AQUACULTURE

1. Introduction

One definition of aquaculture is the rearing of aquatic organisms under controlled or semicontrolled conditions (1). Another, used by the Food and Agriculture Organization (FAO) of the United Nations, is that aquaculture is, "the farming of aquatic organisms, including fish, molluscs, crustaceans, and aquatic plants" (2). Included within those broad definitions are activities in fresh, brackish, marine, and even hypersalinewaters. The term *mariculture* is often used in conjunction with aquaculture in the marine environment.

Public sector aquaculture involves production of aquatic animals to augment or establish recreational and commercial fisheries. Public sector aquaculture is widely practiced in North America and to a lesser extent in other parts of the world. The FAO definition of aquaculture also indicates that farming implies ownership of the organisms being cultured, which would seem to exclude public sector aquaculture.

In recent years, aquaculture has been increasingly used as a means of aiding in the recovery of threatened and endangered species. Those efforts are currently public sector activities, although there is interest in the private sector to become involved. As global awareness of endangered species issues grows, recovery programs for aquatic threatened and endangered species may arise in many more countries. Going hand in hand with attempts to recover endangered species are enhancement stocking programs aimed at releasing juvenile animals to rebuild stocks of aquatic animals that have been reduced due to overfishing. Examples of enhancement programs currently in existence include the stocking of cod in Norway, flounders in Japan, and red drum in the United States.

The bulk of global production from aquaculture is utilized directly as human food, with public aquaculture playing a minor role in many nations or being absent. Private aquaculture is not only about human food production, however. In some regions, well-developed private sector aquaculture is involved in the production of bait and ornamental fishes and invertebrates.

Aquatic plants are cultured in many regions of the world. In fact, aquatic plants, primarily seaweeds, account for nearly 23% of the world's aquaculture production (3). Most of the information available in the literature relates to the production of such aquatic animals as molluscs, crustaceans, and finfish.

The origins of aquaculture are rooted in ancient China and may date back some 4000 years. Today, Asia dominates the world in aquaculture production, with China producing over 10 million metric tons in 1992 and Japan and India each producing well over 1 million metric tons (4). By 1996, China's aquaculture production accounted for over 67% of the global total and had reached over 23 million metric tons (3). India and Japan continued to rank second and third globally in 1996 with 6.7 and 3.1% of global production, respectively (3). In North America, the culture of fish began in the mid-nineteenth century and grew rapidly in the public sector after the establishment of the U.S. Fish and Fisheries Commission in 1871 (5). Private aquaculture existed as a minor industry for many decades, coming into prominance in the 1960s. Since then the United States has become one of the leaders in aquaculture research and development, although production, while significant at over 400,000 metric tons by 1992 (4), amounted to only about 2% of the world's total of nearly 19 million metric tons. The contribution of U.S. aquaculture to the global total had dropped to 1.5% by 1996 (3). The United States commercial aquaculture industry is dominated by channel catfish, (*Ictalurus punctatus*), trout, salmon, minnows, oysters, mussels, clams, and crawfish. A number of other fishes and invertebrates are also being reared. Included are tilapia, (*Oreochromis* spp.), striped bass (*Morone saxatilis*), and hybrid striped bass (*M. saxatilis x M. chrysops*), red drum (*Sciaenops ocellatus*), goldfish (*Carassius auratus*), tropical fishes, and shrimp. In the public sector, hatcheries produce large numbers of such species as salmon, trout, largemouth (*Micropterus salmoides*) and smallmouth bass (*M. dolomieui*), sunfish (*Lepomis* spp.), crappie (*Pomoxis* spp.), northern pike (*Esox lucius*) muskellunge (*E. masquinongy*), walleye (*Stizostedion vitreum vitreum*), and catfish (*Ictalurus* spp.) for stocking or growout.

Aquaculture production continues to grow annually, but increasing competition for suitable land and water, problems associated with wastewater from aquaculture facilities, disease outbreaks, and potential shortages of animal protein for aquatic animal feeds are having, or may have, negative effects on future growth. New technology, including the application of genetic engineering approaches to improving performance and disease resistance in aquatic species, along with the development ofwater reuse (recirculating) systems and the establishment of offshore facilities, may provide the impetus for a resurgence of growth in the industry.

2. Economics

The production of aquatic animals for recreation, in nations where that type of aquaculture exists, is typically funded through user fees such as fishing licenses that support hatcheries and the personnel to run them. In order for most private aquaculture companies to get started, outside funding is required. Funding may come through banks and other commercial lending sources or from venture capitalists. The high risks associated with aquaculture have made it difficult for many startup firms to obtain bank loans, although that situation is changing as bankers become more knowledgeable and comfortable with underwriting aquaculture ventures.

A key factor in obtaining funding support for aquaculture is development of a sound business plan. The plan needs to demonstrate that the prospective culturist has identified all costs associated with establishment of the facility and its day-to-day operation. One or more suitable sites should have been identified and the species to be cultured selected before the business plan is submitted. Cost estimates should be verifiable. Having actual bids for a specific task at a specific location; eg, pond construction, well drilling, building construction, and vehicle costs helps strengthen the business plan.

Land costs vary enormously both between and within countries. Compare the cost of coastal land in south Florida where it might be possible to consider rearing shrimp with that of Mississippi farmland suitable for catfish farming. The former might be thousands of dollars for every meter of ocean front, while the latter may be obtained for one or two thousand dollars per hectare.

The amount of land required varies as well, not only as a function of the amount of production that is anticipated, but also on the type of culture system that is used. It may take several hectares of static culture ponds to produce the same biomass of animals as one modest size raceway through which large volumes of water are constantly flowed. Construction costs vary from one location to another. Local labor and fuel costs must be factored into the equation. The experience of contractors in building aquaculture facilities is another factor to be considered.

The need for redundancy in the culture system needs to be assessed. Failure of a well pump that brings up water to supply a static pond system may not be a serious problem in countries where new pumps can be purchased in a nearby town. However, it can be disastrous in developing countries where new pumps and pump parts are often not available, but must be ordered from another country. Several weeks or months may pass before the situation can be remedied unless the culturist maintains a selection of spares.

The business plan needs to provide projections of annual production. Based on those estimates and assumed food conversion rates (food conversion is calculated by determining the amount of feed consumed by the animals for each kilogram of weight gain), an estimate of feed costs can be made. For many aquaculture ventures, between 40 and 50% of the variable costs involved in aquaculture can be attributed to feed.

Aquaculturists may elect to purchase animals for stocking or maintain their own broodstock and hatchery. The decision may rest on such factors as the availability and cost of fry fish, post-larval fish, oyster spat, or other early life history stages in the location selected for the aquaculture venture.

Land purchases and many of the costs associated with facility development can be accomplished with long-term loans of 15 to 30 years. Equipment such as pumps and trucks are usually depreciated over a few years and are funded with shorter-term loans. Operating expenses for such items as feed, chemicals, fuel, utilities, salaries, taxes, and insurance may require periodic short-term loans to keep the business solvent. The projected income should be based on a realistic estimate of farmgate value of the product and an accurate assessment of anticipated production. Each business plan should project income and expenses projected over the term of all loans in order to demonstrate to the lending agency or venture capitalist that there is a high probability the investment will be repaid.

