

# Recent Major Advances of Biotechnology and Sustainable Aquaculture in China

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## Abstract:

**Background:** Global aquaculture production has increased continuously over the last five decades, and particularly in China. Its aquaculture has become the fastest growing and most efficient agri-sector, with production accounting for more than 70% of the world's aquaculture output. In the new century, with serious challenges regarding population, resources and the environment, China has been working to develop high-quality, effective, healthy, and sustainable blue agriculture through the application of modern biotechnology. Sound knowledge related to the biology and ecology of aquatic organisms has laid a solid foundation and provided the innovation and technology for rapid development of the aquaculture industry. Marine biotechnology, which is enabling solutions for ocean productivity and sustainability, has been promoted since the last decades of the 20th Century in China.

**Objective:** In this article, priority areas of research, mainly genetic breeding, omics studies, novel production systems, biosecurity, bioprocesses and biorefinery, as well as the major progress of marine biotechnology R&D in China are reviewed.

**Conclusion:** Current innovative achievements in China are not enough and the level and frequency of academic advancements must be improved. International cooperation and assistance remain crucial for the success of marine biotechnology.



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**Keywords:** Aquaculture, Marine biotechnology, Genetic breeding, Omics study, Novel production systems, Biosecurity, Bioprocesses and biorefinery, China.

## 1. INTRODUCTION

China has more than 18,000 km of coastline, over 6,500 islands, and the jurisdiction of about 3 million km<sup>2</sup> of sea area, in accordance with the “exclusive economic zone” and “continental shelf” systems defined in the “United Nations Convention on the Law of the Sea”. These vast coastal areas and territorial seas have world-renowned fishing grounds, rich in economically valuable marine resources. Food safety is one of the most important issues to the Chinese people, whose current population is more than 1.3 billion and predicted to reach 1.6 billion by 2030. The terrestrial resources of China are limited. In particular the per capita land-based natural resources suitable for agriculture (0.1 ha/per capita) are much lower than the world's average (0.3 ha/per capita) [1]. To meet the ever-growing food requirement for the continuously increasing population, food security is one of the most important issues facing the Chinese people [2].

Global aquaculture production has increased continuously over the last five decades and, particularly in China, aquaculture has become the fastest growing and most

efficient agri-sector, with production accounting for more than 70% of the world's aquaculture output [3]. Traditionally, China has been a global leader in fisheries production. Since the 1950's fresh water aquaculture in China has been rapidly developed while mariculture only began to grow quickly after the 1980's. The cultured seafood production in China reached 1,100,000 tons in 1987. Six main kinds of cultured seafood including kelp, shrimp, mussel, razor clam and clam ranked first globally in the same year [4]. China's aquaculture production in 2006 reached to 14,456,400 t, the first time it surpassed marine fish capture production (14,420,400 t), with a more reasonable species proportion [5].

## 2. AQUACULTURE AND MARINE BIOTECHNOLOGY

### 2.1. Status of Aquaculture in China

In 2013, China's aquatic products output was the largest in scale in the world. China's aquaculture production reached 45.42 million t, accounting for 73.59% of total fisheries output (61.72million t) [6]; China's fishing trade accounts for 6.8% of global exports, with the exports ranking first or second in the world, and imports being tenth [3]. There are 20.65 million Chinese people whose lives depend on fisheries and aquaculture, and 14.43 million of fishing labor force (fishermen), accounting for 2% of the agricultural

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population in China. Aquatic production provided the Chinese with almost 1/3 of their animal protein, which greatly reduced protein production pressures, prevented a future food crisis, and played an important role in stabilizing prices. It is expected that the total output of aquatic products in 2030 will reach 76 million t. At present, China has become the only country where the output of the mariculture industry is larger than that of the fishing industry. Marine fisheries GDP was 1024.9 billion Yuan in 2014, equivalent to 1.61% of the gross domestic product over the same period [7].

Having developed for 20 years, China's marine fishery progressed from solely capture and aquaculture production, to gradually extending to including aquaculture, aquatic products in-depth processing, pharmaceuticals, and other high-value-added industries. The extension of the marine industrial chain clearly indicated the expansion of production and increase of benefits, promoting greatly the growth of marine economy [8]. China is now actively promoting the integration and innovation of fisheries sciences, leading fisheries science to a new stage of development [9]. However, a wide gap still exists between China and the world's advanced countries and regions at the level of fishery science and technology. The following three figures provide some statistics for national marine fisheries (including mariculture) [6].

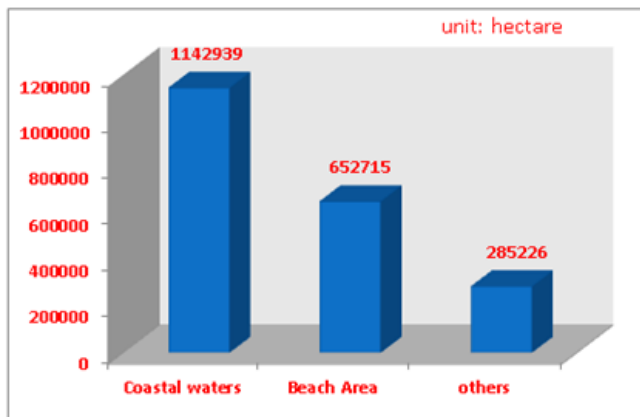


Fig. (1). Mariculture production of China in 2010.

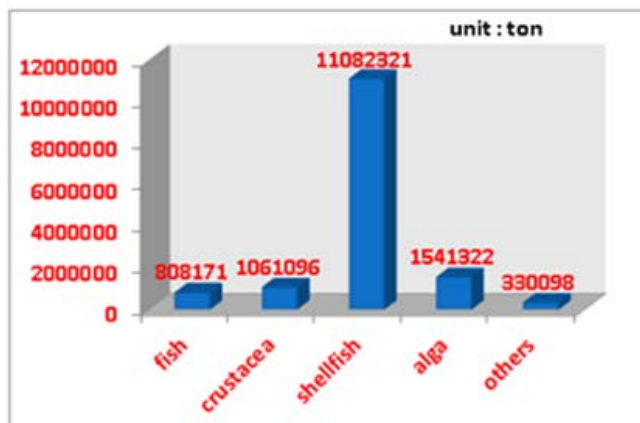


Fig. (2). Area and location of Chinese mariculture in 2010.

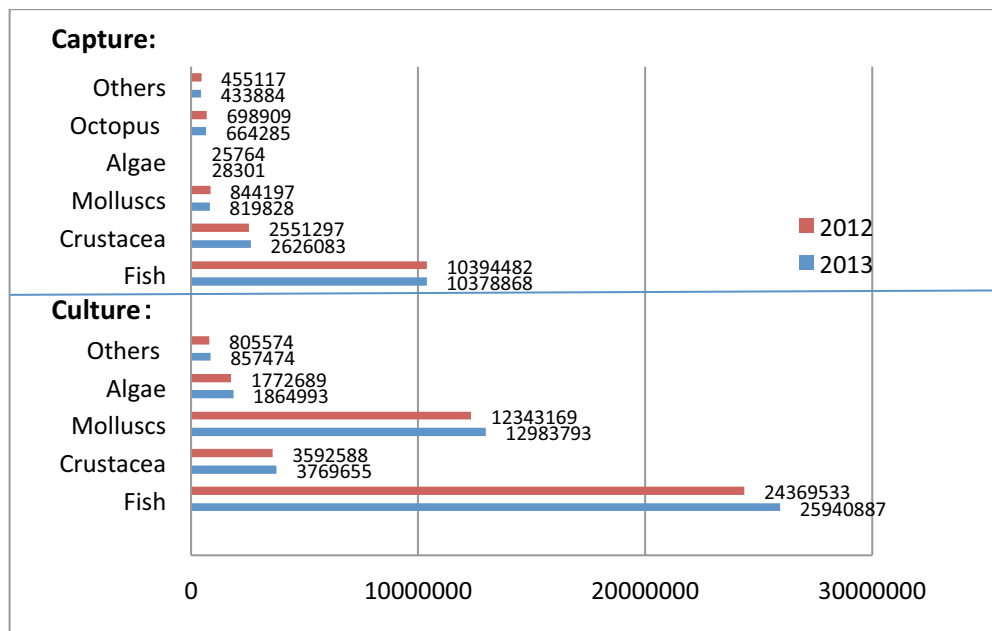
## 2.2. Opportunities and Challenges of Aquaculture Development in China

