ENCYCLOPEDIA OF

AQUACULTURE

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FOREWORD

There are many definitions of the word aquaculture. Those concerned with the collation of statistical data concerning food production through aquaculture tend to be very specific; they embody the concept of stock ownership as well as its management, to distinguish between the harvest from capture fisheries and from farming. One simpler definition[1] of aquaculture is the "cultivation of plants or breeding of animals in water." Many different activities fall within this definition. The farming of aquatic animals and plants for direct or indirect human consumption is the field with which I am most familiar but it is clear that this definition of aquaculture would encompass many other activities, including the rearing of aquatic animals and plants for and within public and private aquariums and research facilities, the production of bait fish, and the hatchery and nursery rearing of stock intended for fisheries enhancement or restocking programs. In aquatic food production the word aquaculture has sometimes erroneously been used to imply culture in freshwater, while the word mariculture has been used to refer to culture in seawater. In fact, the word aquaculture embraces culture in all salinities, ranging from freshwater through brackishwater and full-strength seawater to hypersaline water.

The production of an aquaculture encyclopedia at this moment in history is particularly appropriate, since the positive and negative impacts of food production through aquaculture are frequently discussed by scientists not working in this specific field, by the media, and by the public. Often, such discussions are marred by misunderstandings about the various terms utilized. The public image of aquaculture is not always good. While some ventures have undoubtedly caused environmental and/or socioeconomic harm in the past, the emphasis now is on sustainable aquaculture, which implies responsibility. The FAO Code of Conduct for Responsible Fisheries includes many Articles which are specific or related to aquaculture. Many other attempts are being made to enhance the responsibility of aquaculture producers, which range from large commercial enterprises providing products for domestic and export markets to small-scale rural farmers seeking to produce family food and income. Attempts to mollify consumer concern for the environment through the "eco-labelling" of aquaculture products produced under responsible conditions are on-going.

[1] J.B. Sykes (Editor), 1982. *The Concise Oxford Dictionary*, Oxford University Press, Oxford, Seventh Edition 1982, Reprinted 1989.

The scale and importance of food production through aquaculture can be illustrated by a few examples:

- By 1996, more than nine out of every ten oysters, Atlantic salmon, and cyprinids consumed were products of aquaculture. Four out of every five mussels and three out of four scallops were cultured; 27% of all shrimp originate from aquaculture;
- In 1997 (the most recent year for which international statistics are available), global aquaculture production totalled 28.8 million tons of finfish, crustaceans, and molluscs for direct human consumption, worth US$45.5 billion; 7.2 million tons of seaweed (worth US$4.9 billion) were also produced;
- A considerable proportion of the harvest from capture fisheries is destined for the production of fish meal and fish oil, which are primarily used by the feedstuff industry. Capture fisheries production available for human consumption has been on a plateau or increased only slowly for many years;
- Aquaculture thus remains the major means of maintaining current per capita "fish" availability. It has been estimated that global aquaculture production will need to expand to 62 million tons by 2035 to maintain 1993 global average per capita consumption levels.

The *Encyclopedia of Aquaculture* will assist the many scientists, economists, sociologists, administrators, and politicians who are either directly involved in aquaculture itself or are concerned with resource use and environmental matters. The book will also be useful for those concerned with development and planning issues. In addition, this book provides information of relevance to those in the general public who consume aquaculture products, engage in recreational fisheries or keep aquariums, as well as those who belong to organizations concerned with animal welfare and environmental conservation.

The *Encyclopedia of Aquaculture* will thus serve as an essential handy reference book for a very wide audience, and its Editor-in-Chief and Editorial Board are to be congratulated on undertaking the task of producing this unique document. I hope all its readers will find it as useful as I shall.

Michael B. New
Past President, World Aquaculture Society
Board Member, European Aquaculture Society

PREFACE

Aquaculture is the production of aquatic plants and animals under controlled or semicontrolled conditions, or as is sometimes said, aquaculture is equivalent to underwater agriculture (1). The term mariculture refers to the production of marine organisms; thus, it is less inclusive than aquaculture, which relates to both marine and freshwater culture activities.

