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Analysis of the economic performance of salmon farming in submerged and surface cages in the Black Sea

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Abstract

The production period for salmon farming in the Black Sea comprises the winter period and is limited to seven months, due to high water temperatures during the summer time. As an alternative strategy, temporary cage submersion during the summer season might be a solution for salmon grow-out throughout the year. Therefore, this study was conducted for comparative evaluation of economic performance of submerged and surface cages, by analyzing structural costs and returns for Turkish salmon farming in the Black Sea. As a result of the temporary cage submersion strategy, economic profits increased by nearly 70%, granting higher values of financial indicators with increased net profit (685,652.5 \$ year^{-1}) and margin of safety (89.6%), compared to the traditional surface cage (397,058.5 \$ year^{-1} net profit and 88.4% margin of safety). The "What-if" analysis showed that profits from both cage systems were sensitive to variations in sale price, and the simulation by 10% reduced export market value may decrease revenues, with less financial profit loss for the submerged cage over the surface once. Hence, temporary cage submersion seems to be an alternative farm management strategy with extended production cycle and higher profits for the sustainable development of Turkish salmon farming in the Black Sea.

Keywords Aquaculture economics · Farm management strategy · Cage farming · Cost-benefit analysis · Salmon aquaculture

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Introduction

The world aquaculture production is in an increasing trend and reached its highest rate of 122.6 million tons in 2020, with a total value of USD 281.5 billion (FAO 2022a). Considering the rapid increase of the World's population that is estimated to count for 9 billion in 2037 (Worldometer 2023), the demand of food for human consumption will be an important struggle for the future of human beings. The aquaculture industry is expected to supply about 59% of the seafood for human consumption in 2030 (FAO 2022a).

Three species of *Oncorhynchus*, the Pacific salmon, are intensively cultured in cage farms around the world, namely, (a) the chinook salmon (*O. tshawytscha*), (b) the coho salmon (*O. kisutch*), and (c) the rainbow trout (*O. mykiss*) (Laird 1996, 2001; Cooke et al. 2011). Among these, the rainbow trout, also named as Steelhead (*O. mykiss*), is the most widely farmed salmonid species in the world (Candiotto et al. 2011; Stanković et al. 2015) and Türkiye (Yoğurtçuoğlu et al. 2021). Around 27% (over 140 thousand tons) of the total European production was supplied by Turkish aquaculture facilities (FAO 2022b), which are mainly operating in the Black Sea with its brackish water characteristic, and fish exceeding 2.5 kg harvest weight is delivered to the market as "Turkish Salmon" (TMAF 2020).

The scarcity of available locations suitable for aquaculture in land-based or coastal areas and the innovations in marine technologies shifted cage aquaculture enterprises to more exposed locations (Ferreira et al. 2012), which contributes new opportunities in the resolution of problems introduced by effluents from fish farms, as a result of widely dispersal of farm wastes in exposed offshore conditions (Holmer 2010). It has been underlined that the developments in marine technologies, environmental conditions in farm sites, and socio-economic situations play important roles in the success of offshore marine aquaculture (Edwards et al. 1997; Di Trapani et al. 2014; Grillone et al. 2014).

Cage farming in the Black Sea was initiated with rainbow trout production in early 1990s, when Yigit (1996) and Yigit and Aral (1999) achieved better growth performance in brackish water compared to the individuals raised in freshwater conditions. Turker et al. (2004) focused on the osmoregulation ability of rainbow trout and underlined that the transfer of 10 to 30 g fish from freshwater facilities to the cage farms in the Black Sea could be a good move for better harvest gains that has become a new farm management strategy over time. Recently, Buyukates et al. (2022) evidenced that rainbow trout could be acclimated to even higher saline waters with salinities up to 28 ‰ with no adverse impacts on fish welfare. Over the years, the increasing demand for larger fish has shifted the farm strategy towards salmon production in the Black Sea. Nowadays, rainbow trout are grown in land-based freshwater hatcheries to a certain size, and transferred to exposed marine sites for the on-growing phase. Fish weighing over 2.5 kg is delivered to local -but mainly export market as "Turkish salmon." The harvest weight depends on initial fish size introduced to cages in early November, that is the start point of the production period which is limited to seven months in the Black Sea, and May is the end point of the production when surface water temperatures raise over tolerance limits of 23°C (Elson 1969; Danie et al. 1984; Shepard 1995). Hence, the present cage aquaculture strategy in the Black Sea is based on salmon farming during the winter and warm water fishes such as Guilthead seabream (*Sparus aurata*) and the European seabass (*Dicentrarchus labrax*) during the summer period. However, the growing demand for larger fish in the international market has brought farmers to seek for alternative production strategies to expand the production period to a yearly basis. A fish with initial size of 400 g can weigh more than 3.5–4.0 kg after seven months of feeding (DOKA 2021). The bigger the fish size, the higher the expected sale price. Due to size-variations in market demand, farmers have to figure the most suitable size range for the initial stock, in order to reach the demanded harvest size within the short production period. Usually, farmers are engaged in purchase agreements in advance so that the right fish size for initial biomass can be granted for the following production year in order to reach the expected harvest size according to market demand. Also, the farmers may receive a deal of lower price with an early purchase agreement. Among variable expenses in this study, the fish cost for initial stocking accounts around 18% of the total operational cost. Pursuant to such an early-agreement, land-based fish farms, especially cage farms in lakes are under great pressure to raise around 400 g fish, the so called “salmon candidate,” until the next production season of November.

