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FIELD REPORT

MARINE RECIRCULATING SYSTEMS IN ISRAEL - PERFORMANCE, PRODUCTION COST ANALYSIS AND RATIONALE FOR DESERT CONDITIONS

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Abstract

A semi-commercial 100 m^3 marine recirculating system (RAS) was designed, based on the results of a 5 m^3 experimental system. The system was stocked with gilthead seabream (*Sparus aurata*). After 200 days, the fish in the semi-commercial system had a similar weight (about 330 g) and density (78 kg/m^3) and identical survival (99%) and FCR (1.8) as similar fish grown in a flow-through system (FAS). Annual production in the RAS was calculated as 90 kg/m^3. Seawater consumption was 3.5-4 m^3 per kg fish produced, resulting in an average water exchange rate of 80% of the system volume per day. While this is relatively high compared to freshwater RAS, the marine RAS required only 10% of the sea water consumed in an FAS. Since sea water is an inexpensive input, water consumption was a minor component of the total production costs in the RAS (approximately 6%). The economical analysis for a theoretical 500 ton/y farm showed that the main capital investment components would be the rearing volume (fish tanks) and the biofiltration unit, representing over 60% of the total investment. The highest production costs would be feed, fingerlings and return on the investment, in that order, representing over 50% of the production costs. CO_2 stripping may limit further intensification because the limited surface area of the tank limits the number of paddlewheels that can be used. Also, the DO/TAN ratio may be a factor limiting achievement of a higher nitrification rate and reduction of the biofilter size. Based on the results of this study, a 100 ton/y pilot plant is currently being designed as a model farm.

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Introduction

Expansion of the mariculture industry in Israel is presently facing major limitations. Fish culture in cages in the Red Sea, which produce the bulk of Israel's mariculture products, are being restricted by environmental regulations and growing public pressure that has escalated to a level of national debate. Offshore cage culture on the exposed Israeli Mediterranean coast has not yet proved to be technologically and economically feasible. Coastal areas for land-based mariculture are scarce and expensive, and potential sites are either confined to a few hectares near the coastline or are kilometers inland. Thus, expansion of the industry concentrates on development of intensive land-based cost-efficient recirculating systems.

The National Center for Mariculture (NCM) in Eilat, Israel, developed a super-intensive, low-head recirculating aquaculture system (RAS) for temperate and warm water marine fish production. Development of a semi-commercial 100 m^3 tank RAS followed a small-scale experimental phase in 5 m^3 tanks. The large-scale system was tested for two years and included monitoring of fish growth and water quality. Fish growth was compared with that in a flow-through system (FAS). Based on results in the large-scale RAS, a pilot plant for commercial production of 100 tons of fish per year is currently being designed. In addition, detailed production costs for a theoretical farm with a production scale of 500 tons per year were analyzed. Simulations and sensitivity analysis provided the rationale for design and management decisions regarding the development process. This paper describes the main features of the RAS and the rationale behind the development process.

System development

Up-scaling approach. One of the problems in developing commercial RAS is the up-scaling of experimental systems. During 1998-1999, an experimental RAS was studied in 5 m^3 tanks and, based on performance results, a larger-scale system was designed using the dimension analysis approach (Table 1). A factor of 1:20 was used to up-scale physical and operational parameters such as culture volume, feed, biomass, flow-rates and surface areas. Load parameters, such as fish density, feed load on the biofilter and solid filter, the hydraulic load, and water flow rates per feed unit (loop strength, feed burden and make-up water) were maintained at the same ratio (1:1).

System description. The system (Fig. 1) was built outdoors in a 100 m^3 tank covered by a greenhouse (green PVC sheet) to reduce heat losses and algae growth. Water treatment included a static solid filter and a moving bed biofilter. The total system head loss was 30 cm and water was recirculated by an airlift pump of an innovative design (no mechanical pumps were used). The system was designed by NCM and Kora Ltd. and constructed by Haogenplast Ltd. (Mozes et al., 2001b).