Aquaculture is the fastest growing food-producing sector in the world and is expected to continue to grow and help compensate for the anticipated global supply shortage of capture fisheries [10]. To feed the estimated world population of 9 billion people predicted in 2050, food output must increase by 70%. Obviously, the only way to meet the increasing demand for fish is through aquaculture. Daniel Cressey [11] explored the challenges for fish farmers and what it means for dinner plates in 2030. However, sustainable development of the aquaculture industry faces difficult issues, including lack of captive breeding and domesticated strains, disease control, remediation of polluted water environments, the changing globe climate, and so on. Therefore, development of knowledge-based technologies is urgently needed.

China's rapid socio-economic development has also exerted increasing pressure on the coastal ecosystems with a series of unusual ecological phenomena, such as harmful algal blooms, jellyfish outbreaks, *Enteromorpha* blooms [7], declines in fishery resources and so on, which indicates that the Chinese coastal ecosystems are in a period of significant change. Because of the scale of the mariculture industry in China, the types of mariculture practiced and the cultured organisms produced, the impacts of mariculture on the marine environment and the Chinese ecosystems' responses are unique in the international arena. For these reasons, mariculture in China has been of concern to the international scientific and industrial communities. It is viewed as highly likely to significantly affect the services and the values of the coastal ecosystem [2].

Another environmental challenge is the interference by human activities. Currently, the coastal zone is the region most affected by human activities, with pollution, eutrophication, changes in sediment transport, urbanization, land reclamation, over-fishing, tourism, and mining; these activities constantly threaten the health of coastal ecosystems. China is located on the western side of the Pacific Ocean, with coastal areas on its eastern and southern sides and more than 18,000 km of shoreline. The total area of coastal zone is about 285,000 km<sup>2</sup>, including over 6000 islands that each area is larger than 500 m<sup>2</sup>. Chinese maritime regions are in the middle and low latitudes with distinctive natural environments and resources. However, while rapid economic growth in coastal zones created enormous economic benefits, it also resulted in environment damage to natural areas and adversely influenced the sustainable development of coastal mangroves, corals/coral reefs, spawning grounds in estuaries and gulfs, and different sub-ecosystems [2].

At present and for a fairly long time to come, global-warming leading to environmental change will not only be a hot scientific issue, but also a major political issue of international concern. Thus far, the environmental quality of China's coastal waters is good overall; however, the inshore



**Fig. (3).** Yields of various Chinese captured and cultured aquatic products in 2012 and 2013. (unit: Tonnes).

zones have been polluted to different degrees in some estuaries, bays, ports, and adjacent sea areas of the large and medium-sized cities and major industrial areas. In 2014 [7], the overall level of pollution in Chinese coastal waters was still relatively high. Roughly 150,780 km<sup>2</sup> of the nation's seawater does not meet the clean water quality standards. Pollutants from most of the sewage-discharging sites exceeded the standard for waste water discharge. In addition, the rapid but sometimes unregulated development of the mariculture industry causes negative impacts on coastal ecosystems, leading to problems such as pollution, eutrophication, change of ecosystem structure and function, disease, red tide, etc. Within the marine ecosystems monitored by SOA, including estuaries, coastal bays, beaches, reefs, mangroves and sea grass beds, sub-healthy and non-healthy sub-ecosystems accounted for 71% and 10% respectively [7]. Solving these problems is an important task for scientists in China now and in the future.

### 2.3. Marine Biotechnology Enabling Solutions for Ocean Productivity and Sustainability

Sound knowledge of the biology and ecology of aquatic organisms has laid a solid foundation and provided the innovation and technology for rapid development of the aquaculture industry and other novel products. The application of biotechnology to freshwater and marine resources may help to address the global challenges of food, energy security and health as well as contribute to green growth and sustainable industries [12].

In the new century, with serious challenges regarding population, resources and the environment, China has been working to develop high-quality, effective, healthy, and sustainable blue agriculture through the application of modern biotechnology [13].

Marine biotechnology has been developed since the last decades of the 20th Century in China. At the end of the 1980's, some foresighted Chinese scientists, led by Prof. C.K. Zeng, began to suggest that the government pay close attention to marine biotechnology [4]. Through several years of effort by the scientists and administrators, the subject of Marine Biotechnology gained approval for listing in the National High Tech Project (863 Project) in 1996. The subject's mission focuses on the strategic, foresighted and most advanced marine biotechnology that benefits China's long and medium-term development needs, and thereby promotes the development of innovative technologies and fosters growth of the high-tech marine industry. The objectives are thus to promote the development of key technologies for rational utilization of marine bio-resources, as well as environmental protection technologies that relate to social sustainable development [14].

During the first five years (from 1996 to 2000) of the 863 Project's Marine Biotechnology listing about 97.5 million RMB were funded by the Chinese government and additional funds of 87.5 million RMB were matched by local governments and enterprises. 81 institutions, the majority of which were located in Shandong, Beijing and Guangdong, were involved in the subject. Actually, the marine biotechnology project impelled a lot of national R&D institutions to initiate research in this field. Moreover, biotech scientists who had been conducting terrestrial research were also attracted to the marine field. Thus, the distance between marine biotechnology and land-based biotechnology was greatly reduced. Afterward, during the successive three "Five-Plans" period (from 2001 to 2015), the Chinese government invested more and more R&D funds in marine technology. Through decades of effort using marine biotechnology, China has already attained many remarkable achievements.

### 3. PRIORITY AREAS AND MAJOR R&D PROGRESS OF MARINE BIOTECHNOLOGY IN CHINA

#### 3.1. Genetic Breeding

The precondition of aquaculture production is to continuously obtain different suitable seedlings, larvae or fingerlings. In ancient times, farmers collected wild larval or juvenile aquatic animals to culture. At present, there are still some farms that have to use wild seeds, for example eels and some high-price rock fish etc. However, more and more species have been domesticated and bred under artificially controlled conditions.

Manipulation of reproduction enables growers to intervene and control the reproductive procedure of animals by physical, chemical and biochemical means, in order to fit the needs of aquaculture [15, 16]. Genetic manipulation allows modification and recombination of the genetic structure at the cytological and molecular levels. Reproductive manipulation includes the regulation of maturation, control of gamete spawning, implementation of artificial fertilization and sex ratio control, while genetic manipulation includes hybridization, polyploid induction, gynogenesis and androgenesis, cell fusion, nuclear transplant and foreign gene transfer.