A primary goal of aquaculturists has been to produce food for human consumption. Various species of carp top the list in terms of aquacultural production. Most of that production is in China, though India and certain European nations also produce significant amounts of carp. In North America, channel catfish farming is the largest aquaculture industry. Others of importance include trout, crawfish, and various species of shellfishes. Seaweed culture as human food is a major industry, particularly in Japan and other Asian nations.

Supplementing the human food supply is not the only goal of aquaculturists. Many of the species taken by recreational anglers are produced in hatcheries and reared to a size where they can be expected to have a good chance of survival before being released into the natural environment. Continuous stocking may be necessary in some bodies of water, while in others resident breeding populations may become established. Examples in North America are largemouth bass, northern pike, muskellunge, red drum, various species of trout, Atlantic salmon and Pacific salmon. Many of the fish produced for stocking purposes are reared in public (state or federal) hatcheries, but increasingly, private hatcheries are becoming a source of fish, particularly in conjunction with stocking farm ponds and private lakes.

The ornamental fish industry depends on animals caught in the wild and on those produced by aquaculturists. Most of the bait minnows available in the marketplace come from fish farms. Seaweeds are not only consumed by people as food, they are also a source of such chemicals as carrageenan and agar, which are utilized in everything from toothpaste and cosmetics to automobile tires. Squid and cuttlefish are not being produced to any extent as human food, but they are reared as a source of giant axons for use in biomedical research. An increasing number of potential pharmaceuticals are being identified from marine organisms. Culture of various species from a number of phyla, many of which have held little or no interest for aquaculture in the past, show promise as one means of meeting the demand for cancer-fighting and other types of drugs. A new, and potentially large aquaculture enterprise could be founded upon such species.

The roots of aquaculture can be traced back to China, perhaps as much as 4,000 years ago. Many nations have had some form of aquaculture in place for one or more centuries, but it is only since about the 1960s that scientists began to conduct research that brought the discipline to its current level of development. Since 1960, typical annual pond production rates have jumped from a few hundred kg/ha (one kg/ha is approximately equivalent to one pound/acre) to several thousand kg/ha. Much higher rates of production are possible in such water systems as raceways and marine net-pens, which are known as intensive culture systems. Ponds are generally considered to be extensive culture systems.

Improvements in production over the past few decades have been associated with the development of sound management techniques that include water quality and disease control, provision of nutritionally complete feeds, and the development of improved stocks through selective breeding, hybridization, and the application of molecular genetics technology. Many species that could not be spawned or reared a few decades ago are now being produced, because of technological breakthroughs, in large quantities by aquaculturists around the world.

Predicted peaking of the world's wild capture fishery at 90 million metric tons (about 99 million short tons) occurred in 1989 (2). Since that time global wild capture landings have been relatively stable. Given increasing demand for seafood, including freshwater aquatic species, and a stable to declining wild catch, the shortfall must come from aquaculture. As of 1992, about 18.5% of global fisheries output was attributable to aquaculture (3), and while aquaculture production is increasing, there is some question as to whether the growth of aquaculture can keep pace with demand.

In 1992, 88.5% of the world's aquaculture production came from Asia (3). Because of suitable growing conditions year round, the vast majority of aquaculture production comes from low temperate and tropical regions. Relatively inexpensive land and labor, accompanied by large expenses of undeveloped coastline with abundant supplies of water and few environmental regulations have contributed to the establishment of much of the industry in developing nations. Conditions are changing however. Many of the best areas for aquaculture have been taken, environmental stewardship is beginning to receive the attention of governments in many developing countries, and the once abundant supplies of high quality water are being fully utilized in many areas. Thus, the face of the industry is changing. Closed system technology, which includes continuous water treatment with little or no effluent, and the development of culture systems located in the open ocean are seen as technologies that will provide opportunities for virtually unlimited expansion of aquaculture. Much of the technology for closed and offshore systems has been developed, but in many instances employment of that technology has not translated into economic feasibility. As greater efficiencies in production are achieved, new species which have higher market prices are developed, and demand increases, the economic picture can be expected to improve.