Oxygen supply and CO_2 removal. The culture water was oxygenated by submerged propeller jet aspirators supplied with liquid oxygen (LOX). Paddlewheel aerators were used for CO_2 stripping. Table 2 shows oxygenation and degassing results from earlier experiments.

Solid filtration. A static layer of plastic beads (known as "macaroni") filtered solids out of the system. Total suspended solids (TSS) and filtration efficiency were measured only in the 5 m^3 experimental tank. Typical TSS concentrations were 5-15 mg/l, with more than 50% of the TSS measuring under 15 µm. Overall filtration efficiency was 56%. Particle size distribution analysis revealed that the filtration efficiency varied from 75% to 45% for particles of 400 µm to 15 µm, respectively, and dropped to 10% for particles below 15 µm (Fig. 2)

Biofilter. A moving bed biofilter with plastic media ("macaroni") was used for nitrification. The biofilter was agitated and aerated by bottom air bubbling. Nitrification rates reached 500 g TAN per m^3 media per day (Fig. 3a). "One pass" efficiency was about 40% when the DO/TAN ratio exceeded a value of 3 mg/l (Fig. 3b). This find correlates with the results of Saucier et al. (2000), who showed that nitrification is limited by low DO/TAN levels.

Water pumping. Water was pumped by an airlift at a rate of 150 m^3/h. Head loss was

Table 1. Up-scaling of an experimental mariculture recirculating aquaculture system (RAS) to semi-commercial size.

	Experimental RAS	*Semi-commercial RAS*	*Size Ratio*
Tank volume (m^3)	5.0	100	20
Fish biomass (kg)	250	5,000	20
Feed intake (kg/day)	3.0	60	20
Filter cross-sectional area (m^2)	0.2	4	20
Recirculation flow rate (m^3/h)	6.0	120	20
Make-up flow rate (m^3/day)	5.0	100	20
Load parameters			
Fish density (kg/m^3)	50	50	1
Hydraulic loading rate[1] (cm/s)	0.83	0.83	1
Loop strength[2] (kg feed/m^3)	0.021	0.021	1
Feed burden[3] (kg feed/m^3)	0.6	0.6	1
Water volume exchange rate (times/day)	1	1	1

1 hydraulic loading rate = recirculation flow rate/filter cross-sectional area
2 loop strength = feed intake/recirculation flow rate
3 feed burden = feed intake/make-up flow rate

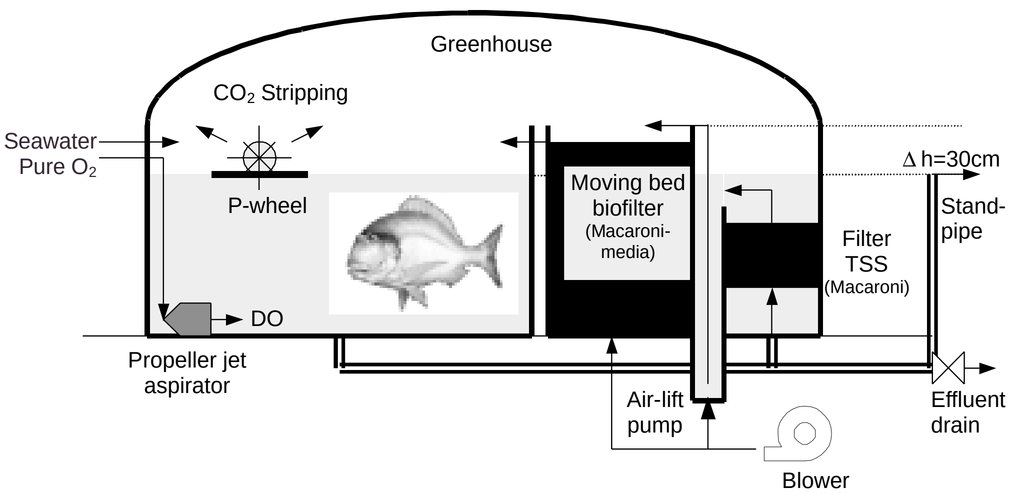

Fig. 1. Layout of the 100 m^3 marine low head recirculating aquaculture system (RAS).

