Recapturing sludge from Atlantic salmon production in closed containment systems in the sea

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Sammendrag

Oppsamling av slam fra lukkede oppdrettsanlegg i sjø åpner nye muligheter. Mulighetene for å samle opp slam (fôrspill og faeces) i lukkede sjøanlegg (CCS), kan gi redusert miljøpåvirkning sammenlignet med konvensjonell produksjon av atlantisk laks i åpne merder. Det finnes teoretiske slamretensjons estimeringer for slike system, men faktisk slamgjenvinning under kommersiell produksjon er ikke-eksisterende. Derfor ble dette vitenskapelig studert på en kommersiell sjølokalitet, der parallelle lukkede Ecomerd system er koblet til en slamutskiller. Gjenfangstsystemet benytter en partikkelfelle kombinert med mekanisk filtrering for seperasjon av vann og partikler. Basert på konsentrasjonene i slammet ble det beregnet at dette systemet kan gjenvinne ~11% tørrstoffet, 3 % av nitrogenet, 9 % av fosforet og 8 % av det organiske karbonet fra det produserte utslippet. Det analyserte slammet har lavt innhold av tungmetaller, og det er derfor ikke begrensninger knyttet til bruk i landbrukssektoren som gjødsel. Denne studien viser at lukkede oppdrettsanlegg i sjø med slamoppsamling kan redusere utslipp til resipienten.

Summary

The ability to collect waste feed and faeces from closed aquaculture systems in the sea (CCS) has been highlighted as an environmental advantage. Theoretical sludge collection efficiencies are available, yet efficiencies during commercial scale CCS production are almost nonexistent. Therefore, this was scientifically studied at a production site using parallel Ecomerd CCS systems connected to a sludge separator. The collection system utilizes a particle trap combined with mechanical filtration for separation of water and particles. Based on the analyzed concentrations in the sludge it was calculated that the system recaptures ~ 11% of the solids, 3 % of the nitrogen, 9 % of the phosphorous and 8% of the organic carbon from the produced waste. The collected sludge was classified as low in heavy metals, hence there are no restrictions in the agricultural/green areas where it could be

used as a fertilizer. The study shows that CCS with sludge collection can reduce discharge to the recipient.

Introduction

Early test productions in closed aquaculture containment systems (CCS) in the sea along the Norwegian coast have showed promising environmental and biological results (i.e. Storsul et al. 2021; Øvrebø et al. 2022). Environmental benefits of CCS compared to open sea cages include reduced sealice exposure and improved ability to collect waste feed and faeces which in turn can be further utilized (Ytrestøyl et al. 2013). However, there is a general lack of documentation on the sludge retention efficiency of these systems, particularly how they perform on a commercial scale. This documentation is important to optimize the way these systems operate as well as offering realistic data to the environmental authorities. Reduced discharge of nutrients and particulate organic matter is one of the claimed environmental benefits from CCS, but to what extent this is possible needs documentation. Data on this matter will be of great importance for regulating agencies, farmers, and businesses with an interest in utilizing sludge recovered from fish farms.

To manage waste discharge, the first and most important step is to remove solid waste (e.g. fecal waste or spilled feed) from the farm effluent before it is discharged. Ideally, all waste particles should be captured in the sludge removal system, and the final sludge should have a high dry matter content so that further transport and handling does not involve large amounts of water (Cripps and Bergheim, 2000). Collecting waste from open sea cages is challenging to say the least, and commercial technologies for doing this on a large scale is very limited/none-existent, even though the interest to utilize sludge is increasing (PwC 2023; Del campo et al. 2010). From most land-based farms, however, sludge is collected. In closed systems at sea fish are mainly separated from the external environment by an impermeable barrier and technologies that trap or direct waste towards outlets can be adapted. Yet, there are several challenges in sludge collection in these systems compared to land-based production, one aspect is the large water exchange which often requires a dual drain outlet, where the particles are trapped at the bottom in reduced water flow, whilst most of the water is evacuated through a drain in the center or a combination of center drains and side drains.