One of the most important factors for sustainable aquaculture is the development of high performance culture strains. Over the last 20 years, significant progress has been made in fish biology and biotechnology, especially in the field of genetic breeding [17]. The development and application of marine biotechnology may improve the genetic performances of aquatic animals with higher output, better quality and more resistance against disease.

Genetic breeding is a process that recodifies some heritable traits targeted to obtain neotype and/or improved varieties. For the purpose of genetic improvement, researchers can select for desirable genetic traits, integrate a suite of traits from different donors, or alter the innate genetic traits of a species [18]. These improved varieties have, in many cases, facilitated the development of the aquaculture industry by lowering costs and increasing both quality and yield [19].

There are many approaches to achieve genetic improvements for aquatic organisms, such as traditional selective breeding and molecular marker-assisted selective breeding [20], hybridization (close- and distant-), cytoengineering (including polyploidization, gynogenesis and androgenesis), genome-wide selective breeding, nuclear transplantation, transplantation of germline stem cells and germ cells [21], modification breeding technologies (transgenic technology) and so on.

Chromosome set manipulation is a useful genetic tool that can artificially change the composition of the normal chromosomal structure in the diploid animals, in order to obtain production gains such as higher growth rate, better resistance against diseases. Sex-control can be achieved *via* chromosome manipulation. Both physical (including temperature, pressure, etc) and chemical methods have been used to produce triploid and tetraploid stocks. The timing, magnitude and rate of application of temperature shock are the critical variables in successful triploid or tetraploid

shrimp induction [22]. Triploids typically exhibit rapid growth, strong disease resistance and high yield, so they are of high economic value. Additionally, the majority of allotriploid fish are infertile, which reduces issues associated with diversion of energy to gametic growth, mixing of genetic lines, and interbreeding with wild stocks [18, 23].

Breeding of important culture animals has made important progress in China. From 1996 to 2011, 109 novel mariculture varieties have been approved by the National Certification Committee for Aquaculture Protospecies and Varieties (NCCAPV) [24]. These varieties were obtained by artificial selection, hybridization, introduction from foreign countries and so on, including fishes, molluscs (scallop, abalone, pearl oyster), crustaceans (shrimp and crabs), echinoderms (sea cucumbers, urchins) and sea weeds (kelp, nori and *Gracilaria*). Fig. (4) shows the rates of different approaches by which the 109 varieties were obtained [24].

Since 2001, the National High-Tech Project of China have founded a key Program "Seed Engineering of Mariculture" through which many novel varieties have been selected. For example, in 2012, 2013 and 2014, nine, seven and fifteen novel aquatic varieties were approved in each year respectively. Table 2 lists major novel varieties approved by the NCCAPV with their primary merits. All of these novel varieties have been playing important roles to increase aquaculture production in China.

For example, Wang *et al.* isolated two pairs of Y and X chromosome-specific markers from yellow catfish (*Pelteobagrus fulvidraco*) by AFLP and SCAR screening, which then were utilized for screening YY super-male individuals. Subsequently, they developed a Y- and X-specific allele marker-assisted sex control process for cultivating all-male populations [17]. This artificially selected stock with stable genetic traits has been approved as a novel variety, referred to as "yellow catfish all-male No. 1" by NCCAPV, because yellow catfish males grow faster than females, and generate individual differences in total size of about 2-3 fold. Because transgenic methods can be easily applied to incorporate the function of a specific gene, this approach is potentially the most direct and rapid method of obtaining a stable and genetically inherited trait in fish. The first transgenic fish was generated by over-expression of human growth hormone (hGH) gene driven by a mouse metallothionein-1 (MT) gene promoter in Chinese goldfish [25]. Since that time, a lot of progress has been made in China. In addition to transgenesis, recently developed genome editing techniques provide an enormously valuable tool for fish breeding that allows researchers to modify multiple genes at precise sites with high efficiency and in a comparably short time [26].

#### 3.2. Omics Study

Fish biology and biotechnology have provided the innovation and technology for rapid development of the aquaculture industry. With regard to marine biology, China has conducted a great deal of research in basic theory, resources investigation, important species cultivation, domestication of varieties, artificial breeding, and culture technology. China has also gradually built the world's largest algae, shrimp, shellfish and fish aquaculture industries.

**Table 1. Major New Varieties in Chinese Aquaculture Approved by NCCAPV Since 2004.**

Species	Novel Variety	Appr. Year	Innovatots	Produced Methods	Major Merits
<i>Laminaria japonica</i> (Sea Kelp)	Rongfu Haidai	2004	OUC <i>et al.</i>	Hybridization & selection	GR(W): +25-27% Tolerate higher temperature
<i>Laminaria japonica</i> (Sea Kelp)	Dongfang 2	2004	Shandong DFMST Ltd.	Hybridization	GR(W): +28-59%
<i>Laminaria japonica</i> (Sea Kelp)	Huangguan 1	2011	YSFRI <i>et al.</i>	Hybridization & mass selection	GR(W): + >27%
<i>Laminaria japonica</i> (Sea Kelp)	Sanhai Haidai	2012	OUC <i>et al.</i>	Hybridization	GR(W): +11.1%, with longitudinal furrow on leaf
<i>Laminaria japonica</i> (Sea Kelp)	Dongfang 6	2013	Shandong DFMST Ltd	Hybridization of two clones of gametophyte	GR(W): + 36-46%
<i>Gracilaria lemaneiformis</i>	Longxucui 2007	2013	OUC & Shantuo University	Metagenic & mass selection	GR(W): +17.7% Higher agar-agar
<i>Undaria pinnatifida</i>	Haibao 1	2013	IOCAS & Dalian Haibao Fishery Ltd	Crossing haploids & selection	GR(W): +48.1%,
<i>Porphyra haitanensis</i> (Nori)	SHENFU 1	2009	SOU	Metagenesis & cell cloning breeding	GR(W): +25%, better quality
<i>Porphyra haitanensis</i> (Nori)	SHENFU 2	2013	SOU, <i>et al.</i>	Metagenesis & cell cloning breeding	GR(W): +28-35% better quality, higherfertility +43%
<i>Porphyra haitanensis</i> (Nori)	Minfeng 1	2012	Jimei University	Metagenesis & clone breeding	GR(W): + >25%, Survivable at 28°C for ten days
<i>Porphyra yezoensis</i>	Sutong 1	2013	JSMFRI	Metagenesis & mass selection	GR(W): +37.8%, Higher Protein & UFA
<i>Meretrix meretrix</i> (Clam)	Kezhe 1	2013	IOCAS & ZJMC	Mass & family selection	GR(W): +31.6%, with black strip
<i>Ostrea gigas</i> (Oyster)	Haida 1	2013	OUC	Mass selection	GR(W): + 18-24%
<i>Patinopecten yessoensis</i> (Scallop)	Haida Jingbei	2009	OUC, & Zhangzi Fishery Ltd.	Mass & family selection	GR(W):+20-30%, SR:+25% Higher carotene
<i>Argopecten irradians</i> (Bay scallop)	Zhongke 2	2011	IOCAS	Family selection with Inbreeding & hybridization	GR(W): +26.57% Purple shell
<i>Pinctada martensi</i> (Pearl scallop)	Haiyou 1	2011	Hainan University	Hybridization & mass selection	GR(W) : +24.9% Pearl beads rate: +15.90%,
<i>Chlamys farreri</i> (Scallop)	Penglai Red 2	2013	OUC <i>et al.</i>	Family selection	GR(W): +53.46%, SR: +27.11%
Hybrids of Abalone <i>Haliotis discus hanai</i>	Dalian 1	2004	IOCAS	Hybridization	GR(W): + >20%, SR: + 180-230%
<i>Haliotis diversicolor</i> (Abalone)	Dongyou 1	2009	Xiamen University	Hybridization	GR(W):+35%, SR: +35%
<i>Fenneropenaeus chinensis</i> (Shrimp)	Huanghai 1	2004	YSFRI	Mass selection	GR(W):+26.9%
<i>Fenneropenaeus chinensis</i> (Shrimp)	Huanghai 2	2008	YSFRI	Mass and family selection	GR(W):+30% SR: +12.25-20.7%
<i>Fenneropenaeus chinensis</i> (Shrimp)	Huanghai 3	2013	YSFRI	Mass selection	GR(W):+11.8% SR: +11.8%
<i>Litopenaeus vannamei</i> (Shrimp)	Kehai 1	2010	IOCAS <i>et al.</i>	Family + mass selection	GR(W):+12.6-41.7% (depend on density)
<i>Litopenaeus vannamei</i> (Shrimp)	Zhongxin 1	2010	Sun Yat-Sen Uni. & Hengxin Ltd.	Family selection	SR(W): +20%
<i>Litopenaeus vannamei</i> (Shrimp)	Zhongke 1	2010	SCSIOCAS <i>et al.</i>	Mass & family selection	GR(W): +21.8%

