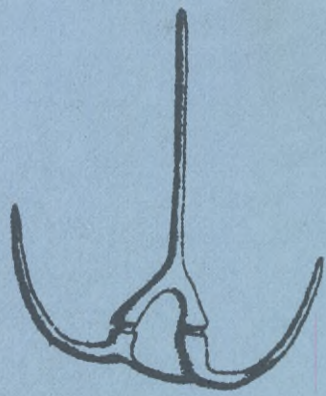
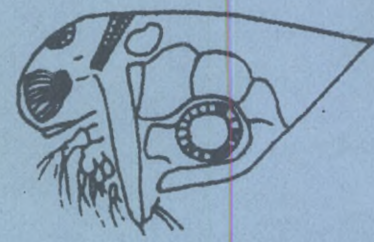
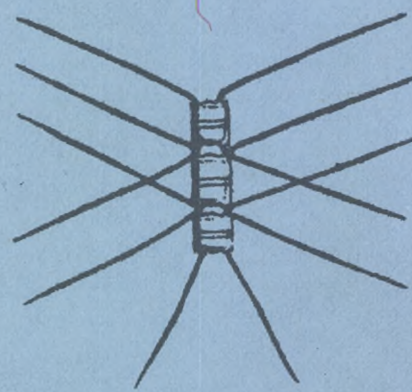
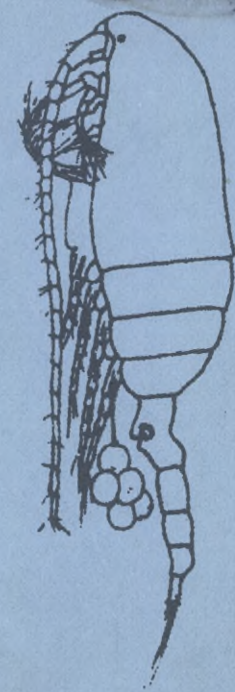
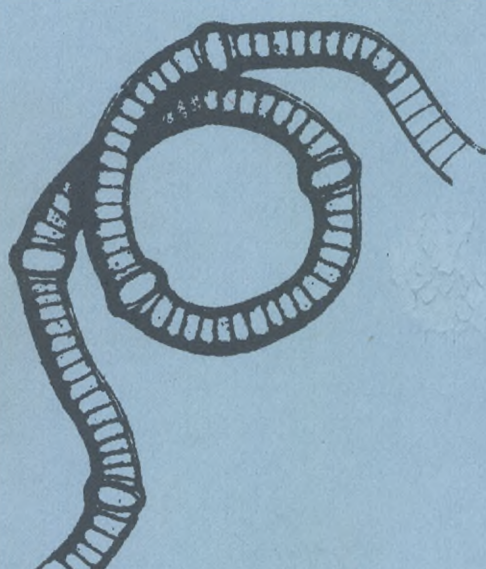
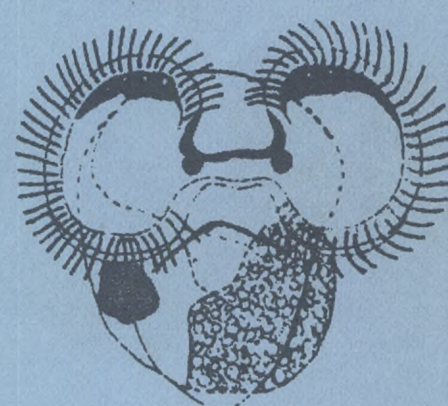












MEDDELANDE från
HAVSFISKELABORATORIET · LYSEKIL

nr
204

AQUACULTURE - MARICULTURE

THE PRESENT STATUS, PROSPECTS AND BASIC PRINCIPLES

by

Hans Ackefors and Carl-Gustaf Rosén

August 1976

AQUACULTURE - MARICULTURE

THE PRESENT STATUS, PROSPECTS AND BASIC PRINCIPLES

by

Hans Ackefors and Carl-Gustaf Rosén

CONTENTS

ABSTRACT

Although on land man has obtained the major part of animal protein from domesticated animals since at least several hundred years, food from lakes and the sea is to at least 90% obtained by methods equivalent to hunting. Culturing aquatic organisms has been practiced since thousands of years, but it is only now that aquaculture is gaining a real significance in food production. It has been estimated by the FAO that by the end of this century nearly half of all fish consumed by man will be obtained from aquaculture. This major change in the utilization of aquatic species by man is bound to have significant influences on land structure and waterways, and the quest for ever more intensive utilization of water volumes calls for developments in applied ecology and the application of several techniques common to process engineering of microbial processes. The basic features of aquaculture are discussed against this background.

INTRODUCTION

Domesticated animals on land have provided the major part of animal protein for man since at least several hundred years. The fraction of meat obtained from hunting is dwindling and of little significance except in certain less industrialized regions. Concomitant with the domestication of animals, extensive ecological changes have taken place, and the cultivated species have undergone profound genetic and physiological changes due to more or less planned breeding.

Unfortunately these changes belong largely to an era, when the scientific consciousness was poorly developed, and we can therefore only make a vague reconstruction of the development. In the aquatic environment the situation is entirely different. Even today more than 90 percent of all fish in the world consumed by man is obtained by "hunting" of wild species. Rearing of fish in enclosing structures, usually ponds, has been practiced for thousands of years (a famous text-book on fish farming was written as early as 475 B.C. by the Chinese Fan-Li!), but only in some eastern countries has aquaculture, as we prefer to call it by a more general term, been of any significance until recently. In later years, however, something like a revolution has begun to take place. Aquaculture is rapidly developing from an ancient craft, practiced much as primitive agriculture,into a sophisticated technology, which builds on recent developments in process technology, sewage treatment, nutrition, genetics and many other disciplines. We shall in this paper attempt to give a unified picture of this dynamic field, which is likely to have significant ecological consequences.

FOOD CHAINS AND ENERGY FLOW

One of the ideas behind aquaculture is the possibility for man to optimize the energy flow in the ecosystem and shorten the food chain which is normally rather long in nature, where biological energy is very often passing 2 to 4 links in the food chain, before man can harvest. In Fig. 1 it is shown that the production is 7×10^{11} tons phytoplankton per year in the seas (1). This food is eaten mainly by zooplankton or other evertebrates and to a lesser extent by phytoplankton feeding fishes such as mullet and anchoveta. The transfer of energy from one trophic level to another implies, that large amounts of energy are lost. The ecological efficiency is estimated to 10 to 20 % in various types of aquatic ecosystems, which means that 100 kgs phytoplankton will only give 10 to 20 kgs organisms on trophic level No. 1. With 10 % ecological efficiency in the next steps of the food chain you get only 1 to 2 kgs biological production on trophic level No. 2 and 0.1 to 0.2 kgs on level No. 3 etc. The biological energy requirements to produce fish from level No. 3 is thus higher than fish from level No. 2. In a natural ecosystem with different kinds of fish and other animals eating on different trophic levels, a yield is harvested coming from various trophic levels in the food chain. Mussels oysters and some species of the genus Tilapia are harvested on level No. 1. Anchoveta, which feeds partly on phytoplankton and partly on zooplankton, is harvested on a level between 1 and 2. Herring are harvested on level No. 2, because it feeds on zooplankton from level No. 1. Small cod feeds on level No. 2 and are harvested on level No. 3 while big cod are harvested on level No. 4 etc.

The present production of about 740 000 million tons of plankton algae per year (2) correspond to a harvest of only 55 million tons fish and other animals and plants in the seas (cf. Fig. 1). This is less than 0.01 % of the basic production of phytoplankton. There are about six times as much vegetable protein, which is involved in the marine production of food for human consumption, than in the production of meat on land. The amount of protein in the form of plankton algae and macroalgae exploited in the whole annual catch of fish is equivalent to 40 world harvests of wheat (3). In view of this fact it seems necessary to enhance the aquaculture activities to produce aquatic-products in short food chains. The forecast by FAO is, that by the year 2000, the aquaculture production will be 10 times higher than now or 50 million tons per year.

In fish farming or in other aquaculture projects it is possible to shorten the food chain with a suitable choice of species which feed on trophic level 0 or the next upper level from the basic production,i.e.

trophic level No. 1. The blue mussel, _Mytilus edulis_, or some species of the genus _Tilapia_ are good examples of species feeding on trophic level No. 0. It is also possible to select species or a subspecies with a very high conversion efficiency. In such species the amount of food is assimilated and transformed into flesh in a better way than in species with a low conversion efficiency. The two ways of species selection are necessary in order to get a good economical revenue _in a monoculture_. In an aquaculture system with many species in the same ecosystem, the species selection is still very important. _In such a polyculture_ it is necessary to find out how many different niches you have in your ecosystem. In principle you can stock your system with one species in every niche.

With a short food chain and a good selection of species it is thus possible for man to utilize the available energy far better than in nature.