The field of aquaculture encompasses many technical disciplines and trade as well as business management and economics. Knowledge of plant and/or animal breeding, animal nutrition, water and soils analysis, surveying, computer science, pathology, carpentry, plumbing, electrical wiring, welding, and bookkeeping are among the skills that are required on a working aquaculture facility.

A good aquaculturist is involved in every aspect of the activity, from reproduction of the parent organisms through rearing of the young, to final disposition, whether that involves direct sales to the public, sales to a processor, or stocking of public or private waters. The job of the aquaculturist is not completed until the consumer, whether a patron at a restaurant, a home fish hobbyist, or the angler who is using bait minnows, has received the produce of the aquaculture facility in acceptable condition.

The *Encyclopedia of Aquaculture* has been designed for use by both those who have some knowledge of the field or may even be aquaculture professionals, as well as for individuals who are interested in learning more about aquaculture, perhaps with the idea of becoming involved. Our intent is to provide information that is readily understandable by people who have at least some science background, without insulting professionals in the field. Some topics are mentioned or briefly summarized in several entries, but when a topic is only given cursory treatment the reader is referred to one or more additional contributions that provide more detailed information on the same topic.

The *Encyclopedia of Aquaculture* was written by experts from academia and government agencies and by practicing aquaculturists in the private sector. Entries are followed by bibliographies designed to document the information present, as well as provide readers with an opportunity to further explore each topic in more depth.

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CONVERSION FACTORS, ABBREVIATIONS, AND UNIT SYMBOLS

SI UNITS (Adopted 1960)

The International System of Units (abbreviated SI) is being implemented throughout the world. This measurement system is a modernized version of the MKSA (meter, kilogram, second, ampere) system, and its details are published and controlled by an international treaty organization (The International Bureau of Weights and Measures).

SI units are divided into three classes:

BASE UNITS		SUPPLEMENTARY UNITS	
length	meter† (m)	plane angle	radian (rad)
mass	solid angle	steradian (sr)	kilogram (kg)
time	second (s)		
electric current	ampere (A)		
thermodynamic temperature‡	kelvin (K)		
amount of substance	mole (mol)		
luminous intensity	candela (cd)		

Quantity	Unit	Symbol	Acceptable equivalent
volume	cubic meter	m^3	
	cubic diameter	dm^3	L (liter) (5)
	cubic centimeter	cm^3	mL
wave number	1 per meter	m^{-1}	
	1 per centimeter	cm^{-1}	

In addition, there are 16 prefixes used to indicate order of magnitude, as follows:

Multiplication factor	Prefix	Symbol
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h[a]
10	deka	da[a]
10^{-1}	deci	d[a]
10^{-2}	centi	c[a]
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

[a] Although hecto, deka, deci, and centi are SI prefixes, their use should be avoided except for SI unit-multiples for area and volume and nontechnical use of centimeter, as for body and clothing measurement.

For a complete description of SI and its use the reader is referred to ASTM E380.

A representative list of conversion factors from non-SI to SI units is presented herewith. Factors are given to four significant figures. Exact relationships are followed by a dagger. A more complete list is given in the latest editions of ASTM E380 and ANSI Z210.1.

† The spellings "metre" and "litre" are preferred by ASTM; however, "-er" is used in the *Encyclopedia*.

‡ Wide use is made of Celsius temperature (t) defined by

$$t = T - T_0$$

where T is the thermodynamic temperature, expressed in kelvin, and $T_0 = 273.15$ K by definition. A temperature interval may be expressed in degrees Celsius as well as in kelvin.