(Table 1) contd....

Species	Novel Variety	Appr. Year	Innovatots	Produced Methods	Major Merits
<i>Litopenaeus vannamei</i> (Shrimp)	Guihai 1	2012	Guangxi FRI	Family selection	GR(W): +13.97-15% SR: +11.32%
<i>Penaeus monodon</i> (Shrimp)	Nanghai 1	2010	SCSFRI	Mass selection	GR(W): +21.6%-24.4% SR: +8.4%
<i>Macrobrachium rosenbergii</i> (Prawn)	Taihu 1	2008	ZJFWFRI	Hybridization & mass selection	GR(W): +36.87%, SR: +7.76%
<i>Eriocheir sinensis</i> (River Crab)	Guanghe 1	2011	Panjing Guangghe Crab Farm Ltd.	Mass selection	GR(W): +25.98% SR: +48.59%
<i>Eriocheir sinensis</i> (River Crab)	Changjiang 1	2011	JSFWFRI	Mass selection	GR(W): +16.7% Better uniformity
<i>Eriocheir sinensis</i> (River Crab)	Changjiang 2	2013	JSFWFRI	Mass selection	GR(W): +18.5% Better uniformity
<i>Portunus trituberculatus</i>	Huangxuan 1	2012	YSFRI <i>et al.</i>	Mass selection	GR(W): +20.12% SR: +30%
<i>Portunus trituberculatus</i>	Keyong 1	2013	IOCAS & Ningbo Uni.	Mass selection	GR(W): +11.4%, SR: +13.9%
<i>Apostichopus japonica</i> (Sea Cucumber)	Shuiyuan 1	2009	DOU <i>et al.</i>	Hybridization & selection	GR(W): +30%
Hybrids of Carp ( $\sigma$ ) and Crucian ( $\delta$ )	Furong Li-Ji	2009	Hunan FSI	Hybridization	7.8 times bigger than the $\delta$ parent about 86.2% of the $\sigma$ parent.
Triploids of Crucian	Xiangyun Ji 2	2008	Hunan Normal Uni.	Hybridization & cyto- engineering	Higher growth rate (1.43-4.21 times) and better taste
Hybrids of Tilapia ( <i>Oreochromis</i> spp.)	Jili Tilapia	2009	SOU, <i>et al.</i>	Hybridization	Cultured in S 15~25%owater, grow up to 500g in 5-6 monthes
Hybrids of Snakehead ( <i>Channa maculate x Ophicephalus argus</i> )	Hang Li 1	2009	Hangzhou ASA	Hybridization	GR(W): +20%-50% 0.5~0.7kg/ind. at 1 Yr age
<i>Xenocypris argentea X Megalobrama amblycephala</i>	Bian-Gu Hybrids	2011	Hunan Normal Uni.	Hybridization	GR(W): +11.67-37.5% Infertility
Hybrids of red carp and mirror carp	Songbu Red Mirror Carp	2008	HLJFRI	Hybridization + mass selection	GR(w): +21.6-35.6% SR: +12.2-12.9%.
Hybrids of <i>Carassius auratus</i> (Crucian)	Jin Xin Wuji	2013	Tianjin Huanxin Breeding Farm	Hybridization & cyto engineering	GR(W): +10-16%
<i>Paralichthys olivaceus</i> (Flatfish)	Pingyou 1	2010	YSFRI <i>et al.</i>		GR(W): +30%, SR: +20%
<i>Scophthalmus maximus</i> (Turbot)	Danfa Ping	2010	YSFRI <i>et al.</i>	Hybridization & mass selection	GR(w): +24% SR: +18%.
<i>Larimichthys crocea</i> (Large yellow croaker)	Mingyou 1	2010	Jimei Uni. <i>et al.</i>	Hybridization of 3 populations & selection	GR(w): +23.9%, SR: +13.7%.
<i>Larimichthys crocea</i> (Large yellow croaker)	Donghai 1	2013	Ningbo Uni. <i>et al.</i>	Mass selection	GR(w): +15.57%, SR (at low temp): +22.5%.
<i>Ictalurus punctatu</i> (Catfish)	Jiang Feng 1	2013	JSFFRI <i>et al.</i>	Hybridization	GR(W) +22.1%-25.3%
<i>Micropterus salmoides</i> (Perch)	Youlu 1	2010	PRFRI <i>et al.</i>	Mass selection	GR(W): +17.8-25.3%
<i>Cyprinus carpio carpio</i> (Carp)	Furui Li	2010	FWFRC	Mass & family selection	GR(W): + >20%
<i>Hypophthalmichthys molitrix</i> (Silver carp)	Changfeng Lian	2010	YRFRI	Gynogenesis & mass selection	GR(W): +13.3-20.5% (depend on age)
<i>Hypophthalmichthys molitrix</i>	Jin Lian	2010	Tianjin Huanxin Breeding Farm	Mass selection	GR(W): +10-13.2% RR : +74%

(Table 1) contd.....

Species	Novel Variety	Appr. Year	Innovatorts	Produced Methods	Major Merits
<i>Oujiang Color carp</i>	Longshen 1	2011	SOU <i>et al.</i>	Mass selection	GR(W): +13.68-24.65%.
All female of (Flatfish) <i>Paralichthys olivaceus</i>	Beiping 1	2011	BDHCES	Hybridization of 2 gynogenesis families	90% female GR(W): +15.59-23.37%
All female of (Flatfish) <i>Paralichthys olivaceus</i>	Beiping 2	2013	BDHCES <i>et al.</i>	Gynogenesis & sex-reversion	90% female GR(W): +50%
All male of Tilapia <i>Oreochromis niloticus</i>	Luxiong 1	2012	Xiamen Luye Fishery Ltd.	Cyto-engineering	Male rate: >99%
All male of yellow catfish <i>Pelteobagrus fulvidraco</i>	Quanxiong 1	2010	IWEECAS <i>et al.</i>	Cyto-engineering	All male GR(W): +43.5-56.8%
Allogynogenetic silver crucian carp	Zhongke 3	2008	IHBCAS	Allogyno-genesis	GR(W): + 13.7-34.4%

Source: Announcements related to Aquaculture Protospecies and Varieties by the Ministry of Agriculture of China from 2004 to 2014.

