insect meal were produced in the EU (Alfiko et al., 2022). There is therefore a limited market for insect feeds. Production is expected to increase and by 2030 an estimated 200.000 tonnes will be used in aquafeed. This is still <1% of fishmeal in the global aquafeed market (FAO, 2022). Insect meal has been included in commercial aquafeeds but issues including off-flavours, waxy consistency, nutrient profile, and price are hurdles in its replacement of fish meal.

Insects in the EU cannot be fed any organic waste products, animal by-products, or manure/sludge (EU 2017/893). This rules out feeding fish sludge or mortalities to insects to make insect meal. Concerns also remain over the bioaccumulation of heavy metals when fed aquaculture sludge. Should these issues be resolved then feeding sludge to insects would go a long way in reducing the emissions from aquaculture sludge and increasing the circularity of the industry.

5.2.4. Costs and benefits of sludge drying

In the above sections, we have talked about the various valorisation options for aquaculture sludge. The options available depend largely on how dry the sludge is (percentage of TS). Dewatering and drying the sludge requires additional processing and this can be energy intensive, depending on the methods employed. The drier the sludge, the larger the CAPEX and OPEX. However, transport constitutes a considerable cost when the sludge has a large moisture content, and this can exceed the costs of buying and operating drying systems. If a farmer is paying to dispose of the sludge, reducing the total volume of the sludge reduces the total cost. At higher moisture levels, run-off increases if used as fertiliser, and biogas production and pyrolysis become more difficult and expensive. When sludge is dried to 90%, it is hygienised, its storage capacity is increased and new valorisation streams can open up, such as food for insect larvae and bioenergy in industries such as cement production. Figure 13 summarises the relationship between transport and drying costs and the level of dryness required for various valorisation options.

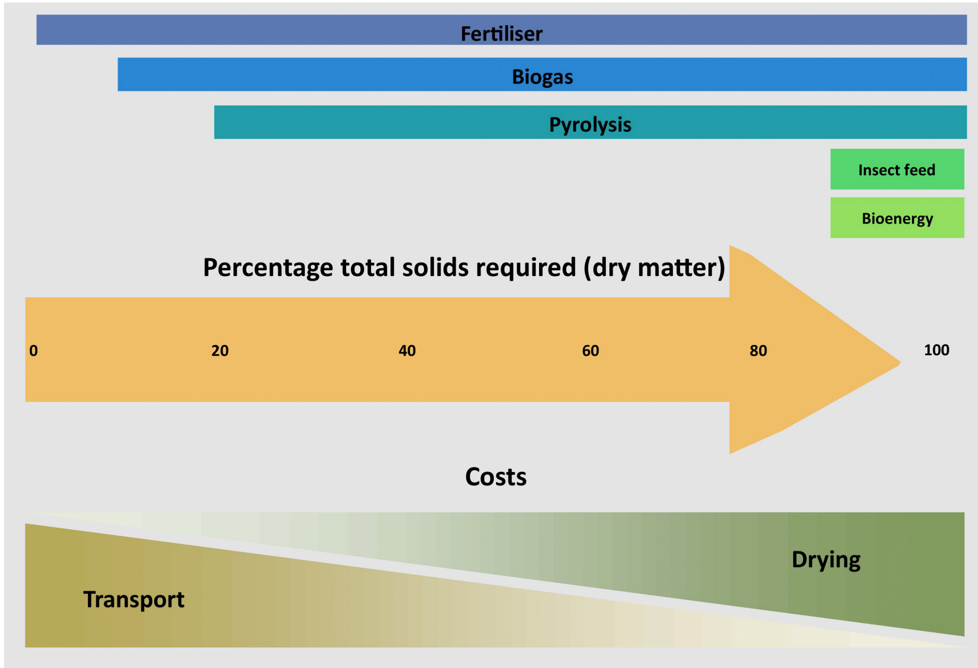


Figure 13. Reuse options for land-based aquaculture sludge and the level of drying required

Case Study 5 – Alternative drying solutions

Various methods of drying aquaculture sludge are commercially available. In earlier case studies we have mentioned mechanical drying such as belt dryers. These can dry sludge to >90%, and when using heat capture this can be achieved with relatively low power consumption. Alternatives to this technology include heat pumps, thermo-mechanical drying, and superheated steam. (This is discussed in the mortalities section.)

Fjell Technology Group AS offers solutions for sludge thickening, dewatering, and drying. A combination of band thickeners and bespoke polymers can effectively capture and thicken suspended solids. Electrocoagulation is installed in two facilities and work is being undertaken to further refine the technology. Decanter centrifuges dewater the sludge before the 20–25% TS sludge is pumped into the drying unit. The patented thermo-mechanical dryer is a type of hammer mill that uses friction to dry the sludge and produces a hygienised and stabilised sludge between 92 and 95% TS. The rotor spins at 600–720 rpm and the internal friction of the materials generates temperatures of 105–120 °C. Fjell reports significant savings compared to the disposal of wet sludge despite the increased energy costs of drying compared to wet disposal. The dry sludge is in the form of a fine powder, and this can improve its use for industries such as fertiliser. Turbo disc dryers are also available, and these use a steam-heated disc to apply indirect heat over a large surface area.

Drying Matter AS use heat pump technology to dry sludge from 15–40% dry matter and up to 95%. Dry and slightly heated air generated using the heat pump flows over the sludge and becomes saturated with water. The cooling side of the heat pump condenses the water, which is drained away. The de-watered air then flows back over the heating element and the cycle begins again. Low temperatures (50–80 °C) and the recycling of air within the system reduce odour from the unit and eliminates emissions. Energy consumption can be as low as 0,3 kWh per litre of water removed. The residency time in the dryer is 60 to 90 minutes, thereby ensuring hygienisation, and the product is a dry sludge of a consistent size. For processes where an external heat source is available, Drying Matter AS has a product range allowing for the substitution of internal heat pumps or a hybrid energy mix using both heat pumps and external sources. A medium-sized unit can process 12 tonnes of mechanically dewatered sludge per day, producing three tonnes of dried sludge. Parallel lines can easily be added if a larger capacity is required.

The Thermo-mechanical Dryer offered by Fjell Technology

A Drying Matter heat pump sludge dryer

5.2.5. Saline sludge

Valorisation options for sludge from marine or brackish aquaculture systems are limited. Production of biogas from saline sludge presents additional challenges with the levels of sodium inhibiting bacterial biogas production (Letelier-Gordo et al., 2020). Dilution of saline sludge with fresh water (Gebauer, 2004) and ultrasonication (Luo et al., 2015) can improve biogas production, although these increase the cost and/or complexity of sludge processing compared to freshwater sludge. Research is being undertaken into developing microbial strains capable of producing biogas in saline conditions, and pilot trials have been promising, but the commercial application of this technology has yet to be shown. Companies are working on alternative methods of sludge dewatering; however, these are currently not commercially available. Even in large biogas facilities, where saline sludge will make up a small part of the wider biomass, the salinity can still cause issues with microbial activity. Pyrolysis to produce bio-oil or syngas is one option, whilst using polychaetes to remove organic material and produce biomass has also been suggested (Gómez et al., 2019). These polychaetes could then be used as feed for aquaculture or in limited cases as bait for fishing. The commercial application of this process has not been demonstrated and the economy of this process remains unknown. Drying the sludge may increase its usability with drying, thought to decrease the salinity of the sludge. A major source of solids is the drum filter, and backwashing with fresh water also produces less-saline sludge but at the cost of added water usage and system complexity. It may be possible to use the sludge to fertilise halophyte plants, which can in turn be used as fodder for livestock. If using freshwater in the backwash or to clean the sludge is not possible, then the simplest option probably remains the combustion of the sludge as a source of energy. In this case, the sludge will be dried like freshwater sludge and transported to an incineration plant for the production of bioenergy.

5.3. Discharge water

5.3.1. Treatment of discharge water

Mechanical filtration does not remove all the suspended and dissolved components that decrease water quality and therefore additional methods of removal are often required. These techniques are routinely applied in RAS, and in addition to ensuring that system water is adequately clean, they also remove compounds that would otherwise be discharged in the wastewater. These approaches are less common in other forms of aquaculture although biological filters are sometimes used alongside raceway aquaculture.

Adsorptive bubble separation (ABS) methods are designed to remove particles, oil and grease from the water and lower biochemical oxygen demand. All floatation methods are based on the principle of separating the particles from the water by making them attach to small air bubbles that rise through a water column to the surface where the accumulated sludge can be removed by various methods. According to Lekang et al. (2007), floatation systems can be divided into groups based on how the bubbles are generated. One classification defines the methods as either mechanical floatation or dissolved air floatation. Mechanical floatation includes dispersed air floatation, induced air floatation and air floatation.

Protein skimming (foam fractionation) is an example of a mechanical ABS technique. Here, foam is created by the mechanical mixing of air and water. The organic material is captured by the foam and removed from the rest of the water on the top of the water column. Lipids, fats and other types of proteins can be removed via foam fractionation. In a protein, skimmer water trickles through a media-filled chamber where bubbles are formed. Hydrophobic long-chain peptides attach to the bubbles via surface tension and can be removed in a form of foam.

Dissolved Air Floatation (DAF) is performed using a pressurised air-in-water solution made possible by injecting air under pressure into the DAF effluent stream (Figure 14). The DAF effluent comes out as microbubbles that attach to the contaminants in the wastewater. The bubbles rise to the surface together with the contaminants and are removed by a surface skimmer. The main difference between protein skimmers and DAF is that in DAF smaller bubbles (more efficient) are created by using pressurised air.

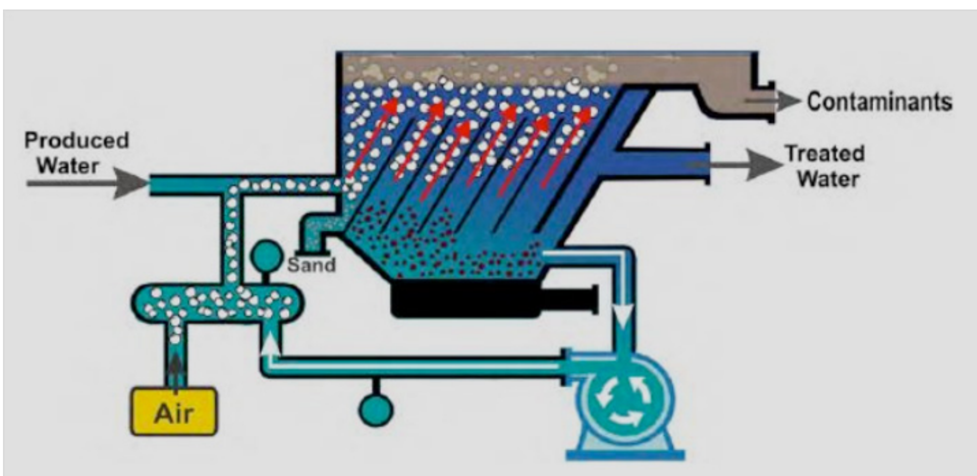


Figure 14. Illustration of DAF process, taken from Ebrahiem et al., 2021

These technologies effectively remove unwanted particles from system water but can produce large amounts of protein-rich foam. Little attention has been paid to limiting the emission of this foam into the environment. The foam is difficult to handle in any meaningful volume and the amount of any valorisable components is low compared to the volume of the foam. In practice, the foam is often mixed with other sludge, dissolved in wastewater and disposed of through drainage systems, or allowed to discharge free into the local environment.