The drastically growth in the market demand for Turkish salmon recently, has increased the pressure towards new investments, which is based on offshore gravity-type cages, made of high-density polyethylene (HDPE) frames filled with Styrofoam for buoyancy, whereas the bottom rim is reinforced with chain to provide negative buoyancy for a volumetric integrity of the net chamber. Over the last decade, cage farm systems in the Black Sea have gradually increased volumetric capacity with constructions of 100 m diameter main float and net chambers of 20–30 m depth. Several problems such as shrinking carrying capacities due to steadily new investments or farm expansions coupled with other issues such as environmental concerns brought farmers to an edge for new production strategies (personal communications with Mr. Osman Parlak, President of Samsun and Sinop Provinces Aquaculture Producers Association - Türkiye, 3–6 October 2022). Further, the water temperature in the Black Sea exceeds lethal limits for salmon tolerance during the summer that reduces the production cycle to 7 months only, namely, from November to May of the year. The seawater temperature in the Black Sea increased over the years since the end of the 1990s, and a maximum monthly average summer temperature exceeds 25°C with an extreme level of 26.9°C reported in August 2010 (Ginzburg et al. 2021). The winter season however provides suitable temperatures for salmon farming in the Black Sea, where surface seawater temperatures have been reported around 8°C in average in the last decade of the 2000s, with a minimum average monthly surface temperature drop below 7°C in 2006 that was reported as 6.42°C in February (Ginzburg et al. 2021). Surface seawater temperatures ranging between 6.9 and 9.0°C have been reported in Sinop area, off the Turkish coast of the Black Sea between December 1995 and March 1996, with a one-day severe drop to 5.5°C in January 1996 (Yigit and Aral 1999). The severe increase of surface seawater temperatures in the summer period forces farmers to harvest the fish prior to the high-temperature season and in order to reach 2.5 kg harvest weight in a production period of 7 months; the initial size of fish introduced should be minimum 300 g (the so-called salmon candidates), which is a challenging issue for the salmon industry in the Black Sea.

Considering all these aspects, temporary cage submersion could be a novel strategy for possible expansion of the production period to yearly basis, through the advantage of the thermocline layer (around 8°C), which during the surface water warming in the summer period shows seasonal formation mainly at 10 to 40 m depths (Miladinova et al. 2016). Wind, waves, and current effects are other problematic issues in harsh sea conditions that might be solved by introducing submerged cages, which have been successfully practiced for several fish species (Pacific threadfin, Ryan 2004; Atlantic cod and haddock, Chambers and Howell 2006; cobia, Rapp et al. 2007); however, the use of submerged cages in salmon farming is still questioned and carefully approached.

One of the main challenges for the Turkish salmon farming in the Black Sea is the short production season that is limited to 7 months due to the warming of seawater surface during summer, raising over lethal temperatures (23°C; Elson 1969; Danie et al. 1984; Shepard 1995) for salmon from May to October. Besides biological and technical challenges, farmers need to be supported with reliable data of real investment quotations for salmon farming in submerged and surface cages that is lacking so far and needs to be answered. Hence, potentially, improvement of farm efficiency and financial turn-over of the investment by increased production period at yearly basis may support farm managers for detailing business plans towards sustainable growth of salmon industry. In order to encourage farmers for a new farm management and production strategy, the present study focused on comparative evaluation of economic performance of submerged versus surface cage systems, through analyzing structural costs and returns in Turkish salmon farming in the Black Sea.

Materials and methods

Model description and assumptions

Initially, a model to evaluate the annual income of a traditional surface cage system that is used for salmon grow-out in the Black Sea, was elaborated with initial investment costs and net profits from harvest after a 7-month production period (from November to May), whereby 400 g fish are purchased and grown in marine cage farms until harvest time when fish reached over 3 kg size, which is the predominant culture practice in the Black Sea. A second model was proposed to simulate the annual income statement from a submerged cage using the benefit from cold water in the deep, potentially increasing the production period from 7 months to yearly basis by temporary cage submersion during the high-temp season, only, and comparatively evaluated the initial investment expenditures and operational costs versus harvest gain and net profit in submerged and surface cage. Based on the estimations obtained, a "What-if" analysis was conducted to evaluate the economic influences of 10% variation in export market for Turkish salmon farmed either in surface cage for 7-months or submerged system throughout the year. The "what-if" analysis applied here, followed the report of Fernández-Sánchez et al. (2022), who noted the sale price as the highest impact factor on net operating profit, and a price reduction by 10% may reduce net operating profit more than every other model parameter regardless of farm size or production strategy. Other model parameters such as survival and growth rates also affected the net operating profit of the farm; however, these were much lower than the sale price variations. Further, Fernández-Sánchez et al. (2022) noted expenditures for fingerling unit cost (initial fish stock) as the model parameter with lowest influence on net operating profits, regardless the farm size or production strategy. Hence, indications made by (Fernández-Sánchez et al. 2022) for the impacts of variations in model parameters were followed, and the 10% reduction in sale price was used as the model parameter for the evaluation of cage model impact on net profit in the present study. The net profit is the amount of cash return and is also called as net earning return, sales income, or liquid revenue (Castilho-Barros et al. 2020; Huang et al. 2022).

