SLUTRAPPORT

GUDP-projekt 2019-2022

Hav-Tek

Udvikling af teknologiske løsninger til miljømæssigt optimeret havbrugs-drift.

1. MARTS 2023

Af Lisbeth Jess Plesner

Dansk Akvakultur

Ministeriet for Fødevarer, Landbrug og Fiskeri

gudp

Grønt Udviklings- og Demonstrationsprogram

Projektet, som er beskrevet i denne rapport, er støttet af Grønt Udviklings- og Demonstrations-program, GUDP, som er en erhvervsstøtteordning under Ministeriet for Fødevarer, Landbrug og Fiskeri.

GUDP giver tilskud til projekter, der understøtter grøn og bæredygtig omstilling af fødevareer-hvervet, og programmet dækker hele værdikæden fra primærproduktion til forarbejdningsindu-stri og afsætningsled.

Det er GUDP's ministerudpegede bestyrelse, som beslutter, hvilke projekter der skal modtage tilskud. Bestyrelsen betjenes af GUDP-sekretariatet i Landbrugsstyrelsen.

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Denne slutrapport er godkendt af GUDP, men det er alene rapportens forfatter/projektlederen, som er ansvarlige for indholdet. Rapporten må citeres med kildeangivelse.

SLUTRAPPORT

FAKTA OM PROJEKTET

Projektperiode: 1. juli 2019 til 31. december 2023

Projektdeltagere: AquaPri, BioMar, DTU Aqua, DTU Mekanik (nu DTU Construct), Dansk Akvakultur og Hvalpsund Net (1. juli 2019 til 30. juni 2020)

Bevilling fra GUDP: 4.127.285 kr.

Projektleder: Lisbeth Jess Plesner, Dansk Akvakultur, Agro Food Park 15, 8200 Aarhus N.

FORMÅL

Formålet med projektet er at styrke den grønne omstilling af den danske havbrugsproduktion. Det vil ske gennem udvikling og vurdering af miljøtekniske løsninger. I projektet vil der blive udviklet og testet et nyt, innovativt foder med en bedre miljøeffektivitet, så den specifik fosfor udledning bliver reduceret (mindre udledning af fosfor per kg produceret fisk). Desuden er der blevet vurderet på muligheder for opsamling af fækalier fra havbrug under danske forhold.

PROJEKTETS RELEVANS

Akvakultur herunder havbrug er sunde fødevarer med et lavt klima- og miljøaftryk samt god areal-effektivitet pr. kilo produceret fisk og skaldyr. Ifølge EU's Farm to Fork strategi[1] skal vores fødevareproduktion, der i dag står for en tredjedel af den globale udledning af drivhusgasser, omstruktureres, og her bør akvakultur spille en central rolle. Kostrådene anbefaler desuden, at danskerne øger deres forbrug af fisk og skaldyr med ca. 66 pct. af hensyn til klima og sundhed[2].

Mangel på effektive renseteknologier til havbrug kan på nogle lokaliteter begrænse muligheden for øget produktionen. En mulig renseteknologi fra havbrug er måske fækalieopsamling og udvikling af et mere miljøeffektivt foder. Der er ikke kendskab til forsøg med fækalieopsamling på havbrug beliggende som under danske forhold på eksponerede lokaliteter. I bl.a. Norge er foretaget en række projekter med mere eller mindre lukkede opdrætsanlæg til havs, hvor det primære formål har været enten at minimere risiko for lakselus eller at reducere risiko for udslip.

[1] https://ec.europa.eu/food/horizontal-topics/farm-fork-strategy_en
[2] https://altomkost.dk/raad-og-anbefalinger/de-officielle-kostraad/spis-mindre-koed-vaelg-baelgfrugter-og-fisk

Yderligere optimering af havbrugsfoder er en mulighed for forbedret miljøeffektivitet, dog er der en række forhold der skal inddrages i forbindelse med foderudvikling herunder vækst, kvalitet, fiskevelfærd og -sundhed, samt økonomi, klimapåvirkning og tilgængelighed af bæredygtige råvarer.

I projektet undersøges muligheder for forbedring af miljøeffektiviteten (reduktion af den specifikke udledning).

HOVEDRESULTATER

Udvikling af mere fosfor-effektivt foder til havbrug

I projektet er der gennemført udvikling og test af foder med reduceret P-indhold i laboratorie og på havbrug med særdeles gode resultater. Projektet har vist, at det er muligt at reducere fosforudledningen væsentligt med det udviklede foder uden at gå på kompromis med foderkvotient, væksthastighed og rognudbytte.

Gennem råvareoptimering og enzymtilsætning kan den specifikke udledning af fosfor totalt reduceres med mindst 39% (fra 5,6 til 3,4 kg fosfor/ton produceret fisk ved en FK_{bio} på 1,2 og et P indhold i fisk på 0,414%) i forhold til et repræsentativt standardfoder med 0,81% fosfor.

Effekten vil, med de nuværende tilgængelige råvarer, være størst for den specifikke udledning af opløst fosfor – og dermed også den mest reaktive del af fosforen i forhold til vandmiljøet: 48% reduktion (ved en FK_{bio} på 1,2 og et P indhold i fisk på 0,414%) fra 2,1 til 1,1 kg fosfor/ton produceret fisk.

Hertil kommer en reduktion af partikulært fosfor på 33% (fra 3,5 til 2,3 kg fosfor/ton produceret fisk). Yderligere reduktion af partikulært fosfor, som er bundet i fækalier og som for størstedelen formentligt falder til bunden, vil kræve, at der udvikles ”nye” råvarer med et lavere og/eller endnu mere tilgængeligt fosforindhold.

Projektets resultater har medvirket til udvikling af nyt kommercielt foder.

Mulighed for opsamling af fækalier fra havbrug

De mest interessante teknologier er brugen af hvirvelteknik, siltgardiner og luft diffusere. Hvirvelteknikken er svær at bruge direkte i et åbent eller halvåbent fiskebur. I stedet kan dette efterlignes med luftbobler, der indføres via diffuser (eller propel). Studiet peger på muligheder for at videreudvikle allerede kendte teknikker fra lukkede systemer til reduktion af hav-lus.

En egentlig udvikling af et koncept-net har ikke været muligt i Hav-Tek projektet. Dette kunne virkeliggøres via et udviklings- og demonstrationsprojekt fokuseret på den fysiske opsamling som kunne bygge videre på potentialet identificeret i Hav-Tek.

Et lukket system og et halvåbent system tilpasset til forholdene på lavt vand som i de indre danske farvande ses som de mest lovende kandidatsystemer til fuldskala demonstrationstest.
Det i projektet udviklede fosfor-reducerede foder, er allerede implementeret i et kommercielt produkt, der er interessant i Danmark og på markeder i de øvrige baltiske lande.

Vedhæftet 2 bilag

Bilag 1: Notat fra DTU Aqua til GUDP slutrapporten (projekt nr. 34009-19-1526) ”Hav-Tek, Udvikling af teknologiske løsninger til miljømæssigt optimeret havbrugsdrift”

Bilag 2: Notat fra DTU Construct (DTU Mek): Practical layouts of hydraulic systems to reduce spill from fish cages

PROJEKTFORLØB OG ERFARINGER

Laboratorieforsøgene i Hirtshals blev først igangsat i 2020, da det i efteråret 2019 ikke var muligt at skaffe ørreder i den rigtigt størrelse og kvalitet til forsøgene. Dette betød at forsøgende i havbrugene først kunne gennemføres i 2021. Projektet blev udskudt til ultimo 2022.

KONKLUSION OG PERSPEKTIVERING

I projektet er der udviklet og testet et nyt innovativt foder med en bedre miljøeffektivitet / reduceret specifik udledning. Det nye foder vil kunne reducerer den specifikke udledning af fosfor med op til 39%.

En egentlig udvikling af et koncept-net har ikke været muligt i Hav-Tek projektet. Dette vil kunne virkeliggøres via et udviklings- og demonstrationsprojekt fokuseret på den fysiske opsamling, som kunne bygge videre på potentialet identificeret i Hav-Tek. Et lukket system og et halvåbent system tilpasset til forholdene på lavt vand som i de indre danske farvande ses som de mest lovende kandidatsystemer til fuldskala demonstrationstest.

FORMIDLING

Der er gennemført en række kommunikationsaktiviteter gennem projektet både intern og eksternt. Nedenfor er oplistet en række af dette.

2019: Pressemeddelelse fra DA: https://www.danskakvakultur.dk/aktuelt/nyheder/2019/danske-havbrug-vil-saette-turbo-paa-den-groenne-omstilling/

27.2.20: Oplæg af DTU Mek, Dansk Akvakultur og BioMar på en temadag om Fiskeopdræt på Åland, hvor et af temaerne er semilukkede havbrug. https://fiskodlarna.ax/wp-content/uploads/2020/03/200227-DTU-AAland-Hav-tek.pdf, Samt https://fiskodlarna.ax/wp-content/uploads/2020/03/Raw-materials-%C3%85land-Februar-2020-20200227-new2.pdf

20.8.2020 og 11.1.2022: Workshop og vidensudveksling med svensk "søster-projekt" 20.8.20 med fokus på opsamling af fækalier og anvendelse af opsamlet slam.

16.12.2020: Præsentation ved 25th International Symposium of Shallow Flows, Hohai University, China, 16-18 December 2020" med titlen "Numerical study on the flow-particle interactions inside an offshore fish cage".