The main aim in this study was to assess sludge retention efficiency at a commercial Atlantic salmon production site for post-smolts in CCS. The total discharge to the recipient with regards to solids, carbon and nutrients was assessed. This study also considers the variations in wastewater and sludge production throughout a day since feeding was restricted to daylight

Ecomerd closed containment system in production at a Mowi site in Matersfjorden (left). The LiftUP sludge collection system on the barge (right). Foto: Sara Calabrese (NIVA) hours only. To assess the potential to use the sludge as a fertilizer, sub-samples of sludge were classified according to the Norwegian regulations for fertilizer products of organic origin.

Material and methods

Experimental site, production and sludge system

The study was performed at a Mowi facility in Matersfjord in southwestern Norway. At the site two Ecomerd systems are in use (Figure 1). Each Ecomerd (EM) has a volume of 30 000m³ and takes in water from 36m via six pumps. Each pump has a capacity of 5167 m³/h. Smolts (89-170 g) were transferred to EM1 on the 18th of December and EM2 was stocked on the 20th of December 2022. Fish were produced in the system for roughly 3 ½ months before transferred to an open sea cage as post-smolts (372 – 615 g). Fish were fed with Mowi commercial feed (5 mm) to satiation daily. Feed was offered as several meals between approximately 7:30 to 16:30 (Figure 2). Each EM was fed with slightly different feeds therefore these systems were studied separately. Production parameters such as fish biomass and feeding are given in table 2.

The EM system has a dual draining system; 99% of the water exits directly to the recipient via a main water outlet (Fig. 1). Suspended solids (feed spill and faeces) are converged with a particle trap to a wastewater drain, from which discharge is pumped up to a Framo LiftUP sludge separator (Fig. 1) on the barge. Through several filtration steps including a drumfilter (pore size: 300µm) and beltfilter (pore size: 300-500 µm) waste is concentrated, and the produced sludge is stored in a tank on the side of the barge (fig. 1). The reject water i.e., the remaining water after sludge removal is discharged to the recipient.

Sampling procedures

During two field studies, suspended solids and nutrient concentration in the wastewater and in the sludge removal process was assessed. The field studies took place at two time points, Feb. 27Th– 1st March (mean water temperature 7,8 °C) and March 13th-15th (mean water temperature -->8,3 °C). During these two studies the sludge removal process from both EM were sampled, one at a time. This was done by first flushing the system with sea water and then connecting just one EM to the sludge separator. Samples were collected according to the timeline in figure 2, sludge sampling relied on the belt filter cycle which varied with load etc. therefore times are not exact, however it was attempted to be as consistent as possible between EM`s and field studies, the last sample from each EM was

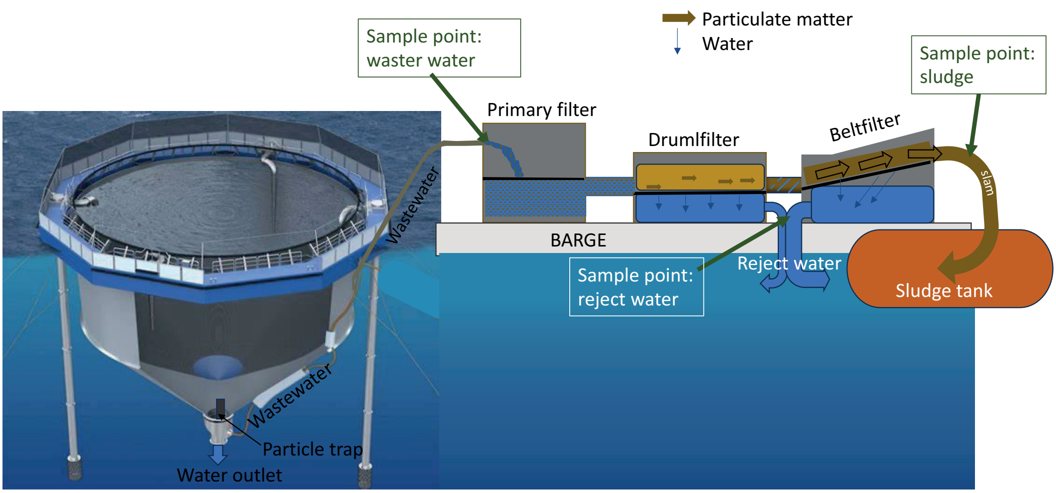

Figure 1. Simplified overview of the Ecomerd (on the left) and the most important filtration steps in the LiftUP sludge collector.