Initially, some assumptions have been made for the standardization of parameters used. The cost for economic variables, and production variables such as fish stocking and fish feeding were assumed to be constant for both surface and submerged cage models. Further, assumption for equality was made for the winter period from November to May in terms of water temperature or other environmental factors, for survival rates, fish stocking size and density, feeding management, and feed quality. Further assumption of equality was made for the cage nets without biofouling occurrence, since biofouling development on fish nettings can reduce oxygen levels in the cage environment that may cause stress and reduce welfare in farmed fish as earlier reported by Bloecher et al. (2013) and Klebert et al. (2013). Another assumption of equality was assessed for the hydrodynamic conditions of the culture environment, since sea bottom and current conditions can affect the mooring design and anchorage system (Kankainen and Mikalsen 2014).

However, since two different models of production systems, namely, (a) surface cage and (b) submerged cage, were used in this study, the production period showed difference among model groups. In the commercial cage aquaculture facilities operating in the Black Sea, salmon farming is practiced from early November to mid-May, when surface seawater temperature exceeds the tolerance limits of 23°C (Elson 1969; Danie et al. 1984; Shepard 1995). Hence, for the present production strategy applied with surface cage systems, the production period for Turkish salmon in a commercial farm was followed here that is limited to 7 months (November-May) in the Black Sea. Hence, the computational planning for the surface cage model was assessed accordingly (grow-out Phase-I) in order to reflect real production strategy in the field, whereas the farm model with submerged cage continued production and entered a second grow-out period (grow-out Phase-II), by submersion to deeper cold water. Hence, the computational planning for the submerged cage model was assessed for yearly base production of 12 months.

Cage design and investment costs

All equipment necessary for manufacturing both cage systems was designed according to a commercial farm size. Both surface and submerged cages were scaled in same size and dimensions, with 30 m (Ø) diameter and 10 m net depth. High-density polyethylene (HDPE) circular float material was used as main float. The mooring system was designed in commercial size according to the Black Sea conditions, which was provided by Akuakare Co. (Aquaculture Equipment Company, Mugla-Türkiye) for this study.

Investment costs for equipment

Submerged grid design was used to ensure flexibility of the mooring system, where corner collectors were uplifted by buoys. Investment costs of mooring systems were quoted based on grid systems with collector rings lowered 5 m below surface for the surface cage and 15 m below surface for the submerged cage model. The 15 m depth in submerged system was used to gain depth when cage shifts to the Phase-II of grow-out during summer period that is the submerged position of the cage.

The initial investment costs for the two cage models were calculated based on equipment value of commercial quotations by Akuakare Co. (Muğla-Türkiye). The Turkish Ministry of Agriculture and Livestock, General Directorate of Fisheries may grant permissions for offshore cage farms that meet basic environmental conditions and carrying capacity assessments of the potential aquaculture sites set in areas with a minimum of 30 m depth, 10 cm sec^{-1} currents and 0.6-mile distance from the shore, which was followed in the design of the cage and mooring systems in this study. Despite the fact that offshore Salmon farms in the Black Sea are located in more exposed marine sites, the minimum condition sets by the government organizations were followed in the present study for standardization of variable costs such as initial fish stocking and feeding costs and other operational expenses comprising fixed costs such as personnel, fuel, health maintenance, other operational expenses, and depreciation costs. All items used for the construction of both surface and submerged systems based on one-cage set-up are shown in Table 1.

Economic analysis and data evaluation

A theoretical static model was projected with the spreadsheet Microsoft Excel for Mac (version 16.66.1) on a Mac macOS Big Sur (version 11.4) computer for the design and stimulation of operational strategies with two different cage systems. Influences of traditional surface cage versus submerged cage models on economic and financial indices from the production of Turkish salmon were subjected to “cost-benefit analysis” for the comparison of cost, revenue, and profit variations in each production model using economic formulations provided by earlier reports (Shang 1990; Martin et al. 1998; Castilho-Barros et al. 2020; Fernández-Sánchez et al. 2022; Huang et al. 2022). The cost-benefit analysis is important in economic decision-making through comparative evaluation of total costs and benefits for the assessment best benefit with minimum cost for a target farm project (Huang et al. 2022), and the cost-benefit analysis is recognized as a useful tool for the evaluation of industrial projects and investments (Farel et al. 2013; Boardman et al. 2018; Liu et al. 2020; Mahony 2021).

In cost-benefit analysis, the costs are divided into operating costs (OPEC) and depreciation cost (DEC), where OPEC consists of variable costs such as feed and fish costs, and DEC is counted as fixed costs along with others such as personnel, energy, veterinary, and health maintenance cost and other costs such as management and marketing, related to cage aquaculture business. Cost inputs and profits have been calculated using following equations:

$$IFC = \frac{IFP \times [IFW \times (CV\ x \times SD)]}{HW}$$

where IFC is the initial fish cost (\$ year^{-1}), IFP is the initial fish price (\$ kg^{-1}), IFW is the initial fish weight (kg), CV is the cage volume (m^3), SD is the stocking density (kg/m^3), and HW is the harvest weight (kg).

$$FC = (FCR \times FP) \times (IFN\ x\ SR) \times FHW$$

where FC is the feed cost (\$ year^{-1}), FCR is the feed conversion rate, FP is the feed price (\$ kg^{-1}), IFN is the initial fish number (#), SR is the survival rate (%), and FHW is the final harvest weight (kg).

$$PC = (MSE \times PP) \times NE$$

where PC is the personnel cost (\$ year^{-1}), MSE is the monthly salary of employee (\$ month^{-1}), PP is the production period (month), and NE is the no of employee (#).

$$FuC = (FuCM \times PP)$$

where FuC is the fuel cost (\$ year^{-1}), FuCM is the fuel cost per month (\$ month^{-1}), and PP is the production period (months).

$$OC = (OC\ x\ PP)$$

where OC is the other cost (\$ year^{-1}; marketing, management, etc.).