GENERAL REVIEW OF AQUACULTURE IN THE WORLD

The total yield from different kinds of aquaculture —freshwater and saltwater—is estimated to 5 million tons per year (4). The main part, 3.6 million tons, of the cultured organisms is finfish. About 1 million tons molluscs (oysters, mussels, snails) and 0.4 million ton seaweed are produced. The production of other groups such as crustaceans (lobsters, shrimps, prawns) as well as reptilians (turtels), amphibians (frogs), etc. is marginal. A rough estimate based on various sources indicates that the freshwater production is 3.2 million tons while the salt and brackish water production is 1.8 million tons. The aquaculture production in freshwater consists mainly of fine fish. The production in brackish and marine water, often referred to as mariculture, consists of 1 million tons molluscs, 0.4 million ton seaweed and only 0.4 million tons finfish.

In 1973 the total world catch from wild harvest (in natural waters) and from farming (in artificial waters) was 66 million tons, 57 million tons from saltwater (marine and brackish water) and 9 million tons from freshwater (5). This means that about 35 % of the freshwater production and 3 % of the saltwater production came from aquaculture activites. Consequently, the total aquaculture production included 8 % of the total world harvest. The production of aquaculture products have doubled in five years (4) while the catch or harvest from wild stocks increased in many years up to 1969 by 5 to 7 % annually but is now stagnating (6). This is mainly due to overfishing but also to natural environmental fluctuations or pollution problems.

The aquaculture in fresh water has a very long tradition, while the salt water farming (except the brackish water farming) is still in its infancy. The fish culture technology in fresh water is very ancient and its origin is back beyond 2000 B.C. in China. The farming of fish and other aquatic organisms has therefore a very long tradition in Asia. About 80 % of the harvest today is coming from that part of the world, i.e. 4 million tons per year. 10 % is from Europe and 8 % from North America. Africa lacks a tradition in fish culture as well as Australia and in no other major area of the world the fish culture is so poorly developed as in Latin America. The total contribution from these three continents is only estimated to 2 % of the aquaculture production.

It is estimated that 2.6 million tons of finfish per year is produced mainly in fishponds by nine countries in Asia (7). About 50 % is produced by China and the rest by India, Pakistan, Indonesia, Thailand, Philippiness, Taiwan, Japan, and Malaysia. Most of that catch is produced on land in extensive cultures with naturally produced fishfood (algae, plankton, evertebrates, fishes) or supplementary feeding. This type of farming has a long tradition and is analogous to a primitive agriculture. The intensive aquaculture activities, where the organisms are grown in ponds, small tanks, silos, cages, fishpens etc., is still a very small fraction of the aquaculture in the world. In such farming the stocking density is very high and the organisms are more or less exclusively dependent on feeding. The latter type of aquaculture is mechanized and usually dependent on sophisticated equipment, and fishfood such as pellets, flakes, etc. produced by industry. A production similar broiler rearing on land, is the ultimate goal for this branch of aquaculture. This type of farming is therefore analogous to a highly mechanized agriculture based on the support from industrial products. We are still waiting, however, for that turning point, when most fish are produced by farming and not by "hunting" as the case of today. This developmental stage was reached on land many hundred, or perhaps thousand, years ago when people started to domesticate wild animals.

CULTIVATED SPECIES

Vertebrates

According to an earlier estimate, about 85 % of the 3 million tons finfish cultivated in fish farming consist of carp (7). This is the same amount of fish as the annual herring catch in the North Atlantic during the 1960's or about 5 % of the total world catch of fish per year. The cultivated carp belong to various groups of carps (common carp, Chines carp, Indian carp), which consist of several species adapted to various food niches. The Chinese group consist of grass carp (feeding on plants), silver carp (phytoplankton and higher plants), sandkhol (phytoplankton), ma lang yu (zooplankton), mud carp (carnivourous), etc. Disregarding the carp harvest, all other species together make 0.5 million tons according to the same estimate (7). To distinguish between the harvest from wild stocks and from farming is in many cases impossible with the present fishery statistics. The following figures are mostly rough estimated and summarized by several authors (8).

A pond fish, which has become very popular in the southeastern part of the USA, is the catfish. In Arkansas, Missisippi and Louisiana many catfish farms are operating and producing a very desirable fish for the market in that part of the USA. The culture is considered to give a very good revenue. This is striking in a country with a high labour cost. By 1969 the production was up to 30 000 tons per year.

Trout culture has been estimated to 2 % or 60 000 tons. The production is mainly located in Europe and North America. France, Denmark and Italy are today the largest European producers of rainbow trout (Salmo gairnderi), each with a yearly production ranging between 10 000 and 15 000 tons. A lot of rainbow trout are nowadays raised in salt water where they are more resistant to diseases, more tolerable to a wider temperature range and have a faster growth rate. Marine fishfarms of saltwater raised rainbow trout are in operation in e.g. Canada and Norway. In the latter country the production in 1971 was in the order of 1 000 tons (9). A potential trout for rearing is brook or speckled trout (Salvelinus fontinalis), which is now cultivated on a very small scale. The rearing of other salmon fishes as the Atlantic salmon (Salmo salar) in Norway and the two species of Pacific salmon, coho (Oncorhynchus kisutch) and chinook (O.tshawytscha) in Canada is of minor importance. The harvest of each species is only in the magnitude of 20 to 100 tons (9).

The only important food fishes cultivated in brackish water are mullet, milkfish and eel. They are very often raised in tidal-gate ponds. The lagoons, the "valli", at the Italian coast of the Northern Adriatic coast is one example, where juvenile mullet and eel, born in the sea, are brought with the tides into the "valli" area, where they are cultivated. The mullet (Mugil cephalus, Liza sp.) and other species of mullet over the whole northern hemisphere prefer rather warm water. They are cultivated in North America (Hawaii and along the coast of the USA), in Europe (France, Italy, Israel) and in Asia (India, China, Japan, etc.). Israel only produces about 500 tons. Since mullet are herbivores and feed on small species of plankton, they are as close as possible to the basic production.

The milkfish (Chanos chanos) is a herring like fish native to many tropical countries bordering the Pacific and Indian ocean. They are herbivorous and feed on blue-green algae and organisms in conjunction with these algae at the fry stage. Later they change to a diet of filamentous green algae. The greatest production in the world is in Indonesia, Philippines and Taiwan. These three countries harvest annually little less than 200 000 tons together.

The cultivation of eel (Anguilla japonica) has a long tradition in Japan. In Japan and Taiwan the traditional food items for eel are fresh and cooked thrash fish, silkworm pupae, offal from slaughterhouse, small crabs, etc. The conversion ratio is very low but recently developed artificial feeds can be assimilated better. In Japan the production of eel is in the magnitude of 2000 tons. The marketable size is only 100 to 200 g, which the stocked elevers (fry) reach within a year after stocking. A growing commercial culture of the Eurcpean eel (Anguilla anguilla) is now developing in Europe (Italy, Soviet Union, West Germany) and in the Near East (Israel, the United Arab Republic).

The cultivation of marine fishes is a new branch of aquaculture. Until recently the whole production of finfish was coming from fresh water and brackish water farming. Since 1928 yellowtail (Seriola quinqueradiata) has been cultivated but not until 1960 it became of major importance as a cultured fish. The production has increased from 300 tons in 1958 to 30 000 tons in 1968 and to 100 000 tons in 1972 (8, 9).

Invertebrates

More than 1 % of the harvest from the sea consist of oysters. In 1971 730 000 tons were harvested. A great deal of this amount came from farming activities. USA is the leading country in the world in this particular field and not less than half of the produced oysters are raised along their coasts. A lot of species are cultivated over the whole world and many of these species have been introduced to new areas far away from their native land. The japanese oyster (Crassostrea gigas) are cultivated outside Asia in North America (USA and Canada) as well as in Europe (France, Netherlands, Portugal, etc.). Other important species are C. commercialis (Australia), C. virginica (USA), C. angulata (Portugal, Spain, France) and Ostrea edulis (France, Spain, Netherlands, Great Britain, Japan, Canada, USA).

The culture of mussels is largely confined to Europe. The blue mussel Mytilus edulis or M. galloprovincialis, which may be the same species, have been cultured in Europe since the 13th century. The main producers are Spain and Holland. The harvest is about 200 000 tons per year from farming activities.

The clam culture uses a similar technique as the oyster culture. The most important clam culturing countries are Japan and USA. A common hard clam is "quahog" (Mercenaria mercenaria), which is very common in the New England area of the US Atlantic coast. In Japan the asari (Tapes semidecussata) dominates.

Plants

The culture of seaweeds (marine macro-algae) has a long tradition in Asia. The red algae nori, Porphyra spp., used for preparation of hoshinori in Japan, have been cultivated since 17th century. About 120 000 tons are produced annually. Additional amounts are harvested in Korea. Green algae of the genera Enteromorpha and Monostroma are also important for preparing the special food item aonori. The brown algae wakame (Undaria pinnatifida) and konbu (Laminaria spp.) are also harvested in great amounts. The harvest of the former species was 40 000 to 60 000 tons a few years ago. In China the increasing demand for the brown algae Laminaria japonica, has induced to start a huge marine aquaculture in this particular field during the 1950´s and 1960´s. The production is in the order of 100 000 tons.

