Received: 9 February 2022 | Revised: 14 April 2022 | Accepted: 13 May 2022

DOI: 10.1111/are.15919

Aquaculture Research WILEY

ORIGINAL ARTICLE

Investigation of growth performance of post-smolt Atlantic salmon (*Salmo salar* L.) in semi closed containment system: A big-scale benchmark study

Tarald Kleppa Øvrebø[1,2] | Pablo Balseiro[2,3] | Albert Kjartan Dagbjartarson Imsland[2,6] | Sigurd Olav Stefansson[2] | Ragnar Tveterås[4] | Harald Sveier[5] | Sigurd Handeland[2]

[1]Akvaplan-Niva Bergen Office, Bergen, Norway

[2]Department of Biological Sciences, High Technology Centre, University of Bergen, Bergen, Norway

[3]High Technology Centre, NORCE, Uni Research, Bergen, Norway

[4]Department of Business Administration, University of Stavanger, Stavanger, Norway

[5]Lerøy Seafood Group ASA, Bergen, Norway

[6]Akvaplan-niva Iceland Office, Kópavogur, Iceland

Correspondence

Albert Kjartan Dagbjartarson Imsland, Akvaplan-niva Iceland Office, Akralind 4, 201 Kópavogur, Iceland.
Email: albert.imsland@akvaplan.niva.no

Funding information

This project was supported by the Research Council of Norway through projects CtrlAQUA SFI, Center for research-based innovation (project number 237856) and KABIS (Kapasitetsløft for bærekraftig og innovativ sjømatproduksjon, project number 280782)

[Corrections added on 9 June 2022, after first online publication: the order of the authors has been updated.]

Abstract

The Norwegian salmon industry faces challenges related to sea lice (*Lepeophtheirus salmonis*) infestations, escapees, diseases and environmental impact. Semi-closed containment systems (S-CCS) have been proposed to abate these challenges. In the S-CCS, cultured fish are separated from the natural environment by a physical barrier, reducing the time fish spend in open sea cages. Production data from six cohorts of salmon were used to compare growth and performance of fish raised in S-CCS and in open sea cages (control group) incorporating different seasons. The study was carried out in two phases. Phase one used post-smolts from approximately 100 to 800 g in seawater, and fish in S-CCS were compared with a reference group from an open sea cage. The second, grow-out phase covered the size range from approximately 800 to 5000 g in open sea cages; here fish previously reared in S-CCS were compared with fish from a control group. The study showed a significantly lower infestation of sea lice in S-CCS (0.02–0.04) fish compared with the control group (0.18–0.62) during the post-smolt phase. Furthermore, in the grow-out phase the S-CCS group showed higher growth rate and higher final weight (4680 g [spring], 4890 g [fall]) for the S-CCS group compared with the control group (3800 g [spring] and 4080 g [fall]). Salmon raised in S-CCS showed significantly higher survival compared with the control group in open pens, indicating increased resilience in fish raised in S-CCS when transferred to open net pens in sea. It is concluded that S-CCS have advantages compared with exposure to the natural environment in open pens in western Norway.

KEYWORDS

Atlantic salmon, open net pens, growth, post-smolt, sea lice, semi-closed containment systems

1 | INTRODUCTION

In 2018, nearly 1.36 million tons of farmed fish were produced in Norway, with the production of Atlantic salmon accounting for 95% of the total aquaculture volume, making Norway the largest producer of Atlantic salmon in the world (Statistics Norway, 2019). However, the governmental projections is to achieve a five-fold increase in aquaculture production by 2050, presuming sustainable environmental growth (Olafsen et al., 2012). But challenges concerning pathogens, diseases and sea lice (Abolofia et al., 2017), escapes and is possible negative effect on wild stocks (Anon., 2011; Costello, 2009a, 2009b; Glover et al., 2012) have lead to stagnation in production volume. A key factor in abating the current challenges of open sea cage farming is to reduce the open sea cage period. This reduction will reduce the exposure period to challenges such as sea lice and diseases. In addition, larger smolts are more resilient and capable of handling the transfer to open net pens in seawater (Ytrestøyl et al., 2015).

The Atlantic salmon is now referred to as post-smolt until it reaches a weight of 1 kg (Hjeltnes et al., 2017). The post-smolt phase in open seawater is considered to be the most critical, due to physiological and environmental challenges such as adaptation to seawater, exposure to pathogens and suboptimal water conditions. Consequently, 20% of the smolt transferred to sea cages are lost before reaching harvest size (Hjeltnes et al., 2017). To mitigate this situation, it has been suggested that farmers should produce larger and more robust post-smolt as a strategy to reduce production-related losses in open sea cages (Hagspiel et al., 2018). Hence, innovative technologies are emerging in the aquaculture industry, making it possible to move part of the post-smolt phase to land-based, closed, recirculating aquaculture systems (RAS) or using floating semi-closed containment systems (S-CCS) in the sea (Thorarensen & Farrell, 2011). One examples of floating semi closed systems in sea is the Preline raceway platform (Preline Fishfarming system and Lerøy AS). Introduction of these systems could have an impact on limiting the environmental challenges, which include sea lice infestations, outbreak of diseases, escapes, organic waste and delousing agent pollution. In addition, the temperature profile will differ between an S-CCS system and an open sea cage system during the season. The temperature in seawater (surface) during summer is higher in an open net pen compared with S-CCS and is the opposite during winter. These variations in temperature will affect growth and feed conversion in fish during seasons (Talbot, 1993). Utilizing water from low layers, allows for more stable conditions (temperature and salinity) that might have a positive effect on the welfare and growth of the fish (Rosten et al., 2011). The S-CCS system may also reduce central environmental challenges, such as organic waste emissions, spreading of sea lice and escapees (Rosten et al., 2011). Recent studies have shown a low mortality rate for post-smolt reared in closed containment systems with optimal density (Calabrese et al., 2017; Ytrestøyl et al., 2015). Further investigation of the biological performance in terms of growth, feed conversion, mortality and resilience of Atlantic post-smolt reared in S-CCS is required to assess the application of this technology.

This study investigates the use of floating S-CCS (Preline) in six grow-out stockings of commercial post-smolts production where the smolt were reared in the S-CCS system prior to grow-out in open sea cages. The aim of the current study was to determine whether different rearing conditions (S-CCS and open net pens) growth of farmed Atlantic salmon.

2 | MATERIALS AND METHODS

2.1 | Experimental fish and conditions

In all cohorts (Table 1), the eggs were incubated at approximately 8–10°C. The alevins were first fed approximately 390-degree days (d°C) post-hatching, in 6 m tanks (circular, green, fibreglass, rearing volume 75 m^3) at constant light and in heated water (approximately 13–14°C).

To stimulate parr-smolt transition, a traditional photoperiod regime was conducted for all cohorts (Handeland & Stefansson, 2001). The treatment included a decrease in day-length from LD24:0 to LD12:12 for 5 weeks, followed by another 4 weeks on LD24:0. At the end of photoperiod treatment, fish in all cohorts showed typical morphological and physiological changes characteristics of smolting, including dark fin margins and silvery scales and high gill NKA activity (McCormick, 1993; Stefansson et al., 2003). When the fish had completed the parr-smolt transformation, the group was split into two equal-sized groups (S-CCS and control group) and transferred to seawater by a well boat within 3 weeks.

2.2 | Experimental design

The fish used in this study were 0+ and 1+ Atlantic salmon smolts of the Salmobreed strain produced by Lerøy Sjøtroll AS (Hordaland, Norway) from hatching to the smolt stage.

Before seawater transfer, each cohort was divided into two groups: Preline (S-CCS) and control group. The groups were then followed through two experimental phases:

TABLE 1 Summary of rearing conditions in freshwater stage (cohort, strain) and production data (smolts, incubation temperature, degree days; from fertilization to first feeding, first feeding date, rearing temperature)

Cohort	Smolt (0+, 1+)	Incubation temperature	Degree days	First feeding date	Rearing temperature
Cohort 1	1+	7.4°C	824	11.05.14	10.2°C
Cohort 2	0+	7.5°C	914	14.02.15	15.1°C
Cohort 3	1+	7.4°C	810	08.05.15	10.1°C
Cohort 4	0+	7.4°C	902	18.02.16	15.0°C
Cohort 5	1+	7.5°C	826	13.05.16	10.2°C
Cohort 6	0+	7.5°C	915	09.02.17	15.1°C

2.2.1 | Phase 1. Post-smolt in seawater

In the period from May 2015 to February 2019, a total of six cohorts of salmon post-smolts were transferred from freshwater to seawater rearing systems (S-CCS and control) by well boat. Cohort 1, 3 and 5 were stocked during spring, and cohort 2, 4 and 6 were stocked during fall.