3. Regulation

The extent to which governments regulate aquaculture varies greatly from one nation to another. In some parts of the world, particularly in developing nations, there has historically been little or no regulation. Inexpensive land and labor, low taxes, excellent climates conducive to rapid growth of aquatic species, and a lack of government interference have drawn many aquaculturists to underdeveloped countries, most of which are in the tropics. Unregulated expansion of aquaculture in some countries has led to pollution problems, destruction of valuable habitats such as mangrove swamps, and has enhanced the spread of disease from one farm to another. The need for imposing regulations is now becoming evident around the world. Response to that need varies considerably from one nation to another.

In developed countries there may or may not be a standardized set of national regulations. The United States is an example of a mixture of local, state, and federal regulations. Permits from a county, state, or federal agency may be required for drilling wells, pumping water, releasing water, use of exotic species, constructing facilities, etc. In the United States, most permits can be obtained at the local or state level. In some instances the federal government has delegated permitting authority to the states when state regulations are as rigorous or more so than national regulations. Federal agencies become involved when aquaculture projects are conducted in navigable waters (U.S. Army Corps of Engineers) in the Exclusive Economic Zone, or might impact threatened or endangered species (U.S. Fish and Wildlife Service).

In general, it is easier to establish an aquaculture facility on private land than in public waters such as a lake or coastal embayment. Prospective aquaculturists who want to establish facilities inpublic waters may be confronted at public hearings by outraged citizens who do not want to see an aquaculture facility in what they consider to be their water. The issue is highly contentious in some nations (eg, the United States). In other countries, aquaculture in public waters is seen as not only a good use of natural resources, but can be considered an amenity (eg, Japan).

Obtaining permits is often not simple. Few states have one office that can accommodate the prospective aquaculturist. In most cases it is necessary to contact a number of state, and often federal agencies to apply for permits. Public hearings may be required before permits are approved. The process can take months or even years to complete. The costs involved in going through the process may be prodigious. After the expenditure of considerable amounts of time and money, there is no guarantee that the permits will ultimately be granted.

Most states now have an aquaculture coordinator, usually housed in the state department of agriculture, who can assist prospective aquaculturists in finding a path through the permitting process. Anyone considering development of an aquaculture facility should become educated on the permitting process of the state or nation in which the facility will be developed. In cases where the process is involved, it should be initiated well in advance of the anticipated time of actual facility construction.

4. Species under Cultivation

This article emphasizes aquatic animal production, but many hundreds of thousands of people are involved, worldwide, in aquatic plant production. The quantity of brown seaweeds, red seaweeds, green seaweeds, and other algae produced in 1996 was estimated at over 7.7 million metric tons (Table 1). Miscellaneous aquatic plants such as watercress and water chestnuts contributed an additional 600,000 metric tons. Microscopic algae and cyanobacteria are sometimes marketed as food or as a nutritional supplement (eg, *Spirulina* sp.). In addition,

Table 1. **World Aquaculture Production in 1996 for Selected Aquaculture Species or Species Groups**[a]

Species group	Production (10^3 tons)
Cyprinids	11,504
Tilapia and other cichlids	801
Atlantic salmon	556
Rainbow trout	380
Milkfish	365
Eels	216
Channel catfish	214
Pacific salmon	88
Japanese seabream	78
Oysters	3,067
Clams, cockles, and arkshells	1,777
Scallops and pectens	1,275
Mussels	1,179
Marine shrimp	915
Crabs	119

[a]Ref. 3.

an undocumented quantity of algae (mostly of the single-celled variety) is produced for use as food for filter-feeding aquatic animals (primarily molluscs and zooplankton). Planktonic organisms such as rotifers are reared on algae and then used to feed the young of crustaceans and fishes that do not accept prepared feeds.

Animal aquaculture is concentrated on finfish, molluscs, and crustaceans. Sponges, echinoderms, tunicates, turtles, frogs, and alligators are also being cultured, but production is insignificant in comparison with the three principal groups. Common and scientific names of many of the species of the finfish, molluscs, and crustaceans currently under culture are presented in Table 2. Included are examples of bait, recreational, and food animals.

Table 2. **Common and Scientific Names of Selected Aquaculture Species**

Type of organism	Common name	Scientific name
finfish	African catfish	*Clarias gariepinus*
	Atlantic halibut	*Hippoglossus hippoglossus*
	Atlantic salmon	*Salmo salar*
	Bighead carp	*Aristichthys nobilis*
	Bigmouth buffalo	*Ictiobus bubalus*
	Black crappie	*Pomoxis nigromaculatus*
	Blue catfish	*Ictalurus furcatus*
	Blue tilapia	*Oreochromis aureus*
	Bluegill	*Lepomis macrochirus*
	Brook trout	*Salvelinus fontinalis*
	Brown trout	*Salmo trutta*
	Catla	*Catla catla*
	Channel catfish	*Ictalurus punctatus*
	Chinook salmon	*Oncorhynchus tshawytscha*
	Chum salmon	*Oncorhynchus keta*
	Coho salmon	*Oncorhynchus kisutch*
	Common carp	*Cyprinus carpio*
	Fathead minnow	*Pimephales promelus*
	Gilthead sea bream	*Sparus aurata*
	Goldfish	*Carassius auratus*
	Grass carp	*Ctenopharyngodon idella*
	Largemouth bass	*Micropterus salmoides*
	Milkfish	*Chanos chanos*
	Mossambique tilapia	*Oreochromis mossambicus*
	Mrigal	*Cirrhinus mrigala*
	Mud carp	*Cirrhina molitorella*
	Muskellunge	*Esox masquinongy*
	Nile tilapia	*Oreochromis niloticus*
	Northern pike	*Esox lucius*
	Pacu	*Colossoma metrei*
	Pink salmon	*Oncorhynchus gorbuscha*
	Plaice	*Pleuronectes platessa*
	Rabbitfish	*Siganus* spp.
	Rainbow trout	*Oncorhynchus mykiss*
	Red drum	*Sciaenops ocellatus*
	Rohu	*Labeo rohita*
	Sea bass	*Dicentrarchus labrax*
	Shiners	*Notropis* spp.

Table 2 (*Continued*)

Type of organism	Common name	Scientific name
	Silver carp	*Hypophthalmichthys molitrix*
	Smallmouth bass	*Micropterus dolomieui*
	Sole	*Solea solea*
	Steelhead	*Oncorhynchus mykiss*
	Striped bass	*Morone saxatilis*
	Walking catfish	*Clarias batrachus*
	Walleye	*Stizostedion vitreum vitreum*
	White crappie	*Pomoxis annularis*
	Yellow perch	*Perca flavescens*
	Yellowtail	*Seriola quinqueradiata*
molluscs	American oyster	*Crassostrea virginica*
	Bay scallop	*Aequipecten irradians*
	Blue mussel	*Mytilus edulis*
	Northern quahog	*Mercenaria mercenaria*
	Pacific oyster	*Crassostrea gigas*
	Southern quahog	*Mercenaria campechiensis*
crustaceans	Freshwater shrimp	*Macrobrachium rosenbergii*
	Blue shrimp	*Litopenaeus stylirostris*
	Kuruma shrimp	*Marsupenaeus japonicus*
	Pacific white shrimp	*Litopenaeus vannamei*
	Red swamp crawfish	*Procambarus clarkii*
	Tiger shrimp	*Penaeus monodon*
	White river crawfish	*Procambarus acutus acutus*
	White shrimp	*Litopenaeus setiferus*
algae (seaweeds)	California giant kelp	*Macrocystis pyrifera*
	Eucheuma	*Eucheuma cottoni*
	False Irish moss	*Gigartina stellata*
	Gracilaria	*Gracilaria* sp.
	Irish moss	*Chondrus crispus*
	Laminaria	*Laminaria* spp.
	Nori or laver	*Porphyra* spp.
	Wakame	*Undaria* spp.