Membrane filtration is a mechanical filter that separates particles and molecules from water. The membrane is semi-permeable and holds back larger particles whilst allowing smaller molecules to go through by adding pressure. There are three main types of membrane filtration:

- *Microfiltration* - Membrane pore size ranges from 0,1 to 10 µm. Such membranes are mainly used for the removal of larger particles, but bacteria, algae and fungi can also be removed by this technique.
- *Ultrafiltration* – Membrane pore size ranges from 0,01 to 1 µm. The smallest pore sizes will filter out bacteria, viruses, algae, fungi, and polypeptides. This technique is widely used in wastewater treatments.
- *Nanofiltration* – Membrane pore size ranges from 1 to 10 nm. Typical applications for nanofiltration may include the removal of colour and total organic carbon (TOC) from surface water and the removal of hardness from well water. Nanofiltration removes all of the above-mentioned agents plus some multivalent ions.

Higher degrees of filtration result in increased head loss and therefore increase pumping costs. Filtration is more typical on inlet water to ensure that system water quality is guaranteed. Some countries have strict requirements as to the size of particles that can be discharged from the RAS.

Nitrification and denitrification are used in RAS for the management of dissolved compounds. As mentioned in Section 4.1., biofilters are used to convert ammonia nitrogen to less harmful forms. Ammonia nitrogen is present in two forms: ammonia (NH_3) and ammonium (NH_4^+), which are measured as a whole and reported as total ammonia nitrogen (TAN). These two forms of ammonia exist in equilibrium and the ratio of the two changes with increasing temperature and pH favouring NH_3 over NH_4^+. Removing one form of ammonia reduces the TAN and the other form as a result. NH_3 is highly toxic to fish but is not actively removed from the system in this form. Instead, the less toxic form, $NH4^+$, is removed and this, in turn, reduces NH_3. NH_4^+ can be removed from the water by ion exchange, or more typically, biofiltration. During biofiltration, ammonium is oxidised to nitrite (NO_2^-). This form of nitrogen is somewhat toxic to fish, but it undergoes further oxidation to the much less toxic nitrate (NO_{3-}). This is often a two-step process involving multiple different microorganisms, although complete conversion to nitrate by single organisms can also occur. The interaction between different microorganisms means that this is one of the most sensitive parts of a RAS, and variations in temperature, pH, oxygen, salinity, alkalinity, pollutants, stocking density, and feed rate can all impact the microbial community present in the filter. Should the filter undergo a microbial crash, it will be unable to process the ammonia present, which can result in catastrophic losses of fish. This presents one of the major downsides of RAS that other forms of aquaculture avoid.

Various types of nitrification filters exist, including those with a fixed medium (trickling, submerged up-flowing, and up-flowing), rotating biofilters, and fluidized or moving bed reactors, which are becoming increasingly popular. All these systems have their advantages and disadvantages, but care must be taken when operating each one to ensure the microbial community can handle the levels of TAN present.

Nitrate is less toxic than nitrite or ammonia, but it can cause fish health and performance issues should it be allowed to concentrate. Nitrate can be removed from system water through water replacements and nitrate levels are often a major reason a specific farm operates at a selected recirculation or replacement ratio. Nitrate can also be removed using a denitrification reactor. Unlike nitrification

reactors, denitrification reactors are anaerobic, which comes with additional costs and complexities. A benefit of using these reactors is that very high recirculation levels can be employed without the risks associated with nitrate buildup.
Denitrification uses a two-step microbial process and requires a carbon source, often methanol, ethanol, or sugar, although solids from mechanical filtration have been used with some success. The main products of denitrification are nitrogen gas (N_2), CO_2, and H_2O. The greenhouse gas N_2O is an intermediary of the denitrification process and can also be emitted.

Degassing systems (Figure 15) may be employed to remove dissolved compounds such as nitrogen gas and CO_2. This process involves improving the contact of water with air to encourage the evaporation of dissolved gases. Increasing the surface area of the water and the contact time with air can be achieved through a variety of methods including stripping towers, surface aerators, and defused aerators. The design and size of degassing systems will depend on the size and stocking density of the farm. Good aeration above the degassing tower is suggested, whilst the gas can also be piped outside of the facility.
Due to these additional steps to improve water quality, in RAS a much smaller percentage of the nutrients put into the system as feed is emitted into the environment in the discharge water. However, as much less water is discharged compared to flow-through or partially recirculating raceways, the concentration of nutrients in the water is often higher and therefore methods to mitigate the potential harm of these compounds are often required.

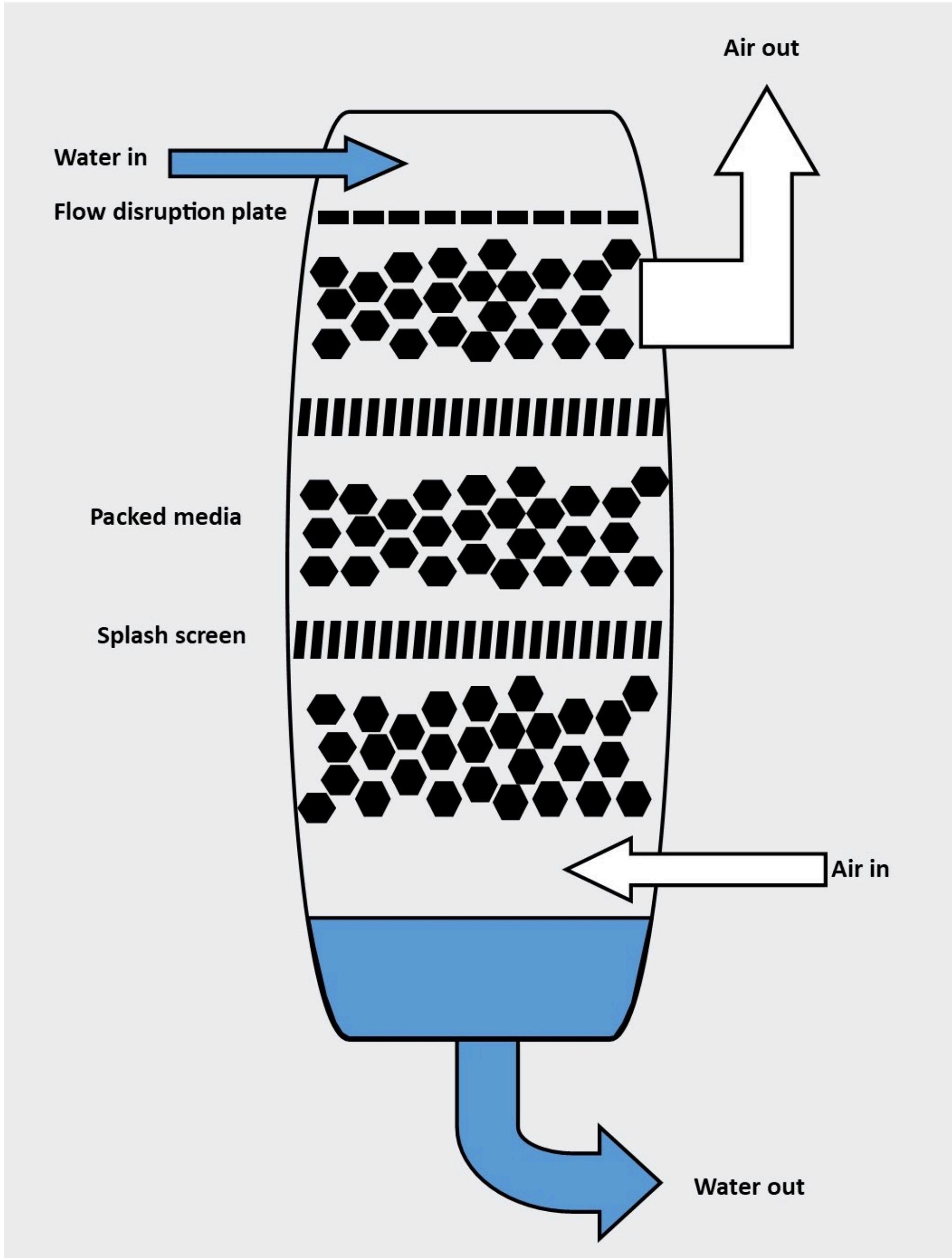


Figure 15. Diagram of a packed media degassing tower

5.4. Reuse of discharge water

5.4.1. Wetlands

The construction of wetlands may be used for the treatment of aquaculture effluent water, although they pose several challenges. Constructed wetlands can remove a range of contaminants such as organic and inorganic matter, pathogens, pharmaceuticals, and nutrients including phosphorus, ammonium, nitrate, nitrite, particulates, and heavy metals. The removal of these contaminants is unstructured and relies on physical (filtration, sedimentation, adsorption, and volatilisation), chemical (precipitation, adsorption, degradation) and biological (plant metabolism, microbial interactions, and natural die-off) mechanisms (Tepe and Temel, 2018). Constructed wetlands require a large area (Tom et al., 2021), and whilst particulate nutrient removal by sedimentation happens quickly, the removal of dissolved nutrients can be slow. Wetlands have been shown to effectively remove nitrites but there is evidence that TAN and phosphorus removal can be limited (Martins et al., 2010). These nutrients become incorporated into the natural wetland growth cycle (Dalsgaard et al., 2021), and their effluent from the system varies over the year. Wetlands must be maintained to ensure that accumulated nutrients are not re-released during plant decomposition, which requires the active removal of dead and withered plants. Nitrate removal is thought to be limited by the availability of carbon, and sludge or other carbon sources can be added to the wetland to improve denitrification (von Ahnen et al., 2020). Woodchip biofilters can be used in conjunction with wetlands to increase the removal of nitrate. These biofilters consist of large trenches filled with woodchips, sometimes covering several thousand cubic metres.