In phase 1 the S-CCS groups were reared for 4–6 months. Rearing conditions are shown in Table 2.

2.2.2 | Phase 2. Grow-out phase in seawater

After undergoing post-smolt phase (4–6 months), the S-CCS fish were transferred by a well boat to a new location equipped with traditional sea cages for a further grow-out phase (Figure 1), where they grew 10–12 months (final weight phase 1) to 3360–5700 g (final weight phase 2). The grow-out experiment lasted until the first of the two groups (S-CCS and control) were slaughtered. Rearing conditions for this part of the study are shown in Table 3.

2.3 | Experimental facilities: S-CCS system (preline)

The six S-CCS groups were stocked at the Lerøy Vest AS facilities at Sagen (60°20.903′ N 5°38.640′ E) in the Trengereidfjord, Samnanger in Hordaland (S-CCS). The S-CCS consisted of a 50 m-long raceway platform with an elliptical cross-section (Figure 2). The S-CCS has a rearing volume of 2000 m^3 with a max water flow of 400 m^3/min. The inlet water was pumped from a depth of 30 m (total depth 100 m). At each end of the system, propellers create a continuous water flow through the raceway and the water exchange rate was approximately 4–5 min (current 12–15 cm/s, Vector 3D acoustic Velocimeter, Nortek AS, Norway). Oxygen concentrations, temperature and feeding were controlled by automatic systems, and all data were registered daily (OxyGuard, Sterner). Daily water measurements were taken in the inlet and outlet drain, and commercial dry diet (Ewos raid air) was fed from automatic feeders. The pellet was designed to have a longer retention time in the system. All husbandry practices, including lice count, were conducted following the standard protocol for salmon rearing for Lerøy Vest AS.

TABLE 2 Location, capacity, area and coordinates of the experimental facilities

Location	Capacity (tons)	Location number	Municipality	Coordinates
Bognøy	1560	13209	Alver	60°37.923 N′ 5 29.731 E'
Buholmen	5460	11543	Austevoll	60°11.255 N′ 5 0.48919 E'
Djupevika	3900	20455	Kvinnherad	60°2.457 N′ 6 0.5620 E'
Hestabyneset	3120	18015	Tysnes	59°57.218 N′ 5 27.084 E'
Rongøy	4680	29276	Øygarden	60°30.560 N′ 4 55.902 E'
Sagen	780	32137	Samnanger	60°20.903 N′ 5 38.642 E'
Sauøy	3120	11758	Øygarden	60°35.637 N′ 4 51.675 E'
Skorpo	3120	32877	Bjørnafjorden	60°10.399 N′ 5 17.621 E'
Tobbholmane	3120	100054	Austevoll	60°1.459 N′ 5 18.489 E'

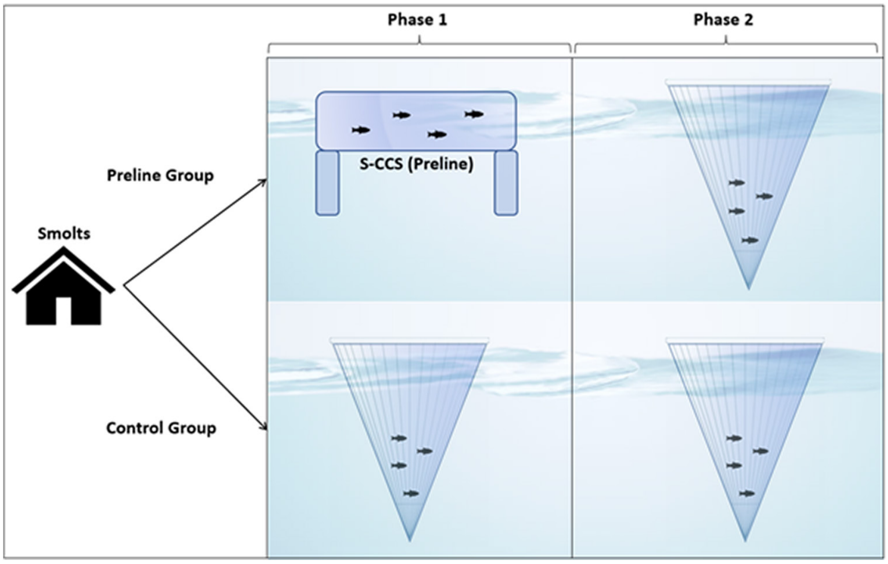

FIGURE 1 Schematic setup of the experimental protocol; phase 1. Post-smolt in seawater (S-CCS and control). Phase 2. Grow-out phase in seawater (S-CCS and control).

TABLE 3 Summary of rearing conditions in six cohorts of post-smolt in phase 1

Period of deployment	Cohort Group	Location	Fish *N*	Temperature (°C) Mean	Min	Max	Oxygen saturation (%) Mean	Min	Max
May 2015	Cohort 1 Control	Rongøy	191,378	11.9	7.4	16	83.2	66	96.5
May 2015	Cohort 1 S-CCS	Sagen	157,283	9.7	8.3	14.2	90.6	75	100
Oct 2015	Cohort 2 Control	Tobbholmane	191,740	7.9	5.1	12.1	92	85	105
Oct 2015	Cohort 2 S-CCS	Sagen	158,761	10.4	6.9	12.5	81	71	93
May 2016	Cohort 3 Control	Skorpo	164,286	14.8	8.7	21.7	96.4	74	105
May 2016	Cohort 3 S-CCS	Sagen	156,273	9.6	7.5	16	95.5	75.3	97
Nov 2016	Cohort 4 Control	Bogno	162,390	7.9	5.4	11.8	100	75	105
Nov 2016	Cohort 4 S-CCS	Sagen	92,643	9.8	6.4	11	79.3	73	97
Apr 2017	Cohort 5 Control	Sauøya	146,338	10.2	6.9	14.5	98.4	86.4	105
Apr 2017	Cohort 5 S-CCS	Sagen	218,363	10.2	8.2	13.5	96	86.5	105.5
Oct 2017	Cohort 6 Control	Bogno	177,105	7.9	3.4	12.2	98	76.2	105.7
Oct 2017	Cohort 6 S-CCS	Sagen	287,435	8.2	5	10.6	87	78.5	95

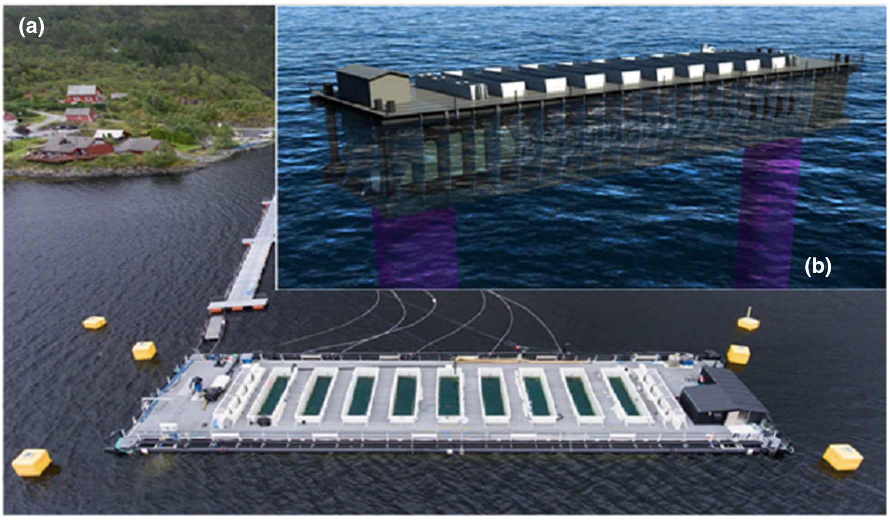

FIGURE 2 S-CCS system placed at the Sagen location (a) and a 3D model (b) of the platform. Photo: (a) Lerøy Vest AS, (b) preline Fishfarming System AS.

