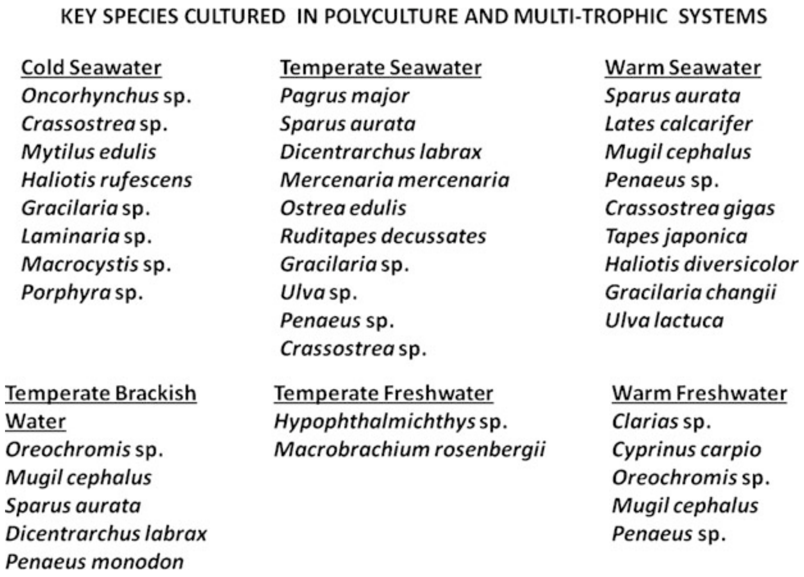
Mariculture Systems, Integrated Land-Based



KEY SPECIES CULTURED IN POLYCULTURE AND MULTI-TROPHIC SYSTEMS

Cold Seawater
Oncorhynchus sp.
Crassostrea sp.
Mytilus edulis
Haliotis rufescens
Gracilaria sp.
Laminaria sp.
Macrocystis sp.
Porphyra sp.

Temperate Seawater
Pagrus major
Sparus aurata
Dicentrarchus labrax
Mercenaria mercenaria
Ostrea edulis
Ruditapes decussates
Gracilaria sp.
Ulva sp.
Penaeus sp.
Crassostrea sp.

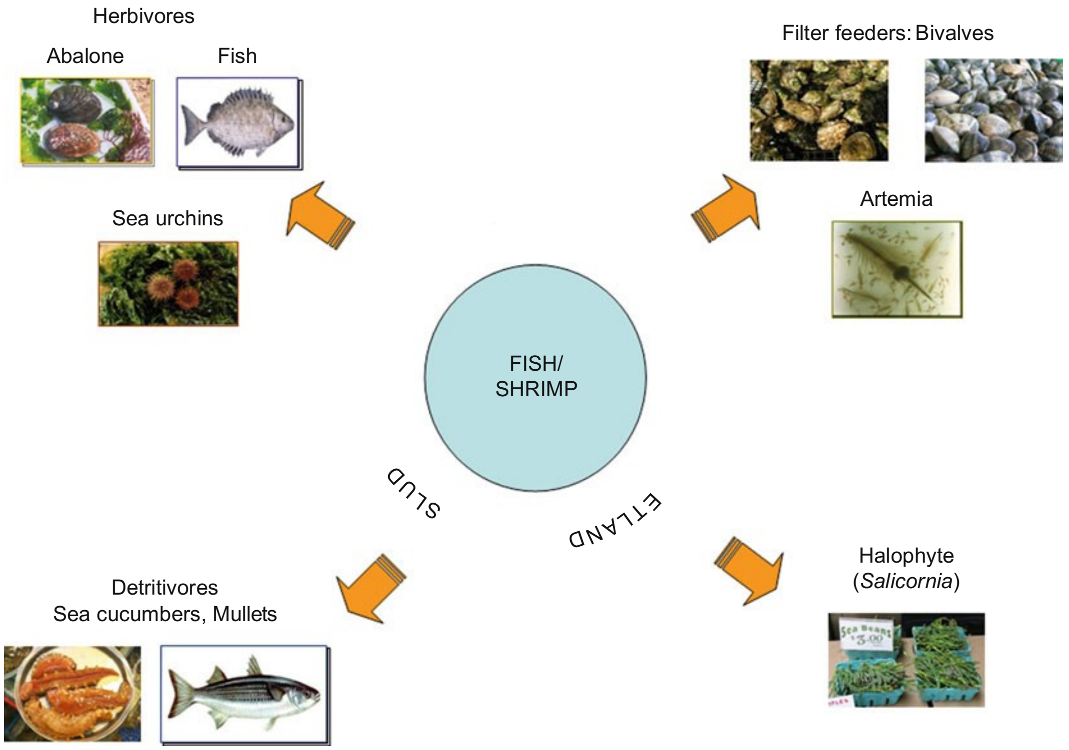
Warm Seawater
Sparus aurata
Lates calcarifer
Mugil cephalus
Penaeus sp.
Crassostrea gigas
Tapes japonica
Haliotis diversicolor
Gracilaria changii
Ulva lactuca