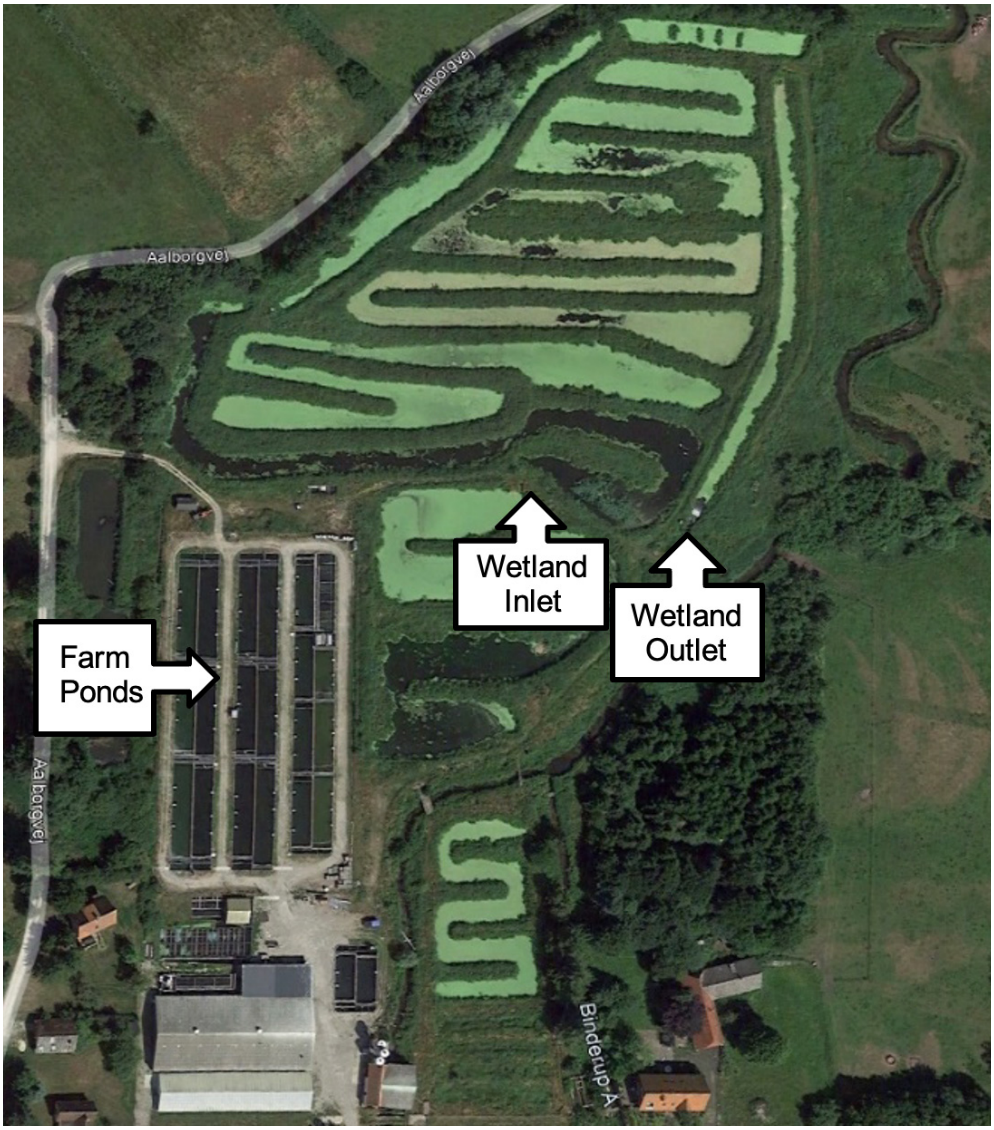


Figure 16. Model trout farm and constructed wetland near Aalborg, Denmark. Google Earth

The long residence time and anoxic conditions allow denitrifying bacteria to flourish, and the woodchips, whilst also slowing the water, are a necessary source of carbon for the bacteria. These systems can remove around 2 kg/m3/year of total nitrogen and can be scaled up or down easily. Hydraulic retention time is the most important characteristic influencing the denitrification rate. Tree species can impact nitrate removal and a species with a high carbon/nitrogen ratio should be used for bacteria to flourish; the woodchips, whilst also slowing the water, are a necessary source of carbon for the bacteria. These systems can remove around 2 kg/m3/year of total nitrogen and can easily be scaled up or down. Hydraulic retention time is the most important characteristic influencing the denitrification rate. Tree species can impact nitrate removal and a species with a high carbon/nitrogen ratio should be used.

If large areas of land are available, then wetlands and woodchip filters present a cheap method of emission reduction. Wetlands have been used regularly in Danish trout production to process discharge water, and building wetlands has been a way to increase the amount of feed input permissible, although this restriction has now been changed to target emissions rather than inputs. These trout farms often employ high levels of recirculation and use wetlands to treat the water. Production volumes are, however, relatively low, and using wetlands to process the water from large, high-density RAS facilities presents a different scenario. Very large areas of land would be needed and effluent from the wetland could still contain regulated amounts of nutrients. All but the least intensive farms that use wetlands employ the use of mechanical filtration, sludge cones, and biofilters to clean discharge water before expulsion into the wetland. As mentioned in the legislation section, Danish BAT-focused legislation has contributed heavily to the state of the Danish aquaculture industry. Regulations on the discharge of nutrients into the environment coupled with advances in recirculating technology have physically changed the layout of trout farms over the years. An example of this can be found in Appendix 2. Figure 16 shows the layout of a Danish trout wetland. Saline effluent can also be treated in a wetland system with certain species of halophyte plants showing high nitrogen removal efficiency (Webb et al., 2012; Diaz et al., 2020). The AquaCombine project is experimenting with growing Salicornia, in saline effluent from aquaculture, whilst also using the part of the plant not consumed by humans in feed for European seabass. Other halophyte plants can also be grown, increasing the economic viability of using this method of waste processing across multiple farm sites.

5.4.2. Fertigation

Solids removal and flocculation can remove most suspended and some dissolved nutrients from the water in a RAS facility. However, the discharge water still often contains a reasonably high concentration of dissolved nutrients. This is especially the case if denitrification has not been used.

There are several available techniques to reuse the dissolved nutrients in the discharge water. One such method is fertigation. Fertigation is the practice of applying fertiliser solutions with irrigation water (Incrocci et al., 2017). Fertigation, especially when coupled with precise irrigation practices such as injection, can reduce fertiliser waste, increase nutrient use efficiency, and increase yields compared to traditional fertilisation and irrigation, (Incrocci et al., 2017). Emissions of nutrients through run-off and as gases will still occur when fertigating but these are smaller than those from fertilisation through normal methods. Another benefit of fertigation using aquaculture discharge water is that usage of fresh water in the region will be reduced, as will the use of fertilisers, which can have environmental impacts both in their use and production.

Fertigation using aquaculture effluent is a recent concept and one which has not been explored in detail. What evidence there is suggests that at least for specific crops (tomatoes and cucumbers) the effluent water from aquaculture (tilapia and barramundi) can provide sufficient nutrients to produce desirable crop yields (Groenveld et al., 2019; Pattillo et al., 2020; Ayipio, 2021). This de-coupled aquaponics allows for the nutritional resources present in aquaculture effluent to be used without dramatically increasing the complexity of farming operations. Fish farmers can focus on growing fish and nearby agricultural farmers can focus on growing crops. The amount of effluent water is a consideration, as is the fact that crops grown outside are not actively watered for large portions of the year. Fertilisation is also not consistent year-round and policies to only fertilise when needed are in place in many Nordic countries. Fertigation is therefore not a process suitable for all crop types, and farmers of high-value crops such as berries or those operating greenhouses are the most likely to use fertigation. For fertigation to be economically feasible, fish farms and agricultural farms must be close enough that effluent water can be piped across. This is not an option for all Nordic farmers, but for those with agricultural farms in proximity, it could be an effective way to reduce emissions for both farmers. This is unlikely to be a solution for saline discharge water.

5.4.3. Algae

An alternative is to cultivate microalgae. Microalgae can use the nutrients present in the effluent and carbon dioxide from the atmosphere to proliferate, generating valuable biomass. Aquaculture discharge water has been shown to stimulate good algal growth with no additional nutrients required. In some cases, growth was better than with an artificial growth medium, although pH regulation may be required (Lugo et al., 2020). The majority of nitrogen present in the discharge water is assimilated by the algae rather than being converted to emissions such as N_2O. Algae grown from aquaculture discharge water are efficient removers of nutrients (Lugo et al., 2020) and have been shown to have a good content of fatty acids (EPA and DHA) and tocopherols (Tossavainen et al., 2019). Further use as a bio-stimulant, fertiliser, and bioenergy source is also possible (Viegas et al., 2021). Growing algae from aquaculture discharge water effluent is theoretically a model case of circularity, reducing the effluent of nutrients by reusing them to grow algae, which can in turn be used to feed fish. The logistics of such a system are, however, challenging. Algae are already being used on a commercial scale in urban discharge water remediation with biomass being used for biomethane, lipid products and biofertiliser. In this case, an algal pond of about 1 ha was needed to treat 1000 m^3/day (All-Gas, Aqualia).

The amount of biomass growth potential and the design of the algal system determine the size required, and this method of wastewater treatment can take up very large areas of space. Egloff et al. (2018) showed the potential of algal treatment using a thin-layer photobioreactor. They calculated that for fish fed a diet containing 35% protein, 1 m^2 of bioreactor surface would be needed to treat every 46 g of feed entering the system per day. Therefore, even at low stocking densities (50 kg fish per m^3), using the thin-layer photobioreactor would occupy 6,5 times the area of the aquaculture facility. Kjos-Hanssen (2021) suggested that an RAS plant producing just 219 tonnes of salmon per year and discharging 900 m^3/day would require a rotating algal biofilm with a surface area of 1 ha (10.000 m^2). This is similar to that of the urban discharge water algal pond. However, due to the biofilm being present on a rotating belt, the footprint of the unit would be between 900 and 1.200 m^2 (0,09-0,12 ha). A similar area of stacked raceway ponds is being used by a Swedish company to grow algae on the discharge water from a nearby salmon RAS facility. The species of microalgae used in this facility have shells consisting of silicon dioxide, which can be used in a variety of products from face creams to solar panels and battery production. Production of high-value algae may be a way to valorise aquaculture discharge water, but using this technique on a scale that can process all the discharge water from a large RAS facility poses a bigger challenge. Light availability during winter presents a further issue in the production of algae in Nordic aquaculture. LED lights are often used to provide the algae with sufficient light at the correct wavelengths, but this increases the cost of the operation. Using marine algae to process saline is a less researched area, but studies suggest that marine algae can grow effectively on saline discharge water and be used to recycle nutrients, although some additional vitamins may be required to facilitate growth (Villar-Navarro Elena et al., 2021). The same restrictions apply for saline discharge water although the costs are likely to be higher.

5.4.4. Heat/energy recovery

Nutrients are not the only resources emitted with RAS discharge water. Both heat and physical energy are often present. Heat exchangers are not a new concept, but they should not be overlooked. If intake water differs from efflux water by even a couple of degrees, the heating or chilling costs will be significant. This temperature differential can be reduced by using a heat exchanger cooling or heating the intake water as required, therefore saving money and likely fossil fuel usage. Heated effluent also poses a risk to the local environment, disrupting local ecosystems. Minimising this impact on the local environment is important for the sustainability of on-land systems. Local limits can require that the effluent does not change the temperature of the water body by as little as 2 °C. Heat exchangers are available from a large number of suppliers and the cost varies depending on factors such as difference in temperature between water sources, temperature increase or decrease desired, acceptable head loss, space available, water quality and salinity. Salt or brackish water requires a heat exchanger with titanium-covered plates, which are much more expensive than stainless steel plates. Fouling is a particular issue when using effluent water and this can not only reduce the efficiency of the unit but also be a refuge for geosmin-producing bacteria. Chemicals can be used to clean biofouling from the system, and care should be taken to ensure they do not enter system water. Technology to reduce fouling is improving constantly, but the potential economic impact of introducing additional maintenance to a RAS facility should be considered against the benefits of capturing the heat present in the effluent water. Heat pumps can be used to transfer large amounts of thermal energy from the effluent water when the temperature increase is quite low. These require an external source of power (electricity) and use refrigerants. Ammonia is often used as a refrigerant, but because it is highly toxic to fish and humans, leaks must be avoided. In recent years, heat pumps have become popular in various industries and can be sourced from a variety of manufacturers.

Depending on the layout of the farm, it may be worthwhile installing mechanisms to capture physical energy. This would be of use if there were a significant hydraulic head between the fish farm and the influx/efflux water course. Farm layout would determine if the capture of effluent energy would be economically viable, but the amount of energy possible to generate can be fairly large, especially in flow-through systems. This is not a common component of a RAS facility but highlights how each farm's unique characteristics should be considered when trying to maximise environmental and economic savings. One survey respondent reported generating 1.5 megawatts/year from intake water using a turbine.

5.4.5. Chemical discharges

An advantage of land-based aquaculture farms is the level of control over inputs into the farm. Disinfection of input water is less common in flow-through or pond aquaculture but is standard in RAS. Disinfection through filtration, UV, or sometimes ozone helps prevent pathogens from entering the system. This in turn reduces the need for antibiotics or therapeutants to treat fish. Vaccination is also commonplace, and the use of oil-based vaccines has led to a 99% decrease in antibiotic use in the Norwegian aquaculture industry since the 1990s (Afewerki et al., 2022).