2.4 | Experimental facilities: conventionally open sea cages

The control groups were reared in open 160 m conical circular sea cages. Each fish farm consisted of six to 10 circular cages with a rearing capacity of up to 200,000 Atlantic salmon each. All the open cage facilities in this experiment are located along the Western Norwegian coast (Table 2). A timeline of the stocking period is shown in Figure 3.

During the experimental periods, all husbandry practices, including sea lice counting, were conducted in accordance with standard Atlantic salmon production protocol for Lerøy Vest AS. The fish were fed a standard dry diet (Ewos, Norway) in relation to environmental temperature and fish size (Austreng et al., 1987). To avoid early maturation (Imsland et al., 2014), all groups were exposed to continuous artificial led-light (35 W/m^2, submerged) from mid-December to the end of June. Temperature and oxygen (Tables 3 and 4) were measured daily at −3 m by automatic sensors (OxyGuard, Sterner), and all environmental data were registered in Fishtalk (AkvaGroup, Bryne, Norway).

2.5 | Data collection

Biological production data and environmental data were collected regularly (daily and weekly) from May 2015 to February 2019 and included six cohorts of Atlantic salmon, from smolt to slaughter (S-CCS and control). Parameters included and investigated in this study are (1) growth (daily), (2) feed conversion (daily), (3) mortality (daily), (4) sea lice infestations (weekly), and (5) biomass estimation. All the measurements were conducted according to regulations for Norwegian aquaculture.

Daily calculations on weight gain based on feed output were completed by FishTalk™. Recent studies of the 3rd generation in the S-CCS system have shown that the estimations based on feed output (FishTalk™ calculations, FCE = 1.2) correspond very well with the weight measurements that were conducted during the post-smolt phase (Moe, 2017). In short, the procedure was as follows: Following transfer to sea-pens (well boats), the total number of fish in all groups were counted. In addition, individual fish weight were measured (N = 200) and biomass calculated. On daily basis during

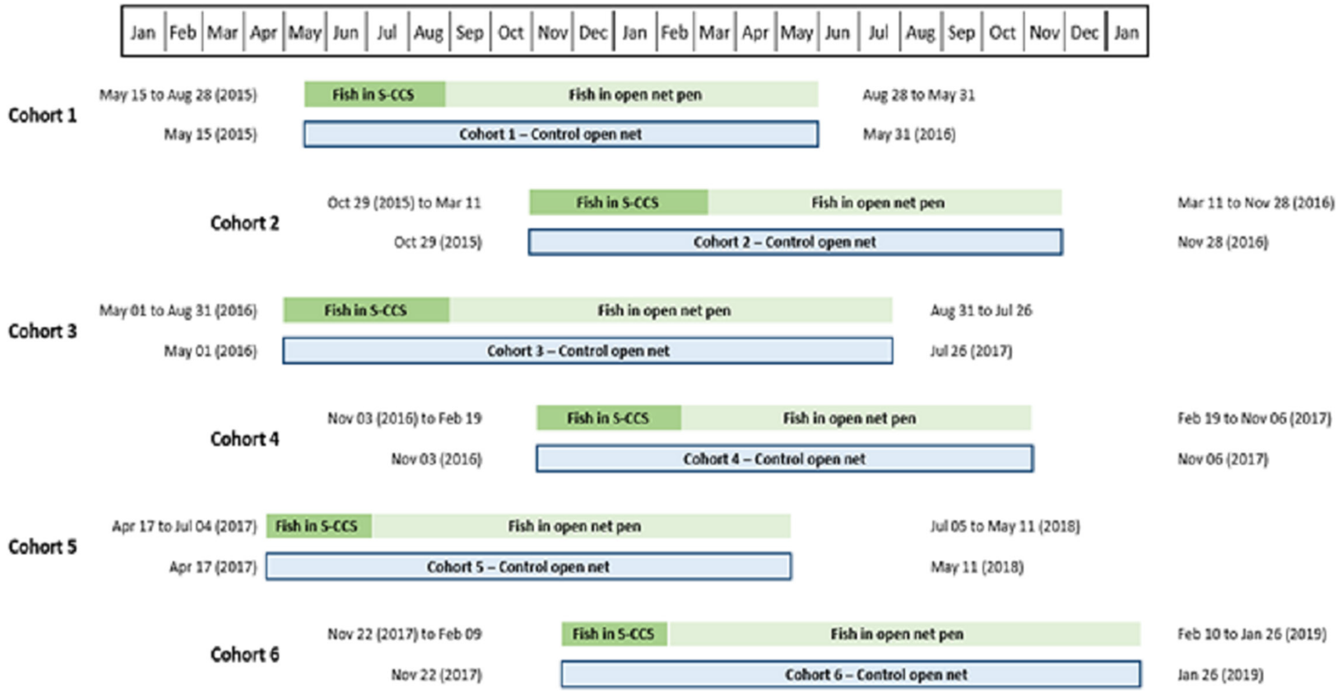

FIGURE 3 Period of stocking for the six cohorts in the experimental period from May 2015 to January 2019. The dark-green rubric represents fish reared in the S-CCS system (Cohort 1, 3 and 5 represents spring stocking and Cohort 2, 4 and 6 represents fall stocking), and the light-green rubric represents the following grow-out phase in open sea cage until harvested. The blue rubric represents the control group reared in a conventional open sea cage over the same periods in each cohort.

TABLE 4 Summary of rearing conditions in six cohorts during phase 2—grow-out. S-CCS fish are now transferred to open net-pen facilities

				Temperature (°C)			Oxygen saturation (%)		
Period of transfer	Cohort group	Location	Fish *N*	Mean	Min	Max	Mean	Min	Max
Aug 2015	Cohort 1 Control	Rongøy	147,383	9.4	4.56	15.1	83.2	66.7	100.9
Aug 2015	Cohort 1 S-CCS	Djupevika	139,182	9.2	5.2	15.4	90.6	74	105
Mar 2016	Cohort 2 Control	Tobbholmane	178,886	11.6	5	17	92	95	105.8
Mar 2016	Cohort 2 S-CCS	Hestabyneset	142,703	11.7	5.2	17.1	81	83.3	93
Sep 2016	Cohort 3 Control	Skorpo	119,118	9.7	3.9	17.2	96.4	74.1	105
Sep 2016	Cohort 3 S-CCS	Buholmen	139,924	9.8	4.9	16.9	95.5	75.3	105
Feb 2017	Cohort 4 Control	Bogno	152,635	11.2	5.9	17.4	100.5	75	105.8
Feb 2017	Cohort 4 S-CCS	Rongøy	77,465	11.7	5.9	16.2	79.2	73	97
July 2017	Cohort 5 Control	Sauøya	111,177	9.5	2.8	15.9	98.4	86.4	105
July 2017	Cohort 5 S-CCS	Djupevika	208,944	9.0	2.7	16.3	96.1	86.5	105.5
Feb 2018	Cohort 6 Control	Bogno	133,304	9.79	2.9	17.3	98	76.2	105.7
Feb 2018	Cohort 6 S-CCS	Hestabyneset	119,033	10.3	4.9	17.8	87	78.5	95

grow-out, dead fish were removed and number of fish in each pen continually adjusted. Daily food rations were calculated in FishTalk based on specific growth rate (%*day^{-1}) per day for different body weights and temperatures (www.skrettingguidelines.com) as well as the biomass and a food conversion factor on 1.2. Mean weekly weight per pen was calculated as accumulated biomass divided by number of fish. This calculation was investigated and if needed calibrated, every second week by measuring mean weight from 20 individual fish when counting for sea lice. This procedure follows national guidelines from Norwegian authorities of biomass control and all numbers were monthly reported to Norwegian Directorate of Fisheries as part of standard biomass surveillance.

