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Marine Aquaculture Solid Waste Treatment: Case Study 19

Research goal	To develop an integrated aquaculture wastewater treatment system for simultaneous microbial reduction of sludge mass, nitrate/nitrite removal and biomethane production from varying organic loads throughout the fish growth cycle.
Beneficiaries	Marine aquaculture and land-based recirculating aquaculture industries
Activities conducted in order to achieve the objectives	Laboratory studies to identify a marine methanogenic consortium and system factors influencing methanogenic activity. Upscaling of laboratory reactors to a semi-commercial marine and brackish recirculating system with integrated modified large volume UASB bioreactors fed with saline sludge.
Funding	2 BARD awards: MB-8707-04 and MB-8707-04; $590,000 Other academic funds: $267,000 million, Industry Funds estimated at $2 – 3 million.
Publications	11 journal publications, of which 10 are in the top quartile impact factor journals.
Students involved	Five graduate students, 8 undergraduates, 1 high school student. Current positions: Five in Academia, of which 3 in the US, 1 in Israel and 1 in Armenia. Six in industry, of which 3 in the US and 3 in Israel.
Stakeholders' collaboration	Knowledge disseminated from these projects has contributed to the ongoing activities of the Israeli firm, Aquatech
Environmental impact	Reduction of water use by recirculation techniques and reduction of solid waste volume resulting in significant reduction in environmental pollution from aquaculture systems
Social impact	The systems can be used in rural or urban locations, distant from seawater sources, which will allow production of fresh aquatic products in close proximity to the consumer. The reduced environmental footprint of the system renders the aquaculture systems to be "socially licensed"
Commercial engagement	The patented method for conversion of solid waste to methane has been licensed to Marine Sustainable Mariculture LLC (MSM). The first commercial application was initiated in Norway in 2018.
Patents	1 Issued, 1 filed
Practical agricultural applications	The system leads to an overall reduction of organic saline waste at inland mariculture farms, generates energy and consequently leads to an improved system efficiency and a reduction in operating costs.
Economic impact	Net present value of the BARD's investment is $28 million, thereof $0 million already attained. The Internal rate of return is 31% Benefit cost ratio is 44, thereof 1 already attained.

Green- Academic information; Yellow - Social and environmental information; Blue - Economic information

1 Objective: Biomethane Recovery from Aquaculture Sludge

Aquaculture has exhibited one of the world's highest growth rates among agricultural products in recent decades. Inland closed recirculating aquaculture systems (RAS's) are being developed as a viable eco-sustainable alternative to traditional aquaculture (e.g. ponds, raceways and cages) because of their minimal environmental impact and controlled operation. The research study aimed to develop on-site, energy recovering techniques to treat saline sludge generated from inland brackish and saline super intensive RAS's whilst ensuring a pathogen-free effluent for near-complete recycling of water into the RAS to conserve water.

2 Research Activities

Inland recirculating marine fish systems conserve water by treating waste water within a closed loop, thereby offering improved control of effluent discharge and reducing the environmental impact of the system. In the U.S., strict EPA regulations on organic matter discharge have motivated the aquaculture industry to implement techniques to reduce sludge volume prior to composting it for land dispersal. However, the high salinity of marine and brackish water sludge limits its use as fertilizers, and it is a source of pollution in landfills and waste outflows. The BARD research aimed to convert the solid saline fish waste to biomethane, thus significantly reducing sludge volume and also generating an energy source for the fish farm system.

The BARD supported research activities focused on the modification of Upflow Anaerobic Sludge Blanket (UASB) reactors for the anaerobic digestion of brackish and marine aquaculture sludge. The process enables robust methane production in spite of the high salinity and sulfate content and ensuring a pathogen-free effluent for complete recycling of water into the RAS.

Research steps included:

- Development and optimization of UASB-like reactors for the treatment of RAS sludge.
- Use of molecular tools to identify methanogenic consortium of fermentors, acetogens and methanogenic archaea, co-existing with sulfate reducing bacteria in both brackish and marine UASB reactors.
- Determination of the Chemical Oxygen Demand/sulfate (COD/SO_4^{-2}) ratio as the key factor affecting methanogenic activity in a sulfate rich environment.
- Development of molecular tools to monitor bacterial fish pathogens in aquaculture sludge, which was followed by a study on the fate of fish pathogens following exposure to hydrogen sulfide.