When disease does enter RAS, rapid treatment is key to ensuring the health of the stocked animals. Antibiotics are still used on occasion, whilst therapeutants such as hydrogen peroxide or formalin are more common. These chemicals can have effects both once discharged and within the system. Biofilter microbial communities are sensitive and too large an input of formalin can negatively affect performance. Low doses are tolerable and the biofilter will also remove formaldehyde, which can prevent too large a concentration from being discharged into the environment (Pedersen et al., 2010). Antibiotics by their design can have a large effect on biofilters, and this is an important consideration before their use in RAS.

Treatment with antibiotics should be minimised, especially with concerns growing over the prevalence of antibiotic-resistant bacteria. Li et al. (2017) found that biofilms can be reservoirs for antibiotic resistance genes, suggesting a need for discharge water sterilisation in these cases. Bath treatments of antibiotics are inefficient and should only be used if fish will not consume the medicated feed. Regardless of the treatment, treating affected fish “off-line” in tanks or vats prevents biofilter failure but also gives the option to dispose of treatment water differently than standard discharge water, should local regulations require.

Antibiotics can be removed from discharge water using biological methods such as filtration with biologically activated carbon, or anaerobic digestion, filtration such as nanofiltration, or reverse osmosis can also achieve good removal. Coagulation/flocculation such as in sludge collection do little to remove antibiotics from the water, nor do wetlands (de Ilurdoz et al., 2022).

5.5. Mortalities

Mortalities are an unfortunate reality on all fish farms. All farmers strive to minimise fish losses, but a large number of factors can lead to mortalities, including disease, technical failure, adverse weather, genetics, and mismanagement. A recent study found that hatcheries in Norway had a median monthly percentage of mortalities ranging from 0,15 to 0,31 depending on size class (Gåsnes Siri et al., 2021). This can represent a significant number of fish that need to be disposed of quickly, safely, and securely. The majority of fish mortalities will be classified as Category 2 waste, restricting their use according to EU legislation (EC Regulation No. 1069/2009). Disposal was previously allowed via incineration, post-pressure sterilisation to landfill, and ensiling. In 2009, ensiled mortalities were allowed for reuse, but this reuse was limited to bioenergy production, technical applications, fertiliser, and feed for animals raised for fur, zoo and circus animals, and other non-food-producing animals. The use of fertiliser as a means of Category 2 disposal has now been removed by the recently implemented EU Regulation No. 2019/1009, but the other reuse options remain permitted.

5.5.1. Ensiling

Ensiling remains far and away the most common method for processing mortalities from aquaculture facilities. Ensiling involves the use of acid (typically formic acid) to preserve raw materials and prevent spoilage (Peñarubia et al., 2020). To produce silage, mortalities are ground and an acid with a pH ≤4 (EFSA Scientific Panel on Biological Hazards 2011) is added to inactivate bacteria that otherwise may proliferate and spoil the product. Hydrolysis enzymes, mainly present in the digestive system of the fish, break down the fish waste into a mix of hydrolysed proteins, lipids, minerals, and nutrients. The viscera should be included to ensure hydrolysis can take place, although exogenous enzymes can also be added (Peñarubia et al., 2020). Incubation time should be at least a few days before the second stage of treatment, but in colder climates, full hydrolysis can take weeks (Peñarubia et al., 2020). Mature fish silage can be stored for several years (Toppe et al., 2018). Fish silage can be used without further processing as agricultural animal feed. It can also be turned into feed pellets for a variety of species, the hydrolysed proteins being highly digestible (Toppe et al., 2018).

Protein isolates and oil can be produced through the processing of hydrolysed silage. They can be used as an ingredient in animal feeds, although the use of these feeds is restricted to fur animals, zoo animals, or dogs and cats in shelters, due to the origin of the silage. To ensure sterilisation and stability, products are heated to >85 °C for >25 minutes. Very large numbers of mortalities could be processed this way, but demand for such products is a major obstacle. Previous examples of products made for this market exist, but there is no longer much interest in protein isolate or food oils from Category 2 waste. Fur animals are a shrinking market, and fur producers are known to pay a premium for high-quality feed seeking improved fur quality (Reid and Ulrich, 2018) and are therefore unlikely to prioritise ensiled mortalities as a source of protein. The emissions from mortalities are reduced by using these methods of processing, instead turning into resources used to grow other animals.

Biofuels, such as biogas and bio-oil, can be produced using mortalities as feedstock. Bio-oil may have various applications, including use in the leather industry. For biogas production, Category 2 waste must be heated to >133 °C for >20 minutes (Ward and Løes, 2011), with the waste being transported to third-party biogas plants. Biogas plants are reportedly receptive to the use of aquaculture mortalities as their high-fat content makes a good biogas feedstock. Biogas produces CO_2 and methane, which are greenhouse gases, but this method of energy production is considered carbon neutral as the carbon was sequestered from the atmosphere initially.

Biodiesel, may be considered as a carbon neutral alternative to fossil fuels, as can biogas. Biodiesel can be produced through a variety of methods including microwave-assisted-lipid extraction, transesterification, and rendering. The resultant product can replace traditional diesel, and aquaculture waste biodiesel has been used in several countries to power buses and boats. Biodiesel is less toxic than traditional diesel, and with a higher flashpoint, is less hazardous to handle.

The volume of biodiesel that the mortalities from a single farm will produce is limited, but central biodiesel plants, in particular those that also incorporate waste from processing plants, could be a viable option. A plant of this nature is being used in the Åland Islands and until recently was used to power the public transport in the capital, Mariehamn (see Case Study 6). Whilst the production process is energy intensive, biodiesel can be used to run the machinery, and the process can become self-sustaining (Yuvaraj et al., 2019). One downside of biodiesel is the high nitrogen oxide emissions. Engine compatibility and increased engine wear are also considerations.

Case Study 6 – The Åland Islands: biodiesel and waste reduction

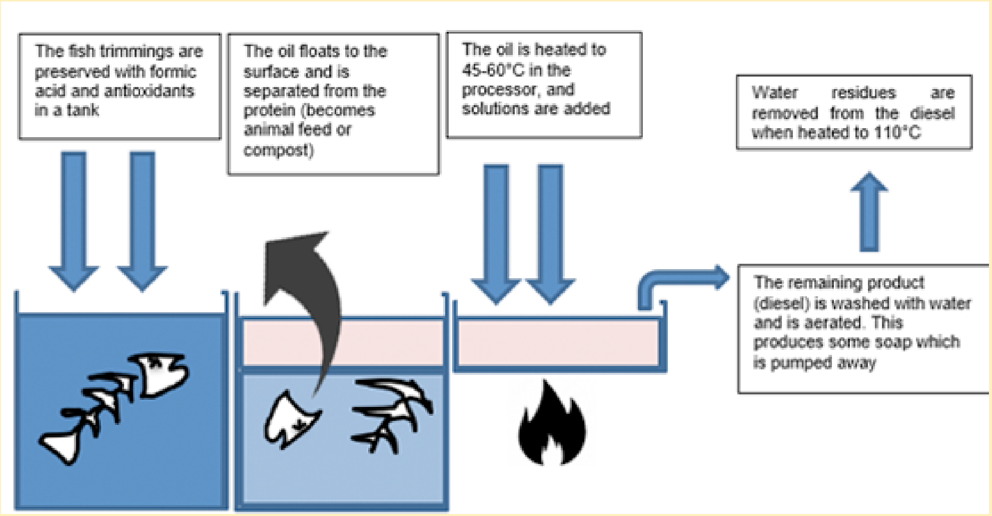
Historically, the region's aquaculture production has been involved in several initiatives that together minimise environmental impacts, such as AQAFIMA, AQUABEST and HELCOM's Baltic Sea Action Program for the Baltic Sea aquaculture sector. The latter project focused on reducing the net load of waste inputs and creating a nutrient-neutral aquaculture sector using Baltic raw material in fish feed for fish. These initiatives complement Åland's Environmental Law and Water Law.

Despite the widespread acknowledgement of the issues, consensus to resolve them, and resultant policies and action programmes, the most recent 2021 review observed that targets have generally not been achieved as envisioned and that the Baltic Sea is still heavily affected by multiple pressures caused by human activities (HELCOM, 2021). According to Åland Environmental and Health Protection Authority, the biggest concern is the excessive emission of nutrients to water. Though cognisant of and potentially regulated by BAT, cage farms have as yet made no efforts to move towards land-based operations where effluent is more easily monitored and controlled. This reticence is due to market forces: there is no premium or value added for RAS produced fish and the competition from Norwegian cage farms is considerable. The only RAS producer in the region has yet to make a profit. Nevertheless, this and another aquaculture producer are pursuing innovative steps to reduce their waste production.

Storfjärdens fisk process their rainbow trout and were aware that the fish oil from the trimmings was a potential commodity, so they began investigating how to make biodiesel from it in 2009. The technology is simple and had existed for decades; fish oil has been used as a fuel for boats in the past. The company invested in a processor for refining the oil, and from this design built a second one themselves.

The plant can produce approximately 400 litres of fish biodiesel a day. In a year, the plant can turn 15–20 m^3 of fish oil into biodiesel. The farm has been able to successfully use this in its own operations and in the public transport system in Mariehamn, the nearest town (population 11.000). From 2013 until recently, the town ran all of its public transport vehicles solely on fish biodiesel. Sixten Sjöblom, the CEO of Storfjärdens fisk, estimates that it has reduced the farm's waste production by 45% and instead added value from a by-product.

Fifax Eckerö is the region's only RAS facility, with a capacity of 3200 tonnes of rainbow trout per year. Driven by the aforementioned concerns of eutrophication in the Baltic Sea, the RAS was designed to meet exceptionally high environmental standards. One of the issues with RAS is the buildup of nitrates and phosphates, which typically are removed by dilution – changing perhaps 10% of the water each day (see Section 4.2). Not only is this a waste of resources (particularly as the water will have to have been treated before and after use), but it is a source of waste. By designing specialist water treatment facilities, Fifax are able to reduce their wastewater to less than 1% of total volume; nitrogen and phosphorous emissions are a very small percentage compared with "traditional RAS".



Biodiesel production from fish trimmings

The leather industry is a potential source of demand for bio-oil. Oil is used in the leather industry to soften the leather and increase water resistance. The oils typically come from processed hydrocarbon oils. Using fish oil would both help reuse aquaculture mortalities and reduce the environmental impact of the leather industry. Fish oil produces a very good level of softness, but overall vegetable oil is considered a superior fatliquor (Reetz et al., 2012). Large volumes of oils are used in the leather industry worldwide and the price of processed fish oil for leather production is over $1000 a ton, making this a potentially attractive valorisation option. The reuse of fish oil reduces the potential emission from mortalities. Although only the lipid portion is used for this purpose, the remaining fraction must be processed or reused alternatively. Fatliqours from organic sources are sulfonated to increase the incorporation of the oil into the leather, which involves the use of sulphuric acid, but this treatment of organic oils is thought to present less environmental impact than the use of hydrocarbon oils.