Minor dips in the weight curve figures (Figure 6) are caused by short periods of malfunctioning feeding equipment. Since the S-CCS and control facilities were located in different places, which varied in seawater temperature, a weight model incorporating growth rate per day dependent on the daily temperature was employed (Thermal-unit Growth Coefficient, TGC). This model takes into account the seasonally temperature for fish growth (Iwama & Tautz, 2011). The following equation was used:

$$\mathrm{TGC} = \left(\text{Final weight}^{1/3} - \text{Start weight}^{1/3}\right) \times 1000/\text{sum of daily temperature}\ ({}^{\circ}\mathrm{C}).$$

The specific growth rate (SGR) for weight was calculated (time interval is total number of days from initial weight to final weight) according to the formula:

$$\mathrm{SGR}\ (\%\text{body weight gain}\ [\%/\text{day}]) = 100 \times [\ln(\text{Final weight}\ [\mathrm{g}]) - \ln(\text{Initial weight}\ [\mathrm{g}]) / (\text{Time interval}\ [\text{days}])].$$

The daily feed conversion ratio (FCR) was registered in each location, and these was calculated using the following equation:

$$\mathrm{FCR} = (\text{feed provided} / \text{biomass increase}).$$

Mortality was counted daily in each group.

Infestation of sea lice was counted every week, according to standard procedures by The Norwegian Food Safety Authority (MTIF, 2017).

The weight gain between cohorts was estimated using following formula:

$$\text{Weight gain} = (W_2 - W_1).$$

2.6 | Statistical analysis

All statistical analyses and figures were generated using RSTUDIO (Version 1.2.500, RStudio, Inc, Boston, MA, USA) and R (Version 3.6.1, R Core Team, Vienna, Austria), including following packages; Rcompanion (Mangiafico, 2018), car (Fox & Weisberg, 2011). The data sets were checked for normality and homogeneity of variance assumptions using the Shapiro–Wilk test and the Levene test, respectively. Data were analysed with a two-way ANOVA followed by the Tukey post hoc test. The level of significance in this study was <0.05. Figure data are presented as mean ± standard error (SE).

3 | RESULTS

3.1 | Phase 1 – (Post-smolt): Feed conversion ratio, mortality, sea lice infestation and growth performance

At the end of the post-smolt phase, the six cohorts varied in estimated weight (two way ANOVA, p 0.05, Figure 4). A higher estimated weight (Tukey post hoc text, $p < 0.05$) was observed for the control group in open net pen in cohort 1 (size 648.8 g), cohort 3 (size 844 g) and cohort 6 (size 366 g) compared with the same cohorts from the S-CCS system (Cohort 1, size 539.7 g; Cohort 3, size 487 g; Cohort 6, size 284 g). In contrast, in cohort 2, 4 and 5 the estimated weight was higher (Tukey post hoc text, $p < 0.05$) at the end of the post-smolt phase in the S-CCS system (Figure 4).

Overall, a better feed conversion was registered in the S-CCS system during spring in comparison with the control groups (Figure 5a). In the fall stockings, no difference in feed conversion was observed. In the spring stockings, a lower mortality was observed in the S-CCS group, whereas for the fall stockings, lower mortality was observed in the control group (Figure 5b), however no overall significant difference was observed for mortality. The sea lice infestations (Figure 5c) for fish reared in the S-CCS system were significantly lower in spring and fall compared with control group. For the initial weight, a significant difference was observed between seasons since the 1+ smolts were bigger than the 0+ smolts. The final weight in spring was higher in control group in contrast to the fall stockings, where final weight was higher in S-CCS group (Figure 5d). Further, specific growth rate (SGR) and thermal growth coefficient (TGC) showed no significant difference between seasons and rearing systems.

3.2 | Phase 2 – (Grow-out): Feed conversion ratio, mortality, sea lice infestation and growth performance

After transfer to open net pen facility and at the end of the study, the final estimated weight was higher in fish from the S-CCS system for cohort 2, 3, 4, 5 and 6, the only exception being cohort 1 (Figure 6).

A significant effect of season was observed for feed conversion ratio ($p < 0.01$, two-way ANOVA). No difference was registered between the S-CCS and control groups in FCR for the spring groups, while a better FCR was observed in S-CCS during fall stockings (Figure 7a). For mortality (Figure 7b), a significant interaction effect between season and system was observed ($p < 0.05$, two-way ANOVA). In the spring stockings, higher mortality was registered in S-CCS group; however, in the fall stockings, a lower mortality was observed in the S-CCS group. The registered sea lice infestation (Figure 7c) in the S-CCS group was lower during spring compared with the control group. Final weight in the spring and fall stockings was significantly higher for the S-CCS fish in comparison with control fish (Figure 7d). In addition, a significantly higher weight gain was observed in fish from S-CCS compared with the control fish ($p < 0.05$, two-way ANOVA).

4 | DISCUSSION

4.1 | Phase 1: Post-smolt growth

The growth performance varied with season, and in the fall stockings, the overall growth performance observed was more promising in fish from the S-CCS system, apart from cohort 6. During spring,

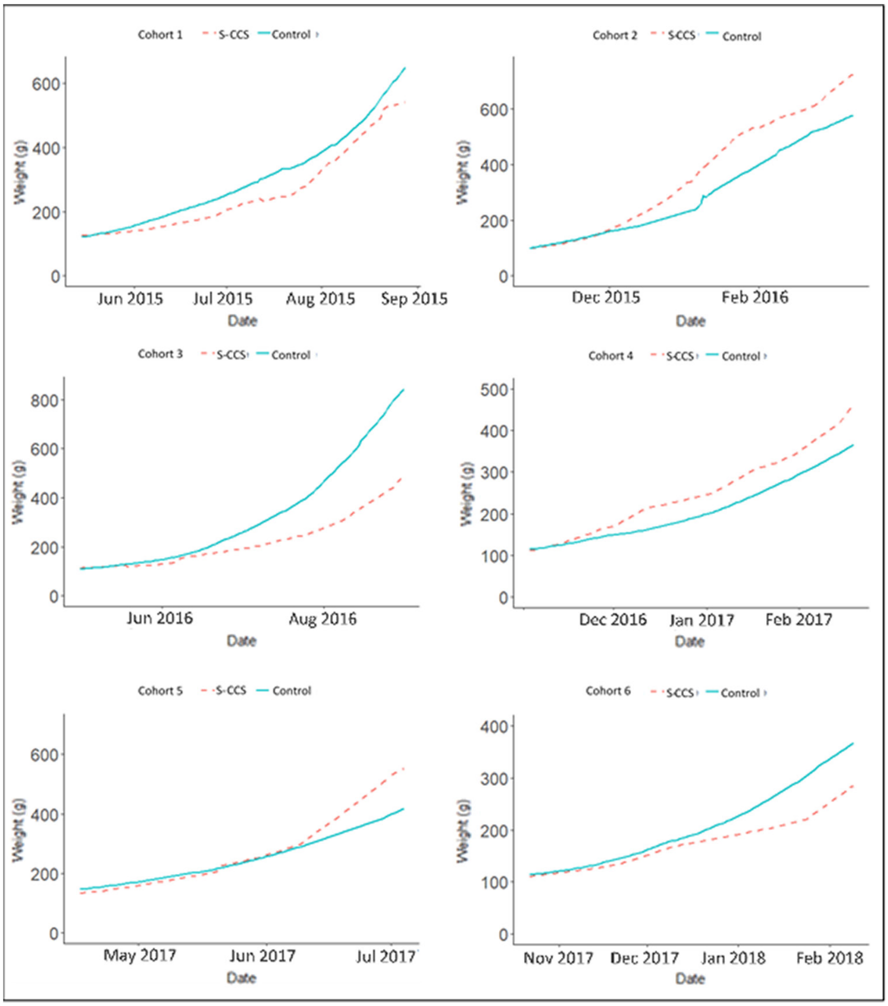

FIGURE 4 Registered growth during phase 1 for the S-CCS and control group in cohort 1–6 from May 2015 to February 2018. The red dashed line represents the S-CCS group, whereas the turquoise line represents the control group.

the observed overall growth performance was higher in the control group, except for in cohort 5, where the growth performance was better in the S-CCS fish. These variations in growth performances could be related to variations in smolt quality and from the freshwater facility.