Temperate Brackish Water
Oreochromis sp.
Mugil cephalus
Sparus aurata
Dicentrarchus labrax
Penaeus monodon

Temperate Freshwater
Hypophthalmichthys sp.
Macrobrachium rosenbergii

Warm Freshwater
Clarias sp.
Cyprinus carpio
Oreochromis sp.
Mugil cephalus
Penaeus sp.

Key species cultured in IMTA and polyculture systems for marine and freshwater environment



Mariculture Systems, Integrated Land-Based. Figure 1

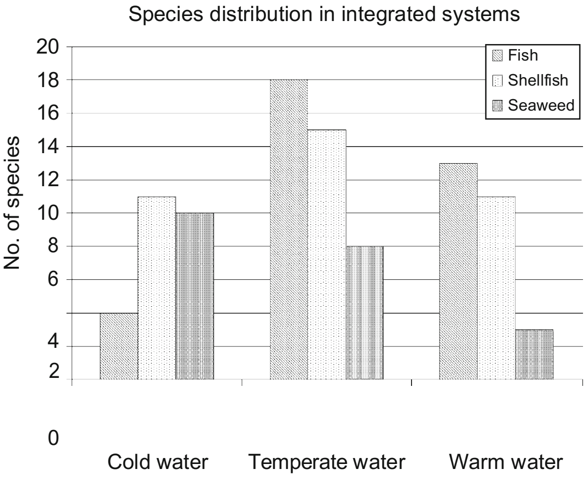
Schematic design of land-based IMTA systems (con. = constructed)

Nutrient Budget in Land-Based IMTA

Protein in fish or shrimp feed is the most expensive component of nitrogen input into the IMTA systems. In conventional cages or ponds, fish or shrimps assimilate only 20–30% of the nitrogen, while the rest is excreted into the water, mainly as dissolved ammonia, feces, and uneaten feed.

Two main practical approaches are emerging for handling the organic and nitrogenous wastes: bacterial dissimilation into gasses in "Recirculating Aquaculture Systems" (RAS), or plant assimilation into biomass (IMTA). Bacterial biofilters are dissimilative. Through a process of nitrification followed by denitrification, bacteria break down the organic pollutants into N_2 and CO_2 gasses. Bacterial biofilters are technically rather effective for aquaculture and allow significant water recirculation. However, the technology is relatively expensive, and not simple. Bacterial biofilter technologies are suitable for relatively small intensive land-based culture of lucrative organisms. There are no suggestions as to how such technologies can be integrated with large-scale, low cost fish or shrimp production. In addition, this system wastes expensive nitrogen by converting this valuable resource into gas, which is lost into the atmosphere.

Nutrient assimilation by other organisms is a more promising method of water treatment. In land-based IMTA ponds, seawater is pumped from the "nuclear species" (fish or shrimp) into the ponds/tanks of secondary organisms or macro-/microalgae. A pellet diet is the only source of nutrients for the primary animals in the system. Nutrient-rich effluent water from these ponds can take three directions: microalgae ponds, macroalgae ponds, or to irrigate halophyte crops (e.g., *Salicornia* sp.). The microalgae can be utilized by filter



Mariculture Systems, Integrated Land-Based. Figure 3 Fish, shellfish, and seaweed species combination in IMTA systems in different bio-geographical regions around the world feeders such as artemia or bivalves. The macroalgae can be utilized by macroalgivores such as abalone, sea urchins, or herbivorous fish. Halophytes such as *Salicornia* can be used as a food product. The remaining detritus can be fed to detritivores such as mullets, sea cucumbers, or polychaete worms, singly or in combination.

Optimization of the IMTA is typically based on the highest value “nuclear” product at any given time. This “nuclear” product may be shifted according to climatic conditions and economic considerations. For example, in a fish-abalone-seaweed integrated system, abalone is the most valuable species, and the entire system is centered around this species. Abalone will be the first organism to receive the incoming water. From the abalone, the water will drain to the ammonia producers and from there to the biofilters.