- Successful scale-up of laboratory reactors to a semi-commercial marine and brackish recirculating system with an integrated modified 1000-L UASB bioreactor fed with saline sludge.
- Reaction rates and pathways were elucidated in each compartment of the RAS using C and N mass balances, and a model was established to predict concentrations of the various nitrogen containing compounds in the system as a function of changing feed applications.

Research Outcomes:

The early research approach (BARD award MB-8707-04) generated low biogas (methane) concentrations, due to the inability of the microbial consortia to adapt to the high salinity and low C:N ratios. In the later research (BARD award US-4453-11), a novel and unique halotolerant methanogenic consortium, optimized for converting brackish and marine solid waste to methane gas, converted > 90% organic solids accumulated in the system during the fish growth cycle to biomethane, without modifying the C:N ratio. Molecular tools were applied to determine the fate of pathogenic bacteria and parasites in this closed system. Result indicates that water from the RAS unit can be safely recirculated back to the fish tank after a retention period in the UASB with minimal risk of infectious disease outbreak

The emissions of greenhouse/toxic gasses (NH_3, N_2O, CH_4, CO_2, H_2S) were monitored, enabling assessment of the environmental footprint of the system.

3 Academic Impact

3.1 Publications

Two book chapters and 11 peer-reviewed publications in top impact factor journals, of which 10 are in the top quartile (Q1) impact factor journals

3.2 Capacity Building

Five graduate students, 8 undergraduates and 1 high school student (part of the US Ingenuity Research Program) were involved in the BARD research. Five currently have positions in Academia, of which 3 in the US, 1 in Israel and 1 in Armenia. Six have positions in industry, of which 3 are in the US and 3 in Israel.

4 Stakeholder's Collaboration

Establishment of two unique pilot scale marine and saline water RASs in the US and Israel that support high density culture of high value fish (in Israel, Sea-bass and Barramundi as well as lower value fish such as Catfish, Tilapia and Carp).

The onsite solid treatment and energy recovery developed in these two BARD projects laid the foundation for two additional developments at the forefront of recirculating aquaculture research, advanced by the Israeli PIs' research group with funding from other research funds and donations. Both systems are directly based on results from the BARD projects.

System 2: A novel near-zero discharge pilot scale microaerophilic assimilation reactor was modeled and then conceptually proven. The study demonstrated assimilation-based RAS with solid waste treatment that is based on side production of microbial biomass that can be further used as fish feed.

In this system, the nitrification process in which ammonia (NH_3 or NH_4^+) is oxidized by bacteria to the less toxic nitrate (NO_3), is omitted. Instead, the N removal is based on microbial assimilation of ammonia from the fish tank, together with carbon from the sludge (and external low-cost sources such as flowers) in a microaerophilic environment and in a side reactor. The latter ensures control over the pond water quality. This protein-rich microbial biomass is harvested and used as a fish feed supplement.

The system is novel in that alternative techniques proposed for microbial protein synthesis were always done in the fishponds so the microbial biomass was directly used as feed, thus allowing the growth of only limited number of fishes. Moreover, water quality was compromised due to high suspended matter and formation of toxic nitrite and the operation required a lot of energy to aerate the fishponds (i.e. the microbial biomass added significant oxygen demand)

This innovative system has direct benefits:

- Carbon and nitrogen are removed onsite from the RAS.
- The highly energy consuming nitrification process is omitted.
- Fishmeal costs are reduced.

System 3: A novel near-zero discharge pilot scale aquaponic (RAS) system with solid waste treatment and biogas production which can potentially be operated off grid (without the need for external electricity). This system is a "combination" of the system developed during the BARD research and system 2. In this aquaponic system, the anaerobic sludge reactors break down the sludge into bioavailable nutrients that can subsequently be used to grow edible plants.

The assimilation of nitrogen and phosphorus to the plant biomass stabilizes the water quality for the fish. Energy in the aquaponic system is needed to supply aeration to the water to sustain fish, plants and reactors, as well as to circulate the water between the various reactors. The carbon released from the sludge together with plant waste (e.g. stalks etc.) is used to generate biogas to run the aquaponic system.