Potential species

A lot of potential species for aquaculture are now reared in various research activities or on a small commercial basis. The biological problems for farming the species are very often elucidated as well as the required technical equipment. The reason for not starting the farming is that the capital investment is too high with the present farming technique in relation to the economical revenue. A good example of this are crustaceans like shrimp, prawn, lobster and fishes like Tilapia spp., pompano (Trichinotus carolinus). The species may be cultivated on a commercial basis in a restricted area with very good prerequisites or in an area with an extremely high demand in the market. Shrimp culture is a good example of this condition. In southeast Asia people have cultivated some species of Penaeid prawns for five centuries. But the production is limited due to the high cost to produce food size shrimp. The kuruma shrimp, Penaeus japonicus, can be raised at a price of $ 7.00 per kg. The market prices are, however, very high for live cultured shrimp in Japan. They range from $ 7.00 to $ 30.00 per kg!! (10).

BIOLOGICAL CONSIDERATIONS

The keeping of fish or other aquatic organisms under enclosed conditions at high densities, which is essential for an economically successful aquaculture operation, introduces a number of problems, which do not exist or are of minor importance under natural conditions. Artificial feeding becomes necessary and, consequently, the efficient utilization of externally produced feed is crucial to the overall economics of the operation. Reproduction may not occur as a spontaneous process and must be closely controlled. Diseases may or may not be a more serious problem in closed systems as compared to open systems. Infections may to a certain extent be kept out of a system, which has a closely controlled water supply, but on the other hand high stocking rates inevitably increases the risk of a floreup of a latent disease. Control of biotic as well as abiotic environmental factor becomes one of the most important features as aquaculture progresses towards more intensive operations. New races, which are better suited to withstand the stresses of intensive culture and which have a better feed utilization, may be created by planned breeding. We will below discuss briefly these aspects of aquaculture.

Nutrition

One reason for the great interest in aquatic animals in food production is their potentially better feed conversion efficiency. Because their density is very close to that of water, they waste no energy in supporting their own weight, and since they are cold-blooded no energy is expended in thermoregulation. On the other hand, depending on the salinity of the water in which they live, they may expend significant amounts of energy on osmoregulation. On a whole, however, fish seem to have a better feed conversion than terrestrial animals. Table 1 gives a comparison between the mot common meat producing animals (11).

The expression conversion efficiency found in the literature is a bit confusing. Values as low as 1:1 are quoted. Of course, this does not imply that 100% of the feed is converted into fish. As it is normally expressed, conversion efficiency means the ratio of dry weight food supply to wet weight of fish produced. The best values based on dry weight/dry weight are in the range 3 to 4:1.

The enthusiasm over the favourable conversion efficiencies is somewhat dampened when one considers the composition of the food yielding such favourable results. Carnivorous fish need food with a protein content of 35-40%, and the best results quoted above are obtained with such feeds as clam meat, fish meal, and dehydrated blood. Whereas conversion efficiencies of 1.3-1.5 are obtained for carp with these feeds, the corresponding value for soybeans is 3.0-5.0. The diet has to be well balanced in terms of fat, protein, and carbohydrates. The fiber content must be within certain, relatively narrow limits, and for best results a well balanced composition of vitamins must be contained. The textbooks by Bardach et al. (8) and Huet (12) quoted in feed composition for all cultured species of fish.

As discussed above, one goal for aquaculture is to shorten the food chains as compared to natural conditions. It is expected that in the future suitably processed protein of microbial and vegetable origin will form the basis for fish feed.

Temperature and other environmental factors strongly influence the conversion efficiency and the optimum feed rate. Brett et al (13) have made a comprehensive study of this field as regards sockeye salmon, <u>Oncorhynchus nerka</u>. This fish as well as rainbow trout have a relatively distinct optimum growth temperature near 15°C, which is, however, displaced according to feeding rate.

The present farm animals have been bred for, among other characteristics, better feed conversion and growth rate with quite dramatic results. Fish of various species have in recent years also been subjected to such planned breeding. The Donaldson trout mentioned below represents one remarkable result of breeding for faster growth.

Reproduction and Breeding

The breeding of cultured organisms is very often not possible in captivity. This means that many aquaculture activities are dependent on wild stocks. There are, however, a wide range of differences between various species and the ability of propagation in captivity varies very much. Hence the stocking technique also varies greatly.

Tilapia spp. are probably the easiest species to obtain spawn. As a matter of fact, they spawn too much and the biggest problem is the overpopulation of ponds. Different methods are therefore used to presvent too much spawning. Methods of preventing overpopulation and stunting are monosex culture, stocking predators in the same pond along with the tilapia or to separate the parcuts from the fry immediately upon hatching. Tilapia spp. spawn in ponds with a soft sandy bottom. The males dig holes and the females deposit their eggs in such a nest. The females pick them up in the mouth. The males deposit their sperm in the holes and this is picked up by the females and the fertilization takes place inside the mouth.

The breeding of the common carp (Cyprinus carpio) is also very easy in captivity. The stimulus for spawning is just to rise the water temperature. The eggs are deposited on grass. Afterwards the eggs or the parents are removed from the pond to allow the eggs to hatch without any predation pressure.

Flatfish such as sole (Solea solea) also spawn in captivity. A brood stock can be kept in outdoor ponds. They are induced to spawn by transferring them to indoor tanks. With a suitable water temperature they spawn without any manipulation of the animals. The floating eggs are scooped off the surface and hatched separately.

A lot of fishes do not spawn in captivity and the only possibility is artificial spawning or fertilization. Sturgeons are induced to ripen in captivity with pituitary injections. Ripe females and males are killed and the gonads are removed. Afterwards the eggs and sperm are mixed. The fertilized eggs are placed in incubators. The propagation of salmon is a similar technique but without pituitary injections. Adult ripe males and females are stripped in order to extract the eggs and sperms, which are gently mixed to effect fertilization. Afterwards the eggs are put in incubators. The hatched fry are stocked in nursery tanks or ponds.

Fish culture of many species is dependent of wild stocks. Fry are captured in natural waters. This is true for most brackish and marine water species as well as the catadromous eel. The production of milkfish (Chanos

chanos) and mullet (_Mugil cephalus_, _Liza_ sp.) is dependent on fry captured in coastal and estaurine waters. The pompano (_Trachinotus carolinus_) culture in USA rely also on wild stocks. From April to November fry are caught along the beaches in Florida. In Japan the salt water species yellowtail (_Seriola quinqueradiata_) is raised by catching fry at sea, which are stocked in fishpens. The eel culture in Japan is also dependent on the catch of the young eel, called "elvers". migrating from the spawning area into the coastal zone of Japan.

Shrimp culture in Japan has a long tradititon. Seedlings are produced partly by growing a broad stock in captivity, and partly by catching gravid females at sea. In the USA the shrimp culture is exclusively dependent on wild stocks caught by trawlers. Gravid females are picked and induced to spawn.

Oyster and mussel culture are normally dependent on spawning in nature. Clean shells are used for settling of the larvae or other methods such as rafts with ropes. The larvae can also be produced by artificial spawning in hatcheries.

One of the most well-known experiment with selected breeding is the Donaldson rainbow trout. After about 40 years of selection the strain exhibits a tremendous growth rate. The rainbow trout grow to a weight of nearly 5 kgs in one year and reach a length of 67 cm in three years. The selective breeding for high fecundity, large egg size, high hatching percentage, rapid growth, early maturity, high temperature tolerance, disease resistance, etc. has been very successfull in farming of salmonoid fishes. There are now stocks of rainbow trout which spawn without any manipulation in any month of the year. This will, of course, promote an even production of food fishes for the market all the year round.

Hybridization between various salmon species or strains of the same species has also been promising for commercial trout culture. Donaldson was able to cross a landlocked and anadromous strains and got a hybrid which grow up at sea and return to the native river at the interval of two years for spawning.

Diseases

Pathological problems may be disastrous for many types of intensive aquaculture activities. A dense stocking rate may induce stress problems and a high susceptibility for diseases caused by pathogenic microorganisms. Factors as higher temperature or salinity than normal, promoting a higher growth rate and a better conversion efficiency, may also promote the growth of noxious microorganisms. A bad water quality caused by accumulated metabolic products is a basis for many disease problems.

Most animals are in fact infected by various microorganisms, but very few get diseased in most well treated fishfarms. Unfortunately our knowledge in this particular field is very limited. We know that in most organisms caught in the sea there are ectoparasites in the gills, skin and fins and/or endoparasites, in the interior part of the body. We also know that viruses, bacteria and fungi are very common as in the human body. But fortunately most of these organisms do not cause any diseases as long as the animals are in a very good condition. The best medicine in most fish farms are therefore a good husbandry.

However, with even the best care taken of the organisms, epidemics still flare up. Disease problems may cause a higher mortality or not quite healthy organisms. In the latter case the growth rate decreases and the economical loss may be conspicuous.