Table 2. Oxygenation and degassing tests results.

	Device	*Field performance*	*Field conditions*
Oxygenation	Propeller Jet Force 7	1.40 kg DO/kwh*	100% DO saturation
CO_2 stripping	Paddlewheel	1.17 kg CO_2/kwh	8 mg CO_2/l, 20°C

* Performance of the propeller jet was up to 3.5 kg DO/kwh when measured at high oxygen flow rates.

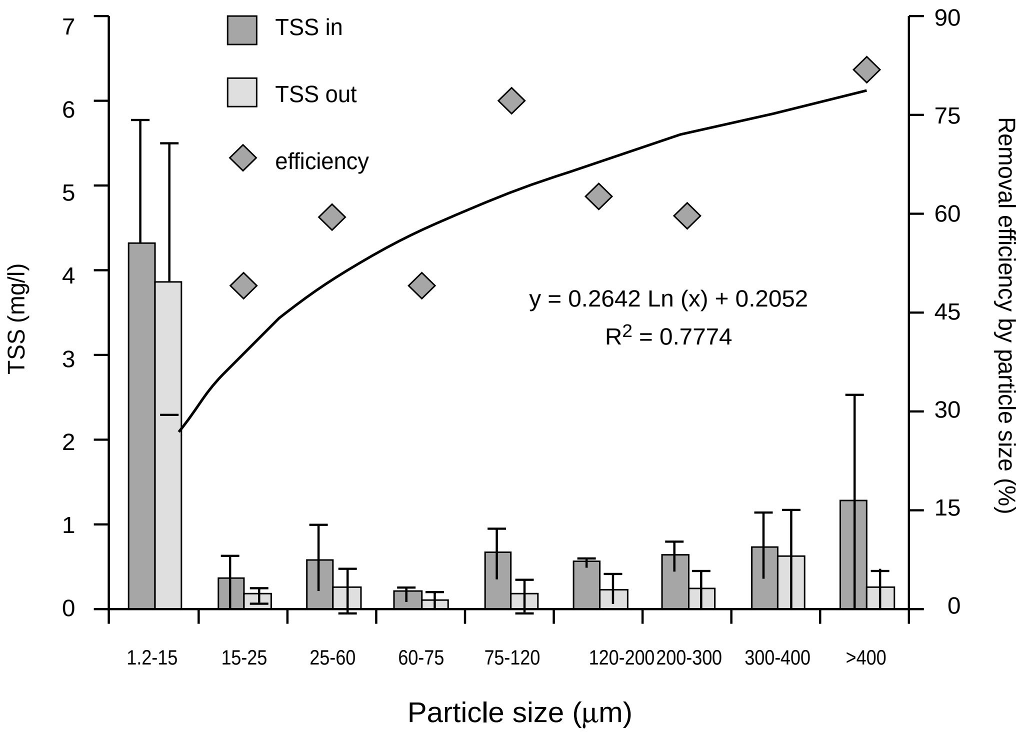

Fig. 2. Solid filtration performance in 5 m^3 tanks of a marine recirculating aquaculture system (RAS).

measured across the system and was 1-2 cm in the solid filter with a total pumping head of 20-30 cm (Fig. 4).