Table 1 Investment costs for equipment used in farm setups of traditional surface cage (SUR-C) and submerged cage system (SUB-C)

Equipment and material specification		Investment cost $ US	
Surface cage	Submerged cage	SUR-C	SUB-C
Cage frame			
HDPE, 280mm PN10 ATU PE100, 16.6mm twin-pipe; 110mm PN10 ATU 6.6mm hand rim; twin-pipe rotation brackets, 40 brackets/cage (20–22kg/bracket); Styrofoam-filled main pipes 12–14 dens; 6×6 bird-net-float, 160mm main pipe, 125mm upper rim	HDPE equipment same as SUR-C, without Styrofoam-filling in pipe	24,000	24,000
Sinker tube; 31mØ, 97m circum., 250mm PN20, 25.2mm thickness; HDPE pipe 32mm chain reinforced	Sinker tube same as SUR-C, with extra load through vertically-stacked buoyancy chamber that helps sink the cage or raising up to surface	12,500	16,000
Mooring system (location depth: 60 m, max wave: 6 m)			
Submerged grid system with 5m collector depth	Submerged grid system with 15m collector depth	15,000	21,000
Fish feeding system; onboard feeding machine, 8000 kg feed capacity; 2 storage, 304 stainless steel, hydraulic	Feed buoy; automated feeding system, with air-bubble generator	10,000	15,000
Collector ring; 100cmØ, 60mm, iron, one per buoy point, 450$/piece *(# item/farm in parenthesis)*		1800 *(4)*	1800 *(4)*
Flash light; 3NML, red color, one per corner point, 160$/piece *(# item/farm in parenthesis)*		640 *(4)*	640 *(4)*
Signal buoy; 25lt, one per corner point, 14$/piece *(# item/farm in parenthesis)*		56 *(4)*	56 *(4)*
Cage net, Poli-Amit Nylon, painted (10+1m depth, 30mØ, 210d, 60no, 10mm mesh, total weight 1000kg)		12,300	12,300
Harvest net; 40m length, 20m depth, 210d48no,18mm, 100kg weight		634	634
Bird Net; 41m Ø, PP 57no 60mm, final wt. 85kg ±%10		816	816
Installation-deployment-supervision		10,000	10,000
Investment cost			
Total investment		87,746.00	102,246,00
+ 18% VAT		15,794.28	18,404,28
Grand total*		103,540.28	120,650.28

*Quotations are for November 2022, and prices of items are subject to change at yearly basis according to foreign currency variations, quality of items, and farm site

$$TSR = \left[\left(IFN\ x\ SR\right)\ x\ HW\right]\ x\ \left(SP\right)$$

where TSR is the total sales return (\$ year^{-1}), SR is the survival rate (%), and SP is the sale price (\$ kg^{-1}).

$$TC = (IFC + FC + PC + FuC + OC + DC)$$

where TC is the total cost (\$ year^{-1}) and DEC is the depreciation cost (\$).

For the TC estimates, depreciation cost is included, whereas initial investment excluded.

$$OPEC = (IFC + FC + PC + FuC + OC)$$

OPEC is the operating costs (\$ year^{-1}).

For the OPEC estimates, both depreciation cost and initial investment are excluded.

$$GR = (HW \times SP)$$

GR is the gross revenue (\$ year^{-1}).

$$NP = LR = (GR - TC)$$

where NP is the net profit (\$ year^{-1}), LR is the liquid revenue (\$ year^{-1}), and GR is the gross revenue (\$ year^{-1}).

$$GM = \frac{(GR - TC)}{TC} \times 100$$

where GM is the gross margin (%).

$$PI = \frac{LR}{GR} \times 100$$

where PI is the profitability index (%).

$$CF_n = GR_n – OPEC_n$$

where CF_n is the cash flow in the n^{th} year ($n = 1$), GR_n is the gross revenue in the n^{th} year, and $OPEC_n$ is the operating cost in the n^{th} year.

$$BCR_n = NP_n – TC_n$$

where BCR_n is benefit-cost ratio in the n^{th} year ($n = 1$), NP_n is the net profit in the n^{th} year, and TC_n is the total cost in the n^{th} year.

$$PR_n = \frac{NP_n}{GR_n}$$

PR_n is the profit rate in the n^{th} year ($n = 1$), NP_n is the net profit in the n^{th} year, and GR_n is the gross revenue in the n^{th} year.