The basis for all types healthy organisms is the sanitary conditions. This concept includes scraping or sweeping your tank or pond to remove accumulated materia at the bottom, to avoid excess feeding, to remove not healthy organisms, etc. Sick organisms may be treated with chemicals, antibiotics and vaccine. Good and cheap methods are now developing. Chemicals may be added directly into the water or the organisms may be dipped in a concentrated chemical solution. Antibiotics or vaccine can be mixed with the food. Even cheap, half automatic methods, where fishes are injected with syringe, have been successful in salmon cultivation (14). A comprehensive manual of diagnosis and control of diseases in mariculture is under preparation. A draft has already been issued (15).

Environmental factors

Knowledge of the ecology, ethology and physiology of cultured species is essential. The environment of a fish farm is often quite different to that to which fish are exposed under natural conditions. Abiotic factors such as temperature, salinity, light conditions, oxygen tension, pH, etc and biotic factors such as competition (predators) and food (preys) differ to various extents from the ecological conditions of the wild stocks. The manipulation of the environment in aquatic husbandry is in fact in many cases a prerequisite for higher production than in natural waters, but the organisms are easily exposed to a stress, which negatively affects a variety of physiological factors, decreases the yield and increases the susceptibility to diseases.

The prime condition for a successful aquaculture is control of the water quality. As discussed below under Effluent treatment, the excretions from the fish result in an accumulation of nitrogeneous compounds, ammonia, nitrite and nitrate, of which the first one usually sets the limits.

The toxicity of ammonia is dependent on pH because of the equilibrium

$$NH_3 + H_3O^+ \rightleftarrows NH_4^+ + H_2O$$

At pH 7.7, which is within the normal range, as little as 1-2 mg/l of ammonia induces pathological changes in the gills, kidneys, and liver of rainbow trout. Ammonia is converted by bacterial action into nitrite and nitrate (cf. below). Particularly nitrite, which binds to the hemoglobin of blood, is harmful. 0.5 mg/l of ammonia and 0.15 mg/l of nitrite are considered safe in normal fish farming operations.

For both direct and indirect (bacterial ecology) reasons the oxygen concentration must be kept fairly high, i.e. in the order of 4 mg/l, which is, i.e. semisaturation. Therefore, in intensive aquaculture systems aeration is a necessity.

Biotic factors such as feeding behaviour and the interaction between individual fishes in relation to stocking density are of great significance. For optimum growth, feed utilization and wellbeing of the animals they must be fed at the right intervals with a feed, which is not only of correct chemical composition but also of preferred texture, particle size, etc. The interplay between biotic and abiotic factors in aquaculture forms a fruitful field of ecological and etological research.

THE PRODUCTION PROCESS

An overall view

The production of fish in an artificial system may be described - at least superficially - in terms of process engineering as a process, in which relatively low grade, low-priced protein-rich material is converted in a reactor into high-priced protein enriched food desirable to human consumers. In analogy with fermentation (microbiological) processes, the aquaculture process also has to be "seeded" with a starter culture of organisms, and it produces an effluent stream, which must be regarded as a potential pollutant. Schematically the process may thus be illustrated as in Figure 2.

The diagram depicts the basic mass flow in the process we call aquaculture. Like a process for production of microbial cell mass, e.g. fodder yeast, the aquaculture process also requires aeration (oxygen), stirring and temperature control. Before proceeding to discuss the process in more detail, we will discuss the conditions in the reactor itself.

The biological system

Although the overall picture of aquaculture may be described in terms of process engineering and in its general features it shows a great resemblance to a fermentation process such as the production of microbial cell mass, the biological system in which the synthesis of protein-rich food takes place is far more complex in the case of aquaculture because of the complexity of the organisms in terms of

- nutritional requirements
- metabolism
- growth characteristics
- reproduction
- response to biotic as well as abiotic ecological influences
- susceptibility to disease and parasites

Optimization of the biological process cannot be achieved without due consideration of all these characteristics and requirements of the animals. We have discussed above in some detail the various problems in these areas and will therefore only summarize some of the requirements, which have a direct technical influence on the process.

The feed must be given at the correct rate to avoid overfeeding and concomitant fouling of the water. Automatic feeders are used for this. Aeration must be adequate for metabolic as well as water conditioning purposes. At high stocking rates mechanically maintained turbulance is necessary to even out concentration differences of oxygen and waste products. Species and culturing conditions strongly influence the possible stocking rate. Depending on climate, heat regulation may be required.

Process characteristics

In earlier phases of aquaculture, i.e. with less intensive forms of production, such as open pond culture, one has relied more or less entirely on natural mechanisms for the maintenance of acceptable environmental conditions, but it is evident that if aquaculture is to expand so as to make a significant contribution to human nutrition, the production forms must become more intensive, and the environmental factors involved must be much more closely controlled. Even if many hybrids between the extensive pond culture and the extremely intensive, completely closed system no doubt exist and will come into being in the future, we find it more illustrative and constructive to consider the latter, where complete control of such phenomena as mass and heat transfer and the physical and chemical environment may (and in several cases must) be closely controlled.

Bearing in mind the need for environmental control and also considering the need for separate fry and fodder production, our diagram may be expanded as in Figure 3.

The quantitative relationships between the various streams are indicated in this diagram. It appears that fodder and water dominate the picture, and it is essentially the price-level of fodder, and the feed conversion efficiency which decide the economics of an aquaculture operation, and it is the supply of pure water which makes it possible. Today most fish or shellfish farms do not take the cost of sewage treatment into account, and it is often this negligence which make them profitable. However, as indicated above, a substantial expansion of aquaculture as an industry cannot build on the ability of natural waters to regenerate themselves by means of spontaneous processes. The cost of maintaining adequate water quality must be built into the calculations and the appropriate technical solutions be developed.

We will now attempt to treat the aquaculture production process in a macroperspective, i.e. to examine the gross flow of material and energy through the fish culturing unit. Later we will discuss in more detail how these flows and balances may be strongly affected by adjustment of environmental factors to suit each individual species subjected to aquaculture and by selective breeding of these species.

Material balance

Most work on intensive fish culture has been made with salmonids and carps. We will therefore use examples from these families to illustrate what is qualitatively true for most species although numbers may differ.

From the vast and sometimes conflicting information available in the literature the following assumptions seem to be realistic as far as a trout culture in a closed, intensive system is concerned.

Feed utilization (conversion efficiency)	25-30%
Growth cycle (holding time)	10 months
Optimum temperature	$15^{\circ}C$

In essence this means that for every ton of fish produced, at least one ton of dry fodder must be fed into the system. Part of the 0.75 ton, which is not accumulated in the system as fish, is spent on energy production (mechanical movement, heat loss, etc), and the rest is by means of respiration, excretion, and defecation converted into gaseous, liquid, or solid waste. In practice, a certain fraction of the fodder will also remain unused. The composition of a typical fodder is given in Table 2.

Although in a large number of studies feed utilization as well as water regeneration have been studied, very few published reports present sufficient data for the calculation of the complete material balance. Kuronuma (16) has published a detailed account of a closed, recirculating system for carp culture, which gives a rough overall balance of feed conversion into fish and waste, but since the actual oxygen uptake of the system is not given, the complete material balance cannot be calculated from the available figures. A more detailed study, which gives the necessary data on a rainbow trout culture, has been published by Scott & Gillespie (17). We will use that example to introduce some figures into our flow diagram in Figure 3.

Scott & Gillespie made an intensive study of the metabolism and growth of rainbow trout in a closed 1600-liter system, in which temperature, oxygen, pH ammonia, and nitrate were satisfactorily controlled. An average weight gain of 8% per week was obtained with a feed rate of 2% of body weight per day. Fish mortality was insignificant at stocking densities up to 75 kg. From the results reported by Scott & Gillespie and estimated data as to feed and fish composition we have derived or deducted the data given in Figure 4, which is analogous to Figure 3.

With the flow rates of water and oxygen given in the figure, the oxygen concentration could generally be maintained above 7 ppm. Except for occasions of component failure, the system was stable throughout the 238-day experimental period reported.

It is evident that the water purifications forms a very essential part of an aquaculture plant. In natural waters as well as in extensive pond cultures the water is conditioned by natural processes (biological, chemical, and mechanical), but environmental concern makes it imperative to attach to an aquaculture plant of any size a sewage treatment unit as indicated in Figure 3. We will give an outline of the functioning of such a unit, but first we will give the production process itself some further consideration.

Productivity

The above example was given mainly because it illustrates better than other published material the overall mass balance of an aquaculture unit including water conditioning. Another example, which may serve to illustrate the productivity of a recirculating system is that described by Kuronuma. There, more or less completely closed conditions were maintained during a 57-day period, in which 2250 kg of carp fingerlings increased their total weight to 4121 kg. This seems impressive and is quoted by Bardach et al (8) as the highest yield ever obtained in Japan, but if the figures are recalculated so as to be expressed in terms which are more in line with process engineering practice, they become less impressive. We then find that the productivity is 7.2 g/m^3h. This pertains for a final stocking rate of 22 kg/m^3.

Extreme examples of high stocking rates have been given by Meske (18) and Buss et al (19). Meske at the Max Planck Institute in Hamburg raised 10 carps to an average weight of 913 g in a 40 l aquarium and claimed a productivity 600 times that of a pond, whereas Buss et al raised rainbow trout in silos at a final stocking rate of 136 kg/m^3. The average productivity was 26 g/m^3h.