Fish culture performance. Gilthead sea bream (*Sparus aurata*) were grown in the RAS for two years, comprising several culture periods of growth. Growth in the RAS was compared with growth in a flow-through system (FAS) for 200 days (October 2000 to April 2001). Twenty-five thousand fish (86 g each) were stocked in a 100 m^3 RAS tank and 25,000 in a 100 m^3 FAS tank. The fish in each tank received the same amount of feed. Fish in the RAS (Fig. 5) had a similar final weight

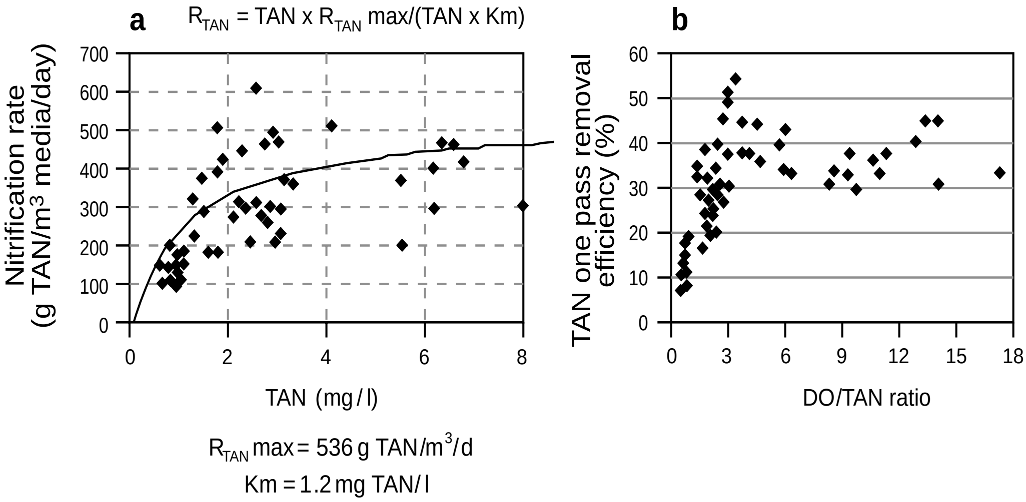

Fig. 3. (a) Nitrification rate vs. TAN concentration in the biofilter and (b) "one pass" removal efficiency vs. DO to TAN ratio.

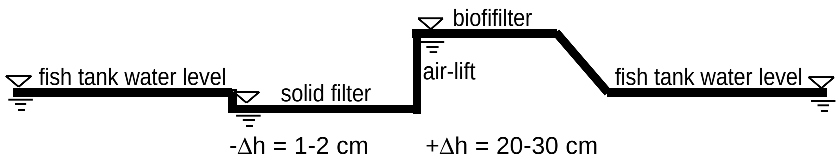

Fig. 4. Diagram of head loss at each system component.

(about 330 g) and density (78 kg/m^3) and identical survival (99%) and FCR (1.8) as the fish in the FAS. Fish in the RAS were grown for an additional 122 days, at the end of which they reached 490 g with 95% survival. The final density was 94 kg/m^3, resulting in an annual production of about 90 kg/m^3/y.

Water quality. Water quality was monitored routinely throughout the experiment. Principal water quality parameters are presented in Table 3. Sea water from the Red Sea was supplied to the system at a rate of 2 m^3 water per kg feed, resulting in an exchange rate of 60-150% per day. The flow rate, together with the greenhouse, maintained the water temperature within a narrow range. pH and alkalinity were dramatically lower than in the original sea water (8.2 and 2.5 meq/l, respectively). The low pH reduced NH_3 concentration to sub-toxic levels although TAN was relatively high, mainly at the end of the culture period.

Economic Analysis

A production cost analysis of the RAS was used to calculate the capital investment and production costs for a theoretical 500 ton/y RAS farm located in the southern Arava Valley, 6-8 km from the Red Sea (Mozes et al., 2001a). Relevant managerial and design issues were determined by a production cost sensitivity analysis. Several issues were ana-