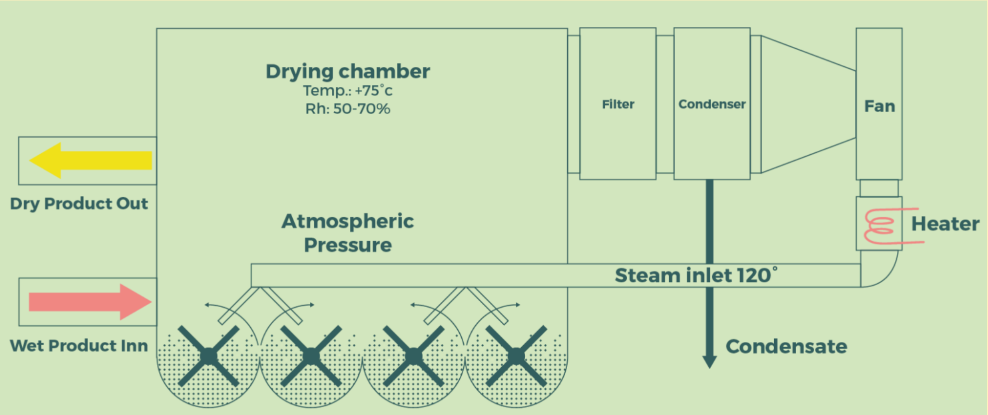
5.5.2. Drying

All the above-mentioned reuse options involve silage as the first processing step. Silage then requires transportation to third parties, which due to the liquid nature of the silage is a costly process. Silage is also a source of hazards, and some cases of fatal injury have been reported. Formic acid can cause chemical burns, is hazardous to the environment and releases nitrogen dioxide. Hazards of ensiling occur on the farm, on boats, and during the transport of ensiled products by road. The cost of ensiling is not insignificant, with the disposal of 20.000 kg of mortalities calculated to cost around €16.500 (Baarset & Johansen, 2019). Another potential avenue for mortalities is drying them. Although several companies offer units that are marketed for drying aquaculture sludge, options are more limited for mortalities. A more recent innovation for drying aquaculture mortalities uses superheated steam (see Case Study 7). Drying mortalities pose significantly fewer hazards than ensiling, and by reducing the water content of the fish, transport costs are significantly reduced. Cristiano et al. (2022) performed a life cycle assessment of potential uses for dried mortalities and traditional ensiling. Dried fish could be converted for bioenergy in industry, used as a substrate for biogas, and depending on legislation, used in pet food (something which is not currently allowed by EU legislation). If water is used for cooling the drying system, this can be reused to heat the RAS facility. The life cycle assessment included significant transport by road for all three valorisation options (bioenergy, biogas, and pet food) but still showed a significant reduction in emissions, resource use, and harm potential compared to ensilage. Water use increased slightly in most drying scenarios, but the increase was minimal compared to the benefits found in other areas. Tirano et al. (2021) showed that the profitability of using drying depends on the farm site. Drying mortality was compared to ensilage on typical cage-based grow-out farms in which ensilage is more automated and RAS smolt facilities where ensilage requires a larger degree of manual labour. On the grow-out farm, only using the dried mortalities for pet food resulted in a profit over ensilage. At the smolt facility, however, the cost of labour resulted in all downstream applications (biogas, bioenergy in the cement industry, and pet food) being over 0.4%/kg more profitable than ensilage. The evidence presented here suggests that compared to ensiling, drying mortality before secondary usage is better for the environment and potentially economically, cutting down on hazards onsite and reducing the cost of transportation for mortalities offsite.

Case Study 7 – Waister AS

Waister AS is based in Åslyveien, Norway, just 45 km from Oslo, and offers an alternative to traditional ensilage. Waister's patented drying technology turns mortalities and discarded fish into a dried and finely ground powder. This approach avoids the use of toxic chemicals such as formic acid and the downstream applications for the dried product range from fertiliser and biogas production to pet food. The €55.000 Waister 15 can process 500kg of mortalities per day in just 2,4 m^2. The company also produces sludge drying machines in a range of sizes, and these can be used to dry mortalities should the capacity of the Waister 15 be too low. Employees must fill the machine with fish, but the machine then operates self-sufficiently. Mortalities are dried using superheated steam and the heat can be reused within the system, resulting in energy consumption of ~0,35 kWh per kg of water removed.

By drying, the weight and volume of the mortalities is reduced by 85% compared to ensilage, cutting down on transportation costs and gate fees at biogas plants. Current legislation preventing use as pet food means that biogas will remain the most likely source for dried mortalities. Drying using this method produces a sanitised and stable product. After six months at room temperature, samples still had no measurable bacteria (Enterobacteriaceae, Salmonella spp, sulphite-reducing clostridia). There has been some interest from pet food producers. However, it is not an option under current EU rules even after testing to ensure the product is disease free. Legislation not designed to fit aquaculture remains, in the eyes of Waister CEO Hallstein Baarset, the biggest challenge to the circular reuse of aquaculture waste products. However, he remains confident that, despite limited downstream application options, the economic, logistic, and safety benefits of drying waste make it the best option. Waister currently supplies mortality drying machines to farms in Croatia and Australia and has plans to build a Nordic demonstration plant in the near future.



The Waister Drying Technology

Waister 15 Mortality Dryer

5.6. Gas emissions

5.6.1. Carbon capture

Land-based aquaculture, whilst often considered the greener option compared to lake or sea-based production, often has increased emissions of greenhouse gases (GHGs) per kg of fish produced (Jones et al., 2022). For finfish aquaculture, no matter the system, much of the GHG emissions occur during the production of feed for fish (Liu et al., 2016). For recirculating land-based systems, electricity often becomes a major source of GHG emission due to the high energy demands of pumping, heating or cooling the water, and maintaining water quality (Liu et al., 2016). Emissions from feed production can be reduced by considering the source of ingredients in feed and using local sources to reduce transport-based emissions, RAS energy demands can be reduced through efficient design, minimising pumping and temperature control costs. The emissions associated with energy use on land can be reduced further through the use of renewable energy sources. There are still onsite options to reduce GHG emissions, and interest in novel methods of GHG reduction has grown in recent years. One option is to capture CO_2 released and reuse this resource. Carbon dioxide is a by-product of respiration in fish, and bacteria, and is excreted from the blood into the water over the gills (Skov, 2019). Of course, respiration occurs in traditional aquaculture, but in RAS this emission is stored in the system water before being emitted into the external atmosphere. This emission presents a capturable and useable resource, both posing the possibility of reducing the carbon emission of a RAS facility and presenting a source of valorisation.

Companies are testing the capture of CO_2 and its use in protein production. CO_2 can be captured by degassing or by using individually covered tanks. The CO_2 is then converted into protein using fermentation, where microbes in a bioreactor filled with an electrolyte solution turn CO_2 gas into protein using hydrogen (H2) as an energy source. A limitation of this process is that it needs the input of hydrogen and oxygen in addition to CO_2. Buying hydrogen for this process is far from economical. Electrolysis is the most effective method of hydrogen production, but it requires large amounts of energy, and for the process to be a viable reducer of carbon emissions, this energy needs to come from a renewable source.

If this can be achieved, then the CO_2 released by the RAS facility can be converted into a local and complete source of protein. The amount of CO_2 captured on a farm would produce a limited amount of protein compared to feed requirements, but CO_2 can also be used from other local industries and even seawater.

The product of this process is reported as having nutritional properties similar to fish meal (Table 8). This technology has the potential to reduce carbon emissions both by capturing CO_2 and by increasing self-sufficiency in feed production. Compared to protein production using traditional agriculture, this method uses considerably less water and land.

Nutrient	Profile
Protein	70-80%
Fibre	0-3%
Vitamins and minerals	<6%
Oils	3-4%
Amino acids	"Similar to fish meal"/"optimal"

Table 14. Typical reported nutritional profile of feed produced using microbial fermentation supplied with captured CO_2 to technology

This technology is still very much in the pilot stage, and it remains to be seen if capturing CO_2 in this manner would be economically viable. The disposal of sludge, discharge water, and mortalities are required and regulated facets of a fish farming operation. Because the processing of these waste streams is necessary, there is an incentive to valorise and reuse the waste. Gas emissions face no such restrictions and therefore there is less incentive to spend money reusing the emissions. The benefits of capturing the carbon would need to outweigh the cost of the capture, the capture would need to provide an economic benefit, or legislation would need to change to require the capture or reduction of CO_2 emissions. Aquaculture farms are not currently covered by the EU emissions trading system (ETS) but should this change, they would need to pay for all CO_2 released beyond a set threshold. The CO_2 permit costs reached a record high of almost €98 per tonne in August 2022. Including feed production and operational emissions, a salmon RAS facility will produce roughly seven tonnes CO_{2eq}/tonne of live weight (Liu et al., 2016).

5.6.2. N_2O reduction

A by-product of the nitrification and denitrification processes is nitrous oxide (N_2O) (Yogev et al., 2018). The emission of this greenhouse gas has received less focus than other sources of pollution. However, N_2O has a significant global warming potential (310x larger than CO_2 over a 100-year lifespan) (Hu et al., 2012). N_2O was shown to account for the emission of 1,23% of the total nitrogen application in a high-intensity brackish RAS facility (Yogev et al., 2018). Aside from improving water quality and effective solids removal before nitrification, anammox (anaerobic ammonium oxidation) enhancement may also decrease N_2O emissions (Yogev et al., 2018). Anammox is a microbial process that converts ammonium via nitrite to N2 gas, skipping the N_2O production of typical nitrification-denitrification processes (Figure 17).

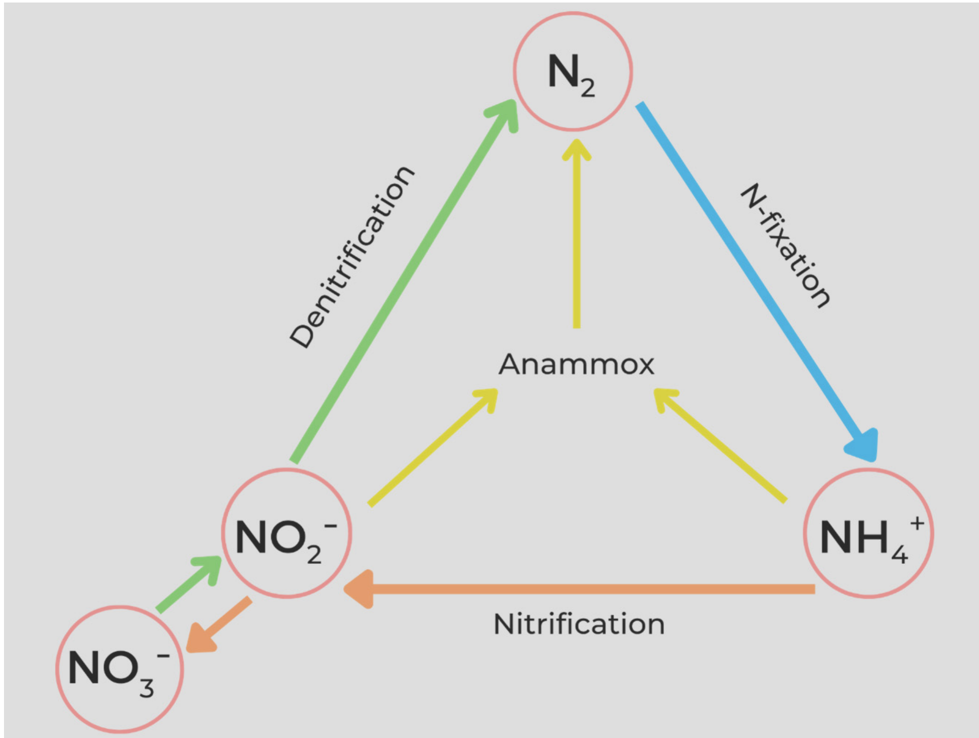


Figure 17. Anammox process

This process has been used in industrial discharge water treatment for quite some time, but because anammox bacteria are easily inhibited by pollutants and environmental parameters (Massara et al., 2017) wide-scale usage of this process has not resulted (Cho et al., 2019). Despite anammox reactor prototypes being reported for both cold and seawater aquaculture applications (Espinal and Matulić, 2019), commercial application of this technology in an aquaculture setting has not been demonstrated. Outside of a specific reactor, anammox still often occurs in RAS. Yogev et al. (2017) reported that 10-20% of the nitrogen removal in the denitrification reactor was by anammox. This phenomenon was also reported in a small number of additional studies (Tal et al., 2003; Klas et al., 2006; Lahav et al., 2009), with anammox bacteria from the gut of the fish accessing the denitrification reactor through the addition of filter backwash (Lahav et al., 2009). Adding filter backwash, which can serve as a carbon source (Suhr et al., 2013), ensures the regular resupply of anammox bacteria. Anammox in the denitrification reactor can be encouraged by increasing solid retention time (Lahav et al., 2009).