The biological and chemical processes in the IMTA system should be balanced between nutrient production by the main organism and nutrient uptake capacity of the micro- and/or macroalgae and downstream by the micro- and macroalgivores. In such systems evaluated in Eilat, Israel, macro-and microalgae were able to assimilate 1–5 g N m^{-2} day^{-1}, while algivores and filter feeders assimilated 0.5–1 g N kg $(WW)^{-1}$ day^{-1} (Table 1 and references therein). However, there will be variation in nutrient uptake depending on season and climate, as algal biomass is influenced by day length (i.e., light hours), water temperature, and the nutrient levels in the water.

For example, in a fish-bivalve-seaweed IMTA system in Eilat, 63% of the nitrogen from the feed was assimilated by edible organisms, 32% sank to the bottom as biodeposit (sludge), and only 4.1% was discharged back to the sea (Fig. 4) [3].

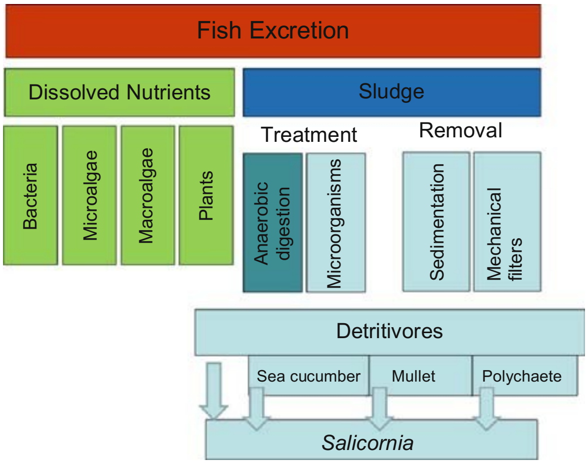
Nitrogen, phosphate, and silicate ratios can vary according to local farm conditions.

Nutrient composition is also affected by additional biochemical processes in the effluent water such as nitrification, denitrification, and ammonification which occurs in the sedimentation pond as well in the pond walls and in the water pipes. These processes can be accelerated or affected by water temperature, nutrient loads, flow rates, and fish feed biochemical composition. Local natural microfauna in the ponds (e.g., zooplankton) and microflora, as well as bloom and crash phenomena, can affect the water quality as well. In most cases, effluent water from fishponds is characterized by a mixture of ammonia, nitrate, and nitrite.

Mariculture Systems, Integrated Land-Based. Table 1 Assimilation rates of the uptake organisms in land-based IMTA in Eilat, Israel

	Assimilation rates	References
Microalgae	1–3 g N m^{-2} day^{-1}	Shpigel and Blaylock (1991)
		Shpigel et al. (1993a)
		Shpigel et al. (2007)
Macroalgae/ *Salicornia*	3–5 g N m^{-2} day^{-1}	Neori et al. (1991)
		Boarder and Shpigel (2001)
		Schuenhoff et al. (2003)
		Neori et al. (2004)
Bivalves/ Artemia	0.3 g N kg^{-1} day^{-1} 6 g N kg^{-1} m^{-3} day^{-1} (20 kg m^{-3})	Shpigel and Blaylock (1992)
		Shpigel et al. (1993a,b, 1994, 1996)
		Zmora and Shpigel (2006)
		Neori et al. (2004, 2006)
Abalone/sea urchins	0.5 g N kg WW day^{-1}	Shpigel et al. (1996, 1999, 2005, 2006)
		Neori et al. (2001)
		Stuart and Shpigel (2009)
Salicornia wetland	2–5 g N m^{-2} day^{-1}	Envirophyte (2010)
		Stuart and Shpigel (2009)

While macro- and microalgae have proven effective components in land-based systems, neither removes 100% of the dissolved matter and they do not remove particulate matter at all. The remaining waste that includes, among other components, feces, uneaten feed, algae and bacteria, sinks to the bottom and becomes what is known as sludge. This sludge contains valuable ingredients, but can also be toxic to the cultured organisms. It can increase stress and



Mariculture Systems, Integrated Land-Based. Figure 4 Different pathways to treat sludge from fishponds

disease risk, and reduce the quality of the water both in situ and for reuse. Ignoring the negative effects of the sludge can thus create serious problems and cause financial losses to the farmers. Removing and dumping sludge into the environment would similarly cause damage, even if moderated by dilution, and "foul the fish farmer's own nest" should he use seawater pumped in from the same area. Using detritivores is a novel option for land-based IMTA. Detritivore organisms such as mullets, cockles, and sea cucumbers will assimilate the waste into their bodies, thereby generating a significant saving in treatment costs, while additionally serving as valuable products in their own right, without requiring the purchase of feed for their culture.