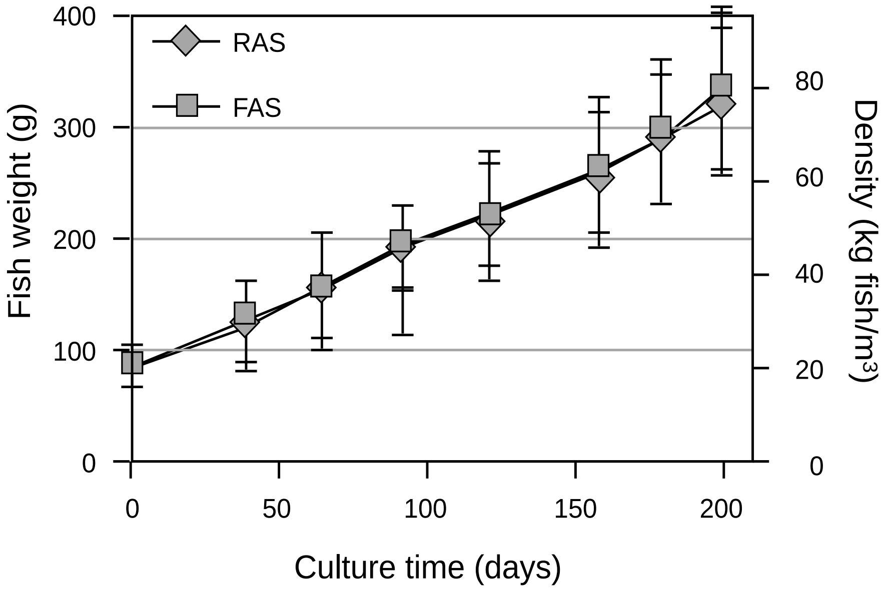

Fig. 5. Growth of gilthead seabream *(Sparus aurata)* in a recirculating system (RAS) and in a flow-through system (FAS) from October 2000 to April 2001.

Table 3. Water quality parameters in mariculture recirculating aquaculture system (RAS), October 2000 - April 2001.

Parameter	*Average*	*SD*	*Max*	*Min*	*n*
DO (mg/l)	6.9	0.5	9.0	5.4	378
Temperature (°C)	22.3	1.0	25.4	19.2	406
pH	6.87	0.10	7.14	6.61	55
Alkalinity (meq/l)	1.44	0.15	1.77	1.22	33
CO_2 (mg/l)	8.4	1.6	13.3	5.0	33
TAN (mg/l)	2.30	1.17	8.70	0.64	53
NH_3 (mg N/l)	0.0078	0.0035	0.0259	0.0027	44
NO_2 (mg N/l)	0.47	0.24	1.09	0.16	45
NO_3 (mg N/l)	15.9	0.75	17.41	13.6	40

lyzed; seawater related aspects and the level of system intensification are discussed below.

Sea water consumption. The general purpose of an RAS, whether it is fresh, brackish or seawater, is to minimize consumption of new water (make-up water). Seawater consumption in our RAS was 3.5-4 m^3 per kg fish produced, resulting in an average water exchange rate of 80% of the system volume per day. This is relatively high compared to freshwater RAS. However, it can be moderated by the following considerations.

Water supply cost. Potential inland mariculture sites in the southern Arava are remote from the sea and, therefore, transport of water has a direct impact on production costs. A preliminary analysis estimated the cost of water, including capital return on investment, costs of energy for pumping, and maintenance costs. Based on this analysis, the increased production cost over that of an FAS (which requires 35-40 m^3/kg fish produced) was 4% per km distance from the sea (Fig. 6a). However, the RAS requires only 3.5-4 m^3 per kg fish produced (10% of that required in an FAS) and the economics are much less sensitive to the distance from the sea (representing an increase of only 0.5% per km in the production costs). Since sea water is an inexpensive input, water consumption is a minor component of the total production costs in the RAS (approximately 6%).

Water temperature considerations. The water temperature of a culture system is related to the water supply. Earlier studies showed that a low water exchange rate results in water temperature extremes during summer and winter. Simulations of production costs were conducted for scenarios using different insulation and heating systems. The simulations showed that relatively low benefit (reduction of production costs) is achieved from a temperature increase, compared to the cost of heating and the capital return on insulation under the conditions in the local desert climate and the tested technology. A reduction of production costs (Fig. 6b) results from shortening the growth period (it slightly reduces the investment in rearing volume) and improvement of the FCR. However, the use of a greenhouse cover to reduce heat loss during winter, together with sufficient water exchange, can maintain suitable temperatures throughout the year.

