LIFECYCLE ASSESSMENT OF CARBON EMISSIONSIN SMART AQUACULTURE FOR OLIVE FLOUNDER (*Paralichthysolivaceus*)

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Abstract

This study assessed the carbon emission characteristics of smart floating farms incorporating climate change response technology, with a focus on olive flounder (*Paralichthys olivaceus*) aquaculture — a species accounting for over 50% of domestic marine fish production in South Korea, with projected output of approximately 46,000 metric tons in 2022. Life cycle assessment was conducted across the raw material production and rearing stages, encompassing freshwater consumption, dissolved oxygen supply, electricity use, feed, and wastewater treatment through the point of shipment. Smart floating farms exhibited water circulation rates equivalent to 40–70% of those in conventional systems, reducing annual freshwater consumption per kilogram of fish produced to 2,000–5,000 L — a reduction of up to 95% relative to the 40,000–50,000 L associated with conventional floating farms. Mortality rates in the experimental group ranged from 6.1 to 8.8%, markedly lower than the 25.4% recorded in the control group, while mean shipment weights of 872–973 g exceeded the conventional farm average of 843 g. Comprehensive carbon emission analysis across all input categories revealed a 63.9% reduction in greenhouse gas emissions relative to conventional floating farms. These findings demonstrate that smart floating farm technology substantially enhances resource use efficiency and production performance while significantly mitigating the environmental footprint of marine fish aquaculture, positioning it as a promising pathway toward low-carbon, sustainable production systems.

Introduction

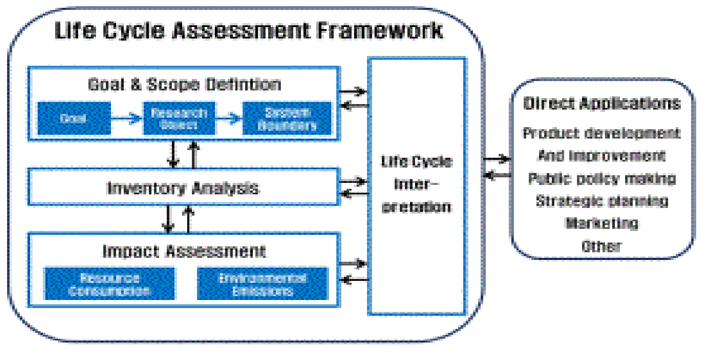


Fig. 1. Life Cycle Assessment (LCA) framework.

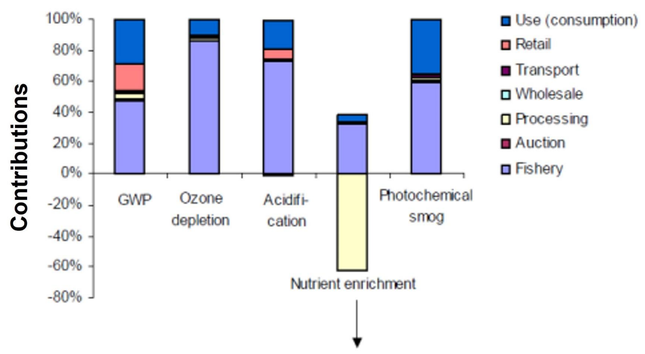


Fig. 2. Stage-wise environmental impact contributions across impact categories at Danish aquaculture sites.

- Global efforts to address climate change have placed mounting pressure on the aquaculture sector to reduce its environmental footprint. Under the Paris Agreement, South Korea has committed to a 53–61% reduction in greenhouse gas emissions by 2035 relative to 2018 baseline levels, with the fisheries sector mandated to contribute a 29.3% reduction. In response, governments worldwide — including South Korea, the EU, and Japan — have identified smart aquaculture as a strategic lever for achieving low-carbon, sustainable fish production. Smart aquaculture, which integrates ICT and artificial intelligence into farm management, is projected to grow from a USD 10 billion global market in 2016 to USD 100 billion by 2030.
- South Korea has set a target to increase its smart aquaculture adoption rate fivefold by 2030, reflecting the sector's broader transition from labor-intensive to knowledge-driven production. In this context, evaluating the greenhouse gas reduction potential of smart aquaculture systems across the full life cycle of fish production has become an increasingly urgent research priority.

