Subject Area 5.1: Microbial studies and technologies supporting waste disposal, management, and remediation of municipal and industrial hazardous wastes

Review Article

Environmental Impact of Aquaculture and Countermeasures to Aquaculture Pollution in China*

Ling Cao[1], Weimin Wang[1], Yi Yang [2], Chengtai Yang [1], Zonghui Yuan[3], Shanbo Xiong[4] and James Diana[5]**

[1] College of Fisheries, Key Lab of Agricultural Animal Genetics, Breeding and Reproduction of Ministry of Education,
Huazhong Agricultural University, Wuhan, Hubei 430070, China
[2] Aquaculture and Aquatic Resources Management, School of Environment, Resources and Development, Asian Institute of Technology,
P.O. Box 4, Klong Luang, Pathum Thani, 12120, Thailand
[3] National Reference Laboratory of Veterinary Drug Residues, Huazhong Agricultural University, Wuhan
[4] College of Food and Science Technology, Huazhong Agricultural University, Wuhan, Hubei 430070, China
[5] School of Natural Resources and Environment, University of Michigan, Ann Arbor, USA

** **Corresponding author** (wangwm@mail.hzau.edu.cn)

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Abstract

Goal, Scope and Background. Aquaculture activities are well known to be the major contributor to the increasing level of organic waste and toxic compounds in the aquaculture industry. Along with the development of intensive aquaculture in China, concerns are evoked about the possible effects of ever-increasing aquaculture waste both on productivity inside the aquaculture system and on the ambient aquatic ecosystem. Therefore, it is apparent that appropriate waste treatment processes are needed for sustaining aquaculture development. This review aims at identifying the current status of aquaculture and aquaculture waste production in China.

Main Features. China is the world's largest fishery nation in terms of total seafood production volume, a position it has maintained continuously since 1990. Freshwater aquaculture is a major part of the Chinese fishery industry. Marine aquaculture in China consists of both land-based and offshore aquaculture, with the latter mostly operated in shallow seas, mud flats and protected bays. The environmental impacts of aquaculture are also striking.

Results. Case studies on pollution hot spots caused by aquaculture have been introduced. The quality and quantity of waste from aquaculture depends mainly on culture system characteristics and the choice of species, but also on feed quality and management. Wastewater without treatment, if continuously discharged into the aquatic environment, could result in remarkable elevation of the total organic matter contents and cause considerable economy lost. Waste treatments can be mainly classified into three categories: physical, chemical and biological methods.

Discussion. The environmental impacts of different aquaculture species are not the same. New waste treatments are introduced as references for the potential development of the waste treatment system in China. The most appropriate waste treatment system for each site should be selected according to the sites' conditions and financial status as well as by weighing the advantages and disadvantages of each system. Strategies and perspectives for sustainable aquaculture development are proposed, with the emphasis on environmental protection.

Conclusions. Negative effects of waste from aquaculture to aquatic environment are increasingly recognized, though they were just a small proportion to land-based pollutants. Properly planned use of aquaculture waste alleviates water pollution problems and not only conserves valuable water resources but also takes advantage of the nutrients contained in effluent. It is highly demanding to develop sustainable aquaculture which keeps stocking density and pollution loadings under environmental capacity.

Recommendations and Perspectives. The traditional procedures for aquaculture waste treatment, mainly based on physical and chemical means, should be overcome by more site-specific approaches, taking into account the characteristics and resistibility of the aquatic environment. Further research needs to improve or optimize the current methods of wastewater treatment and reuse. Proposed new treatment technology should evaluate their feasibility at a larger scale for practical application.

Keywords: Aquaculture; aquaculture pollution; aquaculture waste; China; countermeasures; environmental pollution

Introduction

Aquaculture has been a fast-growing industry because of significant increases in demand for fish and seafood throughout the world. It is growing more rapidly than any other segment of the animal culture industry (Gang et al. 2005). China has a long history in aquaculture back to 2000 years ago. Since the 1970s, under the reform policies and driven by the economic benefits, the rapid development of China's aquaculture both in fresh waters and marine waters has been the focus of the world's attention. China is now the world's largest fishery nation in terms of total seafood production volume, a position it has maintained continuously after 1990s. According to the Fishery Bureau, Chinese Ministry

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* **ESS-Submission Editor:** Dr. Ding Wang (wangd@ihb.ac.cn)

of Agriculture (MOA), the total production in 2005 amounted to 51.0 million metric tons, making up one quarter of the world total (Natural Bureau of Statistics of China 2005). Aquaculture contributes to 65% of the total fishery production, among which freshwater aquaculture is a major part. Without doubt, China's aquaculture will continue to play an important role in the global supply of fish in the future.