Elaborate formulae have been worked out for the estimation of productivity in natural waters (12). In our context it suffices to quote a couple of examples from Huet's book, in which these formulae have been checked against actual results. A one-acre pond in Western Europe was found to produce 24 kg of trout per year, while a 1.5-acre pond in the Far East produced 500 kg of carp per year. In the terms used above, this means roughly 0.6 and 9.5 mg/m^3h, respectively, which is 10^3 - 10^4 times less than in the intensive, recirculating systems described above.

It is thus obvious that the employment of artificial feeding and modern technology (which has by far not yet been employed to its full extent in practical aquaculture) may result in quite impressive increases of productivity. It must be remembered, however, that the capital investments and running costs also spring up by orders of magnitude, and although the productivities achieved in some of the intensive operations seem impressive, they are still very low compared what is obtained in, for instance, microbial processes. A productivity of 4 kg/m^3h is not abnormal in a fodder yeast plant. Although the price level for microbial protein is about one or two orders of magnitude lower than for fish, there is still a gap, which makes it impossible for economic reasons to employ in aquaculture all the technical solutions, which are available and which are being used in fermentation plants and also in many experimental fish farming operations. A breakthrough for recirculating aquaculture plants in practical operation depends on whether it is possible to find acceptable compromises.

Effluent treatment

Carbohydrate and fat are utilized chiefly for energy production, and their predominant chemical end products are carbon dioxide and water. Protein is the main growth component, but it also creates the major pollution problems. Most of the protein is eventually metabolized into ammonia, which is toxic to animals and usually sets the limit as to what fish can tolerate in terms of pollution.

In natural waters, processes called nitrification (Eqs.1 and 2) and denitrification (Eq. 3) convert ammonia via nitrite and nitrate into nitrogen gas, which leaves the system. The reactions, which take place according to Eqs. 1 and 2,

$$2NH_3 + 3.5O_2 \longrightarrow 2NO_2^- + 3H_2O \qquad (1)$$

$$2NO_2^- + O_2 \longrightarrow 2NO_3^- \qquad (2)$$

if the oxygen supply is adequate, are catalyzed by bacteria of the genuses Nitrosomonas and Nitrobacter, respectively. A variety of both heterotrophic and autotrophic bacteria carry out the denitrification

$$4NO_3^- + 3CH_4 \longrightarrow 2N_2 + 3CO_2 + 6H_2O \qquad (3)$$

under either aerobic or anaerobic conditions. As seen from Equation 3, an energy source is needed (methane in this case). An alternative pathway leads to nitrogen oxide, N_2O. The complete picture is outlined in Figure 5.

Results from research activities with closed recirculating systems are now available from laboratories in the USA. In this paper only three examples are given. Mock, Neal and Salser (20) have set up a closed raceway system for the culture of shrimp in Galveston, Texas. Epifanio, Pruder, Hartman, and Srna (21) have made a recirculating system to culture clam and oysters in Lewes, Delaware. Meade and Kenworthy (22) have developed a closed recirculated system for culturing salmon in silos in Kingston, Rhode Island.

The methods used in the various systems are:

1) Physical and mechanical filtration
2) Biological filters
3) UV treatment
4) Aeration
5) Protein skimmer

A schematic picture of a recirculating sea-water system is given in Figure 6. The production of algae for feeding the oysters and clams is in a separate tank and is not included in the circulating system. The algae are brought continuously to the closed circulating system with a foam technique preventing the algae medium (eight other nutrients) to enter the system. The treatment to remove metabolic products is very important in such systems. Ammonia is the principal product. The toxicity of undissociated ammonia is the main obstacle for the development of such culture systems with high density stocking of salmonid fishes. The accumulation of ammonia must therefore be prevented by using biological filters containing nitrification bacteria.

The biochemical processes take place according to the above mentioned formulae with an adequate supply of oxygen. The nitrification filters may be constructed with plastic modules, crushed shells, gravel, etc. to give an increased surface area for the microorganisms. A system with P.V.C. modules inside huge filter boxes ("nitrification towers") is described by Meade and Kenworthy (22).

As we have discussed above, the toxicity of ammonia is a function of pH, temperature and dissolved oxygen. In an acid solution ($pH < 6$) the major part of ammonia exists as ammonium ion, but the fraction of non-protonized ammonia increases with increasing pH towards the alkaline side. As we have noted above, it is particularly the non-protonized form, which is toxic.

In experiments with mildly acid environment it is shown that ammonia toxicity may be greatly reduced. Under such conditions the aerobic microbiological nitrification was also improved. With manipulation of the environmental factors pH, temperature, salinity and with adequate supply of oxygen, it is thus possible to achieve an environment where salmonid fishes can tolerate a certain concentration of ammonia, which may be balanced by the maintenance of bacterial nitrification.

Meade and Kenworthy (22) showed how it is possible to get rid of the accumulated nitrate in a high density water re-use system. The reduction of nitrate to gaseous form N_2 was accomplished by bacterial activity, when organic energy in the form of methanol was added.

It has thus been shown to be possible in a closed, recirculating system to convert the highly toxic ammonia to less toxic nitrate and further to gaseous N_2. The conclusion is that in such farming a totally balanced environmental system can be attained. In practice, however, it does not seem to be economic to achieve 100 percent purification, and as indicated in Figure 4 a small fraction of the water is continuously drained off together with solid waste products and replaced by pure water.

SIGNIFICANCE OF AQUACULTURE AND RELATED RESEARCH

The situation for aquaculture in the world today is that the traditional forms are rapidly being adopted on a wider scale. FAO and other organizations, which promote the development of agriculture and related activities in the less industrialized countries, have instituted a large number of programs, which aim at the development of aquaculture on technologically less advanced stages, i.e. essentially pond culture relying on the ability of natural waters to spontaneously regenerate. Fish farming in more developed countries such as Denmark, France, Italy and the USA is also predominantly of a relatively primitive kind with series of artificial dams bordering natural watercourses. Inevitably such activities will run into environmental difficulties once they are conducted on a sufficiently large scale. It is therefore to be expected that the next step in aquaculture, installations with environmental control (effluent treatment, etc) will be forced into existense at an accelerating rate. An alternative is to operate aquaculture at sea, where the dilution rate of water impurities may be sufficient to avoid the effects of locally high concentrations of e.g. nitrogeneous waste products.

In the development of aquaculture towards higher efficiency, it is possible to fall back to a great extent on the experience gained in agriculture. This applies to areas such as breeding, feed production, nutrition, distribution and land development to mention a few examples. However, culturing animals in the aquatic environment introduces some fundamentally new problems. With the organisms immersed in the water, they are much more intensely exposed to the environment than terrestrial animals. This means that they are more sensitive to the pollution of the environment, whether this be by pesticides or the animals' own excretion products. It calls for a much more "chemical" approach to the development of suitable culturing conditions for aquatic animals, which is in essense an advanced exercise in applied ecology with all its biological and technological aspects. Not only should aquaculture draw on the knowledge generated in ecological research, but the latter branch of science could also benefit from the large-scale study of closely controlled ecological conditions carried out in connection with the development of aquacultural plants.

In this paper we have dealt with the basic aspects of aquaculture as a process and not elaborated the details of the various systems, which are in use or have been proposed. Let us just in summary state that aqaculture essentially in the form in which it has been practiced for thousands of years, i.e. in open freshwater ponds, is developing rapidly in most parts of the world. At the same time a trend towards more sophisticated systems employing modern techniques for water conditioning are being developed, mainly in the industrialized countries. Nearly perfect, self-contained systems based on modern process technology and similar to fermentation plants have been built and exhibit remarkable productiviteis as compared to the less intensive systems. However, the economy of such systems remains doubtful. Inexpensive, yet effective, technical solutions have to be developed, and the productivities per unit of volume and feed must be improved considerably.

In the long perspective we will probably see large-scale aquaculture (or mariculture as it is often called when sea water is used) operations, in which gigantic volumes of sea water are conditioned for the enhanced growth of fish and filter feeders such as mussels and crustaceans (23) or in which algae are grown to make significant contributions to both energy and food supplies (24). It is already realistic to pump nutrient-rich water from a depth of several hundred meters at a rate of thousands of cubic meters per minute and thus fertilize the photosynthesizing surface layers, the energy being derived from the thermal differences in the sea (25). However, the many small-scale aquaculture plants, which grow up along rivers and lakes around the world, are interesting enough to call for the attention not only of land planners, farmers and industrialists but of scientists from many different fields.