Whilst in its early stages in aquaculture, the use of this process would present a good opportunity to remove the emission of a volatile pollutant and increase the green credentials of the industry.

5.6.3 Methane

Like N_2O methane is a potent greenhouse gas. In land-based aquaculture, methane is typically released by microbial digestion either of sludge or suspended solids. If solids are collected and prevented from accumulating at the bottom of tanks or raceways, then methane release is likely to be low. Emissions can, however, be significant from ponds if they are not regularly dredged. As described in Section

5.2.2., biogas plants aim to produce methane to use as a source of energy. This methane is contained and used, but if sludge is stored in sludge lagoons the emission of methane into the environment will be unrestricted. The release of methane from land-based aquaculture (other than ponds and sludge lagoons) has not been well studied. The capture and reuse of any emissions are unlikely. Instead, best practices should be employed to ensure that sludge and solids are not allowed to accumulate and that feeding regimes prevent wasted feed. Mortalities should be handled in such a way that they are not allowed to decompose and release GHGs.

5.6.4 Odour

Odour emissions from land-based aquaculture are less well studied than other forms of emissions. Odour emissions in general can affect the quality of life of neighbouring populations, lead to complaints to local councils, and negatively impact public perception of the relevant industry. In Nordic countries, regulations regarding the emissions of waste minimise the emissions of odour. Immediate and appropriate handling of mortalities prevents these from becoming a health hazard or odour issue. Collecting sludge prevents uncontrolled decomposition, whilst keeping water quality high ensures it remains low in odour. Bad aquaculture practices can generate disagreeable odour, but a combination of legislation and good standards make odour emissions to surrounding areas an issue of minimal concern in Nordic land-based aquaculture production.

5.7. Other forms of waste

Waste is generated in the system (sludge, water, mortalities, and gas), but it also comes from the system itself and the inputs to the system. Plastic is used in many areas of a land-based aquaculture operation from tanks and nets to pipes and feedbags. If not properly handled, these components can become a large source of waste. Fibre-reinforced or glass-reinforced plastics such as those used in tank production are difficult to recycle. Pipes and fittings are often polyvinyl chlorides, and these are also rarely recycled. Polyethylene is sometimes used for pipes and fittings and commonly for buckets, basins, and some ropes and is easily recyclable. Some feed manufacturers are producing easily recyclable bags and even compostable bags in smaller sizes. Wooden pallets are easily recycled.

Landfill is, as in the case of most industries, an unfortunate reality for some of the waste produced. Environmental and waste management plans can help to mitigate unnecessary waste, and reuse should be encouraged whenever feasible and biologically secure. Using materials that can be readily recycled is a simple consideration. Waste on a fish farm is not limited to farming equipment, and waste from employees such as plastic or metal food containers, sewage, and food waste should all be recycled or disposed of in as environmentally friendly a method as possible.

One benefit of land-based aquaculture is that wastes are more easily contained. There is little or no risk of ropes, nets, or other plastic pollution sources accidentally being discharged into the environment.

5.8. Reduction before reuse

The circular economy focuses on the reuse and recycling of resources to cut down on waste. Many of the BATs discussed in this report look at reusing the waste streams created from land-based aquaculture. Much of waste management also focuses on the three R's (reduce, reuse, and recycle), and one should not forget that it is generally cheaper, easier, and more environmentally friendly to reduce waste in the first place than to spend resources trying to reuse or recycle said waste. Whilst it is impossible to remove all waste in land-based aquaculture systems, techniques, technologies, and practices exist that can significantly reduce the amount of waste created. A few simple considerations that can reduce waste production are highlighted in Table 15.

Much of the waste discussed in this report comes from the feed, either directly or following partial use by the fish. Feed is a large component of sludge and provides an influx of nutrients into the discharge water. Removing the nitrogen present in the feed through denitrification creates NO_2 gas. In addition, in an operational RAS facility, feed is often the number one cost. Reducing the amount of feed fed wastefully can have huge benefits for a farm. Outlining in detail how one could reduce feed waste in land-based aquaculture would double the length of this report, but several pathways are briefly described. Mortalities are another source of waste outlined in this report and one with fewer reuse applications than wasted feed (sludge). Reduction of mortalities, be they natural or through a cull, is high on all farmers' lists of priorities, but a few simple considerations on how to reduce this source of waste are outlined below. Much of the waste generated during on-land fish farming has the potential for reuse as an energy source. These can be used externally or on the farm to minimise reliance on external energy sources. This reliance can be reduced further through energy efficiency, saving money and reducing the climate footprint of a farming operation.

Table 15. Methods for reducing waste production in land-based aquaculture

Waste source	Reduction opportunities
Feed	
Uneaten food	- Observe uneaten pellets and adjust feeding – cameras and techni-cian/ machine learning observer - Use feed tables but adjust with observa-tions of feeding and when fish removed - Spread feeding over longer periods - Ensure pellet size is appropriate - Automatic feeders give accurate ration - Place feeders to ensure pellets remains in the tank for long enough - Attractants and palatability can improve uptake
Under-utilised feed	- Diets must be nutritionally appropriate for species, conditions, and life stage - Different feeds can offer variable utilisation - Premature maturation decreases utilisation of resources for growth
Spoiled feed	- Storing feed on the floor, in dry (<6% humidity), and cool <15 °C decreases spoilage - The first in, first out principle ensures feed is not stored for longer than necessary
Disintegrated feed	Choosing RAS-specific feed can improve mechanical removal and water quality
Mortalities	
Disease/preventative culls	- Classify mortalities to identify diseases early - Treat if possible - Keep systems separate - Disinfection of all equipment - Training in biosecurity - Filtration and disinfection of influx water - Quarantine and testing of incoming fish/eggsCheck feed quality - Reduce outside risks, filter air, reduce visitation - Good husbandry keeps fish healthy
Handling	- Ensure adequate training for staff - System designed around the species chosen - Fish gates or pumps can minimise handling - Suitable nets reduce damage to fish
Energy efficiency	
Temperature	- Water source selection is key - System design and heat exchangers can reduce heat loss - A large temperature differential lowers exchange and decreases usage - Proper insulation of the building reduces heating costs
Equipment	- Lower pumping through better design - Equipment running capacity can be changed concerning requirements – does not always need to run at 100% - Energy-efficient models can create savings

6. Results from stakeholder engagement

A large number of stakeholders (Table 16) were approached to gain a better understanding of the current state of the industry and the use of BATs. An initial questionnaire was used to determine participation interest, and a more detailed questionnaire followed for those who responded positively (Appendix 1). The questionnaire was distributed in English, Norwegian, Danish, and Icelandic. Responses from waste producers and other stakeholders were fairly limited; around half of the fish farmers responded. Other stakeholders included universities and research institutions, associations, egg suppliers, national authorities, and waste users. Of those that did respond, not all responses could be used for analysis. Many responders failed to answer every question; this was particularly apparent in questions relating to the handling of specific waste streams. Other responders gave vague or incomplete answers. No farms surveyed reported methods to mitigate gas emissions. Answers that could be used have been organised in Figures 18 – 20, showing the rough location of the responders and the method of waste treatment that they employ. Of the farmers that responded, farm size ranged from 300 kg in a small-scale aquaponics system to farms with over 20.000 tonnes per year. Recirculation levels ranged from 0% (flow-through) to 99% high-intensity RAS. Three-quarters (75%) of the farms solely produced Atlantic salmon, although three responders produced Arctic charr and three produced trout. The life stage of production varied, with grow-out farms alongside hatchery and nursery facilities. The source of water in the facilities varied; 50% of responders reported using borehole water, 27% seawater, 22% lake water, and 17% both river and reservoir water. Some responders reported on multiple farms and therefore the total number of farms is more than 100% of the responders. One responder reported using municipal water whilst another used repurposed industrial wastewater. Of the farms that responded, 38% reported belonging to an environmental certification scheme (ASC, GGAP, Debio).

Table 16. Response rate from stakeholders in Nordic countries.

		Fish Farmers	Waste Processors	Other Stakeholders
Norway	Contacted	22	9	21
	Responded	12	1	3
Iceland	Contacted	12	0	13
	Responded	7	0	2
Denmark	Contacted	7	0	8
	Responded	1	0	2
Finland	Contacted	2	0	6
	Responded	0	0	2
Faroe Islands	Contacted	1	0	1
	Responded	0	0	0
Åland Islands	Contacted	1	1	2
	Responded	1	1	2
Sweden	Contacted	7	0	5
	Responded	3	0	2
Total	Contacted	52	10	56
	Responded	24	2	13
	Percentage responded	46%	20%	23%