Alkalinity considerations. Alkalinity at a rate of about 2 equivalent (bicarbonate) per

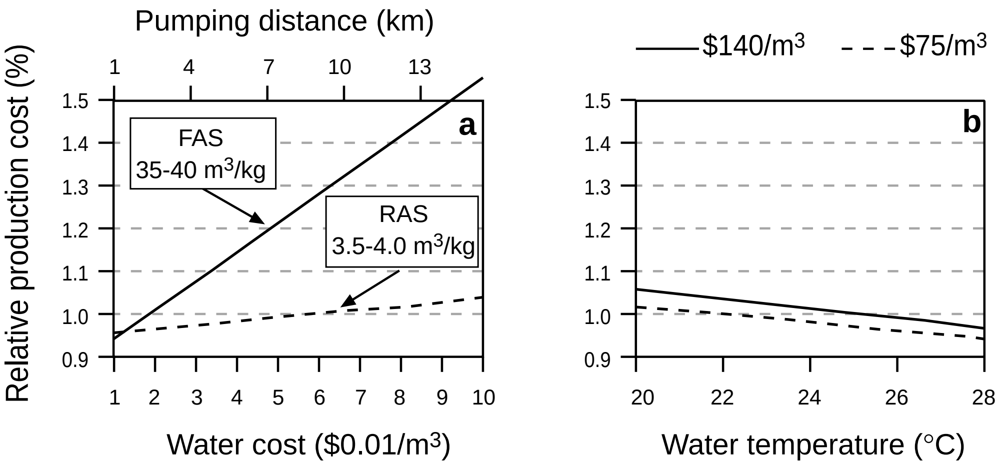

Fig. 6. Relative production cost of fish vs (a) pumping sea water to a distant site in the southern Arava Valley and (b) maintaining a constant water temperature in facilities with a high ($140/$m^3$) or low ($75/m^3) investment in rearing volume (fish tanks).

oxidation of a mole of ammonia is required for nitrification (Bisogni and Timmons, 1994). Ammonia excretion from feed with a protein content of 45% was estimated at 2.5 mole/kg feed (Lupatsch and Kissil, 2001). Therefore, the alkalinity consumption is 5 eq/kg feed. Sea water at a flow rate of 2 m^3/kg feed would supply the alkalinity needed for nitrification. Chemical addition of base can be used as a substitute for the supply of alkalinity by sea water. A cost estimate for the addition of NaOH showed that the use of sea water as a source of alkalinity is cheaper than addition of base.

Other considerations. Alkalinity can be recovered through denitrification, allowing the required amount of sea water to be reduced. However, denitrification in the large-scale RAS has not yet been studied. Also to be considered, the accumulation of colloidal (10^{-6}-10^{-7} m) particulate matter and dissolved organic substances (known as the "tea color" effect) may produce off-flavor in fish. Off-flavor can lower market prices and even prevent sales, unless fish are purged for several days in clean sea water. Organoleptic tests showed no fish off-flavor in the semi-commercial RAS, probably due to the high water exchange rate. Other solutions to this potential problem, such as ozone or foam fractionation, have not yet been studied.

System intensification. Economic analysis of a 500 ton/y farm showed that the main capital investment components would be the rearing volume (fish tanks) and the biofiltration unit, which represent over 60% of the total investment. The highest production costs would be feed, fingerlings and return on the investment, in that order, representing over 50% of the production costs. Better use of the capital investment components would improve economic performance.

Fish culture intensification. A major consideration in the development process was the level to which culture should be intensified. Intensification of fish culture depends mainly on the oxygen supply. Oxygen requirements for low fish densities (less than 25 kg/m^3) can be met with aeration. Increasing the intensity of the culture would require an expensive pure oxygen source (LOX) but reduce the required land and rearing volume. Potential sites for land-based mariculture in the southern Arava Valley are several kilometers inland, where land costs are low. Although the low cost of desert land can permit extensive culture, land-based mariculture rearing volumes require plastic lining to prevent seepage of the sea water into the ground and greenhouse covers that are relatively expensive.