Material and Methods

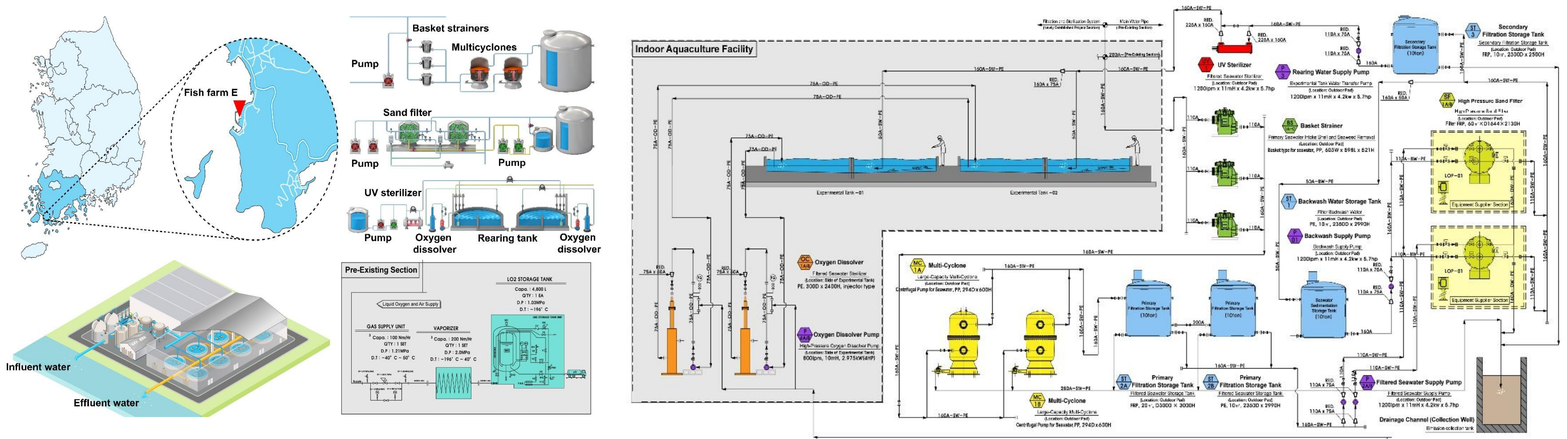


Fig. 3. TSS-PRS consisting of three basket strainers, two multicyclones, and two high-pressure sand filters arranged in sequence. A UV sterilizer was incorporated for bacterial disinfection, and an oxygen dissolver was used to increase the DO levels in the rearing tanks.

- The proposed smart aquaculture system was implemented at a fish farm in Jeollanam-do to enhance water quality and mitigate the risks posed by microbial contamination monitored by IoT methods. Especially, total suspended solids and pathogen removal system (TSS-PRS) consisted of three basket strainers, two multicyclones, and two HPSFs arranged in series. A UV sterilizer was also used for bacterial disinfection, while an oxygen dissolver was employed to enhance dissolved oxygen (DO) levels within the rearing tanks, thus ensuring optimal aquaculture conditions.
- Environmental parameters within the smart floating farm were continuously monitored using an integrated IoT-based sensor network. Sensors measuring water temperature, dissolved oxygen, salinity, pH, and turbidity were deployed throughout the rearing tanks and transmitted real-time data via IoT gateways.

Results

Table 1. Operational parameters of smart aquaculture system.