OUC: Oceanic University of China;

DFMST Ltd: Dongfang Marine Science & Technology Ltd;

IOCAS: Institute of Oceanology, Chinese Academy of Sciences;

JSMFRI: Jiangsu Marine Fisheries Research Institute;

ZJMC: Zhejiang Institute of Mariculture;

SCSIOCAS: South China Sea Institute of Oceanology, Chinese Academy of Sciences;

Guangxi FRI: Guangxi Fisheries Research Institute;

SCSFRI: South China Sea Fisheries Research Institute, Chinese Fisheries Research Academy;

ZJFWFRI: Zhejiang Freshwater Fisheries Research Institute;

JSFWFRI: Jiangsu Freshwater Fisheries Research Institute;

Hangzhou ASA: Hangzhou Agriculture Science Academy;

DOU Dalian Oceanic University;

HLJFRI: Heilongjiang Fisheries Research Institute, Chinese Fisheries Research Academy;

YSFRI: Yellow Sea Fisheries Research Institute, Chinese Fisheries Research Academy;

JSFRI: Jiangsu Freshwater Fisheries Research Institute;

PRFRI: Pearl River Fisheries Research Institute, Chinese Fisheries Research Academy;

FWFRC: Freshwater Fisheries Research Center, Chinese Fisheries Research Academy;

YRFRI: Yangtze River Fisheries Research Institute, Chinese Fisheries Research Academy;

SOU: Shanghai Oceanic University;

BDHCES, CFRA: BeiDaiHe Experimental Center Station;

IWEECAS: Institute of Water Ecology and Engineering, Chinese Academy of Sciences;

IHBCAS: Institute of Hydrobiology, Chinese Academy of Sciences.

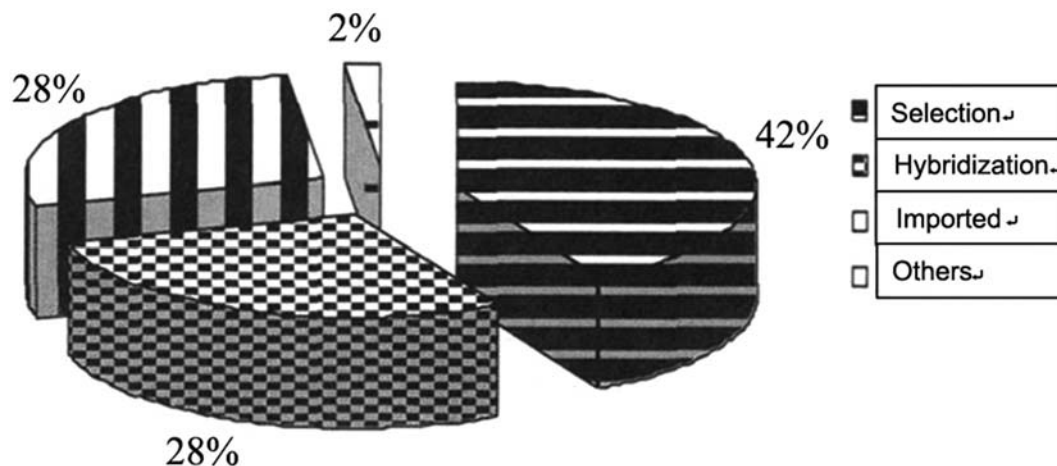


Fig. (4). Rates of the methods used for novel aquatic varieties approved in China.

It is generally agreed that the application of 'omics' technologies in aquatic organisms, as in other farming activities, may significantly contribute to advancement of the aquaculture industry. In recent years, various experimental 'omics' approaches have been applied to farmed organisms to increase the genomic resources available. These tools are utilized to identify genetic markers associated with traits of commercial interest, and to unravel the molecular basis of different physiological processes. In recent years, an

important effort has been directed towards the use of functional genomics, proteomics and metabolomics to better characterize the reproduction, development, nutrition, immunity and toxicology of aquaculture organisms.

Special attention is devoted to genomics, transcriptomics, proteomics, metabolomics and nutrigenomics [27-30]. It is hoped that new bio-information will contribute to increased success in the marine sciences and related industries [31].

Recent advances in genomic and post-genomic technologies have now established the new standard in medical and biotechnological research. The introduction of next-generation sequencing (NGS) has resulted in the generation of thousands of genomes from all domains of life [32]. Genomic and metagenomic analyses of marine organisms and the marine environment are revealing the complexity and biodiversity of marine ecosystems [33].

China's marine functional genomics and genetics research had already started at the beginning of the 21st Century and thus far has catalyzed important progress in functional gene isolation, cloning and application to marine bio-economic organisms. China took the lead within the international community in obtaining expression of a large number of expressed sequence tags (EST) for shrimp, scallops and other marine organisms; completed, for the first time in the world, the whole-genome sequencing of White Spot Syndrome Virus (WSSV) in shrimp [34]; determined several fish Iridovirus genome sequences [35-39]; established specific genetic databases of China's marine bioresources by bioinformatics techniques, laying a foundation of property rights and technology for securing marine functional genomics resources and promoting industrialization.

Whole-genome sequencing is one of the most challenging applications of NGS to accelerate biological and applied research in non-model aquatic species. Some noteworthy progress has been made in recent years in China (Table 2). In 2012, the oyster genome sequencing and assembly were completed, which revealed stress adaptation and complexity of shell formation [40]. In the same year, Xu *et al.* [41] reported genome sequence and genetic diversity of the common carp, *Cyprinus carpio*. Chen *et al.* [42] reported the whole genome sequences of the flatfish *Cynoglossus semilaevis*, which provided insights into ZW sex chromosome evolution and adaptation to a benthic lifestyle. Later, Wu *et al.* [43] published a draft genome of a large yellow croaker *Larimichthys crocea*, which revealed well-

developed innate immunity, while Ao J *et al.* [44] reported a better assembled genome sequencing of the same species that provided insight into the molecular and genetic mechanisms of stress adaptation. Recently, genome sequencing of a kelp *Saccharina japonica* and the grass carp *Ctenopharyngodon idellus* have been published by Ye H *et al.* [45] and Wang Y *et al.* [46], respectively. These results provide novel insight into kelp biology and may help us understand the evolution and vegetarian diet adaptation of the grass carp. The availability of these genomic data have opened up a number of opportunities to advance basic research and develop commercial applications.

Genetic linkage maps are powerful tools in breeding programs and genome evolution studies. Knowledge of the genetics and physiology of economically important marine organisms remains scarce. For some purposes, such as genetic breeding programs, the application of genomics may be a faster approach than the *de novo* sequencing of genomes and further identification of genes and genetic markers. The construction of genetic linkage maps may allow a relatively rapid recognition of quantitative trait loci (QTLs) for marker-assisted selection (MAS) in aquatic organisms [20]. Genetic linkage maps, the necessary framework for any MAS program, have been constructed for over 40 aquaculture species and are currently being constructed for additional species [47]. In China, the genetic linkage maps for sea weeds, shrimp, crabs, molluscs, echinoderms and fishes, such as *Litopenaus vananmei* [48], *Fenneropenaeus chinensis* [49], *Portunus trituberculatus* [50], *Chlamys farreri* [51, 52], *Crassostrea virginica* [53], *Haliotis discus hannai* [54], *Apostichopus japonicas* [55], *Strongylocetrotus nudus* [56], *Larimichthys crocea* [57], *Epinephelus bruneus* [58] etc., have been successively constructed.