Simulations of a 500 ton/y RAS farm showed a dramatic reduction of fish production costs as the culture intensified. Fig. 7a shows the relative production costs for two levels of investment in rearing volumes, assuming the cost of land is zero. Based on this analysis, final fish density targets and the use of LOX were determined.

Ammonia concentration. An important consideration in designing RAS is the permissible total ammonia nitrogen (TAN) concentration. A higher TAN concentration results in a higher nitrification rate and a smaller required biofilter volume. Being a major capital investment component, reduction of the size of the biofilter has a significant effect on fish production costs (Fig. 7b). While high TAN concentrations may raise the level of toxic un-ionized ammonia NH_3, low pH values such as those measured in the RAS (Table 3) reduce the NH_3 fraction to a sub-toxic level (Wajsbrot et al, 1993). The combined effect of low pH and high TAN, together with the effect of pH on CO_2 concentration, is currently being studied and may result in additional economic benefits.

Conclusions and Future Research

Our RAS demonstrated high fish culture performance (production 90 kg/m^3/y, survival over 95%) on a semi-commercial scale. The development of the RAS was based on a detailed study of production costs and sensitivity analysis. Several limitations to further intensification were identified: limited surface area of the tank limits the number of paddlewheels that can be used for CO_2 stripping, and the DO/TAN ratio probably limits achievement of a higher nitrification rate and reduction of the biofilter size.

Current research is focusing on CO_2, pH

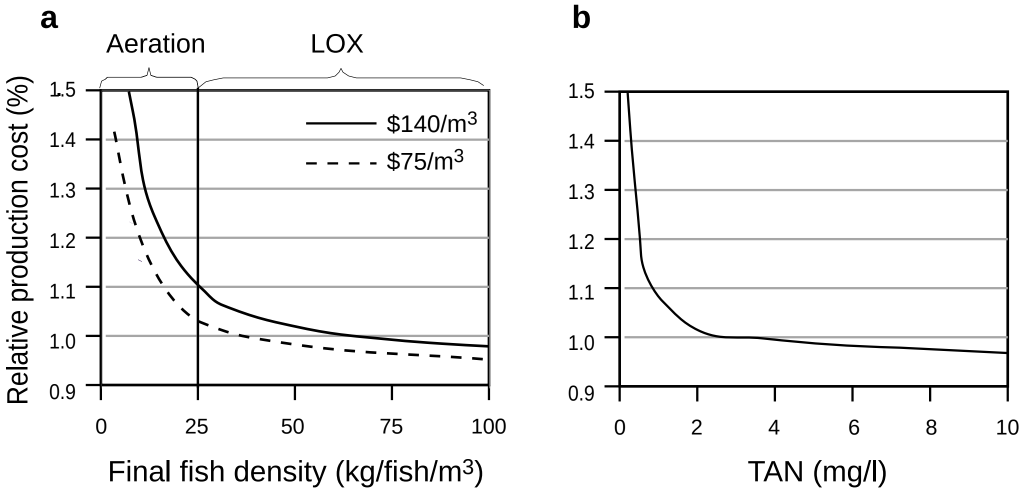

Fig. 7. Relative production cost of fish vs (a) oxygen for various fish densities in facilities with a high ($140/m^3) or low ($75/m^3) investment in rearing volume (fish tanks), assuming that aeration is provided when the fish density is up to 25 kg/m^3 and pure oxygen (LOX) when above 25 kg/m^3 and (b) maintaining the TAN concentration at various levels.

and TAN control. A major aspect to be addressed is the treatment of wastewater by denitrification, which may also contribute to reducing seawater consumption by recovering alkalinity. Another option under consideration for effluent treatment is the use of seaweed.

Based on the results of this study, a 100 ton/y pilot plant is currently being designed as a model farm for further development of the mariculture industry in southern Israel.

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