Parameter	Conventional Farm (Control)	Smart Farm (Exp. 1)	Smart Farm (Exp. 2)
Stocking density (individuals)	4,200	6,500	7,600
Mortality rate (%)	25.4%	8.8%	6.1%
Actual harvest — marketable weight (kg)	2,644.1	5,768.5	6,229.7
Feed consumption (kg)	1,504	2,098	1,856
Electricity consumption (kWh)	499,321	809,383	740,928
Water consumption (ton)	357,120	289,440	264,960
Oxygen consumption (kg)	526	734	650
Wastewater treatment volume (ton)	357,120	144,720	132,480
Mortalities — biomass (kg)	558.5	264.4	217.9
Mortalities — individuals	1,065	572	460
Days of culture	124	201	184
Tank area (m^2)	100	100	100
Tank volume (m^3)	60	60	60
Mean harvest weight (g/individual)	843.4	973.1	872.5

Table 2. Carbon footprint comparison between smart farm vs conventional farm (kg CO_2eq).

Category	Conventional Farm (control)	Smart Farm (Exp. 1)	Smart Farm (Exp. 2)	Reduction vs. Control
Feed	1.14E+03	1.59E+03	1.41E+03	−31%
Electricity	2.47E+05	4.01E+05	3.67E+05	−55%
Water	8.46E+04	6.86E+04	6.28E+04	+22%
Wastewater treatment	4.19E+05	1.70E+05	1.55E+05	+61%
Waste disposal landfill (40%)	9.79E+01	4.63E+01	3.82E+01	+57%
Waste disposal incineration (30%)	1.31E+01	8.26E+00	6.81E+00	+42%
Waste disposal recycling (30%)	1.87E+00	1.18E+00	9.73E−01	+42%
Total emissions	7.52E+05	6.41E+05	5.87E+05	+18%
Functional unit per kg harvested	2.85E+02	1.11E+02	9.42E+01	+64%

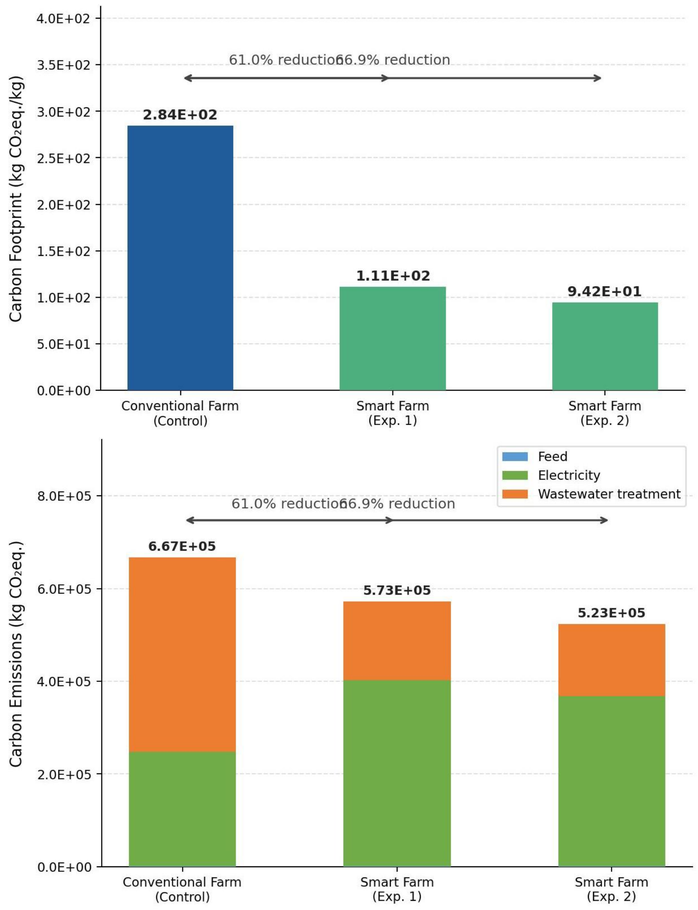


Fig. 4. Life cycle carbon emissions by input category for conventional and smart aquaculture systems.