Various species of carp and other members of the family Cyprinidae lead the world in terms of quantity of animals produced. In 1996 the total was over 11.5 million metric tons (see Table 1). China is the leading carp producing nation, and is the world's leading aquaculture nation overall (Table 3). Significant amounts of carp are also produced in India and parts of Europe.

Fishes in the family Salmonidae (trout and salmon) are in high demand, with the interest in salmon being greatest in developed nations. Salmon, mostly Atlantic salmon (*Salmo salar*), are produced in Canada, Chile, Norway, New Zealand, Scotland, and the United States. Fishes in the family Cichlidae, which includes several cultured species of tilapia, are reared primarily in the tropics, but have been widely introduced throughout both the developed and developing world.

Catfish are not a major contributor to aquaculture production globally, but the channel catfish (*Ictalurus punctatus* industry dominates United States aquaculture. United States catfish production, primarily channel catfish, was 214,154 metric tons in 1996 (4). (3)

Table 3. **Top Aquaculture Producing Nations in 1996 and Percentage of Total Global Production**[a]

Nation	Country Rank	Percentage Share
China	1	67.1
India	2	6.7
Japan	3	3.1
Indonesia	4	2.6
Thailand	5	1.9
United States	6	1.5
Bangladesh	7	1.5
Korean Republic	8	1.4
Philippines	9	1.3
Norway	10	1.2
France	11	1.1
Taiwan	12	1.0
Spain	13	0.9
Chile	14	0.8
all others		7.9

[a]Ref. 3.

Among the invertebrates, most of the world's production is associated with mussels, oysters, shrimp, scallops, and clams. Red swamp crawfish culture is of considerable importance in the United States, but amounted to only 23,581 metric tons in 1996 (4) (3); insignificant compared to some other invertebrate species.

Small amounts of crabs, lobsters, and abalone are being cultured in various nations, and production has been on the increase in recent years. All three bring good prices in the marketplace but have drawbacks associated with their culture. Crabs and lobsters are highly cannibalistic. Rearing them separately to keep them from consuming one another during molting has precluded their economic culture in nearly every instance. Abalone eat seaweeds and can only be reared in conjunction with a concurrent seaweed culture facility or in regions where large supplies of suitable seaweeds are available from nature. In some instances the value of the seaweed for direct human consumption may be the highest and best use of the plants.

In all, there are perhaps 100 species of aquatic animals under culture. Many researchers have turned their attention to species for which there is demand by consumers, but for which the technology required for commercial production is not available, under development, or in the early stages of being tested commercially. Examples are dolphin fish, also known as mahimahi (*Coryphaena hippurus*), Pacific halibut (*Hippoglossus stenolepis*), summer flounder (*Paralichthys dentatus*), winter flounder (*Pseudopleuronectes americanus*), American lobster (*Homarus americanus*), and blue crab (*Callinectes sapidus*). Each of the species mentioned is marine and has small eggs and larvae. Providing the first feeding stages with acceptable food has been a common problem, as has the fragility of the early life stages of many species, and the problem of cannibalism.

Fishes with large eggs, such as trout, salmon, catfish, and tilapia, were among the first to be economically successful in modern times. However, small eggs do not necessarily mean that sophisticated research is required to develop the technology required for successful culture. Carp, which have been cultured in China for millennia, have extremely small eggs. At the time the methodology for carp culture was developed, there were no research scientists, although there must have been dedicated farmers who used their common sense and trial-and-error methods to establish carp aquaculture.

5. Culture Systems

At one extreme aquaculture can be conducted with a small amount of intervention from humans and the employment of little technology. At the other is total environmental control and the use of computers, molecular genetics, and complex modern technology. Many aquaculturists operate between the extremes. The range of culture approaches can be described as running from extensive to intensive, or even hyper-intensive, with extensive systems being relatively simple and intensive systems being complex to very complex. In general, as the level of culture intensity increases, stocking density, and as a consequence, production per unit area of culture system or volume of water, increases.

The most extensive types of aquaculture involve minimal human intervention to promote increases in natural productivity. Good examples can be found relative to oyster and pond fish culture. With respect to oysters, one of the most extensive forms of culture involves placing oyster, clam, or other types of shell (cultch) on the bottom in intertidal areas that are known to have good oyster reproduction, but limited natural cultch material. The additional substrate may subsequently be colonized by oyster larvae (spat), thereby potentially increasing productivity. The next level of intensity might involve placing bags of cultch out in nature to collect spat in a productive area that already has sufficient quantities of natural cultch. After spat settlement, the bags of shells would be moved to an area where limited natural substrate availability has led to low productivity. The growout area may be held as a common resource, or it may be made commercially available on a leasehold basis.

The next step in increasing oyster culture intensity might involve hatchery production and settling of spat on cultch. Once again, the cultch would be later distributed over a bed leased or owned by the oyster culturist (Fig. 1). Control of predators such as starfish and oyster drills could easily be a part of culture at all levels.

The highest level of intensity with respect to oysters involves hatchery production of spat and the rearing of them suspended from rafts, long-lines, or as cultchless oysters in trays. In the raft and longline techniques cultch material to which oyster spat or larval mussels are attached is strung on ropes (longlines) suspended from floating rafts or from other ropes held parallel to the water surface with buoys. The lines of growing oysters suspended from the ropes (called strings) are of such a length that the young shellfish are kept within the photic zone and not allowed to touch the bottom where starfish, oyster drills, and other predators can attack. Scallops, which do not attach to cultch, are sometimes grown in bags suspended from long lines or rafts. Similarly, young mussels can be held in proximity to strings with fine mesh materials that retain the

Fig. 1. Bags of oyster shell used as cultch for the settling of oyster spat. The spat-laden shell is ultimately distributed on leased oyster beds.

animals in place until they attach (by means of what is called a byssus thread) to the string.

The stocking of ponds, lakes, and reservoirs to increase the production of desirable fishes that depend on natural productivity for their food supply and are ultimately captured by recreational fishermen or for subsistence is another example of extensive aquaculture. Some would consider such practices as lying outside of the realm of aquaculture, but since the practice involves human intervention and often employs fishes produced in hatcheries, recreational or subsistence level stocking is associated with, if not a part of aquaculture. Similarly, stocking new ponds or water bodies which have been drained or poisoned to eliminate undesirable species prior to restocking, can lead to increased production of desirable species.

Most of the aquaculture practiced around the world is conducted in static ponds (Fig. 2). Ponds range in size but production units are generally 0.1 to 10 ha in area. The intensity of aquaculture in ponds can range from a few kg/ha to thousands of kg/ha of annual production. Ponds may be of the watershed type where they are constructed in a manner that takes advantage of rain runoff for pond filling, or they may be constructed with levees above the surrounding terrain elevation. The latter requires that the vast majority of the water used to fill the ponds comes from wells or other sources, not runoff. Excavated ponds with the top of their levees at the original ground level are also an option, but if those occur on flat landscapes the amount of runoff available for pond filling is generally insufficient and other sources of water will be required.