However, along with the development, concerns are evoked about the possible effects of ever-increasing aquaculture waste both on productivity inside aquaculture systems and on the ambient aquatic ecosystem. Aquaculture may contribute to the degradation of the environment, but it is still paradoxically dependent on the supply of clean waters. Traditional farming systems (e.g., extensive pond farming) dominate aquaculture production in many regions, but these are now slowly being replaced by intensive western oriented techniques. Rapid scale growth of intensive mariculture systems can often lead to adverse impacts on the environment. Intensive fish and shrimp farming, being defined as throughput-based systems, have a continuous or pulse release of nutrients that adds to eutrophication (Troell et al. 1999). Nitrogenous compounds (ammonia, nitrite, and nitrate) are considered as major contaminants in aquaculture wastewater. Ammonia is the principal nitrogenous waste produced by aquatic animals. Past, obsolete technologies and incomplete arrangement of waste management systems in aquaculture contribute a lot to the deterioration of the aquaculture environment. Ackefors & Enell (1994) estimated that 9.5 kg P and 78 kg N per ton of fish are released into the water column per year when the feed conversion coefficient is 1.5 and the contents in the feed are 0.9% P and 7.2% N. Approximately 72% N and 70% P in feed are not retained by fish. With improvements in feed composition, digestibility, and feed conversion efficiency in recent years, the discharge is probably now reduced to 7.0 kg P and 49.3 kg N per ton of fish per year (Chopin et al. 1999). Aquaculture pollution accidents at a number of 2067 happened in 1999 and 2000, leading to a loss in economy of 0.132 billion dollars (Yang et al. 2002).

Aimed at settling the increasingly aggravated environmental problems raised by aquaculture waste, the Chinese government should adopt a series of regulations and controls. Aquaculture systems which incorporate waste treatment and effluent reuse facilities are rapidly being developed because they have the advantage of minimal water input and wastewater discharge while allowing full control of the cultural environment (Midlen & Redding 1998, Van Rijn 1996). The forms of aquaculture waste treatment systems may vary, but they can generally be classified into three categories: physical treatment, chemical and biological methods. Many studies have been conducted to examine the aquaculture waste treatment efficiency of different treatment system (Cheng et al. 2002, Xiao et al. 2006). However, the disadvantages of each treatment are also obvious, such as excessive sludge production, unstable performance, and nitrate accumulation. Thus, research on new methods for aquaculture wastewater treatment is under way. The purpose of this review was to study the current status of aquaculture in China, analyze the compromise of aquaculture waste and evaluate common waste treatment methods applied in aquaculture in China.

1 Main features

1.1 Aquaculture in China

1.1.1 Freshwater aquaculture

Freshwater aquaculture is a major part of the Chinese fishery industry. It takes place in ponds, lakes, rivers, reservoirs and rice paddy fields, which are wide spread in almost the whole of China. Both main freshwater and marine aquaculture areas which are also considered as pollution hot spots are indicated in **Fig. 1**. The growing trend of aquaculture in China is shown in **Fig. 2**.

Pond culture is the most important method among freshwater aquaculture. The pond yield accounted for over 71% of the total inland aquaculture in 2003. Most pond culture activities are found along the Yangtze River basin Delta and the Pearl River Delta covering 7 provinces: Jiangshu, Guangdong, Hubei, Hunan, Anhui, Jiangxi and Shangdong provinces (see Fig. 1).

Reservoir, lake, river and channel fish farming contributes most to the remaining fresh aquatic production, by making

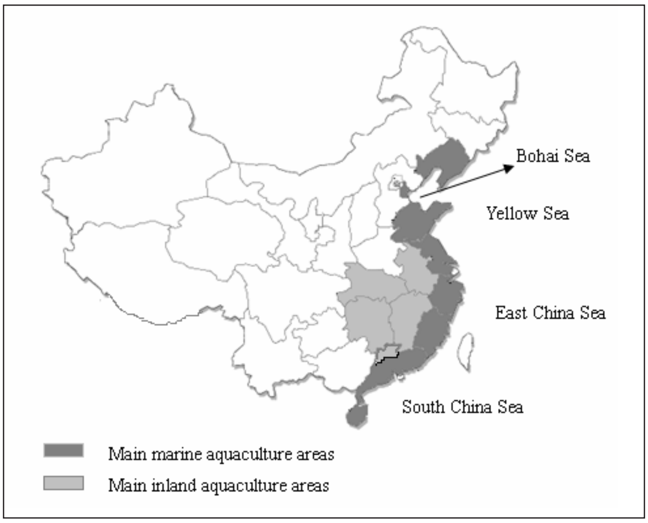

Fig. 1: Illustration of aquaculture concentration areas in China (aquaculture pollution hot spots)

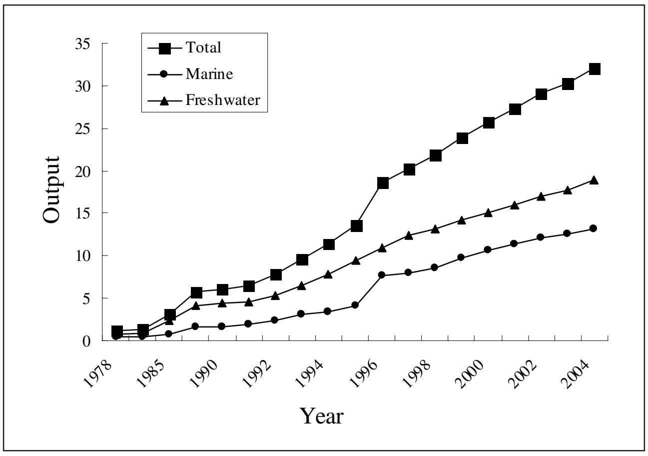

Fig. 2: China aquaculture production by year (unit: million metric tons)

use of cages and nets in open-waters. Rice paddy fish and crab farming has developed into an important and growing commercial activity for rural residents in mountainous areas where open water resources are not available or limited. More than 70 main freshwater aquatic species are farmed in China. Most of them are fish (about 60 species). The most common farmed species are grass carp, silver and bighead carp, common carp and crucian carp. Another important category is crustaceans, 1.1 million tons in 2003.