Growth traits including growth rate, body weight and length are the most important traits in aquaculture species [19]. They can be easily measured. Due to their high heritability in most culture species, they can be improved using traditional selection methods. QTL analysis for growth

**Table 2. Recent progress of whole-genome sequencing.**

Species	Year	1 <sup>st</sup> & Commu. Authors	Genome Size (C50: Contig N50, S50: Scaffold N50)	References
Oyster ( <i>Crassostrea gigas</i> )	2012	G.Zhang J.Wang	559mb (C50: 19.4kb, S50 :401kb)	Nature Vol.490, 49-54.
Common carp, ( <i>Cyprinus carpio</i> )	2014	P.Xu, X. Sun	1.69 Gb (C50: 68.4kb, S50: 1mb)	Nature Genetics Vol. 46 No 11: 1212-1221.
Tongue sole ( <i>Cynoglossus semilaevis</i> )	2014	S.Chen J.Wang	477Mb (C50: 26.5kb, S50 : 867kb)	Nature Genetics Vol.46 No 3 253-260.
Large yellow croaker ( <i>Larimichthys crocea</i> )	2014	C. Wu Y. Liu	728Mb (C50:25.7kb, S50: 498.7kb)	Nature Communications DOI: 10.1038/ncomms6227, 1-7.
Large yellow croaker ( <i>Larimichthys crocea</i> )	2015	J. Ao X.Chen	679Mb (C50:63.1kb, S50:1.03Mb)	PLOS Genetics 11(4): e1005118. DOI:10.1371/journal.pgen.1005118
<i>Saccharina japonica</i> (Kelp)	2015	H.Ye F.Zhao	537Mb (C50:58.87kb S50: 252.0kb)	Nature Communications 16:6986   DOI:10.1038/ncomms7986
<i>Ctenopharyngodon idellus</i> (Grass carp)	2015	Y.Wang Z.Zhu	0.9Gb(F) (C50:40.78kb, S50: 6.46 Mb) 1.07 Gb(M) (C50:18.3kb, S50: 2.28 Mb)	Nature Genetics (advance online) Doi:10.1038/ng.3280



traits has been conducted in many species. For example, Song W. *et al.* [59] constructed high-density genetic linkage maps and mapped growth-related QTLs on it for the Japanese flounder (*Paralichthys olivaceus*). Song W. *et al.* [60] constructed a high-density microsatellite genetic linkage map and mapped sexual and growth-related traits on it in half-smooth tongue sole (*Cynoglossus semilaevis*). Liu L. *et al.* [50] identified QTLs for growth-related traits in the swimming crab *Portunus trituberculatus*.

In terms of value, shrimp are the most important seafood product traded globally, with production from aquaculture estimated at 3.1 million metric tonnes and valued at US\$12 billion in 2008 (Shrimp News International, 2009). Considerable effort has been expended on shrimp genome research since the end of the twentieth century. However, due to the great complexity of conducting a genome survey of *Litopenaeus vannamei*, its genome investigation is behind the progress of genome research for aquatic fishes, molluscs and sea weeds. Zhang X. *et al.* [61] reported construction and characterization of a bacterial artificial chromosome (BAC) library of the Pacific white shrimp, *L. vannamei*. A high density genetic map was constructed using a specific-locus amplified fragment sequencing (SLAF-seq) approach. In the constructed linkage map, a total of 6,146 markers spanning 4,271.43 cM were mapped to 44 sex-averaged linkage groups, with an average marker distance of 0.7 cM. The integration analysis linked 4,908 scaffolds from genome survey analyses and 1,504 BAC clones to the constructed linkage map. With the help of map integration, many markers were annotated. This high-density genetic linkage map reveals the basic genomic architecture and it will be useful for comparative genomics research, genome assembly and genetics-based breeding of *L. vannamei* and other penaeid shrimp [62].

### 3.3. Novel Production Systems

In the development of mariculture industries, paying attention solely to the economic benefits and ignoring the long-term ecological effects can be very detrimental because it can severely hinder sustainable mariculture development. For example, the ill-considered intensification of shrimp and scallop culture in years past caused the massive mortalities in China. So, present-day Chinese mariculture ought to adjust its industrial structure, to reduce environmental pollution and to maintain sustainable development.

There are multiple major aquatic production systems on basis of the eco-habitats, which include the following:

- a. Pond production systems in land-based freshwater or on coastal beaches, for fish, shrimp, crab, sea cucumber and molluscs. Almost half of the total aquaculture yield comes from land-based ponds and water-based pens, cages, longlines and stakes in brackish water and marine habitats.
- b. In-door production in freshwater or on coastal beaches for hatchery and grow-out of fishes, abalone, etc;
- c. Suspended aquaculture in coastal water for sea weeds and scallops;

- d. Cage culture in lakes or in the near-shore sea for fishes.

In view of the current situation, different kinds of cultural modes can clearly coexist. Extensive mariculture in tidal flat ponds and shallow seas are still playing main role in Chinese production. However, the conversion of coastal ecosystems to aquaculture ponds has significantly degraded the wetland and aquatic environments. In order to keep the balance of ecology and environment, i.e., to reduce the impact of cultural effluent on the seawater, integrated multi-trophic aquaculture (IMTA) in marine offshore systems has been studied and practiced, including the recycling of waste nutrients from higher trophic-level species into production of lower trophic-level crops of commercial value; co-location of cultural species, adjustment of the stocking density and utilization of formulated diets with more nutritious components and higher conversion efficiencies, etc [63-66]. In China, the two main forms of marine IMTA systems are sea-ranching and suspended aquaculture. For example, at Zhangzidao Island, which is comprised of nine islets in the northern Yellow Sea, there have been significant efforts to “optimize” or improve ecological conditions at the farm site, including propagation and planting of seaweeds and creation of artificial reefs. Many of the techniques employed at the site benefit from inter-specific relationships and existing infrastructure to co-culture a range of species. Suspended culture in Sungo Bay, in the eastern end of Shandong Peninsula, is one of the most important mariculture regions for scallop *Chlamys farreri* and kelp *Laminaria japonica* in northern China. The abalone *H. discus hannai* is also cultured here, and to a lesser degree blue mussel *M. edulis*. During the culture of *Laminaria* on long lines, abalones are grown in lantern nets hung vertically from the lines, thus allowing the abalone to feed directly on the kelps. Following harvest of *Laminaria*, abalones are fed with dried *Laminaria* until the next crop matures.

Since the late 1990's, a new shrimp production system, the so-called “High-Located Pond” system, has been becoming more popular, especially in the southern coastal provinces of China (Fig. 5). This type of pond is typically constructed with a plastic sheet liner on its bottom to facilitate the removal of the polluted sediments. Increasing stocking densities, in combination with more effective pumping and aeration of the water and better system management produces yields that are higher by a factor of 3-4.