This innovative system has direct benefits:

- Carbon and nitrogen are removed from the water and sludge.
- Assimilation of nutrients into plants, produces another source of income (e.g. vegetables). It can potentially supply (*via* biogas) the energetic demands to run the system off-grid.
- The water and nutrients reuse is efficient to the degree that vegetable production per unit of produced fish is increased 3-fold compared with "traditional" aquaponics[1].

The researchers are working on the implementation of these developments with the head of the Mariculture Division of the Israel Ministry of Agriculture.

5 Commercial Engagement

The patent US9,637,402 is licensed by Marine Sustainable Mariculture LLC (MSM), a US based investor group that is currently recruiting additional investors in order to implement full scale commercialization. Design of a 200-ton production facility has been completed, which incorporates a modular support system for eventual expansion.

K. Sowers initiated a commercial collaboration with Cermaq's salmon hatchery in Forsan, Northern Norway. A methanogenic consortium was developed using the same principles developed in the BARD projects to convert the salmon smolt solid waste into fuel-grade methane.

6 Patents

Conversion of fish waste from marine, brackish and freshwater aquaculture systems to methane by a modified UASB reactor. Y. Tal and K.R. Sowers, US9,637,402. Granted 05/02/2017 to University of Maryland

Patent application No. 15/378,480. *A defined consortium of microbes that catalyze the conversion of mariculture waste to biomethane.* K.R. Sowers. Filed 5/18/17. Status: under review.

7 Practical Agricultural Applications

Environmental constraints and the growing demand for marine products are motivating the aquaculture industry in both the U.S. and Israel to shift from net-pen mariculture to inland intensive production systems (e.g., Israel Red Sea seabream, USA salmon). Major obstacles for this shift are the large volumes of organic brine wastes and the inhibitory energy consumption of the intensive inland RAS systems.

[1] The only known commercial-scale aquaponic system is at the University of the Virgin Islands.

The scale up and implementation of novel technologies and approaches developed in the BARD and follow-up studies have many advantages. It enables super intensive aquaculture (100 kg/m^3 and more) and provides significant improvements in RAS energy balance (both lower operation expenses as well as the saline solid fish waste can be converted to biogas at a >90% efficiency). In addition it has a near zero water exchange, an overall reduction of pollutants and waste production, additional products (e.g. microbial biomass/vegetables) and consequently improved system efficiency and reduction in operating costs.

Due to the near zero water exchange (the water renewal rate is 0.5% of the systems volume per day), this mariculture system can be independent of nearby large water source such as lakes or ocean and can be established inland (employing artificial sea salts and local sources of freshwater).

The first full-scale biogas plant from fish sludge started operation in April 2018 in Norway at Cermaq's salmon hatchery in Forsan, Northern Norway. The bioculture was developed by the research group led by K. Sowers at the Institute of Marine and Environmental Technology (IMET), Maryland. The water purification company Sterner AS developed the pilot biogas facility at smolt producers Smøla Klekkeri and Settefiskanlegg AS with government funding through Innovation Norway. Enova SF supported the development of the waste treatment plant and the 100 m^3 bioreactor at Cermaq's facility in Forsan.

The process is being scaled-up with the expectation of managing 100 percent of the waste at the facility, generating 500,000 kWh per year from the waste from nine million smolt, or juvenile salmon. This energy is used to heat the water that flows through the facility, and the biogas then replaces oil, other fuels and electricity.

8 Social Impact

Closed land-based containment systems have been promoted as a more sustainable solution for aquaculture and enjoy higher levels of social license to operate, therefore becoming the preferred system by policy influencers, consumers and regulators

The small farm population are a significant percentage of the population in developing economies and often suffer from deficiency malnutrition, mainly resulting from a lack of vitamins and protein in their diet. Small aquaponic units such as the one developed by A. Gross (BGU) and colleagues (System 3) might be in the future economically viable for small plots and could potentially alleviate the issue of malnutrition "in-house".

9 Environmental Impact

Positive Impact:

- The innovative systems reduction in concentrations of organic and total ammonia nitrogen pollutants and waste.
- Near zero exchange reduces water utilization
- Inland mariculture enables production facilities to be much closer to the consumer, thus diminishing environmental footprints due to transportation.

Negative Impact:

- Although reduced in comparison to current aquaculture practices, the emission of greenhouse (N_2O) and toxic (H_2S) gasses from the various compartments need to be further studied.