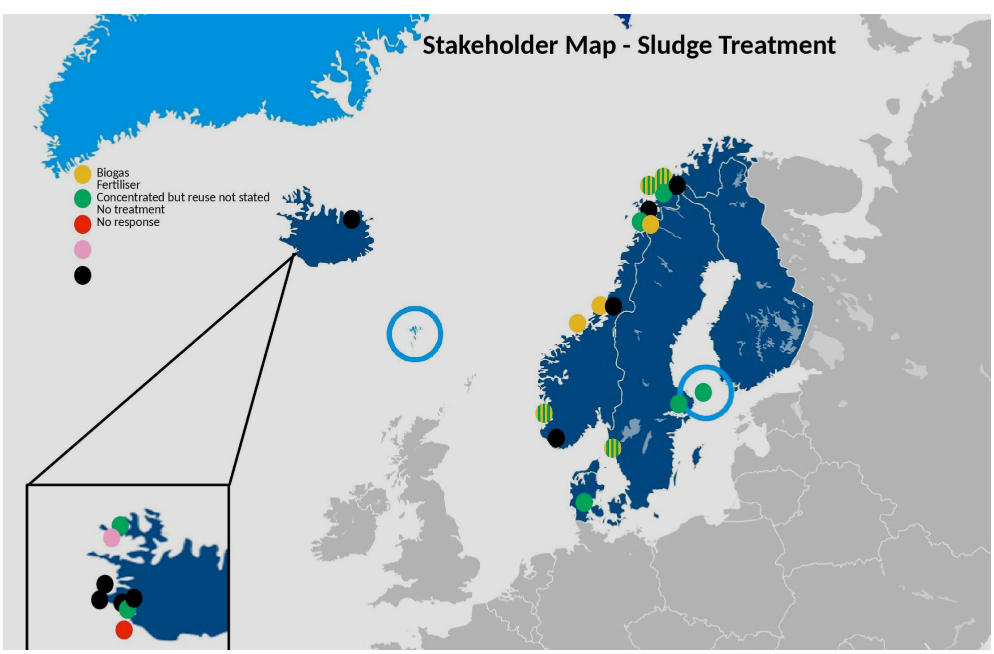


Figure 18. Location of fish farms and the method of sludge treatment employed

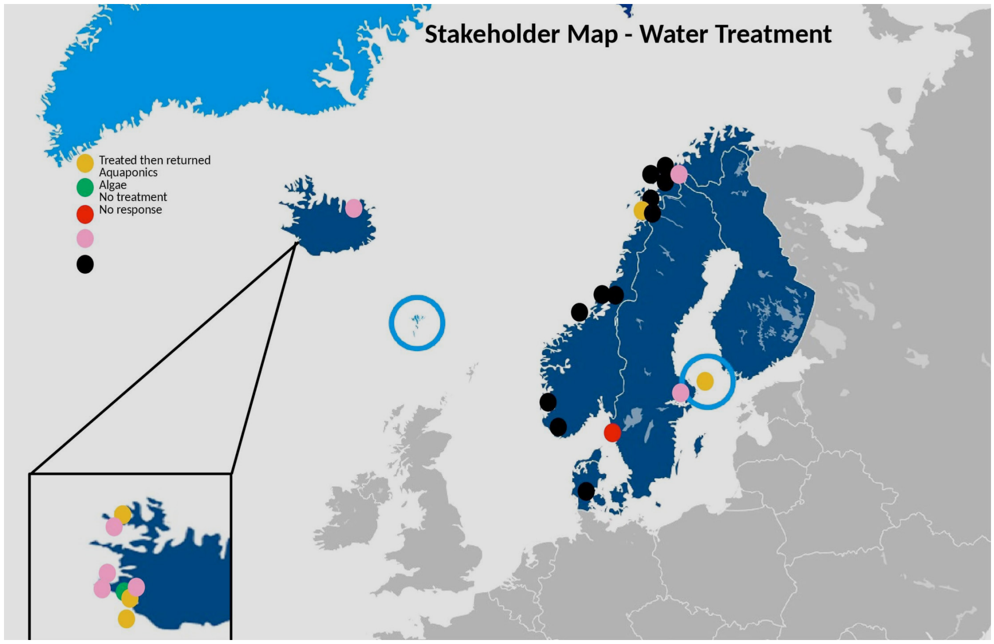


Figure 19. Location of fish farms that responded to the survey and method of water discharge treatment

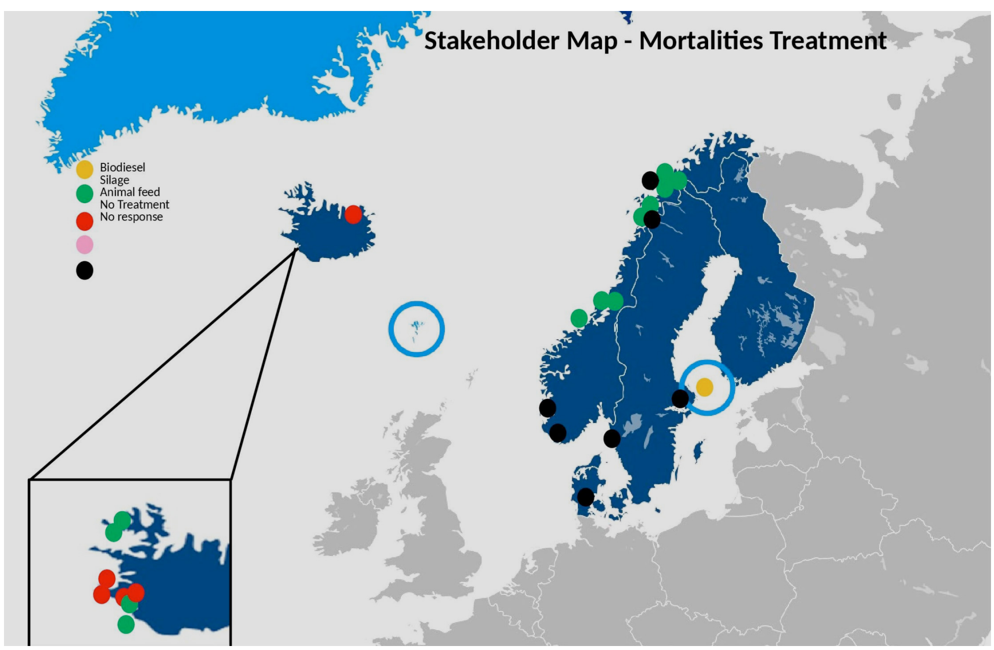


Figure 20. Location of fish farms and the method of mortality treatment employed

7. Recommendations and considerations

Section 5 highlights multiple approaches for the management of waste streams from land-based aquaculture. For each form of waste (e.g., sludge, water, mortalities) there are several methods of waste reduction and reuse to choose from. Each of these methods has benefits and restrictions and no single method presents the best solution in every scenario. Even limited to the Nordics, land-based aquaculture occurs in multiple forms (pond, flow-through, raceway, and RAS), with different species being cultured in facilities ranging in size from less than a hundred tonnes to tens of thousands of tonnes. These facilities are distributed across the Nordics from remote regions with limited infrastructure or local industry to urban areas around major cities. Most aquaculture farms are bespoke constructions making use of the best available system technologies at the time and being designed to fit the unique requirements of the site and farm operator. All these factors combine to make choosing the best available technology for a specific site more difficult than in a more standardised or homogenous industry.

One of the major restrictors on the method of reuse chosen is farm size, as such, Table 17 lists possible BAT choices and indicates potential feasibility based on farm size. The restriction column goes into detail on factors that can limit the viability of the technology such as location, local industry or farm type. Most of the technologies are readily available from commercial suppliers or easily implementable on farm. Others are only recently being developed or tested, require legislative change to become feasible, or require adapting to the aquaculture industry. Key points to consider when defining BATs for the treatment and reuse of waste from land-based aquaculture are described in Table 18.

Table 17. Potential techniques that can be applied as BATs for the treatment and reuse of waste from Nordic land-based aquaculture

BAT	Potentially feasible at farm size (tonne)				Benefit	Restrictions	Availability
	<100	100-1000	1000-10.000	>10.000			
Separation of Solids and Water							
Sedimentation	x	x	x	x	Low energy consumption Used in race-way, pond, and some RAS	Not well demonstrated in large-scale RAS Less easy to scale up than mechanical filtration	Available
Mechanical filtration (drum and disk)		x	x	x	Proven efficient solids removal in RAS and raceway systems Easily scalable for increased production or emergency backup	Energy consumption	Available
Thickening de-watering, and drying		x	x	x	Decreasing water content decreases transport cost per tkm Decreasing volume decreases disposal fees Multiple companies offer different methods to thicken, dewater, and dry sludge Valorisation options increase with reduced water content Collaborative hubs can share costs between multiple farms	Energy costs increase with de-creasing water content May add cost and complexity to farming operations Viability depends on electricity costs	Available
Adsorptive bubble separation		x	x	x	Removal of particles and oils from wa-ter	Benefits limited to RAS	Available
Removal of Dissolved Components							
Nitrification (bio-filtration)	x	x	x	x	Proven in RAS to remove ammonia from water A large number of designs and media depending on requirements	Not common in flow-through or ponds Bacteria sensitive to changes in water chemistry and production volume	Available
Denitrification (biofiltration)		x	x	x	Converts nitrate in water to nitrogen gas May reduce the need for water ex-change	Requires anaerobic reactor and supplementary carbon source CO_2 and N_2O emissions Mostly limited to RAS	Available

Degassing	x	x	x	x	Removes CO_2 and dissolved gases	CO_2 emissions	Available
Reuse of Freshwater Sludge							
Fertiliser	x	x	x	x	Sludge of varying moisture content can be used Simple Potential local application	Seasonal variability of demand Nitrogen and phosphorous leaching Heavy metal content Limit scope for profitability	Available
Biogas (offsite)	x	x	x	x	Reuse energy stored inside of sludge Source of low-carbon energy for local communities Sludge of variable moisture content can be used	A limited number of biogas facilities Gate fees may be limiting Limited chance of revenue for sludge producer	Available
Biogas (onsite)			x	x	No sludge transport fees; only requires digestate Energy for farm operations Suitable for wet sludge Recent solutions for use of 100% fish sludge (without mixing with other substrates)	Increases complexity of farming operations Trained staff required to maintain microbial community Areal footprint	Available
Pyrolysis (on-site)			x	x	Produces by-products and energy The ratio of by-products is adjustable according to market conditions Footprint smaller than biogas reactor	CAPEX Sludge must be dewatered	Available
Incineration for energy (offsite)	x	x	x	x	Alternative to fossil fuel for other industries	Sludge must be dried The level of phosphorus can limit use in the cement industry Substantial transport to incineration plants or cement works can negate benefits	Available
Food for Insects	x				Example of circular economy	Heavy metals require mitigation Not currently permitted	Feasible but legislatively restricted

						Lack of value chain of development	
Reuse of Saline Sludge							
Desalting		x	x	x	Different methods of desalting are available Allows saline sludge to be used as freshwater sludge Simple desalination option	Freshwater consumption	Available
Feed for polychaetes	x	x			Polychaetes have potential use as animal feed	Not demonstrated at commercial scale The market for polychaetes is currently limited	Requires significant development
Pyrolysis (on-site)			x	x	Produces by-products and energy The ratio of by-products is adjustable according to market conditions Footprint smaller than biogas reactor	Limited market for biochar from saline sludge CAPEX Sludge must be dewatered	Available
Incineration for energy (offsite)	x	x	x	x	Can produce energy for local communities	Substantial transport to incineration plant may offset benefits Sludge must be dried Cannot be used in the cement industry due to salt	Available
Fertiliser for halophytes	x	x	x	x	Potentially offers local and simple reuse option Halophyte plants for animal feed	Limited proof of concept at scale Limited market for halophyte Halophytes must be mixed with other feed or processed	Breakthrough technology
Discharge Water Treatment							
Membrane filtration		x	x	x	Filtration can reduce particles in discharge water	CAPEX and OPEX increase as filtration pore size decreases High a filtration rate may increase OPEX	Available
Wetlands	x	x	x		A simple method of suspended and dissolved nutrient removal Can also remove pathogens,	Land use (footprint) Removal of dissolved TAN and phosphorous is limited Present use is restricted to	Available

					pharmaceuticals, and heavy metals Projects underway to treat saline discharge water	freshwater	
Reuse of Discharge Water							
Fertigation	x	x	x	x	Fertigation established practice in some agricultural sectors Reduces freshwater and fertiliser usage Run-off reduced	Limited proof of concept at scale (for fertigation with wastewater) Potential suitability of nutrient profile Only suitable for local application Lack of demand in the Nordics	Requires significant devel-opment
Algae	x	x	x		Algae cultivation is well established globally Established market options for algae	Not well established in the Nordics Costs may be prohibitive Large areas and artificial lighting required Only suitable for local application Possible lack of suitability and consistency in wastewater nutrient profile	Requires significant devel-opment
Heat/ hydraulic energy recovery	x	x	x	x	Proven technology A simple method for reducing energy costs	Not suitable for all farms Hydraulic energy recovery is potentially less feasible than heat recovery Can increase operational complexity and risks	Available
Mortalities							
Ensiling	x	x	x	x	Well-established value chain and protocols Reuse possible	Environmental risks if spillage and health risks Transport costs	Available
Drying		x	x	x	Opens further reuse options Reduces costs of transporting mortality per tkm May reduce labour costs compared to ensiling in some cases Technology may be	The technology is available but is not yet tested on the largest farms Price of electricity	Available

					deployed at different scales Avoids risks associated with ensiling		
Gas Emissions							
Carbon capture and protein production				x	Carbon could be captured from degassing and above tanks Possible reduces of onsite CO_2 emissions Source of protein	Lack of proof of concept at scale Hydrogen is an essential component of protein production, and requires a source of green energy to be sustainable and affordable	Currently un-proven
N2O reduction		x	x	x	Simple practices can help increase Anammox processesReduces emission of N_2O during nitrification and denitrification	Protocols are not well established Anammox process sensitive to changing water quality Specific reactors not commercially available	Requires significant development
Other Forms of Waste							
Reduction and recycling	x	x	x	x	Many other wastes can be reduced and reused using established processes	Some chemicals and plastics used are not possible to recycle	Available
Reduction Before Reuse							
Reduction	x	x	x	x	Simple practices can reduce emissions and waste	Some reduction methods add complexity and costs that may be limiting	Available