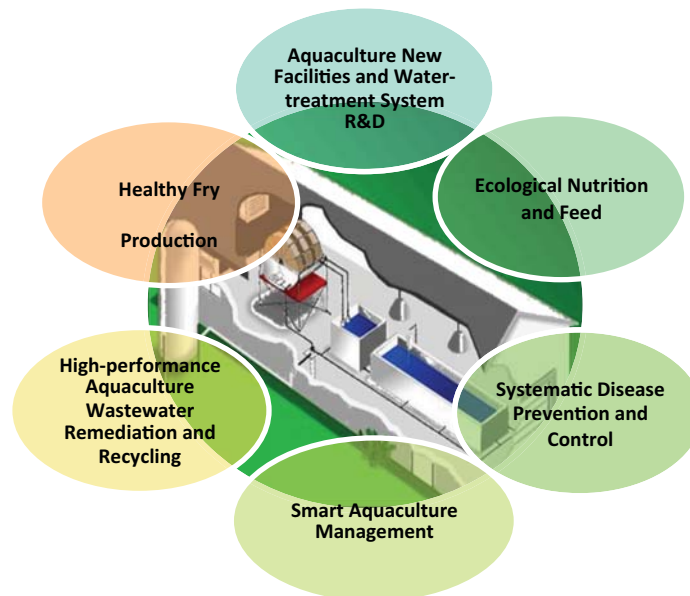
Most recently, indoor intensive culture using recirculating aquaculture systems (RAS) has been rapidly developing in China (Fig. 6). The RAS approach is expected to result in higher yields and lower or null effluents. Fig. (7) shows some new RAS facilities and equipment developed by IOCAS.

High-density rearing of aquatic animals typically requires some waste treatment infrastructure. At its core, biofloc is a waste treatment system [67]. Recently, the biofloc approach has been utilized in Chinese aquaculture production and has shown good results [68-70].

In addition, China is also intensively developing cage mariculture. At present, the most utilized shallow sea culture area in China is within 15m depth. Not surprisingly, this sea



**Fig. (5).** A typical intensive shrimp culture system (High-Located Pond) in Hainan Province.



**Fig. (6).** Modern Industrial Recirculating Aquaculture Systems (RAS).

area is also the most impacted zone from land sources. In order to realize the sustainable development of shallow sea Chinese aquaculture in the new century and minimize the adverse impacts of mariculture on shallow sea area, the fish farming range should be increased to include more offshore areas. Fish farming sites ought expand to 20m depth and some sea areas could possibly support culture at 30-40m depth. The corresponding advanced cultivating and engineering facilities should be made for the future offshore mariculture. The main cultural species number about 40, including perch, turbot, flounder, etc. in the north of China and large yellow croaker, red drum and perch, etc. in the south. The total area of mariculture cages has reached 21,930,000 m<sup>2</sup> and the total production in China was about 305,610t in 2008 [6]. Now modern net-cages and relative facilities suitable for deep-sea and typhoon-resistant aquaculture in China's coastal waters have been developed. Large and deep-setting anti-wave cage technology has developed very quickly, with good applications for large yellow croaker (*Larimichthys crocea*), cobia (*Rachycentron canadum*) and pompano (*Trachinotus ovatus*) [71].

Fig. (8) shows the locations of five novel production systems spread across the coastline of China.

### 3.4. Biosecurity

With the increase of living standards, economic globalization and the rapid worldwide growth in international trade, an increasing number of countries and international organizations have recognized the importance of biosecurity, which involves food safety, animal and plant health and well-being, and environmental risks. Therefore, the FAO of the United Nations has adopted biosecurity as one of the organization's 16 priority areas of interdisciplinary action in medium-term programs, aiming to promote, develop and enhance a common strategy of food, agriculture, fisheries and forestry policy and management framework [72].

Biosecurity of marine aquaculture is concerned with the management of health and the environmental risks of marine aquaculture-related organisms. The risk includes all non-native species, the introduction of disease organisms and pathogenic microorganisms of cultured species, major infectious diseases destroying the biological diversity and cross-sectional diseases resulting in a decrease of large-scale biological production, as well as biological and environmental pollution problems caused by development of biotechnologies.

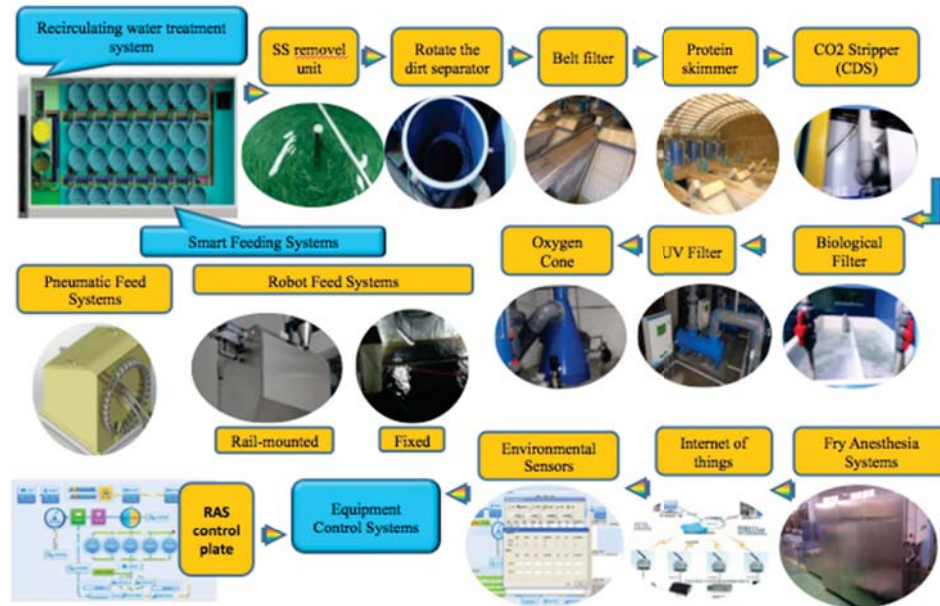


Fig. (7). Some new RAS facilities and equipment have been developed by IOCAS.

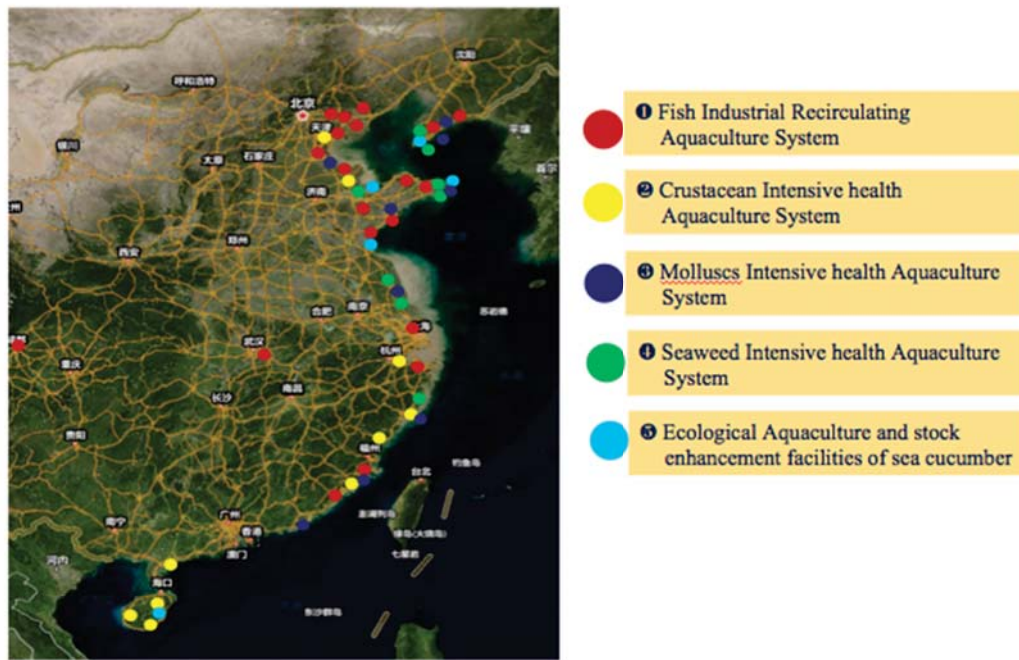


Fig. (8). Five Novel Production Systems have been spread across the coastline of China.