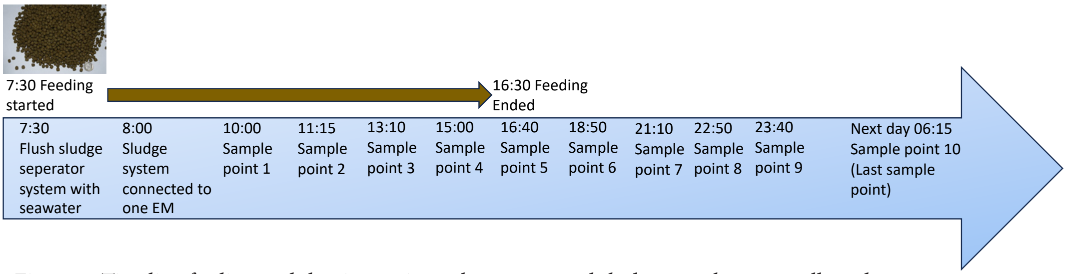

Figure 2. Timeline feeding and the time points when water and sludge samples were collected.

collected at 6:15 AM (Figure 2). EM 1 was sampled for the first 24 hr period and then the system was flushed and EM2 was connected and sampled at the same timepoints for the next 24 hr period.

Wastewater was sampled from the pipe that connects the EM to the sludge separator before the primary filter (Figure 1). Samples were collected by filling a 10L bucket, every few minutes. The 10L bucket was emptied into a 60L tub. This was done for 10-15 min. Replicate samples were collected from the tub after stirring thoroughly. This sampling procedure was done since a large variation in solids content was noticed within a short time span. **Reject water** was collected from a tap mounted on the reject water pipe that empties into the fjord. The sample was collected when the drum- and belt filter were running (Figure 1). To sample the final **sludge,** a hose was mounted on the pipe from the belt filter to sludge tank (Figure 1). Approximately 30 L of sludge was collected in a 60L tub and replicate samples were collected from the tub after stirring thoroughly.

Water chemistry and sludge analysis

All wastewater and sludge samples were analyzed for total nitrogen (N), total phosphorus (P), organic carbon (TOC) and suspended solids (TSS) or dry matter content (DM). Additionally, from the last sampling point during the field trails (6:15 AM), sludge samples were also analyzed for content of heavy metals: lead (Pb), mercury (Hg), nickel (Ni), copper (Cu), chromium (Cr), zink (Zn), copper (Cu) and salt content. All analysis were performed by Eurofins Environment Testing Norway AS according to accredited methods.

Mass balance calculations

To calculate discharge and the cleaning efficiency for tot-P, tot-N and TOC, the calculation model used by the county governor office in Vestland was applied (Equation 1). This model is widely applied in land-based production of smolt and post-smolts in Norway. This mass balance calculation is based on the amount feed used (kg), the biomass of fish produced and predetermined standard values of total N, total P and TOC in the feed and what is assimilated in the fish. Data from chemical analysis of sludge (%TS, N, P and TOC) are inserted into the model, to estimate gross and net discharge and sludge removal efficiency.

(1) Sludge separator efficiency = (Gross discharge-net discharge)/Gross discharge) *100

Results and discussion

Suspended solids, carbon and nutrients: Wastewater and reject water

The water chemistry analysis revealed no difference in the concentration of TSS, TOC, P and N in the wastewater between EM1 and EM2, despite the almost doubled biomass in EM1. When comparing field trial one towards two there was a trend for lower outlet concentrations of TSS and TOC during field trial two, however only P and N were significantly lower during the second field study ($p<0{,}05$; results not shown). Compared to the first field study all parameters (TSS, TOC, P and N) were lower in the reject water during the second field trial ($p<0{,}05$; results not shown). During field study one it was observed that the water leaving the beltfilter contained remains of sludge, therefore the speed of the belt filter cycle was turned down, increasing the process time after the first field study. This seemed to be effective and likely explains that concentrations of TSS, TOC, N and P were lower in the reject water during field study two.