Table 18. Points to consider when defining BATs for the treatment and reuse of waste from land-based aquaculture

BAT selection and adoption	**Context.** BATs may vary with location, farm type and practices, local market conditions, availability of service providers, and relevant regional/national legislation **BATs must be affordable and cost-effective.** Some BATs may become unviable due to changes in market prices (such as the cost of electricity). The financial feasibility of BATs may be de-termined by economy of scale (size of the farm) **Central BAT hubs.** BATs not viable for individual farm sites may become feasible if offered as a service (either through co-operatives or independent service providers) to multiple farms **The potential for environmental problem shifting should be considered.** Reductions of emission or waste achieved through a BAT may be offset by increases in waste and other emissions elsewhere along the value chain (e.g., technology for nutrient emission reduction may in-crease carbon footprint due to electricity use) **Research and Development.** Facilities (either privately or publicly funded) for developing, testing, and optimising techniques and technologies may support and facilitate the adoption of BATs.
Legislation	**Level playing field**. Regulatory requirements should be inclusive across economies of scale and business sizes. They should not unfairly exclude smaller enterprises by enforcing the adoption of BATs with disproportionate financial costs or technological and operational complexity. **Stakeholder engagement.** Legislative development should include a process of stakeholder consultation. Legislation should emphasise/respect the importance of the aquaculture sector in determining the need and choice of BATs.
Reduction	**Best management and operating practices.**Wastes and emissions can be reduced by suitably designed protocols. Basic, practical measures are often sufficient for this end.

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Personal communication – Case studies

- Blue Ocean Technology – Hans Runshaug (CEO) and Jan Henning Legreid (Development/Sales manager)
- Danish Aquaculture Association – Lisbeth Plesner (Chief Advisor)
- Drying Matter – Jonas Christensen (Director/co-owner) and Thomas Eilkær (Director/co-owner)
- Fjell – Roy Olav Hovlid (CCO)
- Norcem – Annika Steien (Process and Environmental manager)
- Sterner – Robert Eliassen (project manager) and Dr Arne Hjalmar Knap (Co-founder/R&D)
- Storfjärdens fisk - Sixten Sjöblom (CEO)
- Waister – Hallstein Baarset (CEO)

Appendix 1

Aquaculture guidelines

Due to the lack of consolidated policy on aquaculture, the European Commission (EC) has issued several communications detailing a development strategy for the sector. The first (COM/2002/551) was titled 'A strategy for the sustainable development of European aquaculture'. This was followed by a second communication in 2009 (COM/2009/0162), which presented a revised version of the strategy. This was replaced in 2013 (COM/2013/0229) by a restructured strategy according to Article 34 of the newly reformed CFP. Article 34 calls for the promotion of the sustainable development of the European aquaculture sector through a coordinated strategy. As part of this approach, the EC must establish strategic guidelines with specific objectives, including the improved application of EU law to aquaculture. It also requires Member States to produce a multiannual national strategy plan for aquaculture, also with defined objectives, including the simplification of administrative procedures, such as the granting of licenses. Of particular relevance to this report, it calls for Member States to engage in an open exchange of information about best practices. The latest EC strategy was adopted in 2021 (COM/2021/236). Titled 'Strategic guidelines for a more sustainable and competitive EU aquaculture' for the period 2021 to 2030', it was produced to align the guidelines with the recently adopted 'European Green Deal' (COM/2019/640) and related 'Farm to Fork Strategy' (COM/2020/381).

Water Framework Directive, Environmental Quality Standards Directive, and other relevant water-related EU legislation

Directive 2000/60/EC, commonly referred to as the Water Framework Directive (WFD), establishes the legislative provisions for the protection of all inland waters and coastal waters extending one nautical mile from the shoreline[3]. Article 4 obliges Member States to implement measures necessary to prevent deterioration of the 'ecological status' and 'chemical status' of 'surfaces waters'. It further obliges Member States to achieve 'good' ecological and chemical status, by 2027 at the latest. Pursuant to Article 13, Member States should detail measures for achieving these goals as part of a river basin management plan, described within a river. Ecological status is classed as being high, good, moderate, or poor, determined according to the various hydrological and physicochemical water quality parameters and 'biological' parameters presented in Annex 5. Chemical status is assessed according to environmental quality standards presented in Directive 2008/105/EC, also referred to as the 'Environmental Quality Standards Directive' (EQSD). Annex 1 of EQSD provides threshold values for the substances listed in Annex 10 of the WFD. The thresholds are set as either the maximum allowable concentration at any one moment or the maximum average concentration calculated for one year. Good

3. Waters beyond this distance are covered by Directive 2008/56/EC (Marine Strategy Framework Directive), which has relevance to aquaculture but is not within the scope of this report. The waters to which the provisions in the WFD apply are defined as being part of the 'river basin.'

chemical status is given to surface waters that do not exceed maximum concentrations for any of the given substances.

As part of the river basin management plans (RBMPs), Annex 2 of the WFD obliges Member States to collect information 'on the type and magnitude of the significant anthropogenic pressures to which the surface water bodies in each river basin district are liable to be subject,' including identification of 'significant' points and diffuse sources of pollution *('from urban, industrial and agricultural and other installations')*, particularly of the substances listed in Annex 8. Among the 12 pollutant types listed list are biocides, *'substances which contribute to eutrophication'*, and substances which have an unfavourable influence on the oxygen balance (e.g., as measured by biological oxygen and chemical oxygen demand). This potentially brings aquaculture activities within the scope of the WFD, and although the directive contains no explicit reference to the sector, some aquaculture activities have been identified as point sources of pollution in the river basin management plan of some Member States and in SWD (2016) 178.

Industrial Emissions Directive and the European Pollutant Release and Transfer Register

Commonly referred to as the *'Industrial Emissions Directive'* (IED), Directive 2010/75/EU on industrial emissions (integrated pollution prevention and control) is the main EU policy for the regulation of pollution from industrial activity. It calls for the implementation of best available techniques, and for *'an integrated approach towards prevention and control of emissions to air, water and soil, to waste management, [and] to energy efficiency'.* Annex 1 of the directive provides a list of activities that require operating permits, to be issued at the national level. It is the responsibility of each Member State to ensure that the conditions under which a permit is granted are under the provisions of the IED. Under normal operating conditions, facilities should not release emissions in quantities exceeding those associated with the best available techniques[4]. These are defined through an exchange of information between Member States and the production to produce the best available technique reference (BREF) documents. The procedure is coordinated by the EC (as required by Article 13 of the IED) through the European Integrated Pollution Prevention and Control Bureau, and the rules for doing so are set into law by Commission Implementing Decision 2012/119/EU, commonly called the *'Sevilla process'.* The resulting BAT conclusions are adopted by the EC. Although some parts of the aquaculture value chain may fall within the scope of the directive,[5] aquaculture production itself is not explicitly mentioned. An evaluation of the IED was published in 2020 (SWD/2020/181) and followed by an assessment of measures for improving its implementation (European Commission, 2021). Among these was the option to include intensive aquaculture among the activities listed in Annex 1. However, the measure was later rejected, and the revised IED proposed in COM (2022) 156 makes no direct reference to aquaculture. Rather, it empowers the EC to make further additions to the listed activities according to set criteria.

4. Emission Limit Values.
5. Production of fishmeal and fish oil is included in a BREF document for slaughterhouses and animal by-product industries, currently under review.

Waste Framework Directive and the European List of Waste

The Waste Framework Directive (2008/98/EC) provides legislation for the regulation of waste management. It establishes a 'waste hierarchy' approach to waste prevention and management, the basic framework for which is given in Article 4. The hierarchy provides a set of five options, ordered according to their priority:

i. prevention of waste generation
ii. preparing for reuse[6]
iii. recycling
iv. other recovery
v. disposal.

Under Article 4, it is the responsibility of Member States to integrate the hierarchy into their national waste management policy and legislation. Further obligations of Member States regarding waste prevention, recycling and preparing for reuse, recovery, and disposal, are given in Articles 9, 10, 11, and 12, respectively.

The WFD also provides various definitions relevant to waste management. Article 3 defines waste as being *'any substance or object which the holder discards or intends or is required to discard.'* Wastes are categorised as being either 'non-hazardous' or 'hazardous,' with hazardous wastes being those with any of the properties listed in Annex 3 of the WFD. The directive provides conditions to which the management of hazardous wastes should be subject, which includes the requirement for their treatment in designated, licenced facilities. Common terminology for the classification of wastes is provided in the 'List of Waste' established by Commission Decision 2000/532/EC. Wastes are assigned a six-digit number denoting the categories to which they belong. The third of the three category levels defines the status of waste regarding its hazardousness. It is composed of three subcategories called 'entries': i) 'absolute hazardous entries' (AH) are wastes that are assigned to absolute hazardous entries and cannot be allocated to non-hazardous entries and are hazardous without any further assessment, ii) 'absolute non-hazardous entries' (ANH) are wastes that are assigned to absolute non-hazardous entries, cannot be allocated to hazardous entries and are non-hazardous without any further assessment, iii) mirror entries are wastes from the same source that might be allocated to a hazardous entry or a non-hazardous entry depending on the context and the composition of the waste. Thus, this category has two subcategories, minor hazardous (MH) and minor non-hazardous (MNH). Wastes from aquaculture and the processing of aquaculture products are defined at the first category level by Code 02. At the third level, there are mostly designated as ANH, other than 'agrochemical waste containing hazardous substances,' which is designated MH.

Article 5 gives conditions by which a 'subject or object' is to be considered a by-product rather than a waste:

- Its further use is certain.

6. Preparing for re-use is defined by Article 3 of the WFD as 'checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing'. This is apparently ambiguous within the context of the waste hierarchy outlined in Article 4.

- It can be used directly without any further processing other than normal industrial practice.
- It is produced as an integral part of a production process.
- Its further use is lawful, i.e., the substance or object fulfils all relevant product environmental and health protection requirements for the specific use and will not lead to overall adverse environmental or human health impacts.

Some waste types and by-products relevant to aquaculture are excluded from the scope of the WFD as they are included in other legislation: i) waste waters, ii) animal by-products including processed products covered by Regulation (EC) No. 1069/2009, except those which are destined for incineration, landfilling or use in a biogas or composting plant, and iii) carcasses of animals that have died other than by being slaughtered, including animals killed to eradicate epizootic diseases, and that are disposed of under Regulation (EC) No. 1069/2009.

Appendix 2

Aquaculture guidelines

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About this publication

BAT for Reduction and Reuse of Emissions in Nordic Land-based Aquaculture

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