10 Economic Impact

10.1 Investment Cost

BARD contributed $590,000 in research funds between 2004 to 2013. Additional funding that contributed to the development of systems 2 and 3 totaled $267,000. More money was invested by the industry, with amounts not-known, estimated at $2 – 3 million.

10.2 Benefits

Extensive research has been conducted throughout the world to establish the most effective yet economically feasible technology for enhancing sludge digestion. The scale up of the research results, as seen in Norway's Cermaq facility, has led to the development and optimization of a sludge digestion in an anaerobic bioreactor for biogas production, the first full-scale biogas plant from fish sludge.

The bacteria consortium was developed with "Norwegian" sludge shipped to the U.S. and imported back into Norway under an assigned product registration in compliance with Norwegian import regulations. This is a viable starter culture for any future salmon smolt facilities that employ conversion of solid fish waste to biogas to initiate biogas generation.

In Norway, new regulations require all new aquaculture facilities or current facilities undergoing renovation and expansion to treat their waste before release. As larger land-based operations are built, the demand for biogas treatment is expected to increase. To assess the future benefits of the developed system we evaluate the expected adoption rate of the technology in Norway.

Anticipated Adoption of the Technology

We first assess the adoption in Norway, where the technology is already implemented and where additional facilities are expected to adopt the technology in the immediate future. We then assess the anticipated adoption in the US where inland intensive salmon aquaculture is being established and for which the industry players have shown interest in the technology. We note the potential global implementation resulting from the increase in inland intensive facilities but do not attribute monetary value to this potential benefit.

Norway:

Today in Norway, To overcome various challenges of the industry, dominantly sea-lice pressure, the trend is to keep salmon longer in close containment systems before transport to sea cages. Billions of krone have been put into increasingly large smolt facilities and older nurseries have been expanded[2]. All these are required by regulation to treat their waste.

Table 4 in Appendix B lists smolt facilities in Norway that are currently being built anew or expanded. The capacity of the facilities is stated as either tub volume or weight production. The traditional salmon farming cycle farms the smolt on land up to 100g before releasing the fish in sea cages for grow-out, but the current trend is to grow out to between 100-400 gr. We consider a smolt size of 250 gr when interchanging between weight and number.

Based on the stated capacities we estimate the size of the biogas facility required to treat the fish sludge relative to that at the Cermaq facility. At Cermaq, the reactor size is 100 m^3 and it will treat annually 260 tons of sludge from 1,600 tons of feed used to produce 9 million smolt. For smolt growth we assume a Food Conversion Ratio of 1 (FCR = tons feed used per tons fish produced)[3]. The column "size ratio" in Table 4 shows the estimated ratio of sludge volume to that at Cermaq based on the estimated feed weights.

To date the technology is more cost-effective for large salmon smolt operations. For smaller operations it is currently more cost effective at this time to dry waste for use as fuel or compost.

The investment amount at Cermaq was $5.5 million. The scale up costs of biogas facilities are not linear and we assume only 50% increase in the investment for doubling the digestor volume[4]. For these 13 facilities we estimate a total investment of $130 million based on our estimates of scale up costs. The facilities in Table 4 comprise between 15-25% of quantities produced in Norway[5].

Based on the cost effectiveness of the system, we assume the producers will gain benefit which is higher than investment[6], and as a low indicator in the calculation we assume that

[2] https://salmonbusiness.com/here-are-norways-10-largest-smolt-sites/
[3] Nofima, Report 19/2017: Estimated content of nutrients and energy in feed spill and faeces in Norwegian salmon culture
[4] https://www.biogasworld.com/news/future-small-scale-anaerobic-digestion/
[5] https://www.fiskeridir.no/English/Aquaculture/Statistics/Atlantic-salmon-and-rainbow-trout
[6] https://www.biogasworld.com/news/future-small-scale-anaerobic-digestion/ Estimated content of nutrients and energy in feed spill and faeces in Norwegian salmon culture

the benefit equals the investment = $130 million. It is based on only those facilities that were identified as being newly built or expanded. The investment is spread out between 2019-2028 yet it is more than likely that additional new or expanded operations will be added in this time span.

For the near future we assume that 100% of the conversion of sludge to biogas will be based on digestion by the bacteria consortium developed by the Sowers group at Maryland. Although other options may yet prove to be commercially and environmentally acceptable, none currently exist.