Diurnal variation

It was expected that concentrations of nutrients and solids would increase throughout the day with feeding and a period after feeding as the feed is metabolized and excreted, also that concentrations would be the lowest at 06:15 the next day before feeding started up again. However, this pattern was not clearly observed and there was no pronounced diurnal variation in the concentrations of TSS, TOC, P and N in the wastewater that was consistent between the two field trials (Figure 3). The only pattern that was observed, that seemed to be related to feeding, was an increase in all parameters from around 15:00 with a peak around 22:30 in EM1 and an increase from 22:25 and a peak at 6:15 the next morning in EM2, during the first field study (Figure 3). The increase in concentrations of suspended solids, carbon and nutrients in wastewater in the evening/night after feeding has stopped is likely due to increased excretion as the feed is metabolized, other studies with post-smolt Atlantic salmon show that gastric evacuation after a single meal is between 6-14 hours (Sveier et al. 1999; Handeland et al. 2008). Since the feed has a higher concentration of nutrients compared to feces, the increased feed-spill and intact pellets observed in the wastewater in EM1 during the first field study could explain why the patterns are different between the two EM`s.

Wastewater vs. reject water

The overall (pooled values both field studies and both EM`s) concentrations of suspended solids, carbon and nutrients between the outlet (wastewater) and the reject water were compared as an approximate performance estimator of the sludge separator and to document the concen-

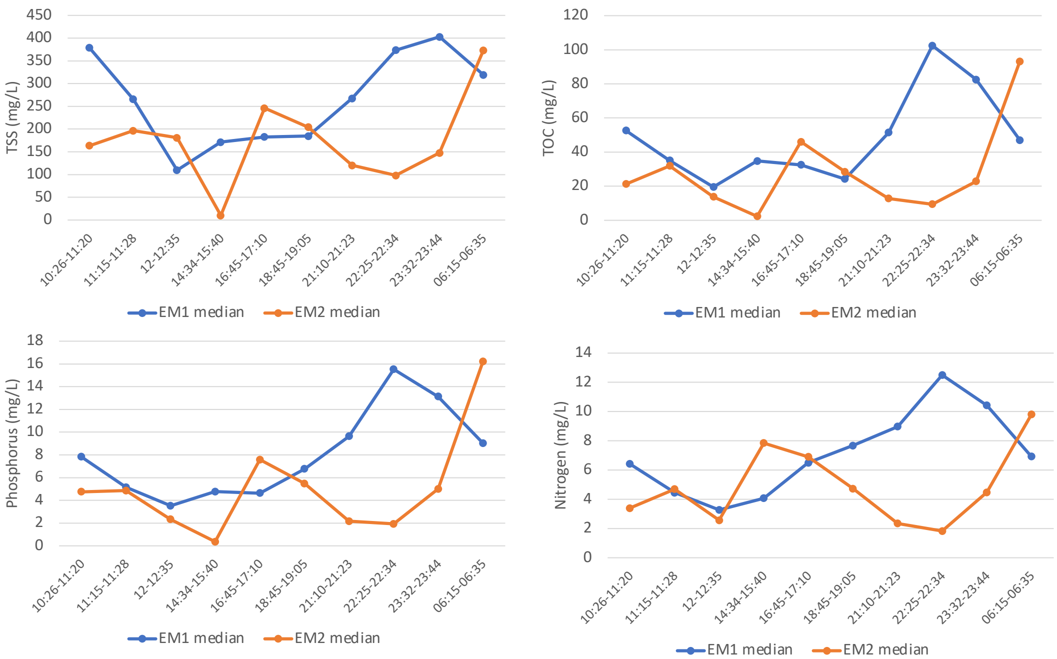

Figure 3. Median concentrations of Total suspended solids (TSS mg/L), Total organic carbon (TOC mg/L), Total phosphorous (P mg/L) and Total Nitrogen (N mg/L) in the wastewater from Ecomerd 1 (EM1) and 2 (EM2) over a 20 hour period monitored during two field studies.