Aquaculture ponds, unlike farm ponds, should be fitted with drains. While many aquaculturists do not drain their ponds on an annual or more frequent basis during harvesting, periodic draining is required. In some cases, harvesting

Fig. 2. Aquaculture ponds are often rectangular in shape. They should be equipped with plumbing for both inflow and drainage of water.

is conducted by capturing animals that are flushed out through the pond drain. Drain structures may be elaborate or quite simple.

Pond levees typically have side slopes of 2:1 or 3:1 (2 or 3 units of measure laterally for each unit of measure in height). Steeper slopes (e.g. 1:1) make construction more difficult and are too steep for easy entry and egress by personnel who are required to enter the pond. If the side slope is less steep than recommended, aquatic plants tend to become a significant problem by invading the shallow and extensive shoreline areas of the pond.

Fertilization of ponds to increase productivity is the next level of intensity with respect to fish culture, followed by provision of supplemental feeds. Fertilization promotes the production of natural foods within a pond. Included are phytoplankton, zooplankton, and benthic organisms. In some cases, aquatic vegetation is also encouraged and its production will benefit from fertilization. In most aquaculture operations, the production of rooted or floating aquatic plants is discouraged. Supplemental feeds are those that provide some additional nutrition but cannot be depended upon to supply all the required nutrients. Provision of complete feeds, those that do provide all of the nutrients required by the fish, translates to another increase in intensity. Associated with one or more of the stages described might be the application of techniques that lead to the maintenance of good water quality. Examples are continuous water exchange, mechanical aeration, and the use of various chemicals used to adjust such factors as pH, alkalinity, and hardness.

With the application of increased technology and control over the culture system, intensity continues to increase. Utilization of specific pathogen-free animals, provision of nutritionally complete feeds, careful monitoring and control of water quality, and the use of animals bred for good performance, can lead to

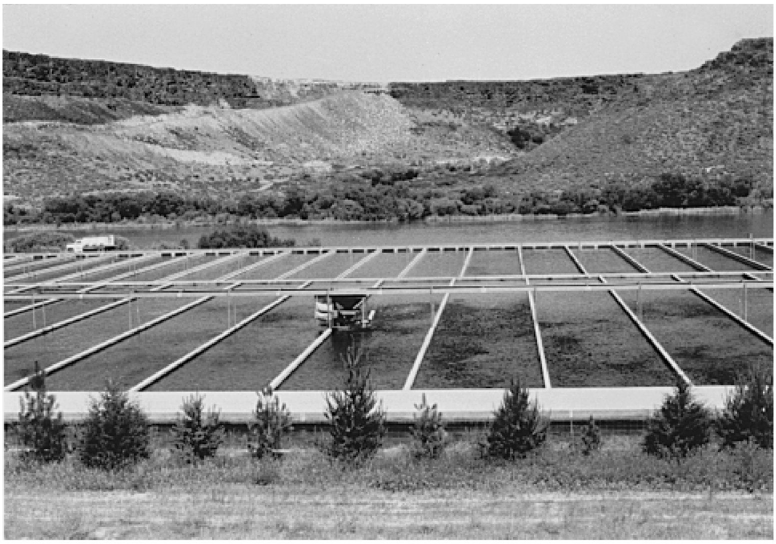

Fig. 3. A commercial trout facility in Idaho, U.S. Linear raceways are commonly used for the production of trout from fry to either release or market and for salmon from fry to smolt size.

impressive production levels. The United States channel catfish industry is a good example. During the early 1960s pond production levels were typically about 1500 kg/ha/yr. As better feeds and management practices were developed, production increased to an average of about 3000 kg/ha/yr by the next decade. In the 1980s, nutritionally complete feeds were perfected, better methods for prediction and amelioration of water quality problems had been developed, and diseases were being better avoided or controlled. Catfish farmers typically produced 4000 kg/ha/yr and some, who used aeration and exchanged water during part of the growing season, were able to produce 10,000 kg/ha/yr or more.

Where water is plentiful and inexpensive, raceway culture is an attractive option and one which allows for production levels well in excess of what is possible in ponds. Trout are frequently reared in linear raceways from hatching to market size. Linear raceways are essentially channels that are longer than they are wide, and are usually no deeper than 1–2 m (Fig. 3). Water flows in one end and out the other. The total volume of the raceway may be exchanged as often as every few minutes. High density raceways used in production facilities are commonly constructed of poured concrete. Small raceways of the type used in hatcheries and research facilities may be constructed of fiberglass or other resilient materials. Water is introduced at one end and flows by gravity through the raceway to exit the other end. Circular raceways, called tanks (Fig. 4), are also used by aquaculturists. Tanks are usually no more than 2 m deep and may be from less than 1 m to as much as 10 m in diameter. Concrete tanks can be found, but most are constructed of fiberglass, metal, or wood that is sealed and covered with epoxy or some other waterproof material. Plastic liners are commonly used in metal or wood tanks to prevent leakage, and in the case of metal, to avoid exposing the aquaculture animals to trace element toxicity.

Fig. 4. Circular tanks are a raceway option. They can be placed outdoors or used in conjunction with indoor water systems. Circular tanks are commonly used in recirculating systems.

Water is introduced into tanks at the surface in most cases. It may be sprayed in (to enhance aeration) or introduced in a manner that does not cause turbulance. Venturi drains, located internally or externally, will collect and remove solids that settle to the bottom of a tank with the drain water.

Linear raceways are commonly used by trout and salmon culturists both for commercial production and for hatchery programs conducted by government agencies. Large numbers of state and federal salmon hatcheries in British Columbia, Canada and in the states of Washington, Idaho and Oregon, along with governmental and private hatcheries in Alaska, collect and fertilize eggs, hatch them, and rear the young fish to the smolt stage at which time they become physiologically adapted to enter seawater.

Commercial salmon culturists can rear their fish to market size in freshwater raceways although most salmon are grown from smolt to market size or adulthood in the marine environment, either as free roaming fish or in confinement. Since salmon instinctively return to spawn in the waters where they were hatched, it is possible to establish hatcheries and smolt-rearing facilities that take advantage of the homing instinct. The technique is known as ocean ranching. When the fish that had been released as smolts return to spawn, sufficient numbers of adults are collected for use as broodfish to continue the cycle. The remainder may be harvested by the aquaculturist or by commercial fishermen after which the fish are processed and marketed.

Salmon, steelhead trout, and a variety of marine fishes are currently being reared in net-pens (Fig. 5). The typical salmon net-pen is several meters on each side and may be as much as 10 m deep or deeper (1). Smaller units, called cages, are sometimes used by freshwater aquaculturists, primarily in freshwater, but also in the marine environment in some instances. Cages tend to have volumes

Fig. 5. Marine net-pens such as the ones shown here in Puget Sound, Washington (U.S.), are used for the rearing of salmon by commercial fish farmers.

of no more than a few cubic meters. Unlike net-pens which have rigid frames at the surface from which netting is hung, cages have rigid frameworks on all sides covered with netting, welded wire mesh, or plastic webbing.

Net-pen technology was developed in the 1960s, but has only been widely employed commercially for salmon production since the 1980s when the Norwegian salmon farming industry was developed. The Japanese began producing large numbers of sea bream and yellowtail in net-pens during the 1960s. Other nations have employed the technology as well. Most net-pens are located in protected waters since they are easily damaged or destroyed by storms.