1.1.2 Marine aquaculture

Marine aquaculture in China consists of both land-based and offshore aquaculture, with the latter mostly operated in shallow seas, mud flats and protected bays. Land-based marine aquaculture applied on abalone, turbot, flounder and other fish species offer high economic values in both north and south coastal provinces. The main production types of offshore aquaculture are floating and semi-floating raft culture, net cage culture, sea ground sowing, vertical (hanging) culture and pond on tidal areas. By the year 2003, the total marine aquaculture area has reached 1,532,152 hectares. Of this, the offshore area used is 590,455 hectares, while the mud flat used is 676,184 hectares and land based farming areas represent 265,513 hectares. Four sea regions were involved in marine aquaculture including Bohai Sea, Yellow Sea, East China Sea and South China Sea. Most important marine aquaculture provinces are Shandong, Fujian, Guangdong, Liaoning, Zhejiang and Guangxi provinces (see Fig. 1). More than 90% of the total marine production comes from these provinces, whose production volumes exceeded 800,000 tons in 2003. There are four main categories: marine fish (finfish), crustaceans (shrimp and crab), mollusks (shellfish) and seaweeds (algae).

Table 1 shows output and area of marine shellfish cultured in China in 2002. Almost 90% of farmed marine finfish comes from the following 5 provinces: Guangdong, Fujian, Shangdong, Zhejiang and Liaoning. In 2003, Guangdong province had the largest production of farmed fish approximately 195,524 tons (Natural Bureau of Statistics of China 2005). Fujian province has 119,226 tons. Others are ranging from 26,000 to 81,000 tons. In northern China, Liaoning and Shandong are two important marine fish farming provinces (Natural Bureau of Statistics of China 2005). The main species are flounder, turbot, halibut, sea bream, Fugu, perch, greenling, mullet fish, etc. In some places there are trials on large yellow croaker and red drums. In southern China, Guangdong, Fujian and Zhejiang are important marine fish farming provinces. There are more wide ranges of warm water or tropical fish species being farmed. Main species are groupers, large yellow croaker, sea bream and snapper fish, red drum, Fugu, perch, cobia, amberjack, pompano, etc.

1.2 Environmental impacts of aquaculture

1.2.1 Habitat modification

Mangrove conversion to shrimp ponds has contributed to the negative press received by aquaculture. This transformation results in loss of essential ecosystem services generated by mangroves, including the provision of fish/crustacean nurseries, wildlife habitat, coastal protection, flood control, sediment trapping and water treatment. Fish pens and cages also degrade nearshore habitats through their physical installations on sea grass beds and sediment communities, or through deposits of uneaten feeds (Primavera 2006).

1.2.2 Aquaculture waste

The quality and quantity of waste from aquaculture depends mainly on culture system characteristics and the choice of species, but also on feed quality and management (Wang et al. 2005). From intensive aquaculture systems, the principal wastes are solid wastes, chemicals, and therapeutics. The release of bacteria, pathogens and farmed species escapees should also be included as waste components (Liu et al. 2002).

Solid wastes, otherwise known as particulate organic matter, often consist of feces or uneaten food. A build up of solid wastes within the system should be prevented as it can cause oxygen depletion and ammonia toxicity when it decomposes. Organic wastes are present in three main forms in the recirculation system: settled solids-accumulate on the bottom of the tank; suspended solids-float in the water column and will not settle out of water; fine and dissolved solids-float in the water column and can cause gill irritation and health damage to fish. The urine and feces from the aquatic animals can cause high content of ammonia nitrogen and an increase of BOD (biochemical oxygen demand). Ammonia is the main nitrogenous waste that is produced by fish via metabolism and is excreted across the gills. Nitrite is a naturally occurring intermediate product of the nitrification process. The nitrate ion (NO_3^-) is the most oxidized form of nitrogen in nature and is relatively non-toxic to fishes (Zhang & Chen 2004). However, when nitrate concentrations become excessive and other essential nutrient factors are present, eutrophication and associated algae blooms can become a serious environmental problem.

A wide range of chemicals is used in aquaculture industry, including compounds applied to construction materials (stabilizers, pigments, antifoulants etc.), pigments incorporated into feeds, disinfectants and chemotherapeutants. Antimicrobials are administered in the diet and most end up in the environment in association with uneaten food and feces. Many studies reported increases in resistance and even multiple resistances in pathogens as a result of the widespread use of antimicrobials by aquaculture (Kerry et al. 1994). The abuse of chemicals can also kill the effective microbes which probably accounts for an unbalance of the aquatic ecology system. It is widely argued that translocated species

Table 1: Output and area of marine shellfish cultured in China (2002) (Wang & Zheng 2004)

Species	Mussel	Scallop	Razor clam	Clam	Blood clam	Oyster	Others	Total
Output (10^4 ton)	66.37	93.55	63.54	230.0	23.75	362.55	125.27	965.17
Culture area (10^4 ha)	1.92	6.12	6.64	36.31	3.9	11.16	17.26	83.34

or strains may carry exotic diseases that could spread and devastate indigenous wild populations and that farmed stock escape and become established, again to the detriment of wild stocks. There is little quantitative information on the numbers of animals that escape from aquaculture operations. Penczak et al (1982) estimated that about 5% of caged rainbow trout escaped each year. The fear is that feral animals become established and reduce biodiversity through habitat modification, competition, or by interbreeding with native stocks.