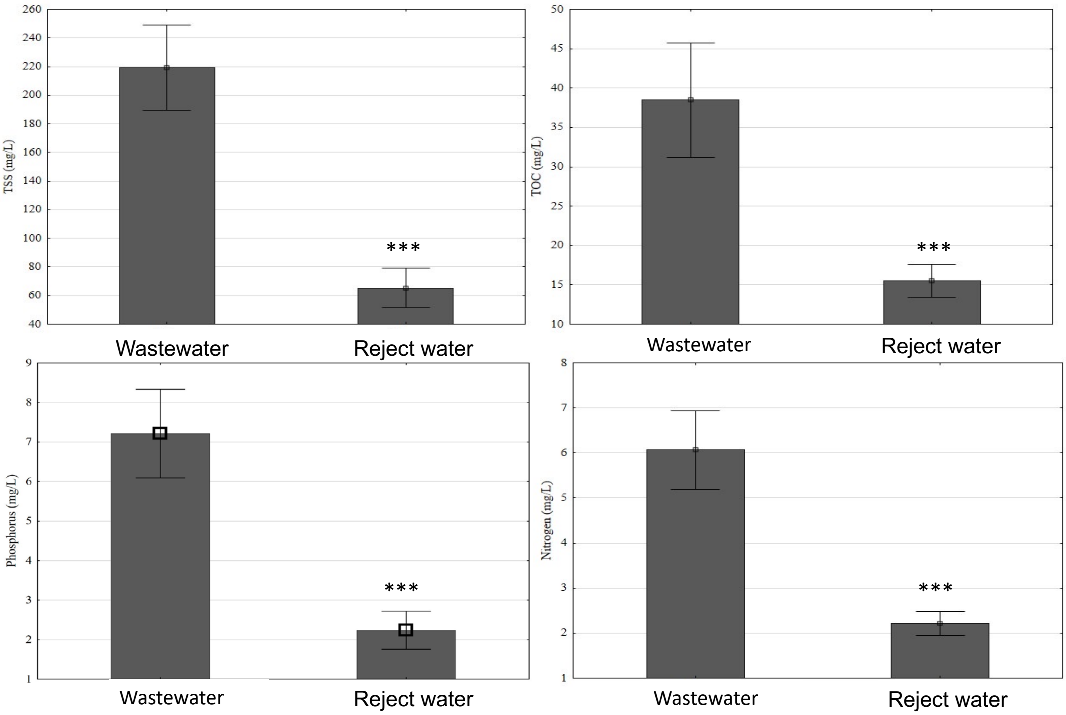

Figure 4. Concentrations of Total suspended solids (TSS mg/L), Total organic carbon (TOC mg/L), Total phosphorous (P mg/L) and Total Nitrogen (N mg/L) in the wastewater and the reject water; values from both field studies and both *Ecomerds pooled (student`s t-test *** indicates a significant difference at the level of P<0.0005).*

trations of these parameters in the reject water that is released to the recipient. This is an approximate sludge separator performance indicator as the reject water is slightly diluted with seawater for the spray nozzles in the filters. TSS was reduced from 220 mg/L in the wastewater to 65 mg/L in the reject water and a similar three to fourfold decrease was also achieved for TOC, P and N (Figure 4).

Dry matter content and nutrient content: Sludge

Ten replicate sludge samples were collected during each field study (Figure 2). The analysis of these sludge samples reveals that the dry matter content (% DM) was significantly higher in dewatered sludge from EM1 compared to EM2 during the first field trial, and also compared to EM1 during the second trial (Figure 5). For reference, the DM content of the dewatered sludge was 16 % in EM1 during the first trial and was 9,5 % during the second field study (Figure 5). The higher TS% in dewatered sludge from EM1, field study one, is likely caused by greater feed-spill and a higher number of intact pellets in the sludge on this occasion. In EM2 (both studies) and EM1 (second trial) the DM in dewatered sludge was approximately 10%, hence 10% might be the realistic DM content of the dewatered sludge under normal circumstances, with little feed waste. TOC and nitrogen content of the sludge followed a similar trend (Figure 5). In contrast phosphorous concentration (mg/kg dry matter) was lower in dewatered sludge from EM1 compared to EM2 on both occasions. This might be explained by the fact that fish in each EM were fed different types of feed, in which the phosphorus content may have differed.