Competition by various user groups for space in protected coastal waters in much of the world has led to strict controls and in some cases prohibitions against the establishment of inshore net-pen facilities. As a result, there is growing interest in developing the technology to move offshore. Various designs for offshore net-pens have been developed and a few have been tested (Fig. 6). A number of different designs, including systems that are semi- or totally submersible, have been able to withstand storm waves of at least 6 m, but the costs of those systems are very high compared with inshore net-pens, so commercial viability has yet to be demonstrated.

The highest levels of intensity that can be found in aquaculture systems are associated with totally closed systems, often called recirculating systems. In these systems, all water passing through the chambers in which the finfish or shellfish are held is continuously treated and reused. Once filled initially, closed systems can theoretically be operated for long periods of time without water replacement. In practice, it is necessary to add some water to such systems to make up for that lost to evaporation, splashout, and in conjunction with solids removal. Most of the recirculating systems in use today are operated in a mode

Fig. 6. A salmon net-pen in Scotland designed for use offshore, and in this case, exposed coastal waters.

between entirely closed and completely open. In many a significant percentage of replacement water is added either continuously or intermittently on a daily basis. Such partial recirculating systems may exchange from a few percent to several hundred percent of system volume each day.

The heart of a recirculating water system is the biofilter, a device that contains solid media on which bacteria that help purify the water become established (Fig. 7). Fish and aquatic invertebrates produce ammonia as their primary metabolic waste product. If not removed or converted to a less toxic chemical, ammonia can quickly reach lethal levels. Two genera of bacteria are responsible for ammonia removal in biofilters. The first, *Nitrosomonas*, converts ammonia (NH_3) to nitrite (NO_2^-). The second, *Nitrobacter*, converts nitrite to nitrate (NO_3^-). Nitrite is highly toxic to aquatic animals, although nitrate can be allowed to accumulate to relatively high levels. If both genera of bacteria are active, the conversion from ammonia through nitrite to nitrate is so rapid that nitrite levels remain within the safe range.

Other than the biofilter and culture chambers, recirculating systems typically also employ one or more settling chambers or mechanical filters to remove solids such as unconsumed feed, feces, and mats of bacteria that slough from the biofilter into the water. Each recirculating system requires a mechanical means of moving water from component to component. That usually means mechanical pumping, though air-lifts can also be used.

Control of circulating bacteria and oxidation of organic matter can be obtained through ozonation of the water. Ozone (O_3) is highly toxic to aquatic organisms. Ozone must be allowed to dissipate prior to exposing the water to the aquaculture animals. With time, and with the assistance ofaeration, ozone can be driven off or converted to molecular oxygen. Various commercial firms market ozone generators and can assist aquaculturists in selecting the proper equipment to meet system needs.

Fig. 7. A bead filter, one of many types of biological filters, shown in association with a laboratory-scale recirculating water system. Small plastic beads inside the fiberglass chamber provide surface area for colonization by bacteria that convert ammonia to nitrate.

Ultraviolet (UV) light has also been used to sterilize the water in aquaculture systems. The effectiveness of UV decreases with the thickness of the water column being treated, so the water is usually flowed past UV lights as a thin film (alternatively, the water may flow through a tube a few cm in diameter that is surrounded by UV lights). UV systems require more routine maintenance than ozone systems. UV bulbs lose their power with time and need to be changed periodically. In addition, organic materials exposed to UV light foul the surface of the transparent quartz (sometimes plastic) tubes past or through which the water flows, thereby causing a film between the water and the UV source that reduces the penetration of the UV light.

Recirculating systems often feature other types of apparatus, such as foam strippers and supplemental aeration. The technology for denitrifying nitrate to nitrogen gas has developed to the point that it may find a place in commercial culture systems in the near future. Computerized water-quality monitoring systems that will sound alarms and call emergency telephone numbers to report system failures to the culturists are also finding increased use.

The technology involved makes recirculating systems expensive to construct and operate. Redundancy in the system, ie, providing backups for all critical components, and automation are important considerations. When a pump fails, for example, the failure must be instantly communicated to the culturist and the culturist must have the ability to keep the system operating while the problem is being addressed. Loss of a critical component for even a few minutes can result in the loss of all animals within the system.

Recirculating systems can make aquaculture feasible in locations where conditions would not otherwise be conducive to successful operations. Such systems can also be used to reduce transportation costs by making it possible to grow animals near markets. In areas where there are concerns about pollution or the use of exotic species, closed systems provide an alternative approach to more extensive types of operations.

Another approach to aquaculture is enhancement, which involves spawning and rearing aquatic organisms to a size large enough that the organisms will have a good chance of survival in nature. Ocean ranching (previously mentioned) is a form of enhancement that is normally conducted with anadromous species. Enhancement in a broader context could be conducted with virtually any aquatic species of economic importance. Once the organisms reach marketable size (that is, when they recurit to a fishery), they could be harvested by commercial or recreational fishermen who would pay a license fee for the opportunity to fish on the enhanced species. This is already being done in conjunction with the recreational red drum fishery in Texas. Before enhancement programs are put into place, research should be conducted to determine the size at which the target organisms should be released and to determine that the addition of large numbers of organisms to a natural ecosytem will not be detrimental to naturally occuring species or overwhelm the food base that exists in the area slated for stocking.

6. Water Sources and Quality

Sources of water for aquaculture include municipal supplies, wells, springs, streams, lakes, reservoirs, estuaries, and the ocean. The water may be used directly from the source or it may be treated in some fashion prior to use (see WATER).

Many municipal water sources are chlorinated with sufficiently high levels of chlorine to be toxic to aquatic life. Chlorine can be removed by passing the water through activated charcoal filters or through the use of sodium thiosulfate metered into the incoming water. Municipal water is usually not used in aquaculture operations that utilize large quantities of water, either continuously or periodically, because of the initial high cost of the water and the cost of pretreatment to remove chlorine.

If polled, most aquaculturists would probably indicate a preference for well water. Both freshwater and saline wells are common sources of water for aquaculture. The most common pretreatments include temperature alteration (either heating or cooling); aeration to add oxygen or to remove or oxidize substances such as carbon dioxide, hydrogen sulfide, and iron; and increasing the salinity (in mariculture systems). Pretreatment may also include adjusting pH, hardness, and alkalinity through the application of appropriate chemicals.

To heat or cool water requires large amounts of energy. A major consideration in locating an aquaculture facility is to have not only a sufficient supply of water, but to have water at or near the optimum temperature for growing the species that has been selected. The vast supply of spring water of almost perfect temperature in the Hagerman Valley of Idaho supports the majority of the trout production in the United States. Where geothermal water is available, tropical species can be grown in locations where ambient winter temperatures would otherwise not allow them to survive.

Another large cost associated with incoming water is associated with its movement. Many aquaculture facilities that utilize surface waters and those that obtain their water from wells other than artesian wells are required to pump the water into their facilities. Pumping costs can be a major expense, particularly when the facility requires continuous inflow.

Surface water can sometimes be obtained through gravity flow by locating aquaculture facilities at elevations below those of adjacent springs, streams, lakes, or reservoirs. Coastal facilities may be able to obtain water through tidal flow.