The break-even point (BEP) shows the level of fish cultured in a year (kg year^{-1}) where the farm begins to receive profits, were estimated for each of the cage system using the following formulae as described earlier by Fernández-Sánchez et al. (2022):

$$BEP = \left(\frac{FC}{SP} - \frac{VC}{BMFP}\right)$$

where BEP is the break-even point, FC is the fixed cost (\$ year^{-1}), SP is the sale price (\$ kg^{-1}), VC is the variable cost (\$ year^{-1}), and BMFP is the biomass of fish produced (kg year^{-1}).

The risk level of the business in reaching the break-even point was assessed by the estimation of Margin of Safety (MOS), an important indicator for economic analyses in support of farm management with operating risk assessment, showing how much reduction in profit can result in break-even (Weygandt et al. 1999). The greater the MOS ratio is, the lower the risk of business. After the calculation of break-even points for each cage system, MOS ratio, indicating the difference between actual sales value and the break-even sales of the farm, has been estimated in percent value using the following formulae according to Weygandt et al. (1999) and Fernández-Sánchez et al. (2022):

$$MOS = \left(\frac{BMFP - BEP}{BMFP}\right) x\ 100$$

where MOS is the margin of safety (%).

Cost parameters for fish production in surface and submerged cages

After the establishment of the two cage models, cost parameters have been estimated by sample data obtained from five cage farms producing Turkish salmon in the Black Sea. The cost values were recorded for the last two years of production period between 2020 and 2022. Indications for revenues and annual cost parameters (fixed and variables) for surface cage system have been assessed for 7-months growth period, whereas a yearly basis (12-month) grow-out period was used for the submerged cage. All data provided in Table 2 are based on the assumption that no diseases or no net failures (no fish escapes) have been encountered during the production cycle, and the fish at harvest were most similar in shape and health conditions that are important indications for the sale price to be obtained in marketing.

Results

The export sales revenues and economic profits in terms of gross revenue, liquid revenue, gross margin, profitability index, and the benefit-cost ratio for submerged and surface cage with sales value of 7.5 \$US/kg and with 10% reduced sales value of 6.75 \$ US/kg ("What-if" analysis) have been given in Table 3.

The average cost and profits with variations in annual net profits have been illustrated in Fig. 1. The average cost as \$ US per kg Turkish salmon production in submerged cage was around 8.6% higher than those farmed in surface cage, whereas the average profit was nearly 6.20% higher for the production in submerged cage. The net profit, expressed in \$ US per annual production was found as 397,058.5 \$ year^{-1} for the surface cage and 685,652.5 \$ year^{-1} for the submerged cage, resulting in 72.7% higher profit for the latter one, when the cage was temporary submerged to cold water in the deep during the summer period. According to the "What-if analysis," when the export sales level reduced by 10% from 7.5 \$ kg^{-1} to 6.75 \$ kg^{-1}, the annual net profits reduced by 21.7% for the surface cage and by 20.2% for the submerged cage.

The break-even points for both surface and submerged cages (10,971.5 and 16,056.1 kg year^{-1}, respectively) were far lower than the annual production yields (94,500 and 153,900

Table 2 Cost parameters for Turkish salmon production in traditional surface cage and submerged cage systems based on one-cage model

Cage type	Production and operational cost ($ US)	
	Surface cage	Submerged cage
Cage volume (m^3 cage^{-1})	7000	7000
Variable cost		
Fish cost		
Biomass (kg/m^3)	15	15
Initial weight (kg fish^{-1})	0.4	0.4
Harvest weight (kg fish^{-1})[a]	3.5	5.7
Absolute growth rate (AGR, g month^{-1})[b]	443.0	443.0
Initial fish per cage (# cage^{-1})	30,000	30,000
Initial fish per cage (kg cage^{-1})	12,000	12,000
Initial fish cost ($ kg^{-1})	4.5	4.5
Initial fish cost per cage ($ cage^{-1})	54,000.0	54,000.0
Feed cost[c]		
Investment per unit production ($ ton^{-1})	1095.7	784.0
Investment per unit production ($ kg^{-1})	1.10	0.78
Feed cost ($ ton fish^{-1})	2175	2175
Feed cost ($ kg^{-1} fish)	2.18	2.18
Feed cost per cage ($ cage^{-1})	205,537.5	334,732.5
Total variable cost	**259,537.5**	**388,732.5**
Fixed cost		
Production period (PP, months)	7	12
No. of employees per cage	2	2
Salary per employee per month ($)	1100	1100
Salary per employee per production period ($)	15,400	26,500
Fuel cost per production period ($)	21,000	36,000
Health maintenance per production period ($)	400	400
Other operating costs per production period ($)	5000	5000
Annual depreciation rate (%)	10	10
Annual depreciation cost per farm ($)	10,354.0	12,065,0
Total fixed cost	**52,154.0**	**79,865.0**
Total cost (variables and fixed cost)	**311,691.5**	**468,597.5**

Values in bold indicate variable costs, fixed costs and the sum of total variable -and fixed costs for surface and submerged cages

[a]Harvest weight: a fish grow-out from an initial weight of 400 g to a harvest weight of 3000 g in a 7-month period is a predominant farming practice for Turkish salmon in the Black Sea

[b]The harvest weight of fish in submerged cage was estimated using absolute growth rate (AGR) obtained from actual AGR of Turkish salmon in surface cage over the 7-month grow-out period and applied for the fish in submersible cage for 12-month grow-out period that resulted in 5700 kg