During phase 1, the average temperature varied between the S-CCS system and the control group in open net pens within the cohorts. This is likely affected by both the seasonal temperature conditions and bathymetric differences (S-CCS fish were exposed to water from 30 m of depth), whereas the fish in the control group that were in open net pens were exposed to surface water. The temperature effect on growth is similar to the studies done for the 3rd S-CCS cohort (also a part of this data set), where fish from the control group (12.9°C on average) had a significantly higher final weight compared with the S-CCS fish (9.5°C on average) at the end of the post-smolt phase (Moe, 2017).

4.2 | Phase 1: Feed conversion ratio (FCR)

Overall, there was a lower FCR during spring in the S-CCS system compared with control. Raceway systems, like S-CCS, are designed to control water velocity, which is known to affect growth performance (Castro et al., 2011; Totland et al., 1987). Atlantic salmon exposed to long-term sustained swimming showed a 38% increase in growth with respect to non-exercised fish (Castro et al., 2011; Totland et al., 1987). Moreover, the feed conversion is also affected by exercise, and several studies have shown that exercise decreases FCR in different salmonid species (Christiansen et al., 1992; Leon, 1986). During phase 1, the S-CCS fish were forced to swim against a moderate current, causing mild aerobic training, in contrast to the fish in the control group that was reared in open net pens. Growth and FCR should be seen in the context of the possible reduction in stressors, aggressive behaviour, fewer interactions and hierarchy development among the fish in the S-CCS system (Adams et al., 1995; Jobling et al., 1993; Solstorm et al., 2016). In addition, fish density can impact the growth performance of post-smolt, and findings in Calabrese et al. (2017) demonstrated the density should not exceed 75 kg/m^3. In the S-CCS system, the average stocking density was higher (M = initial density 10.3 kg/m^3; M = final density 42 kg/m^3) compared with the control group (M = initial density 0.7 kg/m^3; M = final density 3.3 kg/m^3) in all cohorts. However, in this study, no significant difference was registered for growth and FCR between the rearing systems in phase 1. The observed growth

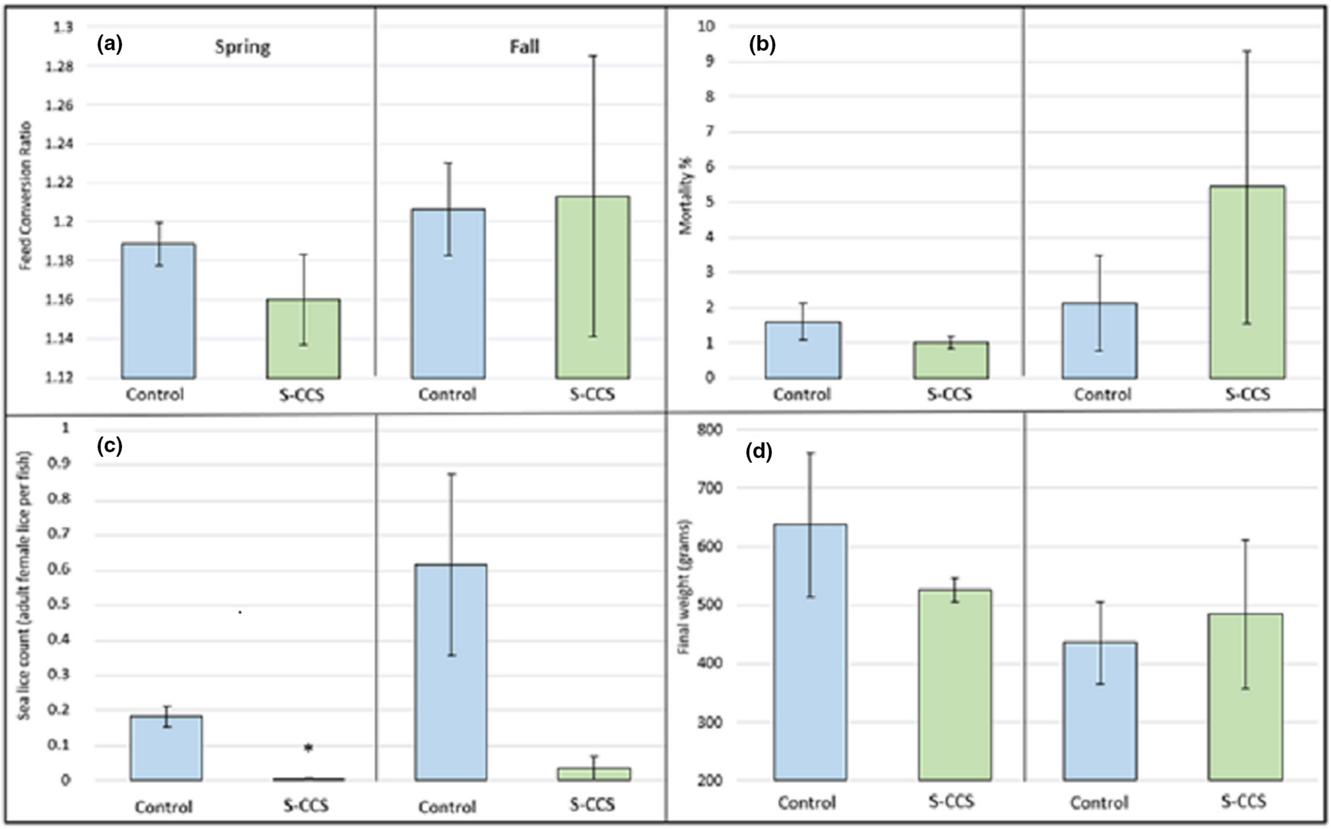

FIGURE 5 Registered feed conversion ratio (a), mortality (b), sea lice infestations (c) and final weight (d) in phase 1 for spring (left) and fall (left) cohorts, mean ± SE ($N = 3$).

performance across the cohorts shows that temperature is the main factor influencing growth, independent of the rearing system.

4.3 | Phase 1: Mortality

Observations from the field have shown that mortality rate for post-smolt may be influenced by the transport from freshwater to seawater (Harald Sveier, Lerøy AS, pers. comm.). During the post-smolt phase, no overall difference in mortality was registered between the S-CCS group and the control group. For phase 1, the rate of mortality in the S-CCS was especially affected by one particular cohort (cohort 6), where a higher mortality rate was observed during both post-smolt and grow-out phase. Mortality cause has not been confirmed.

4.4 | Phase 1: Sea lice

In phase 1, infestations of sea lice were significantly lower in the S-CCS group compared with the control group in open net pens. This observation was expected since the water in the S-CCS system is controlled by a deep-water intake under the sea lice belt, in contrast to open net pens, where the fish are continuously exposed to the natural environment, in which sea lice are abundant (Torrissen et al., 2013). The findings of reduced sea lice pressure on fish in the S-CCS are of great interest and suggest that new technology, such as S-CCS could contribute to reduce sea lice infestations on farmed post-smolt in sea.

4.5 | Phase 2: Growth

At the end of phase 2, harvest, fish from the S-CCS group showed a significantly higher weight gain compared with the control group independent of the season. In addition, fish from the S-CCS group had a significantly higher final weight compared with the control group. These results correspond to studies done for salmonids raised in closed containment systems (CCS) and exposed to moderate water velocity, where an increase in growth as an effect of exercise has been documented (Nilsen et al., 2019). For the observed overall growth performance during fall, higher growth was observed in fish from the S-CCS system, except for cohort 1. During spring, the observed overall growth performance was higher in fish originating from the S-CCS system.