The most common treatment of incoming surface water is removal of particulate matter. This can be effected through the use of settling basins orfiltration. Particle removal may involve the reduction or elimination of suspended inorganic material such asclay, silt, and sand. It may also involve removal of organic material, including living organisms. Organisms that enter aquaculture facilities if not filtered from the incoming water include phytoplankton and zooplankton, plants and plant parts, macroinvertebrates, and fishes. Some of the organisms, if not removed, can survive and grow to become predators on, or competitors with, the target aquaculture species. Very small organisms, such as bacteria, can be removed mechanically. However, other forms of sterilization, such as ozonation and the use of UV radiation, are more efficient and effective.

For many freshwater species that can be characterized as warmwater (such as channel catfish and tilapia) or coldwater (such as trout), the conditions outlined in Table 4 should provide an acceptable environment. So-called midrange species are those with an optimum temperature for growth of about 25C (examples are walleye, northern pike, muskellunge, and yellow perch). Typically they do well under the conditions, other than temperature, specified in Table 4 for coldwater species. Some species have higher or lower tolerances than others. For example, tilapia can tolerate temperatures in excess of 34C, but have poor tolerance for low temperature. Most tilapia species die when the temperature falls below about 12C. Tilapia have a remarkably high tolerance for ammonia compared with such species as trout and salmon, which have a high tolerance for cold water, but cannot tolerate water temperatures much above 20C. Marine fish may be able to tolerate a wide range of salinity (such euryhaline species include flounders, red drum, salmon, and some species of shrimp), or they may have a narrow tolerance range (they are called stenohaline species, examples of which are dolphin, halibut, and lobsters). Recommended water quality conditions for marine fish production systems are presented in Table 3.

Table 4. **General Water Quality Requirements for Cold and Warmwater Aquatic Animals in Fresh Water**[a]

Variable	Acceptable level or range: Coldwater	Warmwater
temperature, °C	<20	26–30
alkalinity, mg/L	10–400	50–400
dissolved oxygen, mg/L	>5	≥5
hardness, mg/L	10–400	50–400
pH	6.5–8.5	6.5–8.5
total ammonia, mg/L	<0.1	<1.0
ferrous iron, mg/L	0	0
ferric iron, mg/L	0.5	0–0.5
carbon dioxide, mg/L	0–10	0–15
hydrogen sulfide, mg/L	0	0
cadmium, μg/L	<10	<10
chromium, μg/L	<100	<100
copper, μg/L	<25	<25
lead, μg/L	<100	<100
mercury, μg/L	<0.1	<0.1
zinc, μg/L	<100	<100

[a]Refs. 1,6,7

The water quality criteria for each species should be determined from the literature or through experimentation when literature information is unavailable. Synergistic effects that occur among water quality variables can have an influence on the tolerance a species has under any given set of circumstances. Ammonia is a good example. Ionized ammonia (NH_4^+) is not particularly lethal to aquatic animals, but unionized ammonia (NH_3) can be toxic even when present at a fraction of a part per million (depending on species). The percentage of unionized ammonia in the water at any given total ammonia concentration changes in relation to such factors as temperature and pH. As either temperature or pH increase, so does the percentage of unionized ammonia relative to the level of total ammonia.

Another example is dissolved oxygen (DO). The amount of DO water can hold at saturation is affected by both temperature and salinity. The warmer and/or more saline the water, the lower the saturation DO level. Oxygen saturation is also affected by atmospheric pressure, decreasing markedly as elevation increases.

Biocides should not be present in water used for aquaculture. Typical sources of herbicides and pesticides are runoff from agricultural land, contamination of the water table, and spray drift from crop-dusting activity. Excessive levels ofphosphorus andnitrogen may occur where runoff from fertilized land enters an aquaculture facility either from surface runoff orgroundwater contamination. Trace metal levels should be low as indicated in Tables 4 and 5.

Most aquaculture facilities release water constantly or periodically into the environment without passing it through a municipal sewage treatment plant. The effects of those effluents on natural systems have become a subject of intense scrutiny in recent years and have, in some instances, resulted in opposition to

Table 5. **Suggested Water Quality Conditions for Marine Fish Production Facilities**[a]

Variable	Acceptable level or range
temperature, °C	1–40 (depends on species)
salinity, g/kg	1–40 (depends on species)
dissolved oxygen, mg/L	>6
pH	<7.9 – 8.2
total ammonia, μg/L as NH_3	<10
iron, μg/L	100
carbon dioxide, mg/L	<10
hydrogen sulfide, μg/L	<1
cadmium, μg/L	<3
chromium, μg/L	<25
copper, μg/L	<3
mercury, μg/L	<0.1
nickel, μg/L	<5
lead, μg/L	<4
zinc, μg/L	<25

[a]Ref. 8

further development of aquaculture facilities in those locales. There have even been demands that some existing operations should be shut down.

Regulation of aquaculture varies greatly both between and within nations. Some governmental agencies with jurisdiction over aquaculture have placed severe restrictions on the levels of nutrients such as phosphorus and nitrogen that can be released into receiving waters. Regulations on levels of suspended solids in effluent water are also common. The installation of settling ponds and constructed wetlands, exposure of the water to filter feeding animals that will remove solids, and mechanical filtration have all been used to treat effluents. Reduction or removal of dissolved nutrients through tertiary treatment is possible, but is generally not economically feasible at present. Research is currently underway to develop feeds containing reduced levels of nutrients or to provide nutrients in forms that can better be utilized by the culture animals. The goal in both approaches is to reduce discharges of nutrients to the environment through excretion.

7. Nutrition and Feeding

There are cases in which intentional fertilization is commonly used by aquaculturists in order to produce desirable types of natural food for the species under culture. This can also cause problems associated with excessive levels of nutrients and unwanted nuisance species. Examples of this situation include inorganic fertilizer applications in ponds to promote phytoplankton and zooplankton blooms that provide food for young fish such as channel catfish, the development of algal mats through fertilization of milkfish ponds, and the use of organicfertilizers (from livestock and human excrement) in Chinese carp ponds to encourage the growth of phytoplankton, macrophytes, and benthic invertebrates. In the latter instance, various species of carp with different food habits are stocked to ensure that all of the types of natural foods produced as a result of fertilization are consumed.

Provision of live foods is currently necessary for the early stages of many aquaculture species because acceptable prepared feeds have yet to be developed. Algae are routinely cultured for the early stages of molluscs produced in hatcheries. Once the molluscs are placed in growout areas, natural productivity is depended upon to provide the algae and other microorganisms upon which the shellfish feed.

In cases where zooplankton are reared as a food for predatory larvae or fry, it may be necessary to maintain three cultures. Though wild zooplankton have been used successfully in some instances (eg, in Norway wild zooplankton have been collected and fed to larval Atlantic halibut, *Hippoglossus*), the normal process involves culturing algae to feed to zooplankton that are fed to young shrimp hippoglossus or fish.

The most popular live foods for first feeding animals such as shrimp and marine fishes that have small eggs and larvae are rotifers and brine shrimp nauplii. After periods ranging from several days to several weeks, depending on the species being reared, the aquaculture animals will become sufficiently large to accept pelleted feeds and can be weaned onto prepared diets. Problems associated with utilizing prepared feeds from first feeding include difficulty in providing very small particles that contain all the required nutrients, loss of soluble nutrients into the water from small particles before the animals consume the feed, and in some cases, the fact that prepared feeds do not behave the same as live foods when placed in the water. For species that are sight feeders, behavior of the food is an important factor.