Diurnal variation

Similar to the wastewater, there were no consistent daily patterns in the concentrations of TSS,

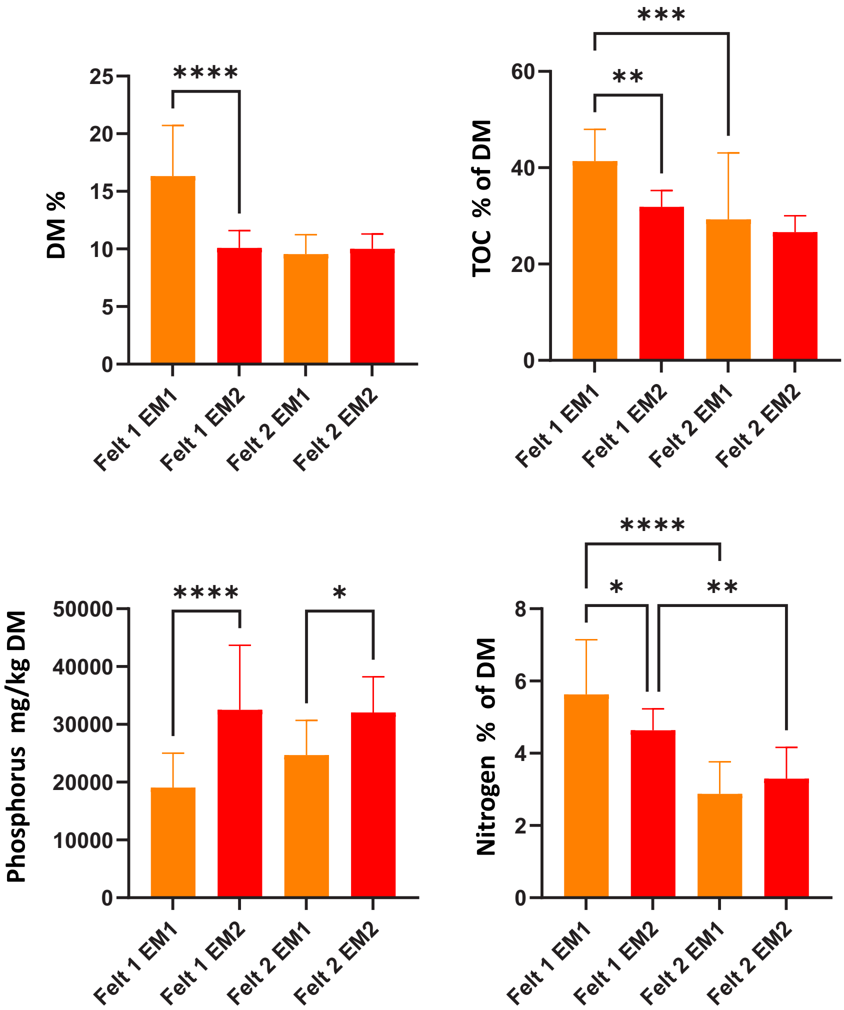

*Figure 5. Dry matter content (TS %), Total organic carbon (% of dry weight), Total phosphorous (P mg/kg dry weight) and Total Nitrogen (% of dry weight) in dewatered sludge collected from the Ecomerd (EM) system during two field studies. Significant differences (P<0,05) between EMs and/or field studies (Felt) are indicated with * (one-way ANOVA).*

TOC, P and N in the sludge. Neither between the two EM`s nor the two field studies.