Not accounted for in our conservative estimate is that as more land-based RAS facilities are built in Norway, sludge will be treated from facilities of the full cycle of growth. And that the sludge volumes from the latter stage of farming are much higher than those of the sludge produced from smolt. Additionally, sludge from closed sea cages is not accounted for. The Norwegian salmon company, AkvaFuture, which targets production of about 72,000 tonnes of salmon in a closed-cage facility, has a contract with Scanship holdings to treat the sludge from their closed sea cages. Waste deposits and sediment are due to be removed during production and the sludge pumped to shore for production of biogas and fertilizers. Currently, at their pilot site (Steinsvik, Norway), Scanship holdings transforms the sludge into fertilizers that are then delivered to Vietnam.

USA

We estimate the benefits of sludge treatment and its transformation to biogas for US land-based RAS salmon farms that are being established. Three major aquaculture companies are in stages of establishing land-based RAS salmon farms in the US. Pure Salmon with facilities in Virginia, Whole Ocean with facilities in Maine and Atlantic Saphhire with facilities in Maine. The projected production from all 3 facilities is 110,000 tons of salmon. Sludge can be treated from both the smolt and grow- out phases. The FCR ratio for grow out phase is 1.15[3] so we can assume an annual total feed weight of 126,500 tons.

This is ~ 80 times the feed volume at Cermaq. As the digestors and reactors will be concentrated on limited sites, they will likely be much larger than the 100 m^3 Cermaq facility, thus reducing investments cost per volume. Likewise, concentrating a number of digestors aside each other in one facility will also lower the scaling costs of increased capacity. Assuming that each of the three facilities will bear the burden of a third of the sludge waste we use the scaling up ratio previously assumed and estimate that the total installation costs will be $112. As the Maryland lab works closely with the aquaculture industry in the US and as currently, it provides the only feasible techniques to convert sludge to energy, we assume that any such treatments will be from collaborations with this research group. Overall, we assume that the technology will be adopted for treatment of ~ 30% of the sludge, leading to a projected investment of $34 million ($112 million × 0.3), and we assume that the farmer's benefit will be at least equal to the investment.

Globally:

Globally, the European Aquaculture Technology and Innovation Platform target better integration of RAS and improved use of outputs as one of 6 challenges of the industry[7]. A non-exhaustive list of land RAS facilities compiled in 2018[8] lists ~ 80 facilities, dominantly in Canada, Chile, Norway, Scotland and the US. It is assumed that by 2030 about 40% of the aquaculture supply will be produced in RAS, as compared to the current <10%[9]. Following identification of appropriate bacteria consortium for each locality, the treatment can be adopted globally.

We do not attribute monetary value to this potential benefit but believe that the technology will undoubtedly be adopted also globally as the number of intensive inland facilities increase.

11 Economic Results

The development of the consortium used in the bioreactors was based upon principles developed in the BARD projects for warm water saline fish sludge. We attribute 15% of the benefits to the foundational role of the BARD studies.

- Net present value of the BARD's investment is $28 million, thereof $0 million already attained
- The Internal rate of return is 31%
- Benefit cost ratio is 44, thereof 1 already attained

Benefits attributed to the project that were not included in the calculation:

- The benefits are calculated only for sludge from non-saline smolt land-based facilities in Norway and for the full cycle salmon facilities being established in the US.
- Potential benefits from the aquaponic system: system 3.
- Potential benefits from production of microbial biomass which can be used to substitute up to 40%, mass wise, of fish feed: system 2.

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[7] A Review of the Strategic Research and Innovation Agenda, European Aquaculture Technology and Innovation Platform 2017

[8] An update on the 2014 report: "Review of Recirculation Aquaculture System Technologies and their Commercial Application; Final Report for Highlands and Islands Enterprise , RAS Lot 1 002, August 2018

[9] https://members.luxresearchinc.com/research/report/16365

Table 1: Main Results, 2018 Million Dollar-Terms

	The Project	BARD	BARD Attained	Thereof to the US	Thereof to Israel	Other Countries
BARD's Share in the Cost	20%					
Share in the Benefit		20%				
Cost	3	1	1	0.3	0.3	
Benefit	141	28	1			
Net Present Value	138	28	0	6	0	22
Internal Rate of Return	42%	31%	9%	24%		
Benefit Cost Ratio	44	44	1	17	-1	

11.1 Sensitivity Analysis

The low and high alternative assumptions used in the sensitivity analysis were brought together to estimate results under pessimistic and optimistic scenarios. Table 2 displays the net present value sensitivity results, between the low result: $6 million, to the high result: $63 million.