Some of the most popular aquaculture species accept prepared feeds from first feeding. Included are catfish, tilapia, salmon, and trout. All of the fishes listed have relatively large eggs (several a few mm diameter) that develop into fry that have large yolk sacs. The nutrients in the yolk sac lead to production of first-feeding fry with well-developed digestive tracts that produce the enzymes required to efficiently digest diets that contain the same types of ingredients used for larger animals.

Fish nutritionists have, over the last few decades, successfully determined the nutritional requirements of many aquaculture species and have developed practical feed formulations based on those requirements. For species such as Atlantic salmon, various species of Pacific salmon and trout, common carp, channel catfish and tilapia sufficient information exists to design diets precisely suited to each species. There is always interest among aquaculturists to develop new species. In each instance, the nutritional requirements of the new species must be investigated. Although there are many similarities among aquatic animals, diets that produce the best growth at the least cost vary significantly and can only be formulated when the nutritional requirements are known. Determination of those requirements may require several years of research, although suitable diets based on existing formulations can be employed while the research is being conducted.

Requirements for energy, protein, carbohydrates, lipids, vitamins and minerals have been determined for the species commonly cultured (9). As a rule of thumb, trout and salmon diets will, if consumed, support growth and survival in virtually any aquaculture species. Such diets often serve as the control against which experimental diets are compared.

Since feeds contain other substances than those required by the animals of interest, knowledge is also required of antinutritional factors in feedstuffs and on the use of additives. Certain feed ingredients contain chemicals that retard growth or may actually be toxic. Examples are gossypol in cottonseed meal and trypsin inhibitor in soybean meal. Restriction on the amount of the feedstuffs used is one way to avoid problems. In some cases, as is true of trypsin inhibitor, proper processing can destroy the antinutritional factor in the feed ingredient. In this case, heating of soybean meal is the method of choice.

Animals that do not readily accept pelleted feeds may be enticed to do so if the feed carries an odor that induces ingestion. Color development is an important consideration in aquarium species and some animals produced for human food. External coloration is desired in aquarium species. Pink flesh in cultured salmonids is desired by the consuming public. Coloration, whether external or of the flesh, can be achieved by incorporating ingredients that contain pigments or by adding extracts or synthetic compounds. One class of additives used to impart color is the carotenoids.

Prepared feeds are marketed in various sizes from very fine small particles (fines) through crumbles, flakes, and pellets. Pelleted rations may be hard, semimoist, or moist. Hard pellets typically contain less than 10% water and can be stored under cool, dry conditions for at least 90 days without deterioration of quality. Semimoist pellets are chemically stabilized to protect them from degradation if they are properly stored, while moist pellets must be frozen if they are not used immediately after manufacture. Moist feeds are produced in machines similar to sausage grinders.

Hard pellets are the type preferred if the species under culture will accept them. Semimoist feeds are most commonly used with young fishes and species that find hard pellets unpalatable. Moist feeds, which contain high percentages of fresh fish, are usually available only in the vicinity of fish-processing plants.

The most widely used types of prepared feeds are produced by pressure pelleting or extrusion. Pressure pelleting involves pushing the ground and mixed feed ingredients through holes in a die that is a few centimeters thick to produce spaghettilike strands of the desired diameter. The strands are cut to length as they exit the die. Steam is often injected into the pellet mill in a location that exposes the feed mixture to moist heat just before the mix enters the die. This improves binding and extends pellet water stability.

Extruded pellets are produced by exposing the ground and mixed ingredients to much higher heat and pressure and for a longer time than is the case with pressure pellets. In the extrusion process the ingredients undergo some cooking that can be beneficial in reducing the levels of certain antinutritional factors, such as trypsin inhibitor. There may be concomitant losses of heat labile nutrients such as vitamin C, so overfortification or the addition of heat stable forms of certain ingredients to obtain the desired level in the final product may be required.

Crumbles are formed by grinding pellets to the desired sizes. Specialty feeds such as flakes can be made by running newly manufactured pellets through a press or through use of a double drum dryer. The latter type of flakes begin as a slurry of feed ingredients and water. When the slurry is pressed between the hot rollers of the double drum dryer, wafer thin sheets of dry feed are produced that are then broken into small pieces. The different colors observed in some tropical fish foods represent a mixture of flakes, each of which contains one or more different additives that impart color.

Pressure pellets sink when placed in water, whereas under the proper conditions, floating pellets can be produced through the extrusion process. That is accomplished when the feed mixture contains high levels of starch that expands and traps air as the cooked pellets leave the barrel of the extruder. This gives the pellets a density of less than 1.0. Floating pellets are desirable for species that come to the surface to feed since the aquaculturist can visually determine that the fish are actively feeding and can control daily feeding rates based on observed consumption.

Sinking extruded pellets are used for shrimp and other species that will not surface to obtain food. Shrimp consume very small particles, so they will nibble pieces from a pellet over an extended period of time. For that reason, both pressure and extruded pellets need to have high water stability. Extruded feeds, whether sinking or floating, may remain intact for up to 24 hours after being placed in the water. Pressure pellets begin to disintegrate after a few minutes, unless supplemental binders are incorporated into the feed mixture. As previously indicated, the use of steam in conjunction with pressure pelleting also enhances pellet stability.

Nearly all aquaculture feeds contain at least some animal protein since theamino acid levels in plant proteins typically cannot meet the requirements of most aquatic animals. Fish meal is the most commonly used source of animal protein in aquaculture feeds, though blood meal, poultry by-product meal, and meat and bone meal have also been successfully used. Commonly used plant proteins include corn meal, cottonseed meal, peanut meal, rice, soybean meal, and wheat. A number of other ingredients have also been used, many of which are only locally available. Most formulations contain a few percent of added fat from such sources as fish oil, tallow, or more commonly, oilseed oils such as corn oil and soybean oil. Complete rations contain added vitamins, and minerals. Purified amino acids, binders, carotenoids, and antioxidants are other components found in many feeds. Growth hormone andantibiotics are sometimes used. Regulations on the incorporation of hormones along with other chemicals and drugs into aquatic animal feeds are in place in the United States and some other countries (Table 6). Few such regulations have been promulgated in developing nations.

Feeding practices vary from species to species. It is important not to overfeed since waste feed not only means wasted money, it can also lead to degradation of water quality. Most species require only three to four percent of body weight in dry feed daily for optimum growth. Very young animals are an exception. They are fed at a higher rate because they are growing rapidly and consume a greater daily percentage of body weight than older animals. It is important to have food readily available to them. Food should be spread evenly over the culture chamber area so the young animals do not have to expend a great deal of energy searching for a meal. Feeding rates as high as 50% of body weight daily are not uncommon for young animals. Since total biomass is small, even

Table 6. **Therapeutants and Disinfecting Agents Approved for Use in United States Aquaculture**[a]

Name of compound	Use of compound
	Therapeutants
copper	antibacterial for shrimp
formalin	parasiticide for various species
furanace (Nifurpyrinol)	antibiotic for aquarium fishes
oxytetracycline (Terramycin)	antibiotic for fishes and lobsters
sodium chloride	osmoregulatory enhancer for fishes
sulfadimethoxine (Romet)	antibacterial for salmonids and catfish
trichlorofon (Masoten)	parasiticide for baitfish and goldfish
	Disinfectants
calcium hypochlorite (HTH)	used in raceways and on equipment
didecyl dimethyl ammonium chloride (Sanaqua)	used in aquaria and fish-holding equipment
povidone–iodine compounds (Argentyne, Betadine, Wescodyne)	disinfection of fish eggs

[a] Ref. 11.

in intensively stocked units such as raceways, the economic cost is not high. Water quality in raceways can be maintained by siphoning out waste feed periodically. In ponds, any unconsumed feed acts as fertilizer and the quantities used are not high enough to affect water quality adversely.