31.1.2023: Temamøde med præsentation af projektets resultater for erhvervet og øvrige interessenter på Ahro Food Prk i Aarhus (45 deltagere) link: https://danskakvakultur.dk/temadag-om-innovations-og-udviklingsmuligheder-for-havbrugserhvervet/

Teknisk notat fra DTU: Notat fra DTU Aqua til GUDP slutrapporten (projekt nr. 34009-19-1526) "Hav-Tek, Udvikling af teknologiske løsninger til miljømæssigt optimeret havbrugsdrift"

Teknisk notat fra DTU Construct (DTU Mek): Practical layouts of hydraulic systems to reduce spill from fish cages.

Videnskabelig artikel fra DTU Aqua

Reducing phosphorus emissions from net cage fish farming by diet manipulation, Dalsgaard, J. et al. Journal of Environmental Management vol. 334, 15.5.2023 Elsevier. link: Reducing phosphorus emissions from net cage fish farming by diet manipulation - ScienceDirect

Læs mere om GUDP´s projekter på www.gudp.dk

Arbejdspakke 2: Foderudvikling med henblik på reduceret fosforudledning

Formål

Formålet med denne arbejdspakke var at udvikle og dokumentere et nyt og mere miljøeffektivt foder, der reducerer udledningen af fosfor per kg produceret fisk (den specifikke udledning) fra havbrug uden at gå på kompromis med fiskens vækst, foderudnyttelse, kvalitet eller rognproduktion. Dette skulle ske ved at forbedre foderets fosforfordøjelighed gennem råvareoptimering og enzymtilsætning mhp. at reducere udledningen af partikulært bundet fosfor, samt matche mængden af tilgængeligt fosfor i foderet til fiskens faktiske behov og dermed reducere deres udskillelse af opløst fosfor. Desuden blev det testet, om tilsætning af en binder til foderet kunne forbedre fækaliernes struktur/synkehastighed ud fra hypotesen om, at det potentielt vil tillade bedre mekanisk opsamling af fækaliemateriale fra bunden af opdrætsburene.

Aktiviteter

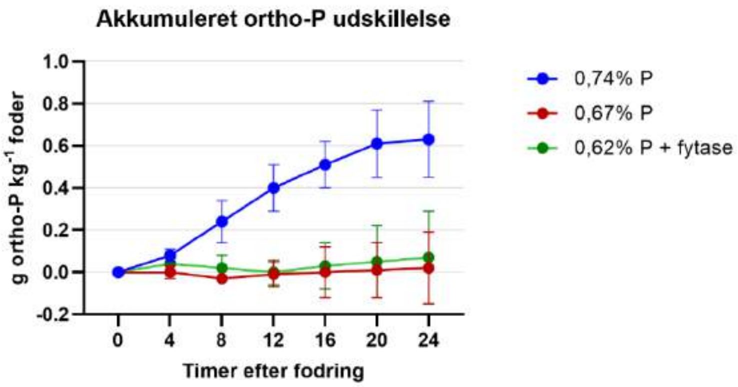
Ud fra baggrundsviden om fiskens forventede fosforbehov samt et indgående råvarekendskab formulerede og producerede BioMar et antal 6 og 8 mm forsøgsdiæter, som blev testet af DTU Aqua i tre kontrollerede massebalanceforsøg i laboratoriet med store udsætningsfisk (> 1 kg) fra AquaPri. Forsøgene skulle vise, hvor fosforen i foderet endte, dvs. hvor stor en andel, der blev tilbageholdt/inkorporeret i fiskene, blev udskilt som partikelbundet fosfor i fækalierne, samt udskilt som opløst fosfor (orthofosfat) direkte til vandet. Desuden blev der optaget et antal videosekvenser af synkende fækalier mhp. at sammenligne synkehastighed og størrelse af fækalier fra fisk foderet et kontrolfoder med eller uden binder. Endeligt blev der gennemført et kontrolleret vækstforsøg i laboratoriet med store udsætningsfisk fra AquaPri for at dokumentere foderets effekt på fiskens rognudvikling samt fordeling af fosfor mellem væv.

Baseret på laboratorieforsøgene formulerede og fremstillede BioMar et lav-fosfor testfoder med fytase, som blev testet mod et kommercielt foder i fuld skala (2x4 netbure) gennem en hel sæson på et af AquaPri's havbrug. Der blev løbende udtaget prøver af foderet, ligesom der blev udtaget prøver af fisk til start og slut i sæsonen. Prøverne er blevet analyseret for fosfor, protein, fedt, aske og tørstof. Desuden blev der udtage prøver at filet og rogn fra slagtede fisk til analyse for fedtsyre- og lipidklassesammensætning.

Hovedresultater

Massebalance – og vækstforsøg i laboratoriet

Samlet set viste laboratorieforsøgene, at det gennem råvareoptimering og tilsætning af fytase var muligt at reducere foderets totale fosforindhold fra 0,78% til 0,62% uden at gå på kompromis med fiskenes vækst, foderudnyttelse, næringsstoffordøjelighed, fosforindhold (inklusiv rogn), eller rognprocent. Specifikt bevirkede tilsætningen af fytase, at fosforfordøjeligheden blev forbedret fra 65% til 70%. Optimeringen af foderet førte til, at den samlede specifikke udskillelse af fosfor faldt signifikant. Reduktionen skyldtes primært, som vist i figur 1, en signifikant lavere udskillelse af opløst fosfor (tilnærmelsesvis nul-udskillelse).



Figur 1. Akkumuleret udskillelse af opløst fosfor (ortho-P) over 24 timer efter fodring fra store udsætningsfisk (> 1 kg). Fiskene blev fodret et 6 mm foder med hhv. 0,74% fosfor, 0,67% fosfor, eller 0,62% fosfor og fytase

Foderets effekt på fækaliernes synkeevne vha. tilsætning af en binder

For at undersøge om tilsætning af en binder til foderet kunne ændre fækaliernes synkehastighed, blev der i et af forsøgene tilsat en binder til foderet. Efterfølgende analyse af videooptagelser af fækaliernes synkehastighed (100+ fækalier pr. foderkode) viste, at tilsætning af en binder til foderet ikke ændrede signifikant på fækliernes størrelse eller synkehastiged sammenlignet med et foder uden binder.

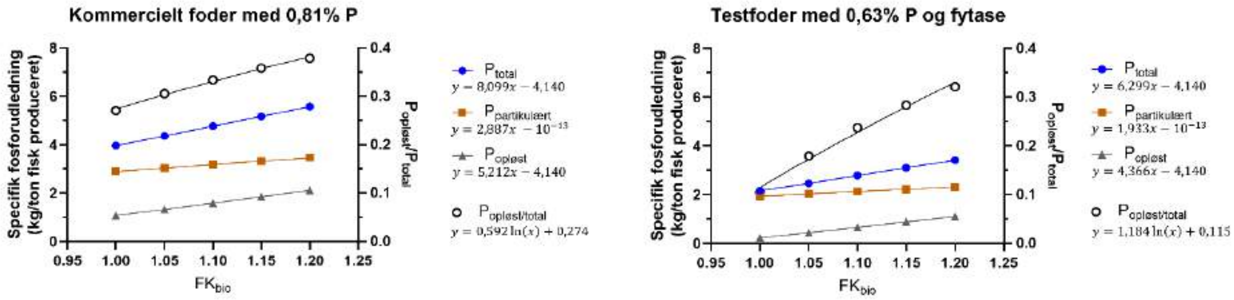
Fuldskala casestudie på havbrug

Det kommercielle foder anvendt i testen på havbruget indeholdt 0,81% fosfor (vådvægt), mens det fosforreducerede testfoder med fytase indeholdt 0,63% fosfor. Reduktionen i foderets fosforindhold havde ingen effekt på fosforindholdet i fisk (0,367 ± 0,016% P) eller på fosforindholdet i rogn (0,421 ± 0,022% P) indsamlet fra netburene i slutningen af oktober 2021 (ca. to-tre uger før forventet slagtning), ligesom der ikke var nogen forskel i fiskenes indhold af protein (17,8 ± 0,5%), fedt (21,9 ± 1,8%) eller aske (1,87 ± 0,09%).

Fisk foderet med testfoderet vejede i gennemsnit 3,54 kg ved slagt mens fisk fodret med standardfoderet vejede 3,59 kg. Tilsvarende var gennemsnitsvægten af rensede fisk, der havde fået testfoderet, lavere (2,81 kg/fisk) end den af fisk, der havde fået det kommercielle foder (2,85 kg/fisk). Forskellen i vægt afspejler sandsynligvis, at netburene med de to grupper af fisk på havbruget var placeret i lidt afstand fra hinanden og derfor oplevede lidt forskellige strøm- og temperaturforhold. Desuden blev fiskene fodret til mæthed, hvilket gør det svært at sammenligne væksten, da foderindtaget derfor vil være forskelligt. Der var ingen forskel i rognprocenten af de slagtede fisk (10,2-10,3%), ligesom der ikke var forskel i lipidklasse- eller fedtsyresammensætningen i filet- eller rognprøver udtaget ifm. slagt.