REFERENCES

(1) M B Schaefer — Transactions American Fishery Society 94, 123 (1965) (Journal)

(2) J H Ryther — Science 166/3901/123/1969 (Journal)

(3) G Borgström — Mat för miljarder (LT:s förlag, Stockholm 1970) p 362 (Book)

(4) W Krone — Fish Farming—A World-Wide Growth Industry (Lecture given at the conference "Fish Farming in Europe—Prospects for Growth and the Problems", 3rd December, 1974, in London)

(5) FAO — Statistical Yearbook for 1973 (1975)

(6) H Ackefors — Production of Fish and other Animals in the Sea (to be published in AMBIO No. 2, 1977)

(7) OECD — International Developments in Fish Production (OECD, Paris 1973) (mimeographed) (Report)

(8) J E Bardach, J H Ryther, W O McLarney — Aquaculture—The Farming and Husbandry of Freshwater and Marine Organisms (Wiley-Interscience, New York, London, Sydney, Toronto, 1972) p 868 (Book)

(9) H R MacCrimmon, J E Stewart, J R Brett — Bull. Fish. Res. Board, Canada 188, 1/1974, (Journal)

(10) H R Schmittou — Aquacultural Survey in Japan (Auburn Univ., Alabama, Project A I D/csd 2780, 1972) (Report)

(11) C-G Rosén — Kemisk Tidskrift 1974 (11), 56 (1974)

(12) M Huet — Textbook of Fish Culture (Fishing News (Books) Ltd., London, 1970) p 281 (Book)

(13)	J R Brett, J E Shelbourn, CT Shoop	Journal Fisheries Research Board Canada 26 (9), 2363 (1969) (Journal)
(14)	A J Novotny	The Marine Culture of Vertebrates -Aquaculture Potential in the Maritimes Region (Internal report, National Marine Fisheries Service, Biological Laboratory, Seattle, Washington 98102, 1972) (Report)
(15)	Anon	Handbook of Diagnosis and Control of Diseases in Mariculture (Informal Rep. No. 19, Oxford Laboratory, National Marine Fisheries Service, NOAA, 1974) (mimeographed) (Book)
(16)	K Kuronuma	New Systems and New Fishes for Culture in the Far East (FAO World Symposium on Warm Water Pond Fish Culture. FR. VIII - IV/R-1, 1966) (Report)
(17)	K R Scott D C Gillespie	Journal Fisheries Research Board of Canada 29 (7), 1071 (1972) (Journal)
(18)	C Meske	Bamidgeh 20 (4), 105 (1968) (Journal)
(19)	K Buss, D R Graff, E R Miller	The Progressive Fish Culturist 32, 187 (1970) (Journal)
(20)	C R Mocke R A Neal, B R Salser	A Closed Raceway for the Culture of Shrimp (Contr. No. 363, National Marine Fish. Service, Gulf Coastal Fish. Cent. Galveston, Texas, 1972) (mimeographed) (Report)
(21)	C E Epifanio, G Pruder, M Hartman, R Srna	Proc. Fourth Annual Workshop World Mariculture Society, 4, 37 (1973) (Journal)
(22)	T L Meade, B R Kenworthy	Denitrification in Water Re-use Systems (University of Rhode Island, Kingston, USA, 1974) (unpubl. Manuscript)

(23)	O A Roels, K C Haines, J B Sunderlin	The Potential Yield of Artificial Upwelling Mariculture (10th European Symposium on Marine Biology, Gstend, Belgium, Sept. 17 - 23, 1975) (Lecture)
(24)	A F Richards	Marine Technology Society Journal 10 (2), 5 (1976) (Journal)
(25)	S L Weeden	Ocean Industry, Sept. 1975, 219 (1975) (Journal)
(26)	S Spotte	Fish and Invertebrate Culture (Wiley-Intersience, New York 1970) p 120 (Book)

Table 1

Feed Conversion in Four Different Animals (11)
(compiled from various sources)

ANIMAL	FEED CONVERSION RATIO BASED ON	
	live weight	shredded weight
cow	7.5:1	12.6:1
pig	3.25:1	4.2:1
chicken	2.25:1	3.0:1
rainbow trout	1.5:1	1.8:1

Table 2

Trout, feed composition (pellets)

Total protein	35-40%
Carbohydrate	30% (9-12% digestible)
Fat	8-10%
Fiber	4%
Vitamins	(Detailed specifications available for at least 13 different)

LEGENDS

Fig. 1 The production of organic material on different trophic levels in the food chains of the seas in the world. The ecological efficiency is estimated to 10 to 20 % in the first step (phytoplankton-herbivores). The ecological efficiencies in the following steps are supposed to be 10 %. Modified after Schaefer (1).

Fig. 2 A simplified model of the aquaculture process.

Fig. 3 A model of a closed recirculating system for fish production in which biological, physical and chemical environment is completely controlled by man.

Fig. 4 Hourly turnover in a recirculating aquaculture system (Based mainly on data from Scott & Gillespie) (17).

Fig. 5 The nitrification and denitrification process in nature which may be copied in a closed recirculating system.

Fig. 6 Schematic picture of a recirculating seawater system after Epifanio et al. (21).

Fig. 1

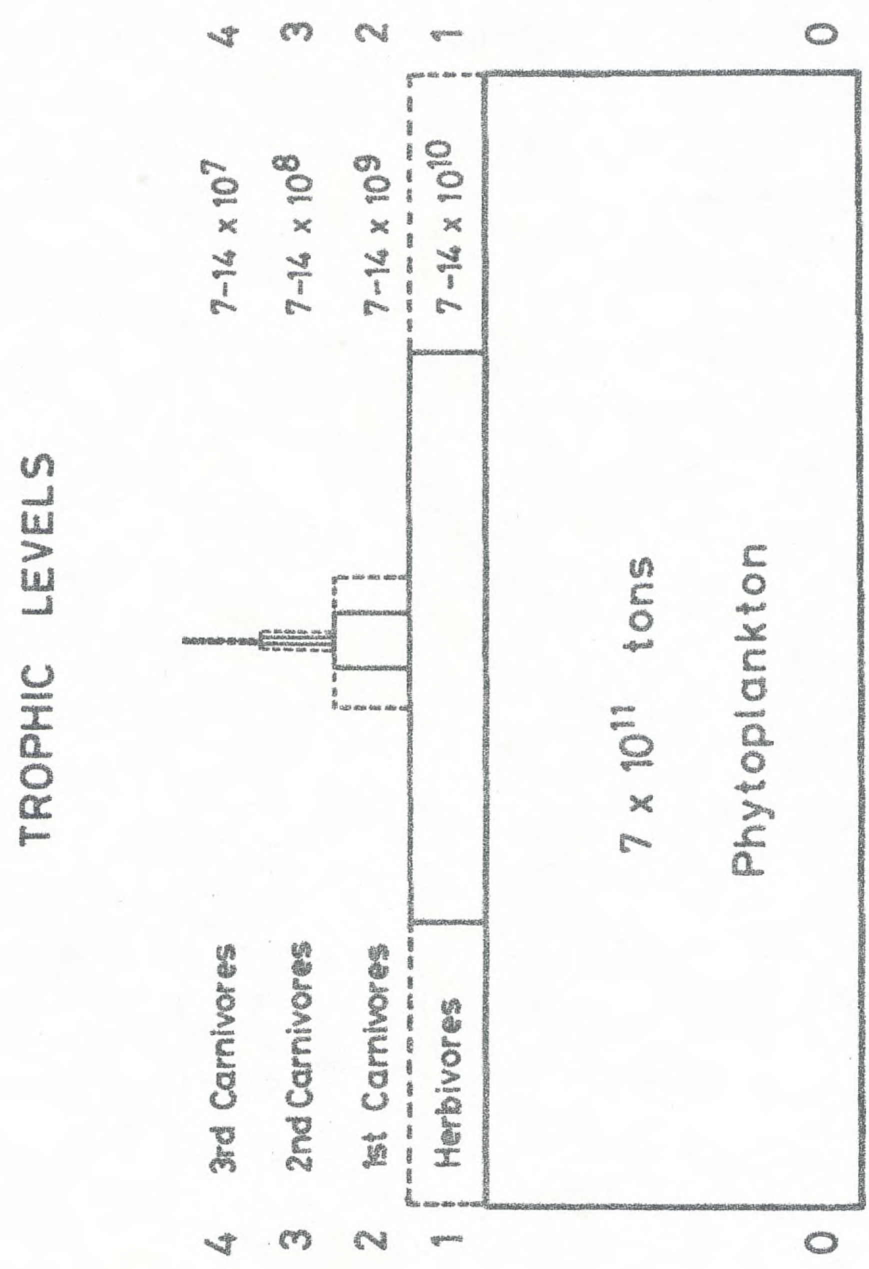

TROPHIC LEVELS
4
3
2
1
0
3rd Carnivores
2nd Carnivores
1st Carnivores
Herbivores
7-14 x 10^7
7-14 x 10^8
7-14 x 10^9
7-14 x 10^10
7 x 10^11 tons
Phytoplankton
4
3
2
1
0