Young animals may be fed several times daily. Examples include the standard practices of feeding fry channel catfish every three hours and young northern pike as frequently as every few minutes. Keeping carnivorous species such as northern pike satiated helps reduce the incidence of cannibalism.

8. Reproduction and Genetics

Species such as carp, salmon, trout, channel catfish, and tilapia have been bred for many generations in captivity though they usually differ little in appearance or genetically from their wild counterparts. A few exceptions exist, such as the leather carp, a common carp strain selectively bred to produce only one row of scales, and the Donaldson trout, a strain of rainbow trout developed over numerous generations to grow more rapidly to larger size and with a stouter body than its wild cousins.

Selective breeding has long been practiced as a mean of improving aquaculture stocks. In some instances it has not been possible or it is quite difficult and expensive to produce broodstock and spawn them in captivity, so culturists continue to rear animals obtained from nature. Most of the species that are being reared in significant quantities around the world are produced in hatcheries using either captured or cultured broodstock. Milkfish is a notable exception. The species has been spawned in captivity, but most of the fish reared in confinement are collected as juveniles in seines and sold to fish culturists. Wild shrimp post-larvae continue to be used to stock ponds in some parts of the world though hatcheries may also be available in the event sufficient numbers of wild post-larvae are unavailable in a given year.

Spawning techniques vary widely from one species to another. Tilapia and catfish are typically allowed to spawn in ponds. Fertilized eggs can be collected from the mouths of female tilapia, but it is common practice to collect schools of fry after they are released from the mother's mouth to forage on their own. Catfish lay eggs in adhesive masses. Spawning chambers such as milk cans and grease cans are placed in ponds and may be examined every few days for the presence of egg masses. Some catfish farmers allow the eggs to hatch in the pond, though most collect eggs and incubate them in a hatchery. Adult Pacific salmon die after spawning. Females are usually sacrificed by cutting open the abdomen to release the eggs. Milt is obtained by squeezing the belly of males. Trout and Atlantic salmon can be reconditioned to spawn annually. Eggs are usually obtained from those species in the same fashion as from male Pacific salmon (1).

Unlike catfish, tilapia, trout and salmon, that produce several hundred to several thousand eggs per female, marine species typically produce large numbers of very small eggs. Hundreds of thousands to millions of eggs are produced by such species as halibut, flounders, red drum, striped bass, and shrimp. Catfish, salmon, and trout spawn once a year, while tilapia and some marine species spawn repeatedly if the proper environmental conditions are maintained (1). Red drum, for example, spawn every few days for periods of several months when light and temperature and are properly controlled (10).

Fish breeders have worked with varying degrees of success to improve growth and disease resistance in a number of species. Asgenetic engineering techniques are adapted to aquatic animals, dramatic and rapid changes in the genetic makeup of aquaculture species may be expected. However, since it is virtually impossible to prevent escapement of aquacultured animals into the natural environment, potential negative impacts of such organisms on wild populations cannot be ignored.

In some species, one sex may grow more rapidly than the other. A prime example is tilapia, which mature at an early age (often within six months of hatching). At maturity, submarketable females divert large amounts of food energy to egg production. Also, since they are mouth brooders (holding the eggs and fry within their mouths for about two weeks) and repeat spawners (spawning about once a month if the water temperature is suitable), the females grow very slowly once they mature. All-male, or predominantly male, populations of tilapia can be produced by feeding androgens to fry, which are still undifferentiated sexually. Various forms of testosterone have been used effectively in sex reversing tilapia and other fishes.

In species such as flatfishes, females may grow more rapidly than males and ultimately reach much larger sizes. For them, producing all-female populations for growout might be beneficial.

9. Diseases and Their Control

Aquatic animals are susceptible to a variety of diseases including those caused by viruses, bacteria, fungi, and parasites. A range of chemicals and vaccines has been developed for treating the known diseases, although some conditions have resisted all control attempts to date. In some nations, severe restrictions on the use of therapeutants has impaired that ability of aquaculturists to control disease outbreaks. The United States is a good example of a nation in which the variety of treatment chemicals is limited by government regulators (Table 6).

Managing conditions in the culture environment to keep stress to a minimum is one of the best methods of avoiding diseases. Vaccines have been developed against several diseases and more are under development. Selective breeding of animals with disease resistance has met with only limited success. Good sanitation and disinfection of contaminated facilities are important avoidance and control measures. Some disinfectants are listed in Table 6. Pond soils can be sterilized with burnt lime (CaO), hydrated lime [$Ca(OH)_2$], or chlorine compounds (12).

When treatment chemicals have to be employed, they may be incorporated in the food, used in dips, flushes and baths, or allowed to remain in the water for extended periods. Since one of the first responses of aquatic animals to disease is reduction or cessation of feeding, treatments with medicated feeds must be initiated as soon as development of an outbreak is suspected. Antibiotics, such as terramycin, can be dissolved in the water, but may be less effective than when given orally.

Vaccines can be administered through injections, orally, or by immersion. Injection is the most effective means of vaccinating aquatic animals but it is stressful, time-consuming, and expensive. The time and expense may be acceptable for use in conjunction with broodfish and other valuable animals. Oral administration of vaccines may be ineffective as many vaccines are deactivated in the digestive tract of the animals the vaccines are intended to protect. Dip treatment by which the vaccines enter the animals through diffusion from the water are not generally as effective as injection but can be used to vaccinate large numbers of animals in short periods of time.

10. Harvesting, Processing, and Marketing

Harvesting techniques vary depending on the type of culture system involved. Seines are often used to capture fish from ponds, or the majority of the animals can be collected by draining the pond through netting. Fish pumps are available that can physically transfer aquatic animals directly onto hauling trucks from ponds, raceways, cages and net-pens without causing skin abrasions, broken fins, or other damage.

Aquaculturists may harvest, and even process their own crops, although custom harvesting and hauling companies are often available in areas where the aquaculture industry is sufficiently developed to support them. Some processing plants also provide harvesting and live-hauling services.

Some species, with channel catfish being a good example, can develop off-flavors. A characteristic off-flavor in catfish is often described as an earthy, musty, or muddy flavor. The problem is associated with the chemical geosmin and related compounds that are produced by certain types of algae (1). Processors often require that a sample fish from each pond scheduled for harvest be brought to the plant about two weeks prior to harvest for a taste test. Subsequent samples are taken to the processor three days before and during the day of processing. If off-flavor is detected, the fish will be rejected. Once the source of geosmin is no longer present, the fish will metabolize the compound. The process may involve moving the fish into clean well water or by merely waiting until the algae bloom dissipates, after which the geosmin will be rapidly metabolized. Within a few days the fish can be retested and if no off-flavor is detected, they can be harvested and processed.

Centralized processing plants specifically designed to handle regional aquaculture crops are established in areas where production is sufficiently high. In coastal regions, aquacultured animals are often processed in plants that also service capture fisheries.

Marketing can be done by aquaculturists who operate their own processing facilities. Most aquaculture operations depend on a regional processing plant to market the final product. In all cases aquaculturists should note well that their job is not complete until the product reaches the consumer in prime condition.

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