[c]Feed cost calculated according to 1.65 $ kg^{-1} feed price and FCR value of 1.5

kg year^{-1}, respectively) (Table 4). Depending on the results for MOS, it can be underlined that there is no remarkable break-even point between operating the farm either with surface cage only, or temporary submersion of the system, but higher net profits and lower risk level in terms of MOS were found for the submerged cage (89.57%) compared to the

Table 3 Sales income by export market for Turkish salmon production in traditional surface cage and submerged cage system for a single production period with baseline -and reduced sale price

Cage type	Export sales revenues and economic profits			
	Surface cage	Submerged cage	Surface cage	Submerged cage
	Baseline sale price		Reduced sale price by 10%	
Unit sale price ($ kg fish^{-1})	7.5		6.75	
Survival rate (%)	90		90	
Harvest fish (kg cage^{-1})*	94.500	153.900	94.500	153.900
Total cost ($ cage^{-1})	311,691.5	468,597.5	311,691.5	468,597.5
Average cost ($ cage^{-1})	3.30	3.04	3.30	3.04
Operational cost ($ cage^{-1})	301,337.5	456,532.5	301,337.5	456,532.5
Gros revenue (GR, $ cage^{-1})	708,750.0	1,154,250.0	637,875.0	1,038,825.0
Liquid revenue (LR, $ cage^{-1})	397,058.5	685,652.5	326,183.5	570,227.5
Gross margin (GM, %)	127.39	146.32	104.65	121.69
Profitability index (PI)	56.02	59.40	51.14	54.89
Profit rate (PR)	0.560	0.594	0.511	0.549
Average profit (AP, $ kg^{-1})	4.20	4.46	3.45	3.71
Benefit-cost ratio (BCR)	1.27	1.46	1.05	1.22
Cash flow (CF)	407,412.5	697,717.5	336,537.5	582,292.5

*Harvest fish: fish grow-out from an initial weight of 400 g to a harvest weight of 3000 g in a 7-month period is a predominant farming practice for Turkish salmon in the Black Sea. The harvest weight of fish in submerged cage was estimated using absolute growth rate (AGR) obtained from actual AGR of Turkish salmon in surface cage over the 7-month grow-out period and applied for the fish in submersible cage for 12-month grow-out period that resulted in 5700 kg.

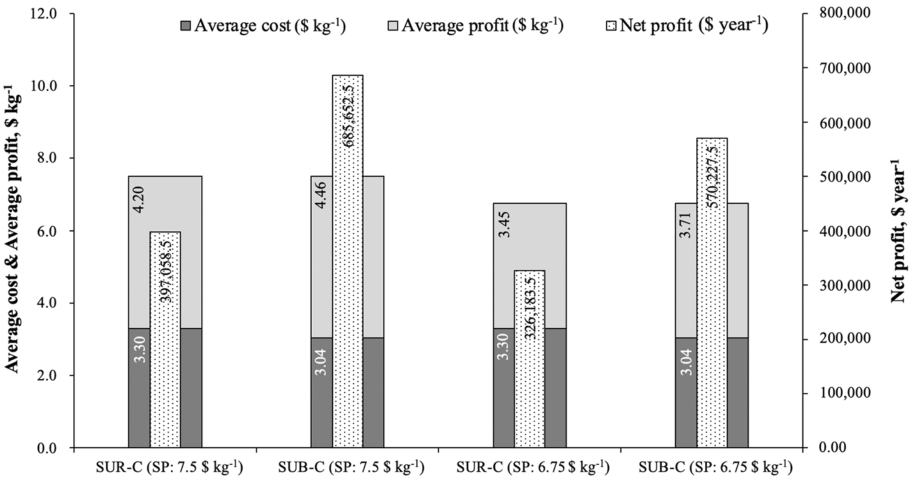

Fig. 1 Economic performance of salmon farming in traditional surface cage (SUR-C) versus submerged cage (SUB-C) system (based on 7.5 $ kg^{-1} fish sale price of export market with a "What-if" analysis of 10% reduction from baseline sales to 6.75 $ kg^{-1}; SP: sale price)

Table 4 Operating risks for salmon grow-out in a traditional surface cage versus submerged cage system for a single production period with baseline -and reduced sale price

Cage type	Surface cage	Submerged cage	Surface cage	Submerged cage
	Baseline sale price		Reduced sale price by 10%	
USP ($ kg fish^{-1})	7.5		6.75	
AP (kg year^{-1})	94,500	153,900	94,500	153,900
NP ($ year^{-1})	397,058.5	685,652.5	326,183.5	570,227.5
BEP (kg year^{-1})	10,971.5	16,056.1	13,026.9	18,906.9
MOS (%)	88.39	89.57	86.21	87.71

USP unit sale price, *AP* annual production, *NP* net profit, *BEP* break-even point, *MOS* margin of safety

traditional surface cage (88.39%). The break-even point and MOS ratio for salmon production in traditional surface cage versus submerged cage were estimated based on 7.5 $ kg^{-1} fish sale price baseline value of export market, and compared with a "What-if" case study when sale price declined by 10% (6.75 $ kg^{-1}) following an unexpected shock wave or fluctuations in global market trends, which are presented in Table 4. Regarding the "What-if analysis" applied for the break-even and MOS ratio, a 10% decline in the export sales value from the baseline sale price of 7.5 $ kg^{-1} to 6.75 $ kg^{-1} resulted in an increase by 18.7% for the break-even with a 2.5% decline in MOS in the traditional surface cage. When applying the same "What-if analyses" to the submerged cage system, the break-even increased by 17.8% and MOS ratio declined by 2.1%. Despite the fact that break-even points were not remarkably different when the export market sales reduced by 10% for both production systems, the annual net profit for the submerged cage (570,227.5 $ year^{-1}) was 74.8% higher than the surface cage model (326,183.5 $ year^{-1}).