På baggrund af analyserne af det anvendte foder, det analyserede fosforindhold i store udsætningsfisk indsamlet ifm. udsætningen i april samt i rognfisk indsamlet ifm. slagt i oktober/november, en antaget fosforfordøjelighed på 65% for standardfoderet og 70% for testfoderet med fytase (baseret på laboratorieforsøgene), et antaget foderspild på 1%, samt en antaget biologisk foderkonvertering (FK_{bio} = foderindtag/biomassetilvækst) på 1,15 kan det beregnes, at den specifikke udledning af fosfor totalt i det aktuelle casestudie faldt med 36% fra 5,5 til 3,5 kg fosfor/ton produceret fisk ved skift fra standardfoderet til det fosforreducerede testfoder med fytase (til sammenligning er den maksimale tilladte specifikke udledning af fosfor sat til 6 kg/ton produceret fisk)[1]. Reduktionen inkluderede et fald i den specifikke udledning af opløst (reaktivt) fosfor på 40% (fra 2,2 til 1,3 kg fosfor/ton produceret fisk) samt et fald i den specifikke udledning af partikulært fosfor på 33% (fra 3,3 til 2,2 kg fosfor/ton produceret fisk).

Figur 2 viser beregninger af den specifikke fosforudledning fra havbrugserhvervet generelt set som funktion af foderkvotienten (FCR_{bio}) ved skift af fodertype. Beregningerne er foretaget med udgangspunkt i samme antagelser om fosforfordøjelighed (65 og 70% for hhv. det kommercielle foder og fytasefoderet) og foderspild (1%) som i casestudiet ovenfor samt et standardiseret fosforindhold i slagtemodne rognfisk på 0,414%[1]. Figuren illustrerer, at den specifikke udledning af fosfor, uafhængig af fodertype, falder jo bedre (dvs. lavere) FK_{bio} er, fordi en større andel af fosforen i foderet inkorporeres i fiskenes tilvækst. Desuden ses det, at andelen af opløst ("biologisk aktivt") fosfor i forhold til den specifikke udledning af fosfor totalt set falder med bedre FK_{bio}. Specifikt viser figuren, at den specifikke udledning af fosfor ved skift fra standardfoder til fytasefoder falder med 39-45% ved en forbedring af FK_{bio} fra 1,2 til 1,0, og at den specifikke udledning af opløst fosfor nærmer sig en nul-udledning.



Figur 2. Den specifikke udledning af fosfor totalt set, samt fordelingen på partikulær -og opløst form, fra et kommercielt foder med 0,81% fosfor (venstre) og det fosforreducerede foder med 0,63% fosfor og fytase (højre), som funktion af den biologiske foderkonvertering (FK_{bio}) indenfor intervallet 1,0 - 1,2. Desuden viser figuren forholdet mellem udskilt opløst fosfor og udskilt fosfor totalt (højre y-akse på figurerne).

Samlet set - og for erhvervet generelt - viser resultaterne fra arbejdspakke 2, at det gennem foderudvikling, råvareoptimering og enzymtilsætning vil være muligt at reducere den specifikke udledning af fosfor totalt med mindst 39% (fra 5,6 til 3,4 kg fosfor/ton produceret fisk ved en FK_{bio} på 1,2 og et P indhold i fisk på

[1] VEJ nr 9141 af 16/03/2020 (Gældende) Vejledning om ændring af vejledning om godkendelse af saltvandsbaseret fiskeopdræt. Miljø- og Fødevareministeriet, den 16. marts 2020.

0,414%) i forhold til et repræsentativt kommercielt foder med 0,81% fosfor. Effekten vil, med de nuværende tilgængelige råvarer, være størst for den specifikke udledning af opløst fosfor – og dermed den mest reaktive del af fosforen i forhold til vandmiljøet: 48% reduktion (ved en FK_{bio} på 1,2 og et P indhold i fisk på 0,414%) fra 2,1 til 1,1 kg fosfor/ton produceret fisk. Hertil kommer en reduktion af partikulært fosfor på 33% (fra 3,5 til 2,3 kg fosfor/ton produceret fisk). Yderligere reduktion af partikulært fosfor, som er bundet i fækalier og som for størstedelen formentligt falder til bunden, vil kræve at der udvikles "nye" råvarer med et lavere og/eller endnu mere tilgængeligt fosforindhold.

Practical layouts of hydraulic systems to reduce spill from fish cages

In Danish:
Udarbejdet og finansieret i regi af GUDP projektet Hav-Tek journal nr. 34009-19-1526

Erik Damgaard Christensen
DTU Civil and Mechanical Engineering
2022

Table of Contents

1 Introduction

The objective of this document is to review the literature on realistic solution for collection of waste and unused feed. It is deliverable to "*D3.2.1 Notat om reelt mulige, praktisk anvendelige løsninger til danske havbrug*", as part of the HAV-TEK project: *"GUDP projektet Hav-Tek journal nr. 34009-19-152"*.

Figure 1 illustrates different challenges to open water fish farming. In Denmark, one of the major concerns relates to release of surplus nutrients to the open water through fish waste and feed. In other countries, the challenges are different. In Norway, the concern is more directed towards the risk of sea lice, spread of deceases and reducing the risk of escapees. However, in Denmark the risk of sea lice is smaller due to brackish water, while the inner Danish waters are more sensitive to excessive nutrients (nitrogen and phosphorus) due to smaller water masses, relatively low depth, and not to forget, the role of other sources, industry, agriculture, and contributions from the Baltic sea.

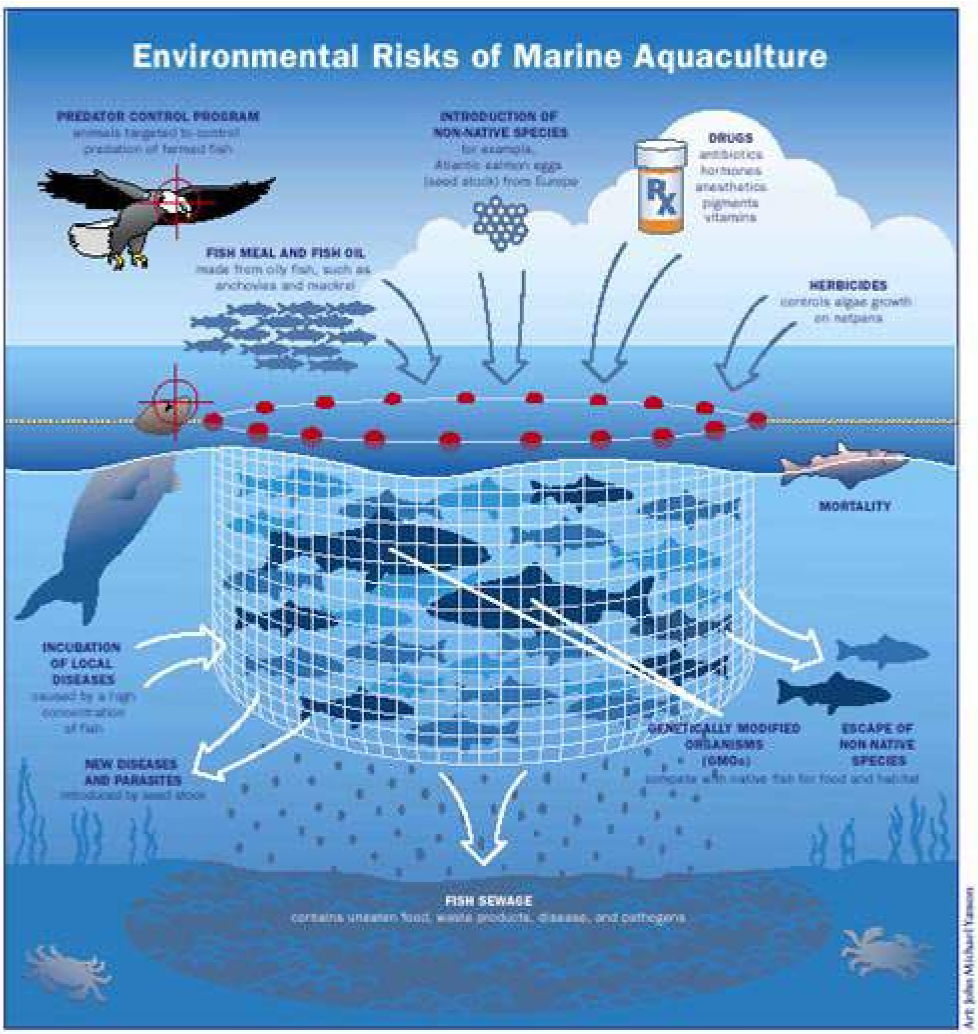


Figure 1 Illustration of the challenges that open water fish cage production faces.

In (Christensen et al., 2015) the differences between the offshore wind industry and open water offshore aquaculture were unravelled. While the most challenging issue for offshore wind industry, the cost of energy (COE) has been addressed and made offshore wind energy business, grow significantly, the aquaculture has stagnated in Denmark. The stagnation is directly related to the environmental issues and peoples perception of the industry. It is of paramount importance to address this issue if aquaculture should expand in Denmark, -and to some extend also worldwide.

Large CAPEX (Capital Expenditure) characterize the offshore wind business, while the OPEX (operating expenditure) is the key driver in aquaculture. In (Liu et al., 2016) land based of offshore aquaculture were compared as illustrated in Figure 2 and Figure 3. It is evident that the OPEX is significant for both land and offshore based aquaculture, but a small difference is seen as the share of feed in offshore based aquaculture is larger (and therefore smaller other costs). This also indicates that offshore aquaculture is more competitive to land based aquaculture, and that cost effective feed is an important key to optimise costs of aquaculture.

(Afewerki et al., 2022) reviewing the Norwegian industry stated that: *As of now, no-one knows what is going to be the production concepts used in salmon farming in the future, or even whether there will be one dominating one or several parallel concepts used.* This indicates that there is still room for innovative and tailored solutions for particular sites and conditions.