1.2.3 Pollution caused by aquaculture wastewater

If continuously discharged wastewater without treatment, which contains high concentration of nitrogen and phosphorus nutrients, may result in a remarkably chronic elevation of the total organic matter contents, especially in badly managed or poorly located sites. Consequently, a series of negative ecological impacts may occur: (1) serious oxygen deficit caused by the decomposing of organic substances. (2) eutrophication or algae bloom caused by the accumulation of organic nutrients like nitrogen and phosphorus, which promotes a high biomass in the superficial water. Apart from increased phytoplankton production, eutrophication can cause many other effects which may be more sensitive and relevant indicators such as changes in: energy and nutrient fluxes, pelagic and benthic biomass and community structure, fish stocks, sedimentation, nutrient cycling, and oxygen depletion (Gregory & Zabel 1990, Fang et al. 2004). (3) Water deterioration will bring about low productivity (4) Diseases may break out. Aside from this, inadequate handling of wastewater has serious consequences for human health, the environment and economic development (Enelld & Lof 1983). It contaminates water supply, increasing the risk of infectious disease and deteriorating groundwater and other local ecosystems, for instance after flooding.

1.2.4 Salinization of soil and water

Pumping large volumes of underground water to achieve brackish water salinity in the 1980s to mid-1990s led to the lowering of groundwater levels, emptying of aquifers, land subsidence and salinization of adjacent land and waterways in China. Even when fresh water is no longer pumped from aquifers, the discharge of salt water from shrimp farms located behind mangroves still causes salinization in adjoining rice and other agricultural lands (Primavera 2006).

2 Results

2.1 Case study on freshwater aquaculture in China

2.1.1 Pen aquaculture in lake

Lake Taihu is the third largest freshwater lake in China, with total water area of 2338 km². The main form of aquaculture in Lake Taihu is pen-fish-culture. Aquaculture has been limited to East Taihu, a macrophyte-dominated bay in the southeast part of the lake with an area of 131 km²,in which 2833 hm² are used for aquaculture (Yang et al. 2003). Within this area, it is estimated that the environmental load of nitrogen and phosphorous of 1 t fish production are 141 kg and 14 kg, respectively (Yang et al. 2003). In pen-fish-culture areas, increased nutrient loading leads to rapid growth of phytoplankton, zooplankton, and bacteria. After one year of fish farming, the phytoplankton abundance was three times higher than in non-culture areas, and heterotrophic bacteria abundance increased 3- to 4-fold (Yang et al. 2003). Total organic carbon, total nitrogen, and total organic nitrogen in surface sediments increased by 141, 87.5, and 86% respectively, after 2 years of fish culturing (Li 2004). Recently, fish culturing has been replaced by the more profitable freshwater crab culturing, which will increase the input of feed, and further increase the deposit of organic materials from the remnants of feed. From 1984 to 1993, fish and crab production of pen aquaculture in East Lake Taihu amounted for 11,165 t and 109 t, respectively. Nitrogen and phosphorous load to this lake were 1,634 t and 166 t, respectively. Compared to non-aquaculture areas, NH_4^+-N and phosphorous load of this area increased 55% and 46%, respectively. For the whole Taihu Lake in 1993, nitrogen, NH_4^+-N, phosphorous and COD contents increased 55%, 180%, 43% and 91% respectively compared to that of 1983 (Yang et al. 2003). The change of water quality in East Lake Taihu influenced by aquaculture in 1990s is presented in **Table 2**. Aquaculture in East Taihu increases nutrient concentrations in water and sediments, which accelerates eutrophication and marsh development.

2.1.2 Cage aquaculture in reservoir

Dahonghu Reservoir is located in southwest China with a total area of 40 km² (Ning et al. 2006). The main form of aquaculture in this reservoir is cage culture. **Table 3** presents comparison of physico-chemical parameters of water

Table 2: Changes of water quality index in East Lake Taihu caused by aquaculture (Qin & Luo 2004)

Year	TN (mg L^{-1})	NH_4^+-N (mg L^{-1})	TP (µg L^{-1})	COD (mg L^{-1})
1991	1.01	0.14	43	5.5
1993	1.04	0.20	75	5.6
1997	1.39	0.19	31	5.5
1999	1.65	0.48	40	6.6

Table 3: Comparison of physico-chemical parameters of water quality between cage inside and outside (Ning et al. 2006)

Parameters	Cage inside	5 meters downstream of cage	500 meters upstream of cage
TN (mg L^{-1})	57.3	56.7	55.6
TP(mg L^{-1})	63.7	63.6	61.5
Secchi disc (cm)	63.9	60.5	59.2
Chlorophyll-a (mg m^{-3})	60.0	59.8	62.8

quality between cage inside and outside. Cage culture in Dahonghu Reservoir increased nutrients content which might easily induce eutrophication. The TN and TP contents of cage inside water were significantly higher than those of cage outside water. Besides, in sediments below cages, the TN and TP contents were 681 mg/l and 30.7 mg/l, respectively, which were significantly higher than the non-culture areas ($P<0.05$). The main impact of cage aquaculture is the increase in the load of N, P, and organic matter that enrich water and underlying sediment. The amount of waste produced by a cage farm will depend on a number of factors such as the stocking density, the feeding regime, and the feeding rate because these three factors together determine the total amount of feeds to be used.