Growth performance of fish in this study indicates that rearing of salmonids in an S-CCS prior to the grow-out phase in open sea cages has a positive effect that continues during the grow-out phase. Interestingly, the temperature conditions between the experimental groups (S-CCS and control) did not differ much during the grow-out

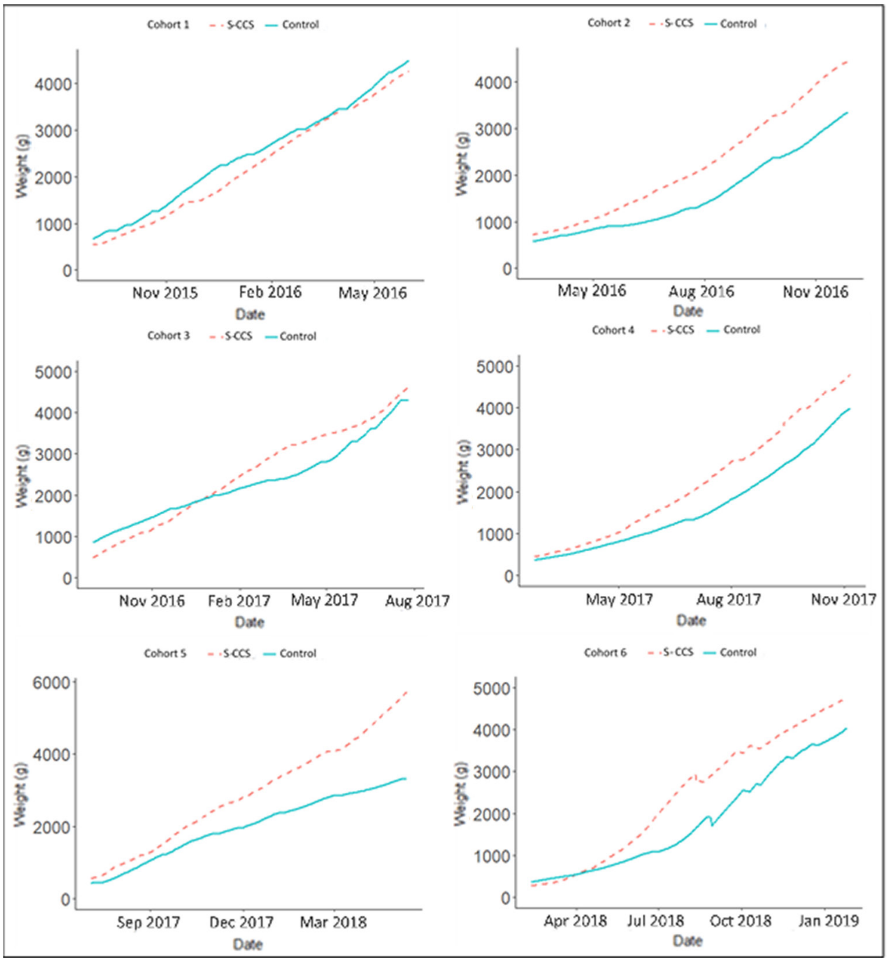

FIGURE 6 Registered growth during phase 2 for the S-CCS and control group in cohort 1–6 from August 2015 to January 2019. The red dashed line represents the S-CCS group, whereas the turquoise line represents the control group.

phase. For SGR in phase 2, no difference between the groups was found.

Moreover, several studies have indicated that water velocities (>0.40 BL/s) can have positive effects on growth through increased number of muscle fibre (hypertrophy, Ibarz et al., 2010; Totland et al., 1987). Moe (2017) showed that fish in the third S-CCS cohort, at the end of the post-smolt phase, had 2.44 times higher frequency of muscle fibres in the smallest interval group (0–20 µm), compared with the control group. Taken together, these observations suggest that the higher growth in S-CCS fish during the grow-out phase could be explained by hypertrophy of the newly recruited muscle fibres.

4.6 | Phase 2: Mortality

At the end of the grow-out phase, a lower mortality for the spring stockings were observed in the control group in comparison with the S-CCS group. In the fall stockings, the control group showed a higher mortality rate in comparison with the S-CCS group. The difference in mortality rate between S-CCS fish and control might relate to the exercise achieved in the S-CCS system, where the exercised fish tend to be more capable of resisting environmental and physical challenges in the sea.

4.7 | Phase 2: Feed conversion ratio (FCR)

In the grow-out phase, the FCR was significantly different during seasons between the S-CCS fish and control fish. The FCR can be described as the amount of mass gained by the fish relative to the amount of feed consumed (Jackson, 2010). Studies have shown that weight gain is achieved with less feed when the appetite is stimulated as an effect of training (Davison, 1989). In open sea cages, freely swimming fish tend to form dominant hierarchies and show increased aggression; this can again lead to less food available for subordinate fish (Adams et al., 1995; Brännäs, 2009). In phase 2, during the fall, the FCR was lower in the S-CCS group in comparison with the control group. The decrease in FCR could be related to a better appetite in the robust and exercised fish from S-CCS.

4.8 | Phase 2: Sea lice

After a free-swimming larvae period, sea lice settle, attach and feed on its fish host (Bjørn & Finstad, 1998). The sea lice cause stress and physical damage to the fish, adversely affecting growth and welfare. Consequently, severe infestations of sea lice can lead to secondary infections and mass mortalities (Costello, 2006; Pike & Wadsworth, 1999; Torrissen et al., 2013). At the end of phase 2, no statistical differences

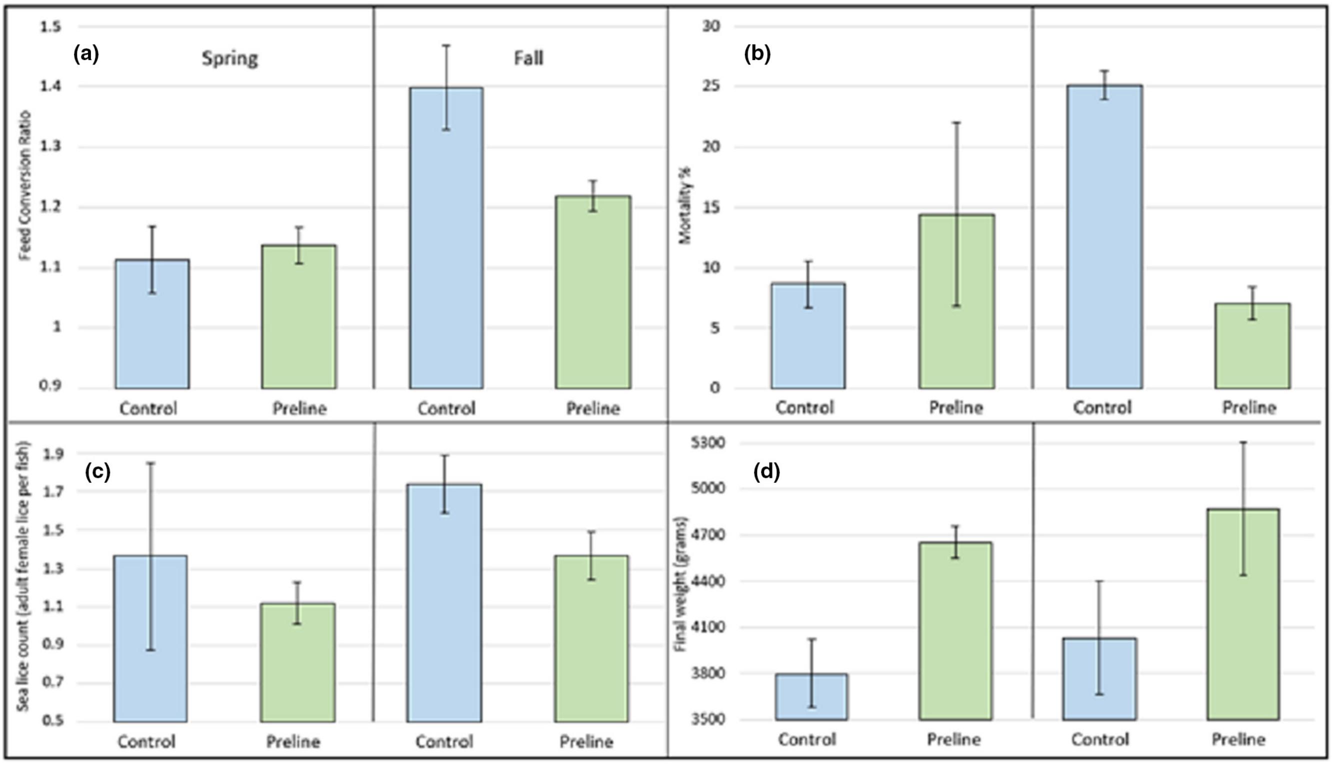

FIGURE 7 Registered feed conversion ratio (a), mortality (b), sea lice infestations (c) and final weight (d) in phase 2 for spring (left) and fall (right) cohorts, mean ± SE ($N = 3$).