CONVERSION FACTORS TO SI UNITS

To convert from	To	Multiply by
acre	square meter (m^2)	4.047×10^{3}
angstrom	meter (m)	$1.0 \times 10^{-10\dagger}$
are	square meter (m^2)	$1.0 \times 10^{2\dagger}$
astronomical unit	meter (m)	1.496×10^{11}
atmosphere, standard	pascal (Pa)	1.013×10^{5}
bar	pascal (Pa)	$1.0 \times 10^{5\dagger}$
barn	square meter (m^2)	$1.0 \times 10^{-28\dagger}$
barrel (42 U.S. liquid gallons)	cubic meter (m^3)	0.1590
Bohr magneton (μ_B)	J/T	9.274×10^{-24}
Btu (International Table)	joule (J)	1.055×10^{3}
Btu (mean)	joule (J)	1.056×10^{3}
Btu (thermochemical)	joule (J)	1.054×10^{3}
bushel	cubic meter (m^3)	3.524×10^{-2}
calorie (International Table)	joule (J)	4.187
calorie (mean)	joule (J)	4.190
calorie (thermochemical)	joule (J)	$4.184^{\dagger}$
centipoise	pascal second (Pa · s)	$1.0 \times 10^{-3\dagger}$
centistokes	square millimeter per second (mm^2/s)	$1.0^{\dagger}$
cfm (cubic foot per minute)	cubic meter per second (m^3/s)	4.72×10^{-4}
cubic inch	cubic meter (m^3)	1.639×10^{-5}
cubic foot	cubic meter (m^3)	2.832×10^{-2}
cubic yard	cubic meter (m^3)	0.7646
curie	becquerel (Bq)	$3.70 \times 10^{10\dagger}$
debye	coulomb meter (C m)	3.336×10^{-30}
degree (angle)	radian (rad)	1.745×10^{-2}
denier (international)	kilogram per meter (kg/m)	1.111×10^{-7}
	$tex^{\ddagger}$	0.1111
dram (apothecaries')	kilogram (kg)	3.888×10^{-3}
dram (avoirdupois)	kilogram (kg)	1.772×10^{-3}
dram (U.S. fluid)	cubic meter (m^3)	3.697×10^{-6}
dyne	newton (N)	$1.0 \times 10^{-5\dagger}$
dyne/cm	newton per meter (N/m)	$1.0 \times 10^{-3\dagger}$
electronvolt	joule (J)	1.602×10^{-19}
erg	joule (J)	$1.0 \times 10^{-7\dagger}$
fathom	meter (m)	1.829
fluid ounce (U.S.)	cubic meter (m^3)	2.957×10^{-5}
foot	meter (m)	$0.3048^{\dagger}$
footcandle	lux (lx)	10.76
furlong	meter (m)	2.012×10^{-2}
gal	meter per second squared (m/s^2)	$1.0 \times 10^{-2\dagger}$
gallon (U.S. dry)	cubic meter (m^3)	4.405×10^{-3}
gallon (U.S. liquid)	cubic meter (m^3)	3.785×10^{-3}
gallon per minute (gpm)	cubic meter per second (m^3/s)	6.309×10^{-5}
	cubic meter per hour (m^3/h)	0.2271
gauss	tesla (T)	1.0×10^{-4}
gilbert	ampere (A)	0.7958
gill (U.S.)	cubic meter (m^3)	1.183×10^{-4}
grade	radian	1.571×10^{-2}
grain	kilogram (kg)	6.480×10^{-5}
gram force per denier	newton per tex (N/tex)	8.826×10^{-2}
hectare	square meter (m^2)	$1.0 \times 10^{4\dagger}$
horsepower (550 ft · lbf/s)	watt (W)	7.457×10^{2}
horsepower (boiler)	watt (W)	9.810×10^{3}
horsepower (electric)	watt (W)	$7.46 \times 10^{2\dagger}$
hundredweight (long)	kilogram (kg)	50.80
hundredweight (short)	kilogram (kg)	45.36
inch	meter (m)	$2.54 \times 10^{-2\dagger}$
inch of mercury (32 °F)	pascal (Pa)	3.386×10^{3}
inch of water (39.2 °F)	pascal (Pa)	2.491×10^{2}
kilogram-force	newton (N)	9.807
kilowatt hour	megajoule (MJ)	$3.6^{\dagger}$