2.2 Case study on marine aquaculture in China

2.2.1 Ponds

Generally, less than 1/3 of the nutrients in feed are removed by harvesting in intensive fish farming (Troell et al. 1999). For intensive shrimp pond farming, it is even less, ranging between 6 and 21% (Robertson & Phillips 1995). Waste produced by shrimp and fish ponds located around Bohai Sea and Yellow Sea was investigated by Cui et al. (2005). Based on the assumption that FCR was 2, 7.9×10^4 metric tons of total shrimp production in Bohai Sea and Yellow Sea areas in 2002 indicated that more than 1.2×10^5 metric tons of uneaten feed was discharged into the sea. According to statistical analysis, rough data of wastewater produced by shrimp culture in Yellow Sea and Bohai Sea in 2002 were shown in **Table 4**.

The average water depth for shrimp culture was 1.0 m, with daily water change at 7.5% of total. Total shrimp culture area was 1.37×10^5 hm^2. Thus, the daily discharge of wastewater from shrimp culture was 1.03×10^8 m^3. Within one culture period (120 d), the total discharge amount of wastewater was 1.2×10^{10} m^3 in 2002. Tovar et al. (2000) estimated that 1 t of fish production could cause 34.61 kg of BOD, 14.25 kg of N and 2.57kg of P discharged into the sea. According to marine fish production in Yellow Sea and Bohai Sea in 2002, 2028 t of N, 376 t of P and 5056 t of BOD could be discharged into the sea (**Table 5**).

In Guangdong province in 2001, the environmental load of nitrogen and phosphorous produced from shrimp pond aquaculture were 4,508.7 t and 994.1 t, respectively (**Table 6**). In which, the discharge amount of COD, inorganic N, inorganic P and suspending solids contained in the wastewater, were 4,887.4 t, 136.8 t, 64.0 t and 17,689.6 t, respectively. The discharge amount of N and P from shrimp ponds were about 0.19% and 0.40% respectively that of the land-derived wastewater (Li et al. 2004).

2.2.2 Cages in open-sea waters

Being an essentially open system, cages are usually characterized by a high degree of interaction with environment and cage systems are highly likely to produce large bulk of wastes that are released directly into the environment. Therefore, large-scale cage aquaculture development has been put into question and concerns have been raised that cage aquaculture produces large bulk of wastes that are rich in organic matter and nutrients and are released into coastal and nearshore environment. For example, the contents of the organic matter in the sediment in the cage culture area of Dapeng'ao Bay (dry weight) ranged from 1.56% to 3.50% with average of 2.57%, and obviously higher than the normal value in the sediment along the Chinese coast waters (1.0%~1.5%) and the first grade of the National Standard (2.0%) (Gan et al. 2006). The mean contents of the organic matter inside and outside the cage area were 2.66% and 2.42%, respectively. It showed that in open sea cage culture, high organic and nutrient loadings were generated and culture areas were risking degradation. Feed wastage and pollutant loadings are much higher in open-sea cage culture systems where trash fish is used as feed (Wu 1995).

Table 4: Rough data of wastewater produced by shrimp culture in Yellow Sea and Bohai Sea in 2002 (Cui et al. 2005)

Province	Culture area (hm^2)	Discharge amount of wastewater (m^3)	N (t)	P (t)	COD (t)
Tianjin	2,960	2.7×10^8	27	2.7	540
Hebei	20,755	18.7×10^8	187	18.7	3,740
Liaoning	39,258	35.3×10^8	353	35.3	7,060
Shandong	60,428	50.4×10^8	504	50.4	10,080
Jiangsu	14,073	12.7×10^8	127	12.7	2,540
TOTAL	180,833	141.91×10^8	1,334.8	183.8	28,847.5

Table 5: Rough data of wastewater produced by fish culture in Yellow Sea and Bohai Sea in 2002 (unit: metric ton) (Cui et al. 2005)

Province	Yield (t)	N (t)	P (t)	BOD (t)
Tianjin	1,760	25	4.5	61
Hebei	11,003	157	28	381
Liaoning	54,330	774	140	1,880
Shandong	70,862	1,010	182	2,453
Jiangsu	8,125	116	21	281
TOTAL	146,080	2,082	376	5,056

Table 6: Evaluation on the waste derived from shrimp pond culture in Guangdong province in 2001 (adapted from Li et al. 2004)