in sea lice infestations were shown between fish from the S-CCS group and the control group. However, the trend points to a lower infestation level in fish reared in S-CCS. In addition, according to observations from the field the need for sea lice treatments in S-CCS groups were reduced in comparison to groups in open net pens (Harald Sveier, Lerøy AS, pers. comm.). This observation could be influenced by many factors, where one aspect could be the skin of the fish. The skin and associated mucus layer of Atlantic salmon constitutes its first line of defence against the environment. The skin of the fish protects both as a physical barrier and as an active and protective layer with immunological capacities that interacts with the surrounding environments (Sveen et al., 2016). In addition, the skin provides protection against external agents and has a high capacity for regeneration and healing (Richardson et al., 2016). Recent studies of the skin barrier, including epidermis and dermis, showed that thickness and mucus cell numbers increased in line with growth after seawater transfer in Atlantic salmon (Karlsen et al., 2018). Accounting for these results and observations, it could be suggested that the fish reared in the S-CCS system as post-smolt before the grow-out phase are more robust in terms of sea lice infestations. The reduced sea lice infestations could also help explain the lower mortality rate observed for S-CCS fish.

5 | CONCLUSION

In the grow-out phase, the S-CCS group showed higher weight gain and higher final weight compared with the control group in open pen. In addition, salmon raised in S-CCS showed significantly higher survival during fall compared with the control group, indicating increased robustness in fish raised in S-CCS when transferred to open net pens in sea. The analysis of the six cohorts also showed significantly lower sea lice infestations in the S-CCS system compared with open net pens during the post-smolt phase. It is concluded that S-CCS has advantages compared with traditional exposure to the natural environment in open sea cages in Norway.

AUTHOR CONTRIBUTIONS

Tarald Kleppa Øvrebø: contributed to writing—original Draft, writing—review and editing, investigation, conceptualization and visualization. **Sigurd Handeland**: contruibuted to writing—review and editing, investigation, conceptualization, visualization, supervision and funding acquisition. **Sigurd Olav Stefansson**: contributed to review and editing, conceptualization and supervision. **Pablo Balseiro**: contributed to review and editing, investigation, supervision. **Ragnar Tveterås**: contributed to review and editing, investigation and conceptualization. **Harald Sveier**: contributed to review and editing, investigation and conceptualization. **Albert Kjartan Dagbjartarson Imsland**: contributed to visualization, writing—original draft, writing—review and editing and supervision.

ACKNOWLEDGEMENTS

The authors would like to thank the technical staff at Marine Development Biology group at BIO (UiB) and the NORCE Integrative

Fish Biology team for valuable assistance prior to and during the experimental period. Opinions expressed and conclusions arrived at, are those of the authors and are not necessarily to be attributed to the funding bodies.

CONFLICT OF INTEREST

There is no conflict of interest in relation to this study.

ETHICAL APPROVAL

The present experiment was approved by the local responsible laboratory animal science specialist under the surveillance of the Norwegian Animal Research Authority (NARA) and registered by the Authority.

DATA AVAILABILITY STATEMENT

Not applicable.

ORCID

Albert Kjartan Dagbjartarson Imsland https://orcid.org/0000-0003-0077-8077

REFERENCES

Abolofia, J., Wilen, J. E., & Asche, F. (2017). The cost of lice: Quantifying the impacts of parasitic sea lice on farmed salmon. *Marine Resource Economics*, *32*, 329–349.

Adams, C., Huntingford, F., Krpal, J., Jobling, M., & Burnett, S. (1995). Exercise, agonistic behaviour and food acquisition in Arctic charr (*Salvelinus alpinus* L). *Environmental Biology of Fishes*, *43*, 213–218. https://doi.org/10.1007/BF00002494

Anon. (2011). *Status for norske laksebestander [The Status of Norwegian Salmon Populations]. Vitenskapelig råd for lakseforvaltning* (Vol. *11*, p. 122). Norsk institutt for naturforsking.

Austreng, E., Storebakken, T., & Åsgård, T. (1987). Growth rate estimates for cultured Atlantic salmon and rainbow trout. *Aquaculture*, *60*, 157–160. https://doi.org/10.1016/0044-8486(87)90307-3

Bjørn, P. A., & Finstad, B. (1998). The development of salmon lice (*Lepeophtheirus salmonis*) on artificially infected post smolts of sea trout (*Salmo trutta*). *Canadian Journal of Zoology*, *76*, 970–977.

Brännäs, E. (2009). The effect of moderate exercise on growth and aggression depending on social rank in groups of Arctic charr (*Salvelinus alpinus L.*). *Applied Animal Behaviour Science*, *119*, 115–119. https://doi.org/10.1016/j.applanim.2009.03.003

Calabrese, S., Nilsen, T. O., Kolarevic, J., Ebbesson, L. O. E., Pedrosa, C., Fivelstad, S., Hosfeld, C., Stefansson, S. O., Terjesen, B. F., Takle, H., Martin, C. I. M., Sveier, H., Mathisen, F., Imsland, A. K., & Handeland, S. O. (2017). Stocking density limits for post-smolt Atlantic salmon (*Salmo salar* L.) with emphasis on production performance and welfare. *Aquaculture*, *468*, 363–370. https://doi.org/10.1016/j.aquaculture.2016.10.041

Castro, V., Grisdale-Helland, B., Helland, S. J., Kristensen, T., Jørgensen, S. M., Helgerud, J., Claireaux, G., Farrell, A. P., Krasnov, A., & Takle, H. (2011). Aerobic training stimulates growth and promotes disease resistance in Atlantic salmon (*Salmo salar*). *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, *160*, 278–290. https://doi.org/10.1016/j.cbpa.2011.06.013

Christiansen, J., Svendsen, Y., & Jobling, M. (1992). The combined effects of stocking density and sustained exercise on the behaviour, food intake, and growth of juvenile Arctic charr (*Salvelinus alpinus* L.). *Canadian Journal of Zoology*, *70*, 115–122. https://doi.org/10.1139/z92-017

Costello, M. J. (2006). Ecology of sea lice parasitic on farmed and wild fish. *Trends in Parasitology*, *22*, 475–483. https://doi.org/10.1016/j.pt.2006.08.006

Costello, M. J. (2009a). The global economic cost of sea lice to the salmonid farming industry. *Journal of Fish Diseases*, *32*, 115–118. https://doi.org/10.1111/j.1365-2761.2008.01011.x

Costello, M. J. (2009b). How sea lice from salmon farms may cause wild salmonid declines in Europe and North America and be a threat to fishes elsewhere. *Proceedings of the Royal Society B: Biological Sciences*, *276*, 3385–3394. https://doi.org/10.1098/rspb.2009.0771

Davison, W. (1989). Training and its effects on teleost fish. *Comparative Biochemistry and Physiology A: Physiology*, *94*, 1–10. https://doi.org/10.1016/0300-9629(89)90775-5

Fox, J., & Weisberg, S. (2011). *An {R} companion to applied regression* (2nd ed.). Sage. Retrieved from. http://socserv.socsci.mcmaster.ca/jfox/Books/Companion

Glover, K. A., Quintela, M., Wennevik, V., Besnier, F., Sørvik, A. G. E., & Skaala, Ø. (2012). Three decades of farmed escapees in the wild: A spatio-temporal analysis of Atlantic salmon population genetic structure throughout Norway. *PLoS ONE*, *7*, e43129. https://doi.org/10.1371/journal.pone.0043129

Hagspiel, V., Hannevik, J., Lavrutich, M., Naustdal, M., & Struksnæs, H. (2018). Real options under technological uncertainty: A case study of investment in a post-smolt facility in Norway. *Marine Policy*, *88*, 158–166.

Handeland, S. O., & Stefansson, S. O. (2001). Photoperiod control and influence of body size on off-season parr–smolt transformation and post-smolt growth. *Aquaculture*, *192*, 291–307. https://doi.org/10.1016/S0044-8486(00)00457-9

Hjeltnes, B., Bornø, G., Jansen, M. D., Haukaas, A., & Walde, C. S. (2017). *Fiskehelserapporten 2016*. Norwegian Veterinary Institute. Retrieved March 2020 from. https://www.vetinst.no/rapporter-og-publikasjoner/rapporter/2017/fiskehelserapporten-2016 (in Norwegian with Abstract in English).