This report will review systems that can handle *sedimentation processes and collection of waste* in related industries. Different solutions already in operations and/or sketches of possible future facility designs will be presented. Finally, ideas for designs realistic in inner Danish waters will be sketched.

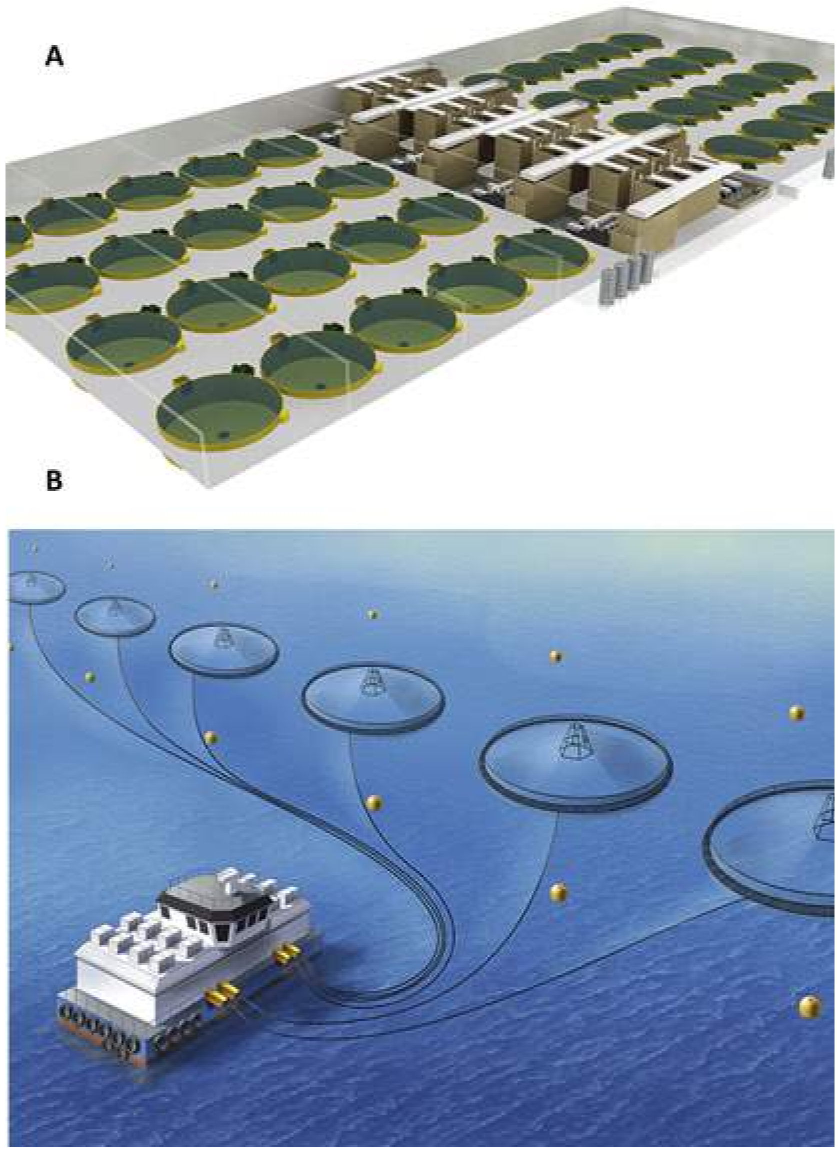


Figure 2 Land based RAS versus Offshore Net Pens, (Liu et al., 2016)

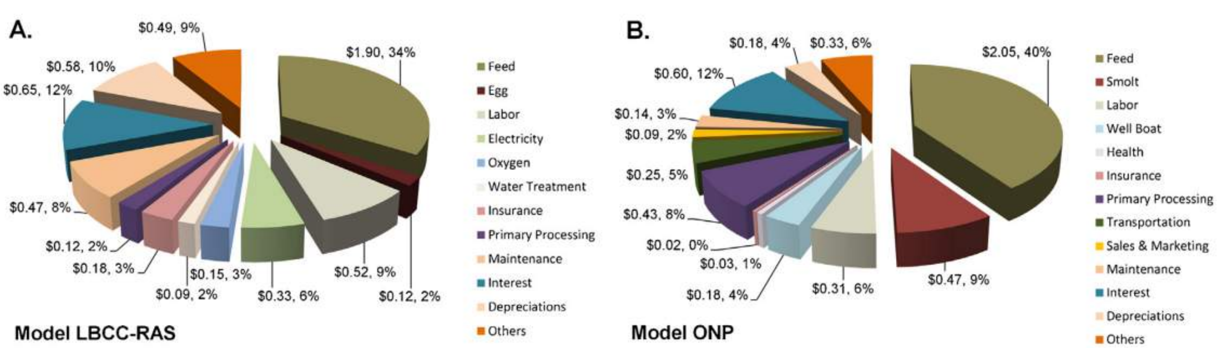


Figure 3 Expenditure for Land-based RAS system (A.) versus offshore based (B.) (Liu et al., 2016)

2 Review of methods for managing settling processes

Sedimentation processes in chemical, industrial and civil engineering is a huge area that will take too long to give a complete review off. However, a few phenomenon will be described to give a better background for topic.

Three major issues have to be considered when dealing with sedimentation processes. Is the sediment non-cohesive (e.g. sand), cohesive (e.g. clay), and whether the sediment undergo or can undergo flocculation (often used in wastewater treatment plants).

Research within non-cohesive, often sand, is a relatively well-established area. See for instance (Fredsøe and Deigaard, 1992; Soulsby, 1997) and many others, have described this area related to sediment transport in rivers and in the marine environment. Lately, the methodologies has also been used in a related field, the deposition of micro-plastic in the coastal environment, (Gokhan et al., 2022).

We split the sediment transport into bed load, q_b, and suspended load, q_s. A third type of sediment transport is the wash load. Wash load is typically fines that not always is a part of the local sediment transport mechanisms as it is freely floating. Wash load will in general be very difficult to treat in open fish cages, while in closed systems wash load can be retained using filters. Therefore, we will allow us not to address this type of the sediment. The transport loads in association with transport of non-cohesive sediments will in most cases be a combination of bed load and suspended load, see Figure 4.

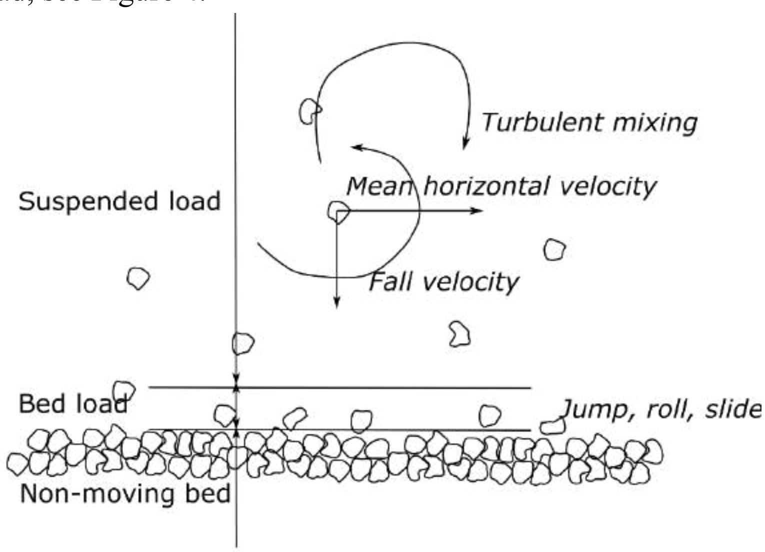


Figure 4 Sketch of the concepts for bed load and suspended load. From (Christensen, 2019).

The bed friction (shear stress) governs the bed load. The suspended load is determined by the fall velocity, turbulent fluctuations, and overall flow pattern. In settling devices the idea is basically to generate a path-way for letting the suspended sediment settle and have wall-stresses (flow) that are sufficient strong to move it to a collector.

2.1 Closed process tanks

In closed process tanks you can increase the settling of particles by having a long and slow flow. Then eventually the sediment will fall to the bottom and settle. Even though, it is simple principle, it has several drawbacks. Firstly, the tank has to be relatively large which will increase costs of the installation. Secondly, the deposited sediment will be distributed over a large area, wherefrom it can be cumbersome to collect. To address these draw backs other systems have been developed that will be shortly introduced in the following.

The lamellae sedimentation systems increases the flows pathway by lamels that direct the water flow in a certain direction. The system contain numerous inclined plates throughout the volume of the settling tank. These inclined plates act as settling beds and provide a large effective settling area for a comparatively small footprint. The lamella clarifier's operating principle was first observed by (Boycott, 1920). Boycott's effect (the acceleration of sedimentation process by tilting the settling bed), is today a well-known physical phenomenon.

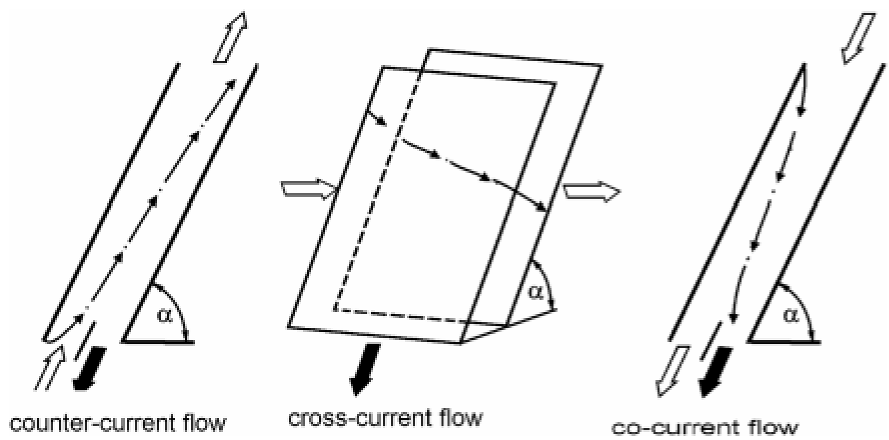


Figure 5 Sketch of lamella sedimentation systems(Hirom and Devi, 2022). *A broader introduction to lamella sedimentation systems, see* (Forsell and Hedström, 1975).