City	Area (hm^2)	Production (ton)	Feed input (t·a^{-1})	Feed residuals (t·a^{-1})	N load (t·a^{-1})	P load (t·a^{-1})	Discharge amount of wastewater (x10^{8}m^3·a^{-1})	Pollutants discharged (t·a^{-1})			
								N	P	COD	Suspending solids
Chaozhou	1,165	2,790	3,627	725	127.8	28.2	0.59	3.9	1.8	138.5	501.4
Shantou	1,322	4,118	5,353	1,071	188.6	41.6	0.67	5.7	2.7	204.5	740.0
Huizhou	1,533	4,549	5,914	1,183	208.3	45.9	0.78	6.3	3.0	225.9	817.5
Shanwei	3,366	10,033	13,043	2,609	459.5	101.3	1.72	13.9	6.5	498.1	1,802.9
Guangzhou	371	796	1,035	207	36.5	8.0	0.19	1.1	0.5	39.5	143.0
Shenzhen	699	2,155	2,802	560	98.7	21.8	0.36	3.0	1.4	107.0	387.3
Zhuhai	2,311	2,332	3,032	606	106.8	23.6	1.18	3.2	1.5	115.8	419.1
Dongguan	768	1,050	1,365	273	48.1	10.6	0.39	1.5	0.7	52.1	188.7
Zhongshan	438	1,211	1,574	315	55.5	12.2	0.22	1.7	0.8	60.1	217.6
Jiangmen	2,229	6,687	8,693	1,739	306.3	67.5	1.14	9.3	4.3	332.0	1,201.7
Yangjiang	5,903	13,855	18,012	3,602	634.6	139.9	3.01	19.3	9.0	687.9	2,489.7
Zhanjiang	19,408	38,445	49,979	9,996	1,760.8	388.3	9.90	53.4	25.0	1,908.8	6,908.6
Maoming	3,580	9,618	12,503	2,501	440.5	97.1	1.83	13.4	6.3	477.5	1,728.4
Jieyang	159	491	638	128	22.5	5.0	0.08	0.7	0.3	24.4	88.2
Others	107	309	402	80	14.2	3.1	0.05	0.4	0.2	15.3	55.5
TOTAL	43,359	98,439	127,972	25,595	4,508.7	994.1	22.11	136.8	64.0	4,887.4	17,689.6

2.3 Comparison between land-derived waste and aquaculture waste

Compared to land-based wastes, the pollutants derived from aquaculture, including N, P and COD, accounted for 2.8%, 5.3% and 1.8% respectively (**Table 7**). Although they were just a small proportion compared to land-based pollutants, the negative effects such as red tide generated by aquaculture are increasingly recognized. In Hong Kong, BOD and N generated by the mariculture, constituted about 3% of total loading discharged into Hong Kong waters. However, it should be noted that fish-farm waste is not directly comparable to domestic sewage, mainly because of different C:N:P ratios and significant differences in settleable and soluble wastes (Wu 1995).

Table 7: Comparison between amount discharged to sea of marine culture and land-based pollutants in the Yellow Sea and Bohai Sea (Cui et al. 2005)

Sources	Pollutants discharged (t)		
	N	P	COD
Industry and life sewage	21.2×10^4	1.7×10^4	162×10^4
Shrimp culture	1,198	120	23,960
Fish culture	2,082	376	5,056
Shellfish culture	2,630	428	–
Ratio of pollutants from aquaculture to that of land-derived (%)	2.8	5.3	1.8

2.4 Waste treatment methods

Physical methods, aimed at removing the suspended solids obtained and reducing the BOD and chemical oxygen demand (COD), are most widely applied on waste treatment in aquaculture in China. They include sedimentation, mechanic filtration, and sand filtration. These kinds of methods are usually simple and inexpensive. However, they belong to water quality pretreatment and primary processing, which has only moderate effects on removing the soluble organic matter such as N and P. During extensive tests conducted by the Norwegian Hydrotechnical Laboratory, the treatment efficiency of a 60-mm pore size drum screen varied considerably within the ranges SS (67–97%), TP (21–86%) and TN (4–89%) (Cripps & Bergheim 2000). Chemical methods, including neutralization, coagulation, sterilization and oxidation, are usually the fastest ways to annihilate pathogens. However, the cost for this type of treatment is rather high. Additionally, some of these methods may bring about toxic effects such as a high concentration of organic chlorine.

Biological methods, including aerobe treatment, anaerobe treatment and aquatic life-form treatment, are based on microorganisms to convert organic substances into the harmless carbonates or nitrates. With low investment and no second pollution, these methods are regarded as the most promising treatment technology. To enable reuse of water in these systems, biological treatment is considered the most economically feasible approach. Integrated aquaculture systems are considered a promising technology, but recent efforts have been essentially devoted to macroalgae (Troell et al. 2003). Methods for treating effluents from enclosed mariculture systems with macroalgae were initiated in the mid 1970s (Troell et al. 1999). The utilization of aquatic macroalgae for the removal of nutrients in aquaculture wastewater effluents and water bodies is well documented (Redding et al. 1997). The resulting gains in vegetative biomass can provide economic returns when harvested. However, in open culture systems such as cage culture, the continuous exchange of water makes waste disposal difficult to control and, so far, few studies have investigated the possibilities of integrating seaweeds with such cultures (Hirata & Kohirata 1993, Troell et al. 1997). There is also a serious dearth of literature focusing on the feasibility or application of integrated cultures of seaweeds and shrimps (Troell et al. 1999). Research on microalgae treatment systems has been neglected and there were only a few studies on marine integrated systems (Lefebvre et al. 1996, Hussenot et al. 1998). The obstacles for its full scale development include the need for system characterization and adaptation to each region, effluent type, effluent final disposal and algal species (Hussenot 2003). In addition, utilization of bivalve mollusks as biofilters such as growing giant clams (*Tridacna derasa*) in aquaculture effluents for microalgae produced on wastewater reuse systems is also a profitable option. But existing literature refers mainly to oysters fed mixed phytoplankton or diatom species, naturally existing and induced to bloom (Hussenot et al. 1998, Troell et al. 2003). Conventional treatment systems have the disadvantages of sludge production, high-energy demand, and frequent maintenance requirements. Natural treatment systems, including constructed wetlands, have grown in popularity for wastewater treatment since the early 1990s in China (Gao 2000). Constructed wetlands have been used to treat mine drainage, storm water runoff, municipal wastewater, industrial wastewater, and agricultural effluent from livestock operations. Treatment wetland systems can remove significant amounts of suspended solids, organic matter, nitrogen, phosphorus, trace elements, and microorganisms contained in wastewater (Kadlec & Knight 1996). Constructed wetland systems are characterized by the advantages of moderate capital costs, low energy consumption and maintenance requirements, and benefits of increased wildlife habitat (International Water Association 2000, Lin et al. 2002).