The halophyte *Salicornia* sp. as a biofilter in constructed wetlands was evaluated in the "Genesis" and "Envirophyte" EU projects [34, 45, 46]. Using constructed wetlands (CW) planted with halophytes, which would take up the nutrient-rich wastewater and convert it into valuable plant biomass, is a new option for land-based IMTA. This system was developed to a practical stage for cold (UK) and warm (Israel) water. It was found that CW is efficient in clearing water of nutrients and suspended solids, some materials being purified through incorporation into the plants' biomass and others attaching to the substrate or being broken down by bacteria living therein. CW has the benefit of being low cost, is simple to operate, and can be given an aesthetically pleasing appearance. These plants have commercial value as a health food and are potential candidates for the health, beauty, and nutraceutical industries.

Pilot Scale Systems

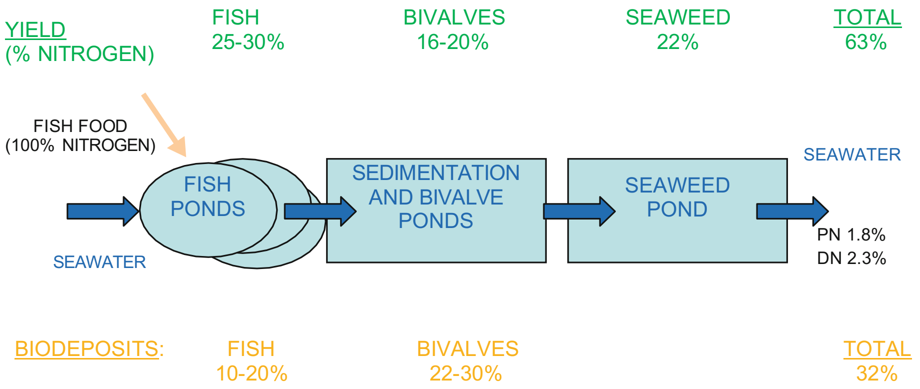
In R&D projects in Eilat, Israel, three different types of IMTA systems were developed:

1. Fish (seabream *Sparus aurata*) – seaweed (*Ulva lactuca*)
2. Fish (seabream *Sparus aurata*) – abalone (*Haliotis discus hannai*)/sea urchin (*Paracentrotus lividus*) (macroalgivores) – seaweed (*Ulva lactuca*)
3. Fish (seabream *Sparus aurata*) – bivalve (*Crassostrea gigas* and *Tapes philippinarum*) – seaweed (*Ulva lactuca*)

In the seabream-*Ulva* system, a daily ration of 1.3 t of feed supported 250 t of fish. This amount of food is equivalent to 64 kg of nitrogen. The fish assimilate around 16 kg of nitrogen. About 9.6 kg of the nitrogen is drained as particulate nitrogen, and 38.4 kg is drained as dissolved nitrogen. One hectare (ha) of macroalgae (*Ulva lactuca*) is required to remove most of the dissolved nitrogen from the water. This system using 500 t of food per year would require an area of 3.4 ha, at a ratio of 1 ha fish to 2.5 ha *Ulva*. Expected yield is approximately 220 t of fish and 1,600 t of *Ulva* (modified from [5] and [47]) (Table 2).

In the seabream-*Ulva*-macroalgivores (sea urchins/abalone) IMTA system, 1 ha of macroalgae produces 1,600 t of *Ulva* annually. This *Ulva* supports 133 t (WW) of abalone (*Haliotis discus hannai*) or 200 t of sea urchins (*Paracentrotus lividus*). A seabream-*Ulva*-sea urchins/abalone IMTA system in Eilat, Israel, using 500 t of food per year will need an area of 5.3 ha, at a ratio of 1 ha for fish, 2.5 ha for *Ulva*, and 1.8 ha for the macroalgivores (modified from [5] and [47]) (Table 2).

In the seabream, microalgae, and bivalves (*Crassostrea gigas* and *Tapes philippinarum*) IMTA system, a daily ration of 1.3 t of feed supports 250 t of fish. The fish assimilate around 16 kg of nitrogen; 38.4 kg of nitrogen is drained as dissolved nitrogen. This system using 500 t of food per year would need an area of 2 ha of phytoplankton pond (with assimilation efficiency of 1–2 g N m^{-2} day^{-1}) to support



Mariculture Systems, Integrated Land-Based. Figure 5
Nitrogen budget of fish-bivalve-seaweed IMTA system in Eilat, Israel

Mariculture Systems, Integrated Land-Based. Table 2 Expected performance of land-based IMTA (WW = wet weight)