Another way of increasing sedimentation and collection of sediments is the whirlpool separator, swirl separator, or cyclone separator. The principle has been recognized for a long time and also called "the tea cup principle". Albert Einstein (yes that Einstein) published a short paper on this, in 1926, (Einstein, 1926) wrote (translated to English): *"If the liquid is made to rotate by a spoon, the leaves will soon collect in the center of the bottom of the cup"*. The phenomenon is also very important to other fields such as meandering of river bends. The meandering process is a complex interaction of flow, turbulence, and sediment transport. (Jakubowski, 2015) analysed the principle of a system based on a swirl separator. The flow that enters a circular tank generates a rotation of the flow (could also be generated by a propeller). Due to the centrifugal forces, the pressure at the sides of the tank will be higher. Near the walls and at the bottom of the tank, the flow velocities will be smaller due to boundary layer effects; the speed is always small close to a wall. Therefore, the centrifugal forces are smaller here and not in equilibrium with the pressure gradient in the main domain of the tank. This pressure gradient generate a secondary flow towards the center of the tank near the bottom. Eventually the sediment particles ends here when having a larger density than the fluid. Figure 6 show an example of the system. In wastewater treatment plants the system has often additional mechanisms to mix and separate particles from for instance foam etc.

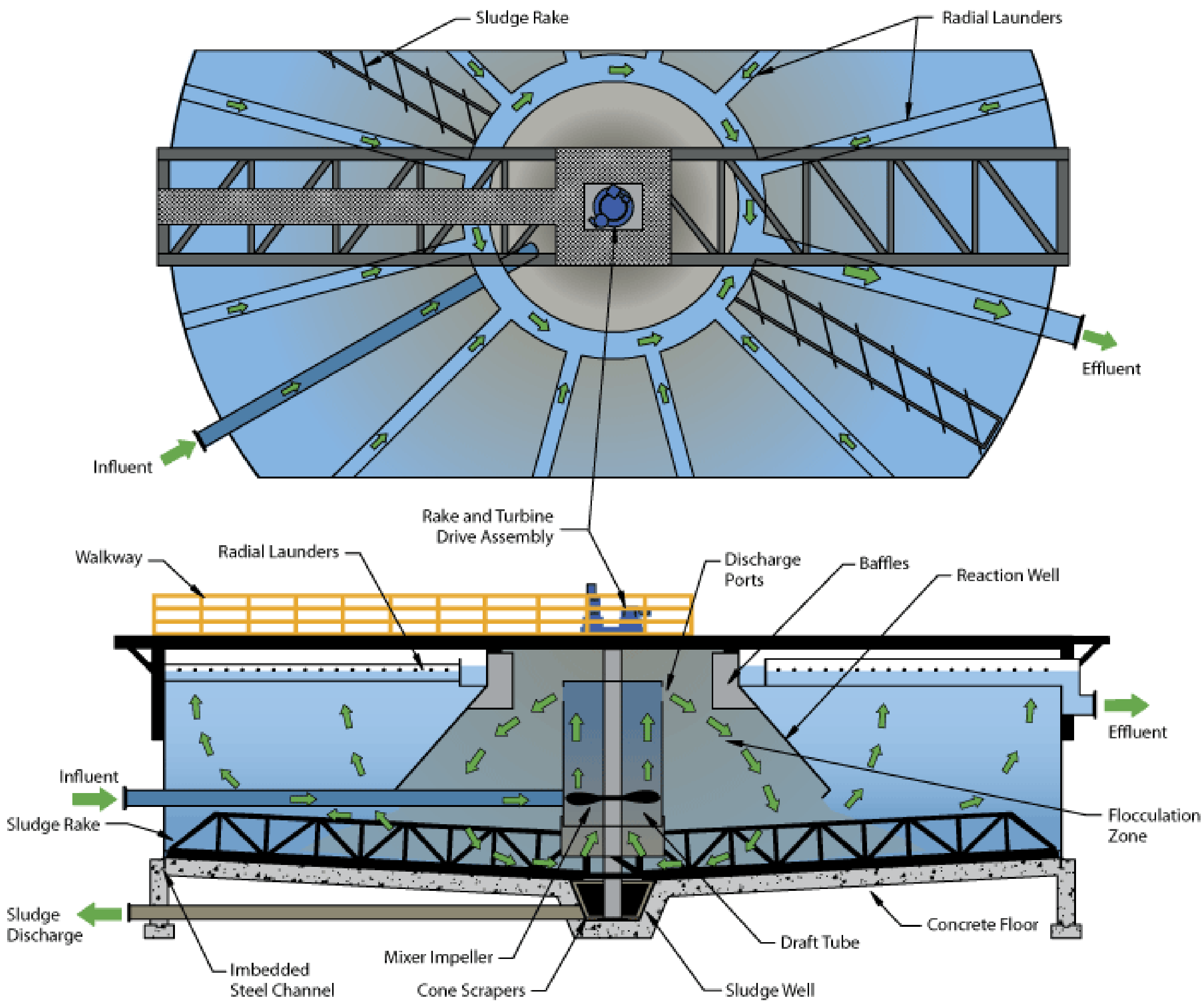


Figure 6 Waste water treatment tank partly based on the whirlpool principle, (Environmental, 2022)

2.2 Dredging and reclamation

Spillage and dispersion of dredged material into the ambient waters is one of the major environmental impacts during offshore/coastal construction and maintenance projects. Among the many adverse environmental impacts are increase in turbidity, burial of benthic life and introduction of contaminated material to the local ecosystem. The three main parameters determining the scales of the spillage and dispersion into the ambient are 1)The in situ sediment characteristics, 2) The type of dredging equipment and methods which determine the properties of the source of the spillage, 3) The ambient conditions including water depths, local currents and other external mechanisms.

If the constituents of the dredged material are mostly coarse grained (e.g. sand) with negligible amounts of fines, the spilled material settle soon and hardly contribute in formation of turbidity plumes. However, if there exists considerable amounts of fine sediment (fine sand and smaller) in the mother material, the chances are high for the spilled material to disperse, mix and form turbidity plumes which can remain in the water column for longer periods.

Using grabs or backhoes to dislodge the material increases the turbidity levels at the dredging site due to the spillage from the grab while removing the material towards the surface. Usage of closed grabs may have considerable effect in reducing this type of sediment spillage. The overflow spill from the barge is an inevitable process during dredging works. Using barges with overflow shafts rigged inside the barge (rather than overflowing from the sides of the barge to the water surface) and incorporating the Green valve (or similar techniques) to reduce the air entrainment into the overflow mixture will alleviate the mixing and hindered settling of the plumes.

2.2.1 Limiting the transport of sediment spill by enclosing the operation area

Floating silt screens are elastic barrier curtains that extend from the water surface down to a specific depth that are installed to enhance sedimentation locally on the sea bed, (Aschmoneit et al., 2020). By enclosing sediment plumes or turbid water, silt curtains allow controlled, local sedimentation. The curtain extends so deep to leave a gap above the sea bed or mud layer that allows turbid water to disperse into the surrounding sea water. Through optimal deployment of the curtain, the turbidity dispersion can be controlled under careful considerations of the ambient hydrodynamic conditions, see Figure 7. Dredging and reclamation sites often use silt screens. Other application examples include the control of sediment plumes at harbour constructions sites or at industrial water intakes (Wu et al., 2016). The relative turbidity reduction outside the enclosed area defines their effectiveness. Turbidity reduction in the ambient water of up to 90% are seen for effective silt screen applications according to (JBF Scientific Corporation, 1978).