Knowledge of comparative immunology is crucial to our understanding of the defense mechanisms of different aquatic animals, such as fishes, shrimp, molluscs and others, against relevant pathogens. Two Major State Basic Research Development Programs in China (973 programs) which integrated several research teams from the Institute of Oceanology, Chinese Academy of Sciences; the Third Institute of Oceanology, State Oceanic Administration; Zhejiang University; SUN YAT-SEN University; and Shandong University were undertaken from 2000 until 2010 to focus on aquatic animal immunology and disease control. These studies made great progress on the immunology of shrimp, molluscs and fishes. A special issue on

“Comparative Immunology in China” was invited for publication in *Developmental and Comparative Immunology* [73], six papers of which reviewed the major studies and advances in knowledge and its application of innate and adaptive immunology from shrimp, molluscs and fishes. The review paper “Advances in research of fish immune-relevant genes: A comparative overview of innate and adaptive immunity in teleosts” [74] has been one of the most cited in the DCI journal for quite some time.

Due to the importance of shrimp aquaculture in China, researchers have paid considerable attention to the molecular mechanisms of shrimp disease occurrence and tried to develop an efficient control strategy for disease. The first

line of defense against microbial infections in animals is the innate immune response, which triggers diverse humoral and cellular activities *via* signal transduction pathways [75]. Based on the recent data, a brief outline of the immune system of shrimp was drawn, which will help us to understand the immune responses of shrimp to different pathogens [76].

For this industry, viral infection poses a significant threat and causes heavy economic losses. Simple, rapid and accurate methods for detecting pathogens directly from aquatic animal samples are therefore crucial for monitoring the infected fishes and minimizing economic losses. Molecular technology of pathogen detection has been established in China for a series of fish, shrimp, and scallops [77-82].

The most realistic approach to combat diseases is combining good husbandry and good feed with the use of prophylactic agents, including immunostimulants and probiotics [83-85].

*Edwardsiella tarda*, *Vibrio*, *Streptococcus iniae*, and *Pseudomonas fluorescens* are severe bacterial pathogens in a wide range of farmed freshwater and marine fish. Against these pathogens, Sun's team constructed multiple different types of monovalent and multivalent vaccines, including DNA vaccines, attenuated vaccines, subunit vaccines, and inactivated vaccines [86-90]. They have designed and developed DNA vaccines and subunit vaccines delivered by live attenuated pathogens *via* natural infection, which induces cross-genus protection. These vaccines induce effective protection against pathogens and have good application prospects.

Over the past few decades, Asian aquaculture production has intensified rapidly through the adoption of technological advances, and the use of a wide array of chemical and biological products to control sediment and water quality and to treat and prevent disease outbreaks [91].

Seafood safety is a crucial issue in the consumption chain, pathogens (including bacteria, viruses and parasites) and hazards (such as pollutants, toxins, drug residues etc.) are major contaminants of concern. In 2000, China's Ministry of Agriculture (MOA) mandated a nationwide quality standard that awards a green label to qualified safer seafood (MOA, Fishery Administrative, Year 2000, Document #17). Since then, R&D for seafood security has been undertaken. Traceability systems, including tracking and tracing approaches, have been gradually established and improved [92, 93]. According to China's 2010 government statistics, 787 seafood brands were granted a green label, to ensure the safety of food in China. In actuality, there is still a long way to go to guarantee the safety of seafood for consumers.

Environmental biotechnology can and should play an important role in addressing challenges related to the marine environment, as well as the threat of pollution of the aquatic products in it. Although great advances have been made in the detection and analysis of trace pollutants during recent decades, due to the continued development and refinement of specific techniques, a wide array of undetected contaminants of emerging environmental concern must be identified and

quantified in various environmental components and biological tissues [94].

### 3.5. Bioprocess and Biorefinery

Marine biotechnology is expected to affect many value-added sectors: pharmaceuticals, food, industrial processing, nutraceuticals, etc. Tools based on marine biotechnology can be widely used in industrial processing and manufacturing and can play an important role in global green growth efforts [12]. For example, in addition to their fuel potential, algae and other marine biomass represent largely untapped alternatives to so-called platform chemicals and even functional food products. From 2003 to 2012, China's seafood processing industry grew at an annual rate at 10.7%, twice that of its aquaculture sector [95]. China, the world's leading aquaculture producer, has a huge annual production biomass. In addition to the material for direct consumption, there is much waste. Use of aquaculture wastes provides an important opportunity for meeting domestic fishmeal and oil demands, reducing use of trash fish in feeds, and minimizing waste discharges and pollution from processing plants. Cao *L. et al.* [95] estimated the potential of fishmeal and oil production from China's fish processing industry.

To convert the huge aquatic biomass into value-added chemicals and fuels, biotechnology and nano-technologies are becoming accepted as important players, along with conventional biomass refinery technologies [96]. The objective of a biorefinery is to utilize biomass ingredients efficiently, similar to petroleum refineries in which oil is fractionated into fuels and a variety of products with higher value. Microalgae are a potential source for various valuable chemicals for commercial applications ranging from nutraceuticals to fuels. The identification and application of novel, marine-derived pharmaceuticals, cosmetics, nutritional supplements, enzymes, and pigments have already been realized.

The seaweed resources in China are very rich, with an annual output of 7.9 million tonnes from aquaculture alone (FAO 2011). Seaweeds supply not only a lot of good seafood directly for humans, but also an abundance of materials for value-added substances, such as different phycocolloids used to produce algin, agar and carrageenan, iodine and mannito. In China, the annual seaweed industry production of algin, agar, carrageenan, iodine and mannito is 20,000t, 1000t, 7500t, 180t and 4000t respectively [97]. Also some drugs (PSS and Shenhaikang) for treating cardiovascular and kidney disease are produced from seaweed.

Until 2008, there were up to 684 varieties of marine *materia medica* and potential medicinal resources investigated by modern pharmacology and chemistry researchers including plant medica, animal medica and mineral medica of 205, 468 and 11 varieties, respectively [98]. Novel peptides from sponges, ascidians, molluscs, sea anemones and seaweeds are presented in association with their pharmacological properties and acquisition methods. More recent studies have indicated that halogenated natural products are actually common in some sources. In fact, more than 5000 halogenated natural products had been discovered as of 2011 [99].

## CONCLUSION

The marine biotechnological fields in China have scored unprecedented achievements under the joint efforts of the scientific research technical staff during the past decades. The blue economy is emerging at a critical juncture of the world economic transformation during the global recession. Obviously, marine biotechnology R&D is vital for advancing sectors of the blue bioeconomy. Innovative achievements in China are not enough and the level and frequency of academic achievements must be improved. More technology and products with independent intellectual property rights are needed.

Last but not least, international cooperation and assistance remain crucial for the success of marine biotechnology. China has always attached great importance to the academic exchange and cooperation with the international science and technology communities and, following the country's opening to the outside world after 1979, it has established channels for scientific and technological cooperation and exchange with many well-known universities, institutions and hi-tech enterprises globally.

There is no doubt that international cooperation, from private enterprises to government, has become increasingly prevalent. In light of the growing global economy, such cooperation is beneficial for almost every country in the world. China fully participates in the activities of relevant organizations, for example, FAO, UNEP, EU Framework Programme for Research, the ASEM (Asia-Europe Meeting) Aquaculture, World Aquaculture Society, International Marine Biotechnology Association and so on.

## CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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