Fig. 2

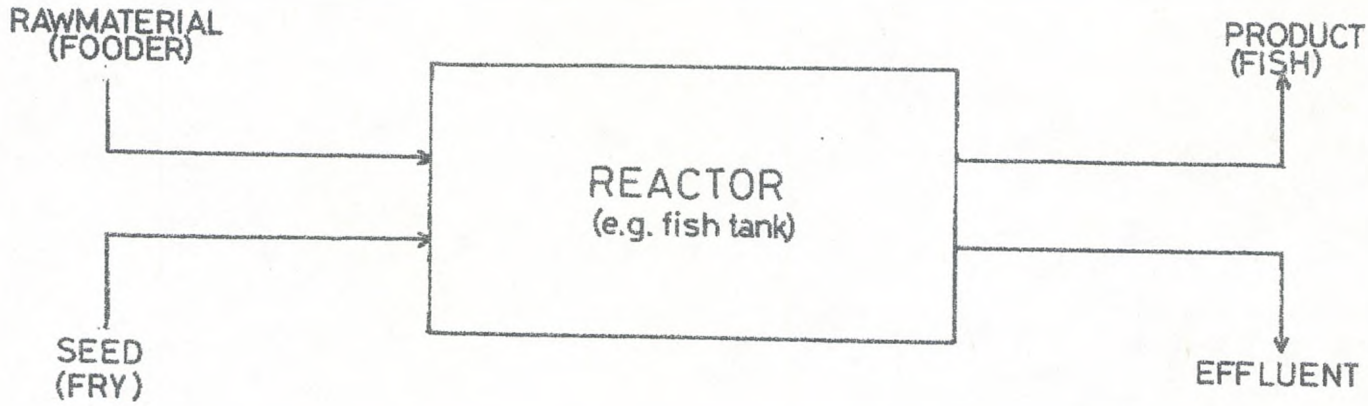

RAWMATERIAL
(FOODER)
SEED
(FRY)
REACTOR
(e.g. fish tank)
PRODUCT
(FISH)
EFFLUENT

Fig. 3

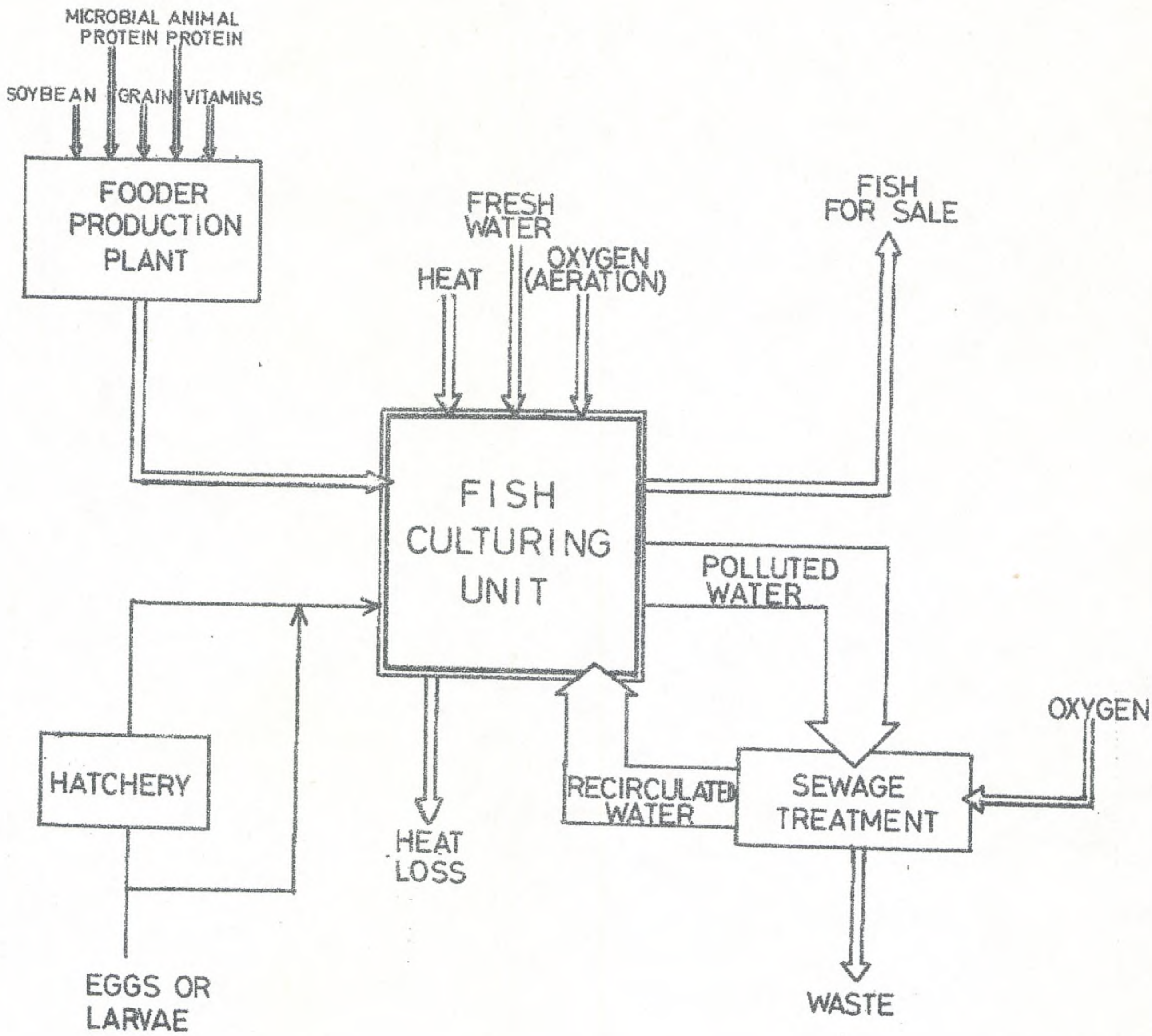
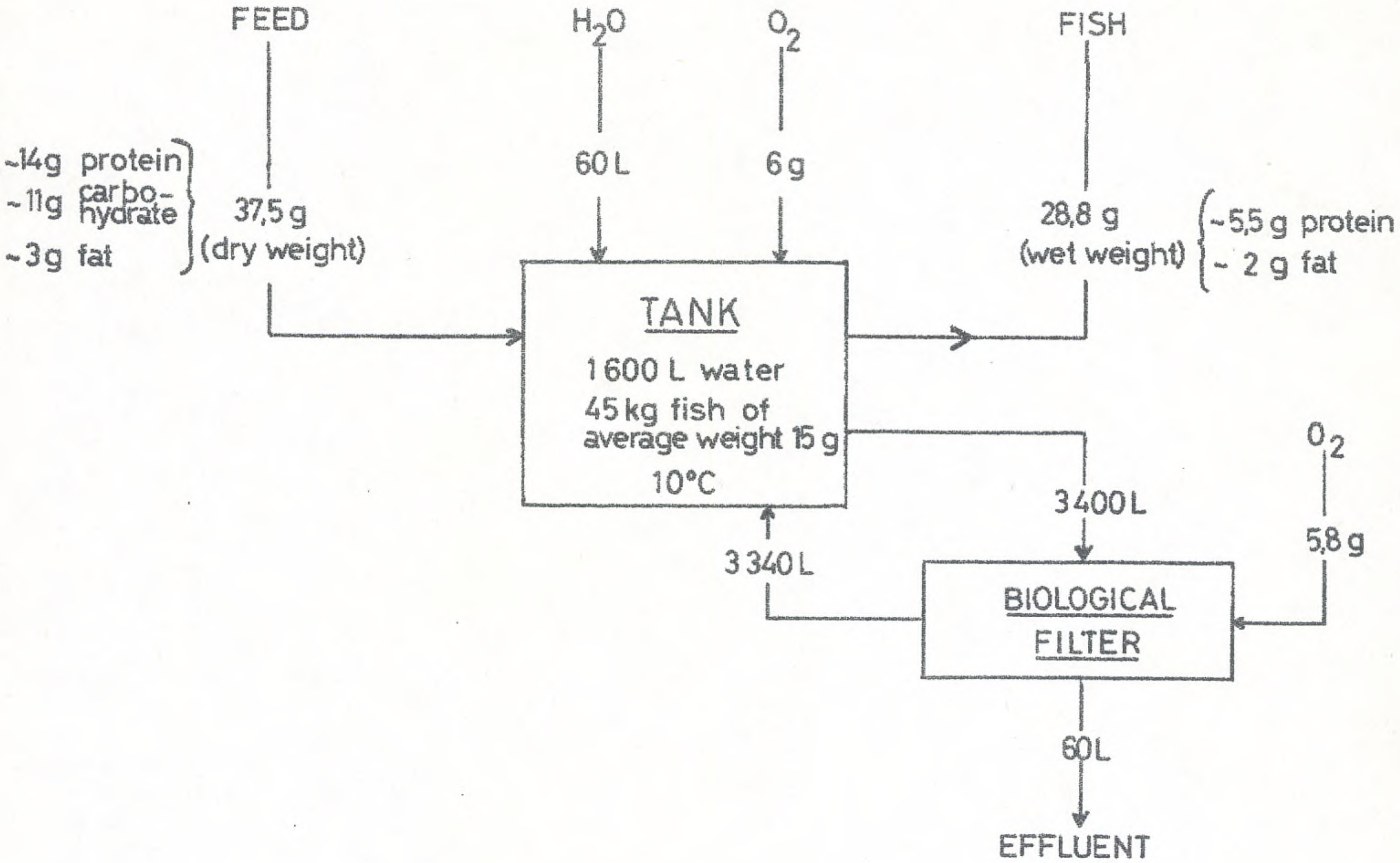
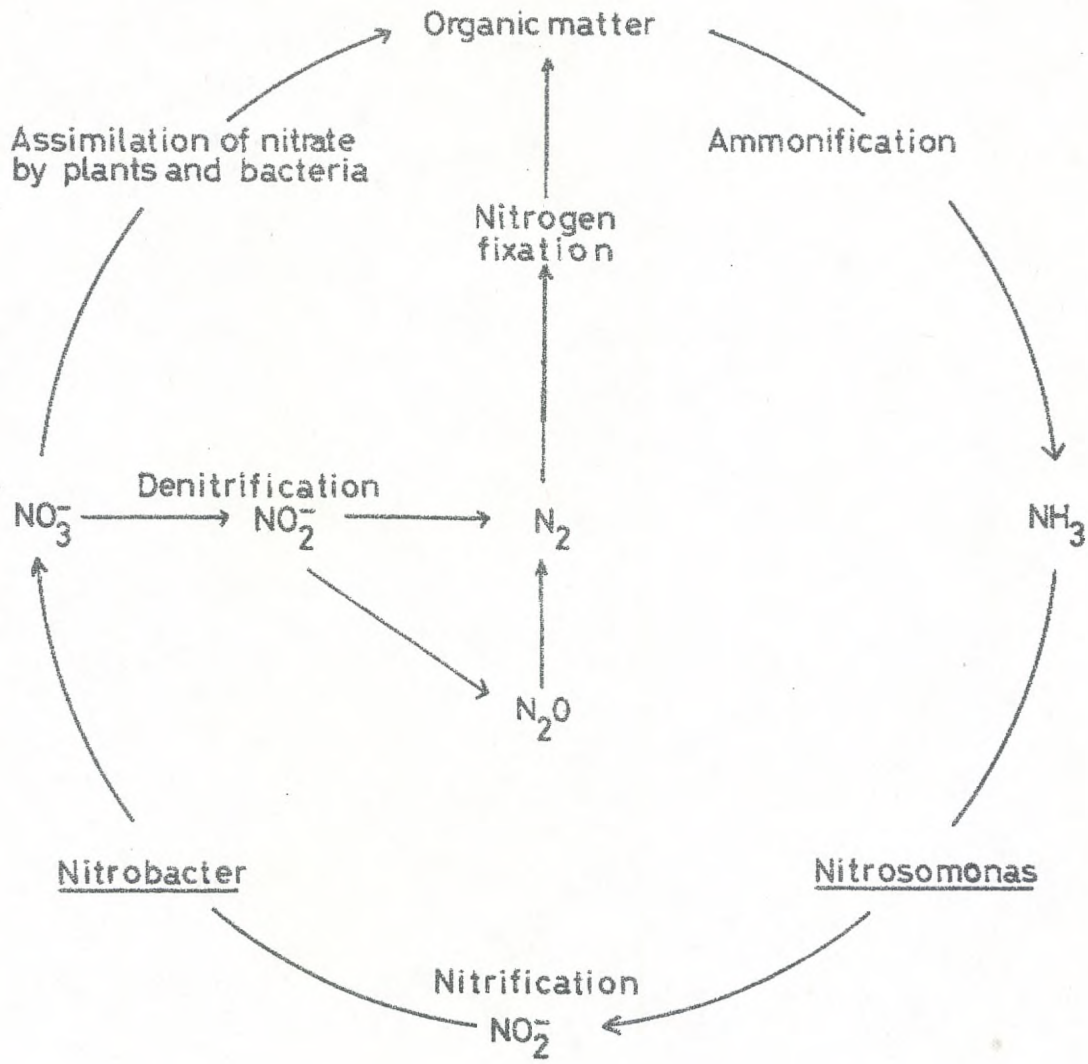