Discussion

The competition for profitability in offshore aquaculture is highly dependent on several factors such as strong weather conditions, material quality, management and operational success, and also the potentials. The production capacities are usually triggered by increasing levels of sale price in the market that in turn may result in overproduction which is followed by a remarkable decline in market price, which has been a challenging issue for smaller-sized fish farms (Fernández-Polanco and Llorente 2019), which either increased production volume (high sales-less price), or improved quality for the supply of a new product for overcoming these struggles. Similar to the case of the seabass aquaculture industry in the Mediterranean in the 2000s (Llorente et al. 2020), the economic performance of rainbow trout farms engaged several strategy challenges with efforts of producing bigger fish that was also the case for rainbow trout grow-out with a target of 2.5 kg or bigger in a limited production period in the Black Sea. This was a new path towards the establishment of the rapidly growing Turkish salmon industry. Higher farm performance has been reported for seabass aquaculture when fish were grown to larger size that eventually improved economic sustainability for seabass aquaculture in the Mediterranean (Fernández-Sánchez et al. 2022). Fernández-Sánchez et al. (2022) reported that the production of smaller seabass of 450 g fish was the worst strategy and producing fish of 2 kg resulted in highest profit with increased economic performance of the farm when larger fish was supplied to the market. The present study revealed that the net profits and cash flow of Turkish salmon business in the Black Sea could be increased up to 72 %, when the fish production cycle is increased from seven months to yearly basis through temporary cage submersion taking the advantage of deep cold water during the high temperature season from June to October. This type of production strategy might increase net profits with reduced risks for the business. From the outcomes of this study, it can be underlined that the amount of annual production is an important criterion for improved economic benefits in fish production at industrial level, which is in line with earlier reports of Fernández-Sánchez et al. (2020) and Llorente et al. (2020), who indicated that the farm scale was the main indicator of farm revenues and a farm with larger production capacities provided better economic profits.

In the present study, feed cost at yearly basis demonstrated the highest level with around 66% and 71% for surface and submerged cage, respectively, which is in line with Huang et al. (2011) in terms of the highest proportion of cost percentage for feed expenditures. The initial fish stocking expenses in this study presented around 17% and 12% of the total cost for the surface and submerged cages, respectively, which was in line with earlier report of Kim et al. (2012) in offshore cage aquaculture of red sea bream. The total variable costs covering initial fish stocking -and feed expenses presented 83.3% and 82.9%, whereas the fixed costs demonstrated 16.7 and 17.0% for the surface -and submerged cage models, respectively. The variable cost was reported as more than 65% of the production cost for grouper farming in Taiwan (Miao and Tang 2002), whereas variable costs comprising fry and feed was found as 88–89% of the total investment for grouper farming (Bombeo-Tuburan et al. 2001), which are more or less similar to the findings in this study.

Several assumptions for equality were made for the standardization of parameters used, and the comparison was based on a “one-cage system.” The cost for economic -and production variables such as fish stocking and fish feeding were assumed to be constant for both surface and submerged cage models. Further, assumption for equality was made for the winter period from November to May in terms of water temperature or other environmental parameters. It is obviously understandable that a farm with larger scale would receive higher profits and revenues than a “one-cage model” applied in this study. This was also reported earlier by Asche et al. (2013), who indicated that the degree of farm size in salmon production increases farm revenues. This was also in agreement with seabass farms in the Mediterranean, in terms of higher profits with bigger farm scales (Fernández-Sánchez et al. 2022).

Considering the results from cost-benefit analysis in this study, it was revealed that entrepreneurs may gain net profits with low risks, whether using the traditional surface cage model for a limited period of seven months, or updating their production strategy with an annual production cycle by temporary cage submersion during the high temperature season in the Black Sea, as the break-event points for both production strategies were below the level of apparent production amounts, and the margin of safety ratios were remarkably high for both cage systems evaluated in this study. However, the results indicated that the yearly-base production via submerged cage might increase the net profit by 72% compared to the traditional surface cage production system, which provides remarkable indication for improvement of economic performance towards a sustainable management for Turkish salmon farming in the Black Sea. Considering the increased cash flow in the production strategy with submerged cage model, a rapid cash turnover may reduce unexpected risks, such as fish escapes due to net failures under harsh storms or disease outbreak, etc. A variety of uncertainties linked to pandemic outbreaks and lockdowns such as Covid-19 in 2020, or regional conflicts such as Ukraine and Russian war in 2022 are unforeseen shock waves on global market chain, with severe impacts and multiple ramifications for trade, price, logistics, production, new investment, economic growth, and livelihoods, with remarkable impacts also on the fisheries and aquaculture industries (FAO 2022a). Consequently, any deviation in these assumptions might result in different projections for aquaculture enterprises, which was considered in this study by the "What-if" analysis projected on reduced export sale price, which was reported as the most affecting factor on net operating profit (Fernández-Sánchez et al. 2022), who noted that price reduction by 10% can impact net operating profits more than any other parameter unconditional to farm size or production strategy. As a result of the "What-if analysis" performed in this study, even in a reduction of export value by 10%, higher revenues were obtained for the submerged cage model compared to the traditional surface system based on cost-benefit evaluation. These are useful indications for farm managers challenging unexpected shock waves of various crisis.