3 Discussion

3.1 Environmental impacts of different culture species

The environmental impact of aquaculture depends very much on species, as well as culture method, hydrography of culture site, feed type and husbandry practices.

3.1.1 Shrimp

Chinese shrimp farms are distributed along almost 18,000 km of coastline from Hainan Province in the tropics to Liaoning Province in the temperate zone (Xie & Yu 2007). Farmers usually culture two crops of shrimp per year in southern China, while to the north of Yangtze River farmers can harvest only one crop. China possess about 14,000 shrimp farms, of which 5% belong to the intensive type, with 54.0 individuals/m^2, an average acreage of 6.9 ha, a feed conversion rate of 2.1 and a yield of 2,808 kg/ha (Xie & Yu 2007). The majority (85%) of farms, are half intensively managed with 19.7 individuals/m^2, an average acreage of 24.9 ha, a feed conversion rate of 2.1 and a yield of 848 kg/ha. Main shrimp types cultured in China are *Penaeus chinensis, P. monodon, P. japonicus, P. merguinsis, P. penicillatus, Metapenaeus ensis* and *P. vannamei* (Pan 2001).

Rapid development of shrimp farming brings a series of environmental, human health and safety problems, as well as considerable profit and interests, thus causing concern about its sustainability. About 43 billion tons of waste water from shrimp farming and shrimp breeding system spill into the coastal waters in China every year (Xie & Yu 2007). The Bohai Bay has reached a critical point beyond which it could become a 'dead'sea due to pollution. As reported by Feng in 1996, in one Bohai Sea area where large-scale shrimp farming and production took place, the COD level is over 200 times higher, and active phosphorous is 900 times higher than those of the surround environment. The levels of COD, active phosphorus, and ammonium tested at the same area are 3.7, 7.8 and 2.4 times higher in comparison with those of pre-shrimp production time (Feng 1996), indicating a significant imbalance in the material recycle of the adjacent environment. If the annual feed consumption efficiency is 15–20% and the feed conversion ratio is 2, China would produce 200,000 tons of the shrimp and drains 320,000~340,000 tons of the farming effluents into the sea. In 1998 in Fujiang Province, the shrimp production discharged as much as 3.73×10^8 tons of the shrimp sewage, including 5,589 tons of COD, 658 tons of nitrogen and 307 tons of phosphorus. Du et al (2002) reported that red tides occurring in large areas offshore Guangdong and in Bohai Sea caused a great loss in the aquaculture industry in 1998 and 1999.

As reported by Wang et al. (1995), healthy and sustainable shrimp industry can only flourish if marine ecosystem was kept in good balance; rational development plans were designed; environmental friendly farming models were chosen; and practical farming measures was implemented, in accordance with specific local conditions. Management measures to improve coastal water quality and mitigate the adverse environmental impact of shrimp aquaculture development are now required urgently and necessarily. Deliberately implementing advanced wastewater treatment in the watershed and by reducing the nutrient inputs from fertilizers and shrimp food could be the best way to reduce the nutrient loadings to the coastal creeks. So far, no countries or regions have established the specific measures of the sustainable development of shrimp farming, but without doubt, all of them are making efforts toward it (Xie & Yu 2007).

3.1.2 Shellfish and finfish

The main resource of pollution from shellfish culture is the excreta of shellfish. It has resulted in local anoxia of bottom sediments. Raft culture of shellfish can alter the speed and direction of water current, which speed up the accumulation of suspending solids and siltation. **Table 8** shows the

Table 8: Research of organic matter produced by shellfish in China (Zhao & Zhang 2004)

Species	Culturing area	Results
Oyster	Guangdao Bay	During 9 month culture period, total of 16 t excreta was produced by 420,000 of oysters
Chlamys farreri	Sanggou Bay	Producing 18,520 t of excreta (dry basis) annually
Placopecten magellanicus	Jiaozhou Bay	Producing 8.2~12.0 kg (hm$^2\cdot$ d)$^{-1}$ of excreta
	Sishili Bay	Producing 2,000~2,500 t of excreta (wet basis) annually

study results of organic matter produced by shellfish. However, compared to shrimp culture, waste from shellfish culture is less. Some filterfeeding bivalves such as *Patipectin yessoensis* even act as cleaners to be used in integrated fish-bivalve system.