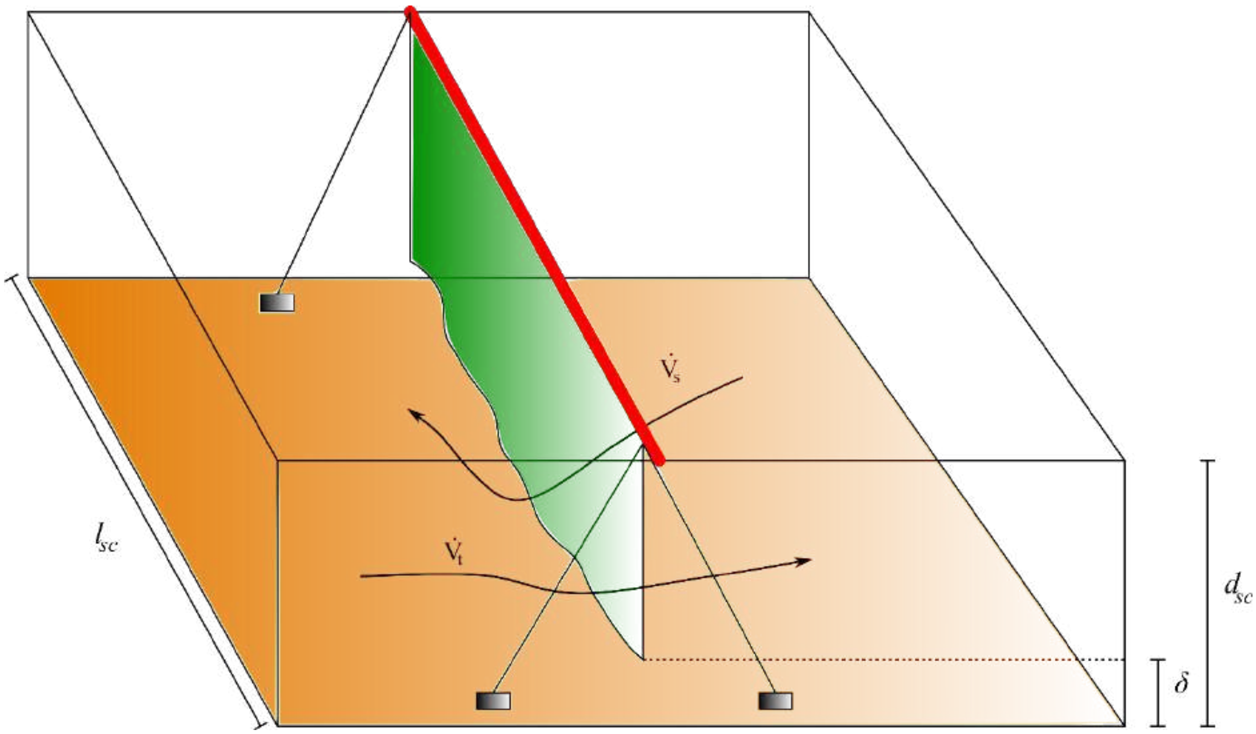


Figure 7 Sketch of the functionality of floating silt screen separating a turbid water reservoir to the left from the sea water on to the right. Reproduced from (Aschmoneit et al., 2020).

Silt screen construction and deployment have been addressed in scientific articles since the late 1970s. An extensive theoretical analysis of ideal screen design, including the screen material, its buoyant swimmers, the screen connectors, and the screen deployment, in terms of screen depth, was presented in (JBF Scientific Corporation, 1978). Vu and Tan (2010) presented experimental work on silt screen deformation for perpendicularly incident flow (cross current), concluding that the screen deployment affects the flow distribution, which might even lead to sediment entrapping. In Wu et al. (2016), a numerical analysis of the screen deployment configuration around a water intake was presented. However, this two-dimensional study did not investigate the effect of ambient currents or the silt screen depth. Yasui et al. (1999) defined the performance of screen deployment by the turbidity flux, for both floating and standing silt screens, and analysed the effect of various deployment combinations. In Radermacher et al. (2016), the cross-current of an elastic silt screen was simulated through a computational fluid dynamics (CFD) model, which is supported by investigations of small-scale experiments of the same setup, concluding that floating silt screens are not effective in cross-current applications.

Figure 8 *Example of silt curtain from* ("Aquaticengineering," 2022)

Line plumes, curtains, or screens of air bubbles are encountered in the management and engineering of water resources at different spatial scales. They have been widely used for promoting destratification and aeration in lakes (Schladow, 1992), reservoirs (Sahoo and Luketina, 2006). Bubble curtains have been installed perpendicular to the base flow in harbor entrances to prevent saltwater intrusion (Nakai and Arita, 2002), as fish barriers to stop the spread of invasive species in estuaries (Welton et al., 2002).

(Blanckaert et al., 2008) conducted experiments to study the effect of bubble curtains on, the development of a cross-stream circulation cell in a river to improve navigation depth. In this context they studied the characteristics, such as the intensity or the spanwise extent, of such a bubble generated cross-stream circulation cell and the interaction between the bubble and curvature-generated cross-stream circulation cells. The study documented convincingly that a bubble screen can generate cross-stream circulation in straight and curved flows, which redistributes the velocities and the bed-shear stress and thus would modify the bed topography. (Dugué et al., 2015) studied numerically the same problem as outlined in (Blanckaert et al., 2008). The water entrainment efficiency, defined as ratio between the vertical velocity of the entrained water and the rising velocity of the air bubbles, was estimated to be about 25%.

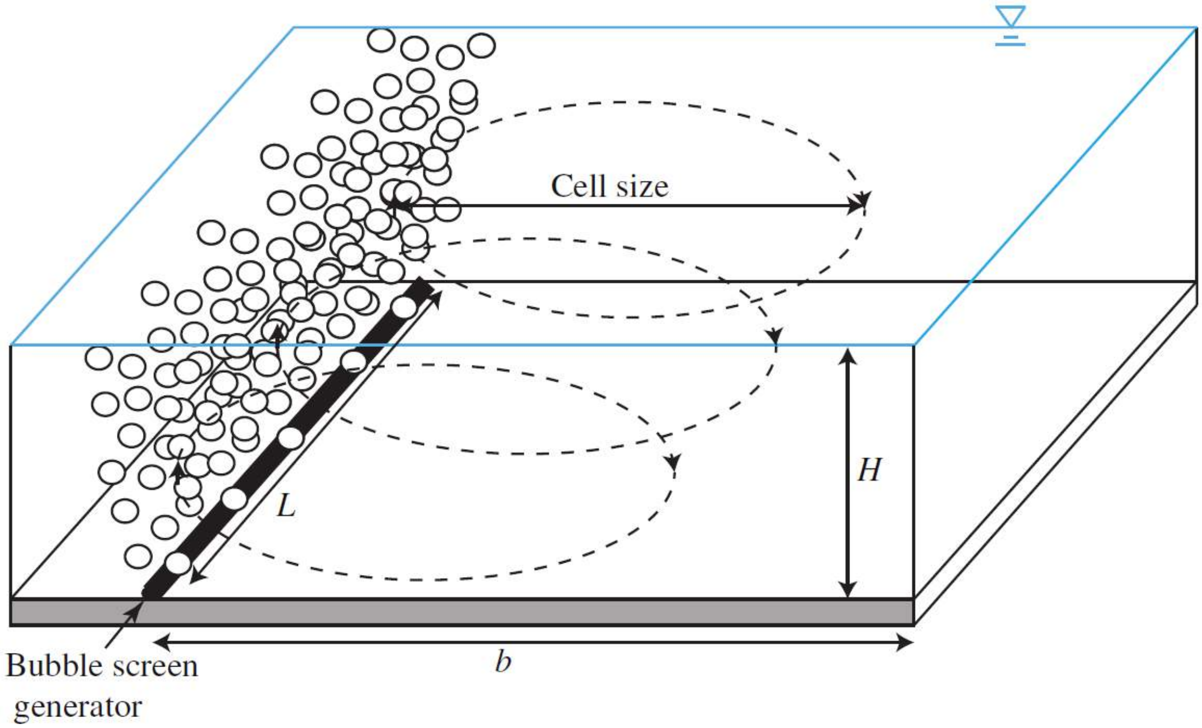


Figure 9 Illustration of the concept of a bubble screen separator. From (Dugué et al., 2015).

According to (DPS, n.d.) air curtains can be applied for numereus purposes such as:

- Mitigate damage in marine environments from noise and the effect of blasting due to mining, drilling, seismic surveys and underwater.
- Containing oil spills within a given area.
- Fish guiding and containment systems in waterways such as rivers
- Motion control and direction of floating debris.
- Silt barrier and turbidity curtains to contain sediments in suspension
- Prevention of algae and jellyfish from entering fish cages.

Figure 10 illustrates the functionality of the air bubble curtain. Several companies sell the technology and should be seen as a relatively mature industry with on the shelf-solutions for many purposes. See for instance (Davis, 2018), (CLEANERS, 2022), (Flores Martin et al., 2021), (Feiler, 2021),and (Faundez, 2020).

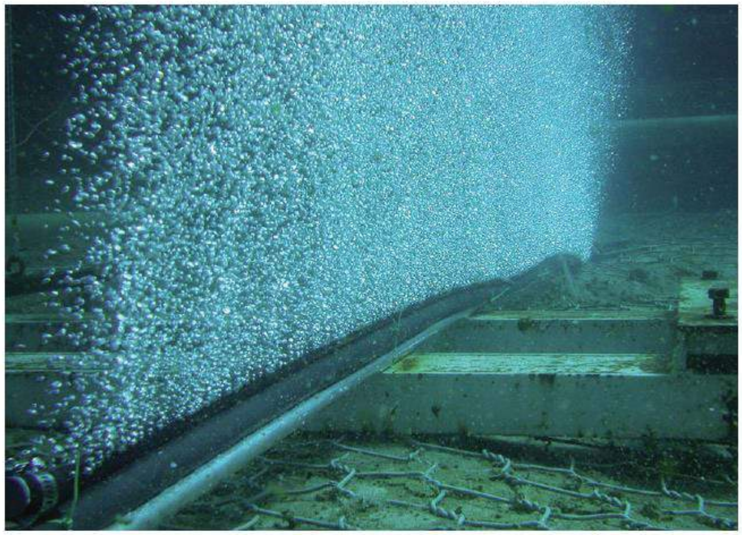


Figure 10 Example of an air bubble curtain. From (DPS, n.d.)

2.3 Conclusions

Related industries have shown numerous of solutions to collect waste or prevent intrusion of unwanted substances or species. Some of these techniques is mainly relevant for closed systems on land, swirl-technique, while other techniques is already widely use in the marine environment such as the silt-curtains and air bubble curtains. These might serve as the first way to look for a reliable system for collecting waste from fish cages.