Besides economic benefits of submerged cage systems in salmon farming, the effective use of sea space in more exposed conditions may provide social advantages for submerged cage systems through reduced conflicts among coastal zone users (Sanchez-Jerez et al. 2016) and also environmental advantages through wide dispersal of dissolved wastes with lower nutrient loads in offshore marine environment (Holmer 2010).

In regard to fish welfare and physiological status in deeper waters, the barotrauma effect is another challenge for salmon due to the cut of air-access in submerged cages and fish may suffer from deflated swim bladder. In this perspective, swimming speed has been reported to increase by 1.6-fold as behavioral compensation compared to the individuals provided with air access (Dempster et al. 2008, 2009; Korsøen et al. 2009, 2012a; Oppedal et al. 2020). Long-term maintenance of salmon in submerged cage resulted problematically with tilted swimming behavior (Korsøen et al. 2009, 2012a), as a result compressed vertebrae and exhaustion has been observed (Ablett et al. 1989). However, short-term submergence for several days or even some weeks showed less influence on growths and welfare of salmon (Dempster et al. 2008, 2009). Smith (1982) underlined that salmon needs surface access to fill the swim bladder and keep buoyancy, which seems to be the main biological challenge for salmon farming with submerged cages. However, Korsøen et al. (2012b) reported that the swim bladder matter could be solved by the use of an air dome deployed inside the cage, or by up-lifting the cage to surface from time to time, which could be best during the night hours when surface seawater temperature is relatively lower than day-time hours. Further, salmon was succeeded to grow in submerged cage coupled with an air dome for around 2 months without any negative influence on behavior, growth or welfare, and fish up to 1.5 kg could maintain neutral buoyancy in submerged conditions (Oppedal et al. 2020). Despite the lack of information about the pressure effect and longer exposure time caused by lowering the cage system into deeper water, findings in earlier reports (Dempster et al. 2008, 2009; Korsøen et al. 2012b; Oppedal et al. 2020) indicate that fish maintained in submerged cage for short-term or event up to 2 months would not cause any serious problem. An ocean cage aquaculture technology (OCAT) system was tested in the Black Sea, 2 km off the Batumi coast of Georgia, where steelhead trout (*O. mykiss*) with mean initial weight of 197 g were maintained in submerged cage for 2 months, presenting 94% survival by the end of the study when fish reached a harvest weight of about 502 g and a feed-conversion ratio of 1:1.38 was obtained. The specific growth rate was recorded as 1.56%/day. However, due to two unexpected storms occurred while the cage was up-lifted to the surface, the top net was torn and the study had to be terminated by the end of the 2-month according to the report of Chambers et al. (2011). Unfortunately, there are lack of data regarding long-term exposures of salmon to deep water pressures. Hence, further investigations with long-term exposures to higher pressure levels are encouraged to fully answer these questions. Nevertheless, based on available data so far, short-term cage submersion seems to be an alternative solution for the prevention of barotrauma effect. For the submersion, the simple method of "water-in and air-out" can be applied by a buoyancy chamber vertically-stacked below the cage, which was also applied for the OCAT cage reported by Chambers et al. (2011).

Conclusion

Results from this study showed improved economic profitability in Turkish salmon production with temporary cage submersion during the high temperature season that comprises the period from May to October when surface temperature exceeds temperature limits for salmon, granting higher values of financial indicators with a net profit of around 685,652.5 \$ year^{-1} and a MOS ratio of 89.6%, compared to the traditional surface cage model that accounted a profit of 397,058.5 \$ year^{-1} with 88.4% MOS. It is worth underlining that greater the MOS ratio, the lower is the business risk. Despite higher investment (16.5%) and production costs (50.3%) for the submerged cage model, higher net profit obtained was due essentially to an increased production period throughout the year in respect to the surface cage system with limited production course. Additionally, the "What-if" analysis revealed that economic performance of both cage systems has been sensitive to variation in sales value. In particular, the simulations with 10% reduction in export market price may cause clear declines of financial indicators, with less profit loss for the submerged cage model compared to the surface cage. Therefore, the use of submerged cages may provide reasonable solution for production cycle extension throughout the year, an important support for the sustainable development of the Turkish salmon business with higher profits in the Black Sea. In future investigations, accurate understanding of aquaculture management with more detailed studies introducing stocking density, survival rate, and deep-sea feeding systems, as well as cost analyses in different depth may definitely support the overall business performance and economic dynamics in the progress of submerged offshore cage aquaculture industry.

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Author contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Ümüt Yigit, Murat Yigit, Sebahattin Ergün, Hüseyin Ek, and Halit Kusku. The first draft of the manuscript was written by Ümüt Yigit, Murat Yigit, and Masashi Maita, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval The study is based on economic data collected from commercial Turkish salmon farms. Hence, no ethical approval required for this study as no animals were used.

Competing Interests The authors declare no competing interests.

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