Table 2: NPV - Sensitivity Analysis, 2018 Million Dollar-Terms

			BARD's Share in the Benefit		
			Low	Central	High
			10%	20%	30%
Change in Benefit	Low	50%	6	13	21
	Central	100%	13	28	42
	High	150%	21	42	63

12 Appendix A: BARD Awards

Table 3: The 2 BARD awards

Project No	Full Title				
	Investigators	Institutes	Budget	Duration	Start Year
MB-8707-**04**	Waste recycling for recirculated aquaculture systems: conversion of fish waste from marine and brackish water systems to methane				
	Tal. Y.	UMD Marine BioTech	$300,000	3 years	2004

	Gross. A. Sowers, R	Ben Gurion University UMD Marine BioTech			
US-4453-**11**	Development of near zero-discharge land-based recirculated mariculture systems: recycling solid waste for bioenergy				
	Sowers, R Gross, A. Ronen, Z.R. Zilberg, D. Mozes, N.	UMD Marine BioTech Ben Gurion University Ben Gurion University Ben Gurion University Fisheries & Aquaculture Department	$290,000	3 years	2011

13 Appendix B: New and Expanding Smolt facilities in Norway

Table 4: Partial list of smolt facilities in Norway that are currently being built a new or expanded.

	Company and Location	Target Capacity	Size ratio *
	New facilities		
1	Tytlandsvik Aqua Rogaland, Western Norway (OPEN Summer 2019)	Beginning at 3000 tons smolt to expand to 9000 tons smolt	5
2	Tytlandsvik Aqua Ardal Aqua (start in 2021, ready 2022)[10]	15,000 tonnes post smolt (0.5 at 1000 gr, 0.5 at 2000gr)	10
3	Norway Royal Salmon in Dåfjord[11] (Construction begin Sep 2019, smolt release in 2021)	2,400 metric tons, 10 million smolt at a weight between 100 to 400 gr.	1.5
4	Marine Harvest, Skjervoy Troms	1,700 tonnes of young fish = 7 million large (250 gr) smolt	1
5	SinkabergHansen, in Naeroy[12] (construction starts in Sep 2019)	10 million smolt with an annual feed consumption of up to 4,000t.	2.5
6	Leroy Sjotroll's Kjaerelva site	24.000m³.	3

[10] https://salmonbusiness.com/e832-million-smolt-plant-planned-for-2021/
[11] https://www.fishfarmingexpert.com/article/norwegian-salmon-farmer-announces-68m-smolt-plant/
[12] https://www.undercurrentnews.com/2019/03/26/sinkaberghansen-plans-new-norwegian-salmon-smolt-facility/

7	Salangfisk at Sagfjord [13]	6 million smolt at 250 gr.	1
Expansion of facilities			
8	Eide Fjordbruk og Lingalaks at Kvinnherad.	Expand to 20 million large smolt a year	2.5
9	Leroy-owned Laksefjord	8.500 m^3 to 16.000 m^3. (500gr)	2
10	Bremnes Seashore north of Stavanger	13.000 m^3 to 20.000 m^3.	2.5
11	Lerøy Midt in Belsvika	11,000 m^3 -21,000 m^3 (700 gr)	2.5
12	The Nordlaks site: Hamarøy island	3.600 m^3 to 29.000 m^3	4
13	Marine Harvest Nordheim	13,000 m^3, 7.5 million fish 450 gr	2

* size ratio is the estimated ratio of sludge volume to be produced at the facility relative to the sludge volume at Cermaq (260 tons from 1600 tons of feed).

14 Appendix B: Information providers: Personal communication

- Kevin Sowers - PI for BARD grants, Department of Marine Biotechnology, University of Maryland Baltimore County and Institute of Marine & Environmental Technology.
- Amit Gross – PI for BARD grants, Department of Environmental Hydrology & Microbiology (EHM), Zuckerberg Institute for Water Research, The Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev.
- Yonathan Zohar - Professor and Chair of marine biotechnology, UMBC-IMET

[13] https://www.graakjaer.com/Nyhedsvisning-11/High-tech-smolt-facility-makes-a-big-impression?Action=1&M=NewsV2&PID=36989