3 Solutions from aquaculture

In this chapter, a few systems already proposed or in use in offshore fish farming will be listed shortly. These solutions should serve as inspiration for development of possible solutions for retrieving fish waste inside the fish cage and thereby significantly reducing the environmental impact from fish cages.

3.1 Closed structures

The main objective of the closed system as illustrated in Figure 11 was to eliminate attack of sea lice. Sea lice is a large problem for salmon production in for instance Norway. In (Greaker et al., 2020) two solutions was suggested; in-shore closed-cage production technology, and a genetically lice-resistant salmon. As a side effect, the solution reduces escape of fish, and has a potential for reduced loss of waste and fish pellets to ambient waters. The closed systems has been implemented in full scale, but no certain information on the reduction of waste to surrounding waters have been possible to retrieve.

(Moe Føre et al., 2022) described innovative initiatives initiated in Norway in order to attain production permits. They found that closed farms and PE-rings were the most popular concept among the application. Further, all of the concepts awarded for sheltered coastal areas were closed farms, thus containing what the applicants claim are effective barriers against sea lice, escapees, pathogens and pollution (e.g. feces and feed residues). Most of the awarded concepts are still under development and testing and will continue to be so for several years.

Due to the massive construction, the CAPAX is expected to be significantly higher for this type for system compared to net-based systems. Wave and current forces will probably be large on the structure in more open environments, while deformation under wave and current conditions will not be an issue. Wave and current loads on such structures will be relatively easy to determine knowing the correct met-ocean conditions.

Figure 11 *Example of a fully closed system from Aquafarm – Sustainable Aquaculture in Closed Fish Cages in Norway.* https://aquafarm.no/

Another, but still closed system is shown in Figure 12. In this case the walls are flexible fabric. Due to the flexible walls, wave forces on the total system, and thereby mooring systems could turn out to be smaller than for the rigid wall type sketched in Figure 11. Deformation of the walls should be expected under wave and current interaction. One on the models said to be a robust closed pen that can be installed at exposed locations with up to 2.5 meters significant wave height (highest wave in inner Danish waters often smaller than 2.5 m) and currents of up to 2 knot (1m/s). As above no certain information on the reduction of waste to surrounding waters have been possible to retrieve, but the system has been tested in full scale. CAPEX is also expected to be higher for this type of closed system. The OPEX is also expected to be larger due to expenditure for recirculation of water and handling of a more complex system compared to typical open net pens.

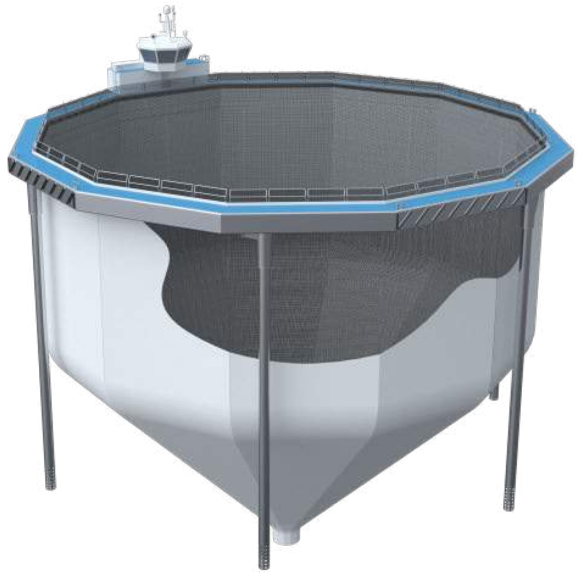


Figure 12 https://fiizk.com/en/

3.2 Semi-closed structures

In semi-closed systems, the focus is either on reducing risk from sea lice or collect waste from the production. The following examples shown in Figure 13 and Figure 14 Aqua Innovation Ltd (aquainnovations.co.uk), https://aquainnovations.co.uk/Figure 14 focus on the collection problem. Information on implemented semi-closed systems are scarce, while more information on closed systems are available in for instance (Moe Føre et al., 2022).

Both OPEX and CAPEX can be expected to be smaller than for the fully closed systems. However, the risk of waste being transported away from the fish cage is not eliminated. Depending on fall velocity of relevant particles and current velocities there will be exchange of water and waste with the ambient sea. The handling of the semi-closed systems will be slightly more cumbersome than for traditional open systems.

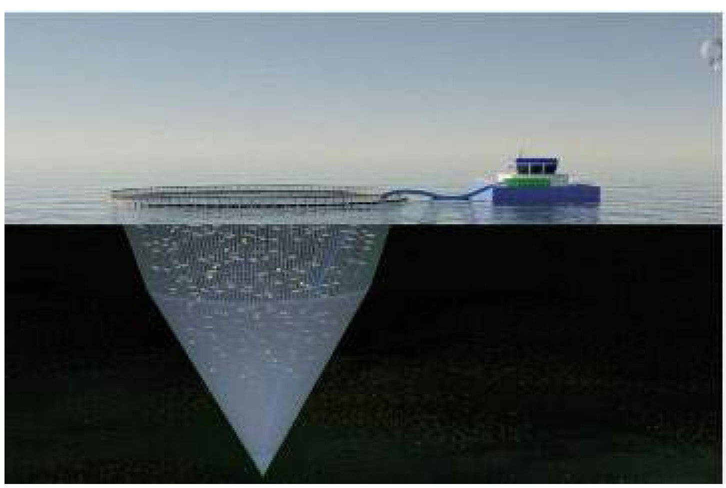


Figure 13 Semi-closed structure

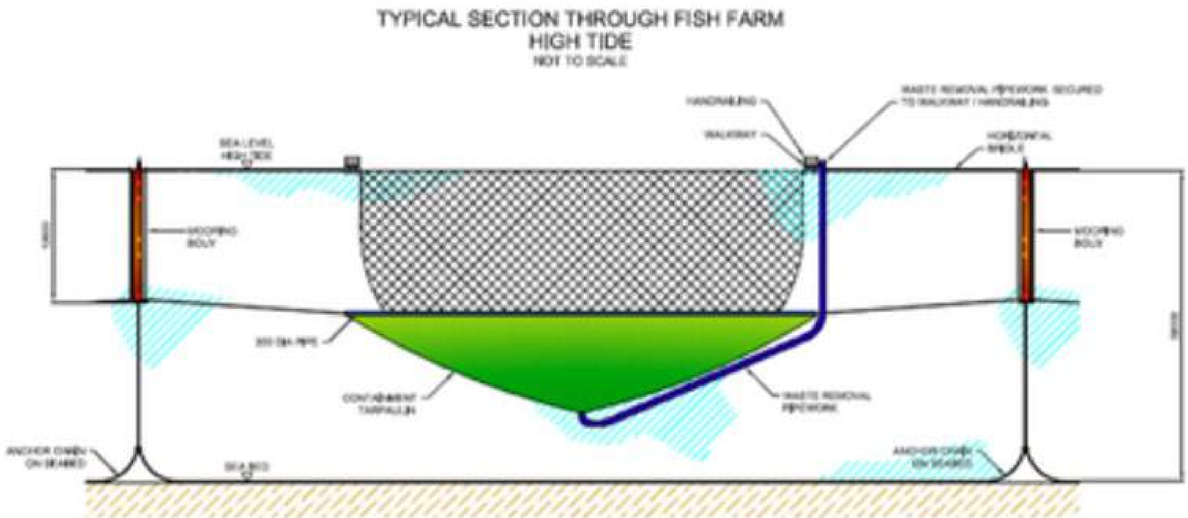


Figure 14 [Aqua Innovation Ltd (aquainnovations.co.uk)](https://aquainnovations.co.uk/), https://aquainnovations.co.uk/

3.3 Going offshore

A final opportunity to avoid the negative impact from fish farming is to locate the fish cages in sufficiently open water and thereby reducing the impact by dilution. In open seas, i.e. the Atlantic Ocean, the concentration of nutrients is in general very low. Often upwelling of nutrients a necessary source for life. It is out of scope of this report how to point out how far you have to go offshore to have a sufficiently large effect of dilution. However, when moving to more offshore sites, especially the wave forces will increase significantly, and therefore require a stronger design. See for instance (Buck et al., 2018) and Figure 15 and Figure 16. (Moe Føre et al., 2022) also described large open facilities as part of the Norwegian innovation initiatives.

Figure 15 *Example of exposed offshore aquaculture. From* (Buck et al., 2018)

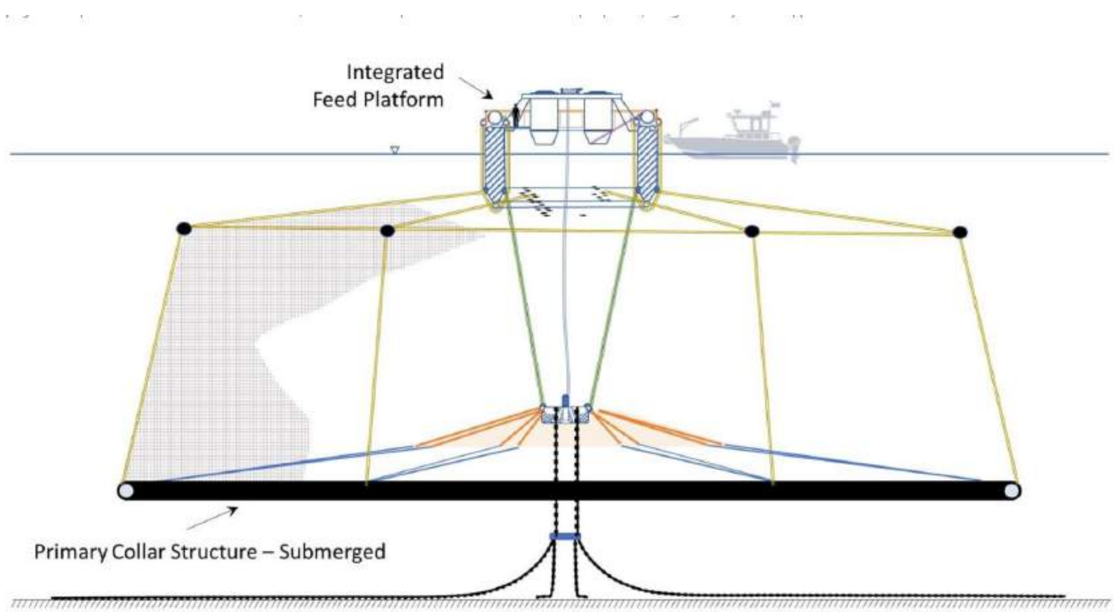


Figure 16 Idea from https://www.impact-9.com/ for an open water fish cage system.