Sludge quality and fertilizer classification

To assess sludge quality according to Norwegian regulations of fertilizer products of organic origin, an in-depth analysis of the sludge was performed on replicate sludge samples that were collected from each EM (n=4) during the field studies. These samples were collected during the last sampling point at approximately 6 AM before feeding started (Figure 2). This was done to minimize the amount of intact feed pellets in the sludge. Results are presented in Table 1. The quality classification of the sludge is based on the content of heavy metals, which class the sludge falls within further decides the amount of the sludge that can used for certain purposes (Fertilizer regulations: §10. Quality standards). The sludge from both EM systems contained relatively low levels of heavy metals, concentrations are similar or slightly lower than previously found in sludge samples from RAS (Hess-Erga et al. 2022). For lead (Pb), mercury (Hg), nickel (Ni), copper (Cu) and chromium (Cr) all samples were within the quality class 0. The mean concentration of cadmium in the sludge was 0,72 mg/kg dry matter and mean concentration of zinc was 399 mg/kg dry matter (Table 1), so both these metals are within quality class 1. Hence, there are no restrictions in the areas (agricultural land, private gardens, parks, green spaces) the sludge can be used as a fertilizer (§27. Quality requirements and applications). However, since both cadmium and zinc are in class 1 there may be restrictions in the quantity that can be used. Sludge intended for use as fertilizer coming from aquaculture must also declare salinity (salt content), the mean salinity in the sludge samples calculated from conductivity from these two Mowi operated systems was approximately 40 ppt.

Discharge and sludge separator efficiency

To calculate the overall discharge for the two EM during the production period, mean values of all analyzed sludge parameters (38 replicate samples) were used. Total sludge production, feed and biomass data were provided by Mowi. During this production period, a net-biomass of 528 tons was produced (biomass out- biomass in), and fish were feed 613 tons of feed, resulting in a feed conversion ratio (FCR) of 1,16 (Table 2). From the whole production cycle 180 tons of

Table 1.Results from the extended sludge analysis of samples collected during the last sampling round (6:15 AM) from both field studies.

Parameter	Unit	Ecomerd 1 (EM1)	Ecomerd 2 (EM2)	Quality class according to fertilizer regulations (max value in mg/kg DM for the class)
		Average (n=4)	Average (n=4)	
Dry matter (DM)	%	11,075	9,425	
pH measured at 23 +/- 2°C		6,4	7,0	
Conductivity (measured at 23 +/- 2°C)	mS/m	602,5	605	
Salinity in sludge (*calculated)	ppt	40,2	40,4	
Chloride (Cl)	mg/kg dry matter (DM)	90950	183500	
Aluminium (Al)	g/100 g DM	0,014	0,020	
Boron (B)	mg/kg DM	92	115	
Phosphorus (P)	g/100 g DM	2,2	3,6	
Iron (Fe)	g/100 g DM	0,10	0,18	
Calsium (Ca)	g/100 g DM	4,5	7,4	
Manganese (Mn)	mg/kg DM	105	135	
Sulfide (S)	g/100 g DM	1,31	1,225	
Arsen (As)	mg/kg DM	<3,4-<7,1	<3,4-<7,1	
Palladium (Pb)	mg/kg DM	<3,4-<7,1	<3,4-<7,1	0 (max 40)
Cadmium (Cd)	mg/kg DM	0,71	0,72	I (max 0,8)
Copper (Cu)	mg/kg DM	11,5	15,625	0 (max 50)
Chromium (Cr)	mg/kg DM	<3,4-<7,1	<3,4-<7,1	0 (max 50)
Mercury (Hg)	mg/kg DM	0,064	0,0435	0 (max 0,2)
Nickel (Ni)	mg/kg DM	<3,4-<7,1	<3,4-<7,1	0 (max 20)
Zinc (Zn)	mg/kg DM	315	482,5	I (max 400)

Table 2. Input data on the overall production provided by Mowi

Ecomerd	EM1	EM2	Total for both systems
Production period	18.12.2022-01.04.2023	20.12.2022-15.04.2022	
Total feeding (kg)	370 194	242 806	**613 000**
Produced biomass (kg)	319 529	208 473	**528 002**
Feed conversion ratio	1,16	1,16	
Make up water (MUW; m^3/day)	487 989	487 989	**975978**
Cumulative feed burden (kg feed/m^3 MUW	0,007	0,004	**0,01**
Sludge produced (kg)			**180 000**
Dry matter (kg) recaptured			**20 520**

Table 3. Specific discharge of N, P and TOC and the recapture efficiency of sludge remover for the overall production. Results are obtained using the county governor, Vestland discharge model with average values from sludge sample analysis from field studies and input data on feed, biomass, pump capacity (intake and outlet) from MOWI.