MICROBIAL PROTEIN
ANIMAL PROTEIN
SOYBEAN
GRAIN
VITAMINS
FOODER PRODUCTION PLANT
FRESH WATER
HEAT
OXYGEN (AERATION)
FISH FOR SALE
FISH CULTURING UNIT
POLLUTED WATER
HATCHERY
RECIRCULATED WATER
SEWAGE TREATMENT
OXYGEN
HEAT LOSS
EGGS OR LARVAE
WASTE

Fig.4



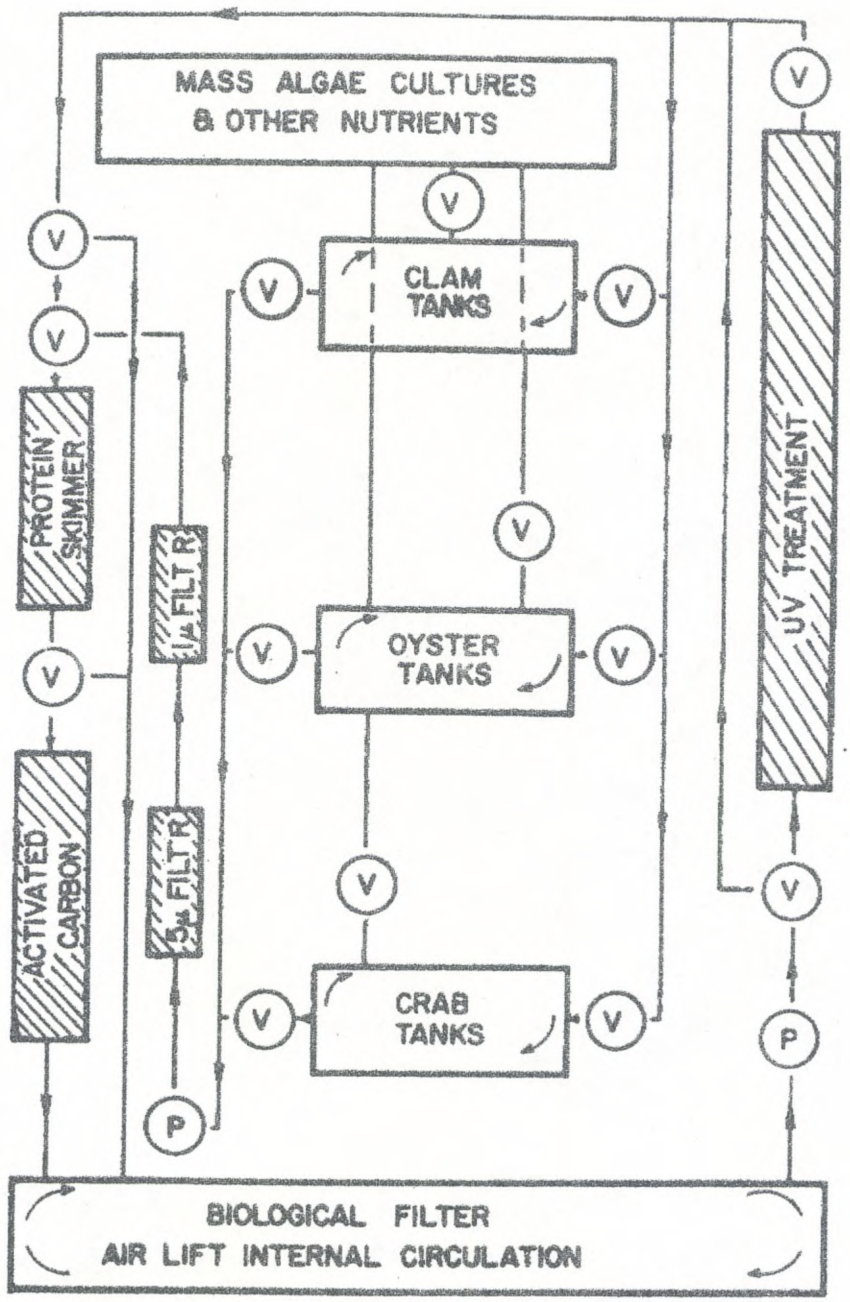
FEED
H_2O
O_2
FISH
~14g protein
~11g carbo-hydrate
~3g fat
37,5 g
(dry weight)
60 L
6 g
28,8 g
(wet weight)
~5,5 g protein
~ 2 g fat
TANK
1600 L water
45 kg fish of average weight 15 g
10°C
O_2
3400 L
5,8 g
3340 L
BIOLOGICAL FILTER
60 L
EFFLUENT

Fig. 5



Organic matter
Assimilation of nitrate by plants and bacteria
Ammonification
Nitrogen fixation
Denitrification
NO_3^-
NO_2^-
N_2
NH_3
N_2O
Nitrobacter
Nitrosomonas
Nitrification
NO_2^-

Fig.6


MASS ALGAE CULTURES
& OTHER NUTRIENTS
CLAM TANKS
OYSTER TANKS
CRAB TANKS
PROTEIN SKIMMER
ACTIVATED CARBON
1μ FILTR
5μ FILTR
UV TREATMENT
V
P
BIOLOGICAL FILTER
AIR LIFT INTERNAL CIRCULATION