4 Sketches of possible solutions

Some of the closed system solutions that were presented in the previous chapter could potential be a solution for inner Danish waters. They need to be adjusted to the conditions in Denmark as they aimed to reduce the risk of sea lice. In the inner Danish waters the risk of sea lice is small due to brackish water, while the environmental impact from a surplus of nutrients can be significant. The CAPAX and OPEX would eventually be significantly closer to land based systems.

Combinations of semi-closed systems with other systems to control sediments could potentially reduce the CAPAX and OPEX of closed systems. In this work, the hypothesis is that most efficient way would be to combine air-bubble systems with the semi-closed system. Such a system would potentially work fine for moderate ocean current velocities and waves, but less effective for stronger currents and waves. Therefore, the feeding is suggested stopped under these conditions. Fish will be able to survive for a shorter period without food.

4.1 Air bubble curtain with semi-closed system

Figure 17 illustrates an idea of combined semi-closed system with a circular air bubble curtain. As the air bubble curtain already is used to keep unwanted particles and species out of on open fish cage it can keep waste inside the fish cage. The design can to some extend rely on technology already available. As the chance of fish cage net is a common procedure in aquaculture the extra operation of handling the waste collector and air bubble diffuser system appears manageable.

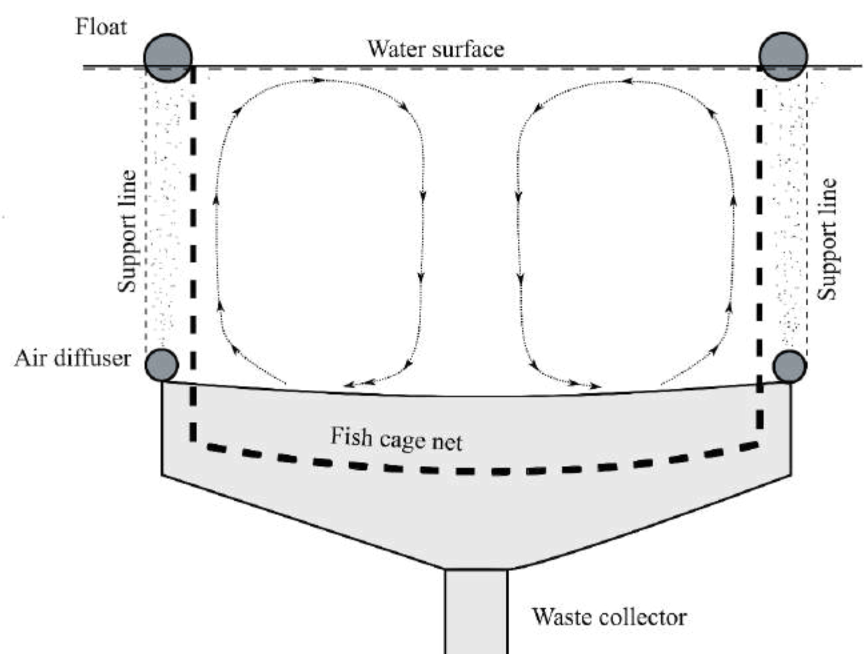


Figure 17 Combination of air bubble curtain with semi-closed system © Erik Damgaard Christensen

Pros:

- Can be further developed based on already existing technology.
- The extra operation is manageable as the operators already are able to replace net under during production.
- The fish cage is open and expected to exchange water with high oxygen content with surrounding sea.

Cons:

- Will increase CAPAX and OPEX
- The air bubble might have a negative effect on fish welfare. For instance, too high nitrogen levels in deeper areas of the net.
- Might limit feeding fish under strong wave and current conditions.

4.2 Air diffuser combined with semi-closed system.

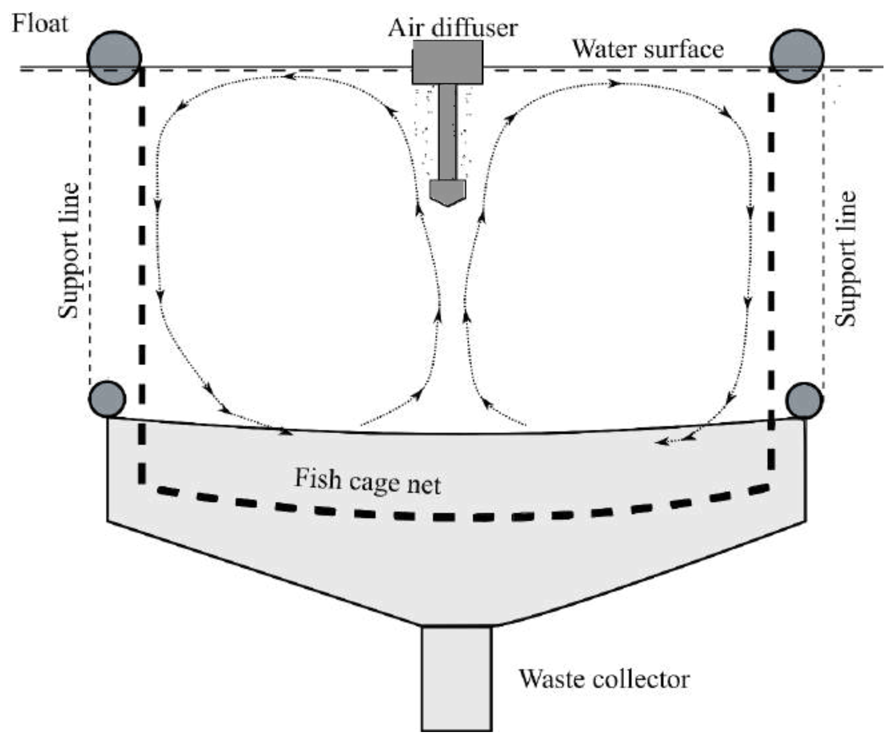


Figure 18 Combination of air diffusor with semi-closed system © Erik Damgaard Christensen

The combination of a centred air-diffuser and semi-open fish-cage attempts to mimic the tea-cup principle. The secondary flow will have some similarities with the secondary flow in a swirl-separator. However, as Figure 18 shows, the fish cage will be open to the surrounding sea. This could lead to flow leaving the fish cage in the upper layers while entrained in the lower layers. Depending on fall velocities of waste, turbulence levels and the strength air bubble induced secondary flow the system collects and deposits waste in the middle of the closed part. A bad designed system spreads the waste to the surrounding sea. A propeller could be an alternatively to air bubble diffuser.

Pros:
- Can be further developed based on already existing technology.
- The extra operation is manageable as the operators already are able to replace net under during production.
- The fish cage can easily exchange water with high oxygen content with surrounding sea.
- The air-diffuser will have a very little negative impact on fish welfare.

Cons:
- Will increase CAPAX and OPEX.
- It might be difficult to achieve a sufficiently large effect with a centred air diffuser.
- Even moderate to strong wave and current conditions might limit fish feeding.

5 Summary and future perspectives

This note reviewed relevant processes in related industries for waste collection from open water fish cages. Most interesting technologies are the use of swirl technique, silt curtains and air diffusers. The swirl technique is difficult to use directly in an open or semi-open fish cage. Instead, this can be mimicked with an air bubble diffuser (or propeller). Commercial technologies for air bubble curtains are available. With some modifications, these might be combined with semi-closed systems. All systems will increase CAPEX and OPEX.

Closed systems developed for reduction of sea lice has also shown positive side effects to reduce environmental impact. An adjustment of closed systems could turn out to be the easiest way to collect waste from open water systems. Again, this will increase CAPEX and OPEX and the increase will probably be larger than for semi-open systems. Eventually the closed systems ends up with similar characteristics as land-based systems that is another alternative not investigated in this project. Finally, fully open cages but far offshore systems is another alternative not investigated in this project. The first offshore systems far from shore have been implemented in Norway for salmon. The development should learn from experiences from Norwegian innovative tests, still ongoing, as described in (Moe Føre et al., 2022).

The future perspectives of waste collection points in the direction of a combined demonstration and development project. Such a project should consist of:

1) Initial inception phase,
2) Laboratory and desk studies,
3) Selection phase of the preferred one or two solutions for full scale testing, and
4) Finally full scale testing.

One closed system and one semi-open system adjusted for the conditions in shallow water as in the inner Danish waters are seen as the most promising candidate systems for full scale testing. The scale of such a demonstration and development project is on a larger scale than possible in this project. However, the solutions has the potential to solve one on the most important issues in open water aquaculture, the environmental impact.

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