	Nitrogen (N)	Phosphorus (P)	Total organic carbon (TOC)
Gross discharge (kg)	29 836	6 180	85 125
Net discharge (kg)	29 011	5 624	78 558
Specific discharge (kg/ ton biomass)	55	11	149
Specific discharge (g/ kg feed)	47	9	128
Specific discharge (g/m^3 MUW)	0,3	0,1	0,7
Recapture effciency (%)	2,8	9	8

sludge was produced (Table 2). The mean dry content of all dewatered sludge samples collected was 11,4 %, or 20 520 kg DM in total, an equivalent of 33g recovered DM /kg feed that was added to the system. According to the model, this will produce the following net discharges to the recipient: 29 015 kg of N waste, 5 626 kg of P waste and 78 558kg of TOC waste (Table 3). The specific discharge was found to be 47g N/kg feed, 9 g P/kg feed and 128g TOC/kg feed. Overall, this gives an estimated recapture efficiency of the sludge of 3 % for N, 9 % for P and 8% for TOC (Table 3).

In this study the estimated recapture efficiency of the N, P and TOC from waste produced during production of salmon in CCS was approximately 30% of what has been achieved in land-based recirculating aquaculture systems (RAS) (Økland and Rosten, 2023). However, RAS farms operate with much lower water exchange rates of makeup water (MUW) and a higher number of dewatering filter areas than what is possible for floating CCS systems. In addition, newer RAS farms usually have several dewatering steps and are not solely dependent on mechanical filtration for removing particles. In a report including discharge from all land-based farms (both flow-through and RAS) in Vestlandet in the period 2017-2021, sludge and discharge rates within and between farms was highly variable (Hess-Erga et al. 2022). The high variability in dry matter and nutrient content in the sludge from land-based production could be due to the technology used for production (RAS vs. flow-through), technology for sludge collection, feed type and feeding strategies (Cripps and Bergheim, 2000), however variation is also likely due to an unsystematic sampling regime and frequency (Hess-Erga et al. 2022). Interestingly the recapture efficiency of the total produced solids, N, P and TOC was only slightly lower from the EM sea systems compared to the land-based farms in Hess-Erga 2022, which is surprising since only 1% of the water that exits the system passes through the sludge separator. However, in similarity to the land-based farms in Hess-Erga 2022, data from this study demonstrates that relative to the estimated produced waste using the county governor model, and the planned and theoretical sludge collection ability only modest amounts of sludge are in fact collected.

The estimated total discharge of N, P and TOC in kg/tons biomass, was ~35% higher in the present study than the reported mean discharge from land-based farms (Hess-Erga et al. 2022). This is presumed to be due to the huge water flow through the system with dual drains, where a significant portion of the production water is not processed through the sludge separator. Dissolved and very diluted, metabolites will have the opportunity to exit through the main water drain. However, it needs to be considered, that due to the huge volumes of water in the EM systems, the release rate of N, P and TOC per cubic meter that exits the systems (Table 3) and enters the recipient is low compared to a concentrated plume release.

Conclusion

Water samples collected before and after the sludge separation process reveal a three to fourfold decrease in the concentrations of TSS, TOC, P and N in the water rejected to the fjord compared to the wastewater. Some diurnal variations were observed in concentrations of suspended solids, carbon and nutrients in the wastewater; however, these were not consistent between field studies. From the total waste produced during a production cycle of Atlantic salmon post-smolts (~3 ½ months) the estimated recapture efficiency of the sludge separator was 3 % for N, 9 % for P and 8% for TOC. Overall, this shows that closed sea systems with sludge collection can reduce waste discharge to the recipient. However, the extent of recapture is significantly less than what is achieved in land-based RAS using newer technologies for sludge removal and likely much lower than the projected amounts of sludge expected to be collected. The discharge produced exits as reject water from the sludge separator, but also as dissolved waste through the main water drains of the EM`s. The high exchange rate of water in the EM systems gives a low specific discharge of TSS, TOC, N and P per m^3 of water that enters the recipient, i.e. low local load. Furthermore, the analyzed collected sludge from the CCS systems was classified as low in heavy metals, with no restrictions in the agricultural/green areas the sludge can be used as a fertilizer.

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