CONVERSION FACTORS TO SI UNITS

To convert from	To	Multiply by
kip	newton (N)	4.448×10^3
knot (international)	meter per second (m/S)	0.5144
lambert	candela per square meter (cd/m^3)	3.183×10^3
league (British nautical)	meter (m)	5.559×10^3
league (statute)	meter (m)	4.828×10^3
light year	meter (m)	9.461×10^{15}
liter (for fluids only)	cubic meter (m^3)	$1.0 \times 10^{-3\dagger}$
maxwell	weber (Wb)	$1.0 \times 10^{-8\dagger}$
micron	meter (m)	$1.0 \times 10^{-6\dagger}$
mil	meter (m)	$2.54 \times 10^{-5\dagger}$
mile (statute)	meter (m)	1.609×10^3
mile (U.S. nautical)	meter (m)	$1.852 \times 10^{3\dagger}$
mile per hour	meter per second (m/s)	0.4470
millibar	pascal (Pa)	1.0×10^2
millimeter of mercury (0 °C)	pascal (Pa)	$1.333 \times 10^{2\dagger}$
minute (angular)	radian	2.909×10^{-4}
myriagram	kilogram (kg)	10
myriameter	kilometer (km)	10
oersted	ampere per meter (A/m)	79.58
ounce (avoirdupois)	kilogram (kg)	2.835×10^{-2}
ounce (troy)	kilogram (kg)	3.110×10^{-2}
ounce (U.S. fluid)	cubic meter (m^3)	2.957×10^{-5}
ounce-force	newton (N)	0.2780
peck (U.S.)	cubic meter (m^3)	8.810×10^{-3}
pennyweight	kilogram (kg)	1.555×10^{-3}
pint (U.S. dry)	cubic meter (m^3)	5.506×10^{-4}
pint (U.S. liquid)	cubic meter (m^3)	4.732×10^{-4}
poise (absolute viscosity)	pascal second (Pa · s)	$0.10^\dagger$
pound (avoirdupois)	kilogram (kg)	0.4536
pound (troy)	kilogram (kg)	0.3732
poundal	newton (N)	0.1383
pound-force	newton (N)	4.448
pound force per square inch (psi)	pascal (Pa)	6.895×10^3
quart (U.S. dry)	cubic meter (m^3)	1.101×10^{-3}
quart (U.S. liquid)	cubic meter (m^3)	9.464×10^{-4}
quintal	kilogram (kg)	$1.0 \times 10^{2\dagger}$
rad	gray (Gy)	$1.0 \times 10^{-2\dagger}$
rod	meter (m)	5.029
roentgen	coulomb per kilogram (C/kg)	2.58×10^{-4}
second (angle)	radian (rad)	$4.848 \times 10^{-6\dagger}$
section	square meter (m^2)	2.590×10^6
slug	kilogram (kg)	14.59
spherical candle power	lumen (lm)	12.57
square inch	square meter (m^2)	6.452×10^{-4}
square foot	square meter (m^2)	9.290×10^{-2}
square mile	square meter (m^2)	2.590×10^6
square yard	square meter (m^2)	0.8361
stere	cubic meter (m^3)	$1.0^\dagger$
stokes (kinematic viscosity)	square meter per second (m^2/s)	$1.0 \times 10^{-4\dagger}$
tex	kilogram per meter (kg/m)	$1.0 \times 10^{-6\dagger}$
ton (long, 2240 pounds)	kilogram (kg)	1.016×10^3
ton (metric) (tonne)	kilogram (kg)	$1.0 \times 10^{3\dagger}$
ton (short, 2000 pounds)	kilogram (kg)	9.072×10^2
torr	pascal (Pa)	1.333×10^2
unit pole	weber (Wb)	1.257×10^{-7}
yard	meter (m)	$0.9144^\dagger$

† Exact.
‡ This non-SI unit is recognized by the CIPM as having to be retained because of practical importance or use in specialized fields.