Ibarz, A., Felip, O., Fernández-Borràs, J., Martín-Pérez, M., Blasco, J., & Torrella, J. (2010). Sustained swimming improves muscle growth and cellularity in gilthead sea bream. *Journal of Comparative Physiology B: Biochemical, Systems, and Environmental Physiology*, *181*, 209–217. https://doi.org/10.1007/s00360-010-0516-4

Imsland, A. K., Handeland, S., & Stefansson, S. O. (2014). Growth and maturation of Atlantic salmon (*Salmo salar*) reared under constant temperatures and photoperiods in fresh- and seawater. *Aquaculture International*, *22*, 1331–1345.

Iwama, G., & Tautz, A. (2011). A simple growth model for salmonids in hatcheries. *Canadian Journal of Fisheries and Aquatic Sciences*, *38*, 649–656. https://doi.org/10.1139/f81-087

Jackson, A. (2010). *Fish in-fish out (FIFO) ratios explained*. International Fish Meal and Fish Oil Organization (IFFO).

Jobling, M., Jørgensen, E., Arnesen, A., & Ringoe, E. (1993). Feeding, growth and environmental requirements of Artic charr: A review of aquaculture potential. *Aquaculture International*, *1*, 20–46. https://doi.org/10.1007/BF00692662

Karlsen, C., Ytteborg, E., Timmerhaus, G., Høst, V., Handeland, S., Jørgensen, S. M., & Krasnov, A. (2018). Atlantic salmon skin barrier functions gradually enhance after seawater transfer. *Scientific Reports*, *8*, 9510. https://doi.org/10.1038/s41598-018-27818-y

Leon, K. (1986). Effect of exercise on feed consumption, growth, food conversion, and stamina of brook trout. *The Progressive Fish Culturist*, *48*, 43–46. https://doi.org/10.1577/1548-8640(1986)48<43:EOEOFC>2.0.CO;2

Mangiafico, S. (2018). *Rcompanion: Functions to support extension education program evaluation*. R package version 2.0.3. Retrieved from https://CRAN.R-project.org/package=rcompanion

McCormick, S. D. (1993). Methods for nonlethal gill biopsy and measurement of Na+, K+-ATPase activity. *Canadian Journal of Fisheries and Aquatic Sciences*, *50*, 656–658. https://doi.org/10.1139/f93-075

Moe, Ø. G. (2017). *The effect of aerobic training on growth, muscle development and heart condition in Atlantic salmon (Salmo salar) post-smolts in large-scale semi-closed containment systems* [Thesis for the degree Master of science in Aquaculture Biology, University of Bergen]. https://bora.uib.no/bora-xmlui/handle/1956/16316

MTIF. (2017). *Råd fra styringsgruppen for vurdering av lusepåvirkning – September 2017*. The Norwegian Ministry of Trade, Industry and Fisheries.

Nilsen, A., Hagen, Ø., Johnsen, C. A., Prytz, H., Zhou, B., Nielsen, K. V., & Bjørnevik, M. (2019). The importance of exercise: Increased water velocity improves growth of Atlantic salmon in closed cages. *Aquaculture*, *501*, 537–546. https://doi.org/10.1016/j.aquaculture.2018.09.057

Olafsen, T., Winther, U., Olsen, Y., & Skjermo, J. (2012). *Value creation from productive seas in 2050*. Trondheim, Norway. Report Sintef. https://www.sintef.no/en/latest-news/2012/value-created-from-productive-oceans-in-2050/

Pike, A. W., & Wadsworth, S. L. (1999). Sealice on salmonids: Their biology and control. *Advances in Parasitology*, *44*, 233–337.

Richardson, R., Metzger, M., Knyphausen, P., Ramezani, T., Slanchev, K., Kraus, C., Schmelzer, E., & Hammerschmidt, M. (2016). Re-epithelialization of cutaneous wounds in adult zebrafish combines mechanisms of wound closure in embryonic and adult mammals. *Development*, *143*, 2077–2088. https://doi.org/10.1242/dev.130492

Rosten, T. W., Ulgenes, Y., Henriksen, K., Terjesen, B. F., Biering, E., & Winther, U. (2011). *Oppdrett av laks og ørret i lukkede anlegg – forprosjekt. FHF – Norwegian Seafood Research Fund. SINTEF Fiskeri og havbruk AS*. Rapportnr. A21169 (74 pp.).

Solstorm, F., Solstorm, D., Oppedal, F., Olsen, R., Stien, L., & Fernö, A. (2016). Not too slow, not too fast: Water currents affect group structure, aggression and welfare in postsmolt Atlantic salmon *Salmo salar*. *Aquaculture Environment Interactions*, *8*, 339–347. https://doi.org/10.3354/aei00178

Statistics Norway. (2019). *Biomass production of Atlantic salmon in Norway 2010–2018 and first-hand value*. Retrieved from https://www.ssb.no/jord-skog-jakt-og-fiskeri/statistikker/fiskeoppdrett/aar

Stefansson, S. O., Björnsson, B. T., Sundell, K., Nyhammer, G., & McCormick, S. D. (2003). Physiological characteristics of wild Atlantic salmon post-smolts during estuarine and coastal migration. *Journal of Fish Biology*, *63*, 942–955.

Sveen, L. R., Timmerhaus, G., Torgersen, J. S., Ytteborg, E., Jørgensen, S. M., Handeland, S., Stefansson, S. O., Nilsen, T. O., Calabrese, S., Ebbeson, L., Terjesen, B. F., & Takle, H. (2016). Impact of fish density and specific water flow on skin properties in Atlantic salmon (*Salmo salar* L.) post-smolts. *Aquaculture*, *464*, 629–637. https://doi.org/10.1016/j.aquaculture.2016.08.012

Talbot, C. (1993). Some aspects of the biology of feeding and growth in fish. *Proceedings of the Nutrition Society*, *52*, 403–416. https://doi.org/10.1079/PNS19930081

Thorarensen, H., & Farrell, A. (2011). The biological requirements for post-smolt Atlantic salmon in closed-containment systems. *Aquaculture*, *312*, 1–14. https://doi.org/10.1016/j.aquaculture.2010.11.043

Torrissen, O., Jones, S., Asche, F., Guttormsen, A., Skilbrei, O. T., Nilsen, F., Horberg, T. E., & Jackson, D. (2013). Salmon lice—impact on wild salmonids and salmon aquaculture. *Journal of Fish Diseases*, *36*, 171–194. https://doi.org/10.1111/jfd.12061

Totland, G. K., Kryvi, H., Jødestøl, K. A., Christiansen, E. N., Tangerås, A., & Slinde, E. (1987). Growth and composition of the swimming muscle of adult Atlantic salmon (*Salmo salar* L.) during long-term sustained swimming. *Aquaculture*, *66*, 299–313. https://doi.org/10.1016/0044-8486(87)90115-3

Ytrestøyl, T., Takle, H., Kolarevic, J., Calabrese, S., Timmerhaus, G., Nilsen, T. O., Handeland, S. O., Stefansson, S. O., Ebbesson, L. O. E., & Terjesen, B. (2015). Atlantic salmon post-smolts in RAS: effects of salinity, exercise and timing of seawater transfer on performance, physiology and welfare. In A. J. T. Dalsgaard (Ed.), *3rd NordicRAS Workshop on Recirculating Aquaculture Systems. Molde, Norway, 30 September - 1 October 2015. Book of Abstracts. DTU Aqua Report No. 301–15* (p. 56). National Institute of Aquatic Resources, Technical University of Denmark.

How to cite this article: Øvrebø, T. K., Balseiro, P., Imsland, A. K. D., Stefansson, S. O., Tveterås, R., Sveier, H., & Handeland, S. (2022). Investigation of growth performance of post-smolt Atlantic salmon (*Salmo salar* L.) in semi closed containment system: A big-scale benchmark study. *Aquaculture Research*, *53*, 4178–4189. https://doi.org/10.1111/are.15919