IMTA system	Organism	Pond size Ratio/ha	Yield (WW t year^{-1})	Yield (kg WW m^{-2} year^{-1})
Fish-*Ulva* (500 t feed y^{-1})	Seabream	1	220	22
	Ulva	2.5	1,600	64
	Total		1,820	86
Fish-*Ulva* abalone/sea urchin (500 t feed y^{-1})	Seabream	1	220	22
	Ulva	2.5	1,600	64
	Abalone	1.8	185	10
	Sea urchins	1.8	140	8
	Total		1960–2005	94
Fish-*Ulva*-clam/oyster (500 t feed y^{-1})	Seabream	1	220	20
	Clams/*oysters*	4	140	8
	Ulva	0.5	70	64
	Total		430	92

production of 140 t bivalves and 70 t of seaweed (modified from [5] and [47]) (Table 2).

The economics of these types of land-based IMTA systems were summarized in [5]. However, the economics of a land-based IMTA are site specific since they depend on variables including local construction and operating costs and market prices for the farm's products at any given time [34].

Additional anticipated parameters based on the same model of using 500 t feed per year in each of the three IMTA systems tested in Eilat, Israel, with the projected yields as depicted in Table 2, can be seen in Table 3.

Future Directions: Challenges and Constraints

Although considerable information is already available for putting land-based IMTA systems into practice, much of it is designed around commercial exploitation of a few high value species that are not affordable for the masses. The challenge for the future is to produce a large quantity of aquaculture products that will be cost-effective for producers, at a reasonable price for consumers, and ecologically sustainable.

Additional studies are required to overcome further constraints, including biological, engineering, and economical aspects:

Mariculture Systems, Integrated Land-Based. Table 3 Anticipated parameters for organisms in the three IMTA systems tested in Eilat, Israel, based on 500 t feed per year

Seabream
FCR = 1.9; Feed protein content = 49%
Fish stocking density = 200 t ha^{-1}; Annual fish yield —300 t ha^{-1}
Seabream farm gate price = €4 kg^{-1}
Seaweed
Ammonia uptake rate–4 g m^{-2} day^{-1}; ammonia uptake efficiency = 85%
Annual Ulva yield = 900 t ha^{-1}
Seaweed (WW) price = €0.5 kg^{-1}
Abalone
FCR = 12; stocking density = 25 kg m^{-2}
Annual yield = 10 kg m^{-2};
Farm gate price = €35 kg^{-1}
Sea urchins
FCR = 8 t *Ulva* 1 t of production; stocking density = 10 kg m^{-2}
Annual yield = 8 kg m^{-2}
Farm gate price = €10 kg^{-1}
Clams/Oysters
Clam annual yield = 6–8 kg m^{-2}
Clams farm gate price = €4.5 kg^{-1}
Oyster annual yield = 25 kg m^{-3}
Oyster farm gate price = €3.5 kg^{-1}

Biological Aspects

- To acquire the knowledge necessary to maintain the correct balance between nutrient production by the system's core organism, nutrient uptake capacity of microalgae and macroalgae, shellfish filtering efficiency, and macroalgivores' activity in the system
- To acquire the knowledge necessary to maintain steady populations of microalgae (mainly diatoms) for the filter feeders and of macroalgae for the macroalgivores within the system in order to avoid blooms and crashes

- To acquire the knowledge necessary for the efficient regeneration of the biodeposit (sludge) from the bottom back to dissolved nutrients for the macro- and microalgae
- To effectively control diseases of the cultured organ- isms in IMTA systems and transmission of patho- gens between components of the system

Engineering Aspects

- To reduce construction and operating costs byengi- neering improvements
- To minimize heat loss or gain in downstream com- ponents of the system
- To increase the use of greenhouse-covered modular systems, gravitation, low head upwelling, water semi-recirculation and other promising energy- saving methods

Economical Aspects

- To render cost effective the use of the extensive areas required for cultivating micro- and macroalgae which cannot be done in a fully recirculating system and for which the facilities must thus be located not too far from the sea
- To develop and diversify the market of seaweed for human consumption from IMTA in Europe and North America
- To develop new markets and consumer acceptance of IMTA products

With the dramatic increase in population and food requirements, traditional extensive production systems cannot satisfy present and future market needs. Modern intensive monoculture systems are not ideal for mass production because they focus on few and expensive species, require high levels of resources, and produce undesirable wastes. To achieve high produc- tion rates and environmental conservation, food pro- duction using land-based IMTA systems is one of the most promising routes. The IMTA method assimilates expensive nitrogen waste into a valuable product that will increase profit for the farmer, improve FCR, diversify the mariculture products, create additional jobs, and, most importantly, reduce environmental pollution.