Almost all studies on the environmental impact of marine fish farming have been carried out in temperate regions where salmonid fish were cultured in ponds/cages and fed with artificial feed. Fluxes and mass balances of C, P and N determined for a salmonid cage farm (rainbow trout fed with dry feed) indicated that 80% of C, 76% of N and 82% of P of feed input into the system were lost to the environment (Wu 1995). In trout cage farms, some 19% to 28% of total nitrogen input could be harvested in the form of fish production (Islam 2005). A decrease in dissolved oxygen and increases in BOD, nutrients (P, organic and inorganic N and total C) have been generally found in the water column around fish farms. However, for freshwater culture, there are no specified data for pollution investigation on each specific fish. Some fiterfeeding freshwater fish such as silver carp, bighead carp and tilapias, even can be used in polyculture system to better utilize the surplus nutrients.

3.2 New approaches of waste treatment

A number of new approaches to aquaculture effluent management are being innovated. Nevertheless, most of them have been mainly based on laboratory tests. The commercial and practical values of these new approaches are needed to be evaluated before applied. The potential of ultra-low pressure polyethersulfone (PES) membranes for the treatment of aquaculture wastewater were investigated recently. It is found that the membranes prepared exhibited an excellent performance in terms of a high rejection of total ammonium and total phosphorus up to 85.70% and 96.49%, respectively (Nora'aini et al. 2005). Whether this approach can be utilized on a large scale still needs further investigation because of the costly expenses.

One of the most advanced techniques for wastewater treatment and reuse is the reverse osmosis (RO) process, which is widely used to produce potable water from brackish water and seawater in order to reclaim contaminated water sources and to reduce water salinity for industrial applications (Asano 1998, Gang et al. 2005). But the application of RO membrane for aquaculture wastewater treatment has been largely limited. One of the major problems is the energy cost during the membrane filtration process. In order to reduce the energy cost for RO membrane operation, researchers have turned to renewable energy sources for solutions. According to Gang et al (2005), the wind-driven RO system for nitrogen removal was technically feasible and environmentally friendly. The most unique and important feature of this system was that it could treat and recycle aquaculture wastewater using renewable energy, making it suitable for use in remote areas where electricity was hard to obtain. The system was able to work at an average wind speed as low as 3.0 m/s. Depending on the wind speed, it can generate and recycle freshwater at a flow rate of 228–366 L/h. The permeate production increased linearly with the wind speed. About 70–84% of aquaculture wastewater can be recycled using this system, which was capable of removing 90–97% of nitrogenous waste present in tilapia culture effluent. The average recovery rate of the membrane used in this system is about 39.2–57.5%. The estimated cost of producing 1 m^3 of freshwater from the aquaculture effluent is US$ 4.00. Although producing water using the wind-driven RO system seems too expensive in the current situation, this technology has great promise once the system scale can be upgraded.

3.3 Proposals for sustainable aquaculture development

3.3.1 Feed quality and feeding improvement

Feed wastage is one of the most important sources contributing to organic and nutrient loadings. Wastage may range from 1–38%, depending on the feed type, feed practices, culture method and species (Wu 1995). Improving feed quality by feed additives in recent years, such as microbial phytase, has resulted in enhanced bioavailability of phosphorus and nitrogen, at lower concentrations (Cripps & Bergheim 2000, Cao et al. 2007). Thus, the quantity of fecal solids produced by fish was reduced and there was less phosphorous load to the ambient aquatic environment. Research has shown that a significant reduction in the level of incorporation of fish meal is possible without affecting the growth rates or flesh quality in several species of interest to aquaculture (Mente et al. 2006, Cao et al. 2007). Improved pellet integrity, with subsequent slower breakdown rates, further reduced feed losses. The development of high energy diet with increased fat content, reduced carbohydrate levels, reduced protein levels, and improved digestibility will significantly decrease waste production. The close relationship between feed quality and feed-derived waste production has been demonstrated in several reports (Cripps & Bergheim 2000).

Optimized feeding systems and protocols have also reduced wastage. There are three ways possible to achieve control of feed impacts from aquaculture: (1) control of the sites where the culture farms are located; (2) control of the released effluents; (3) monitoring of impacts generated by effluents once the farm begins its work. Polyculture, or integrated aquaculture associating shellfish and algae culture with fish culture, may be part of the solution (Mente et al. 2006). The feeding regime and technology used to both deliver rations to the stocks and monitor its intake can be used to minimize waste losses. Feed utilization should be maximized by optimally supplying feed to the fish stock to minimize the uneaten quantity. The required capacity of treatment systems can then be reduced, thus saving capital and operating costs. Additionally, in water reuse systems that generally have a fixed carrying capacity based on the ability of the system to handle the daily feed application, removing the waste feed load can effectively increase fish rearing capacity. Technology for monitoring uneaten pellets has been shown to be a useful means of reducing wastage (Summerfelt et al. 1995). When pellets are detected in the tank effluent, the devices discontinue feeding. A pre-set timer is then activated to control the interval between feedings. As well as optimizing the timing of feeding, the feeding location can affect both the quantity of solids wasted and their distribution within the culture facility. Fish usually do not graze feed pellets off the bottom, thus tank hydrodynamics, pellet structure and feeder location need to be adjusted to maintain the feed solid suspension as long as possible.

Feed development may need to place increased emphasis on the efficient use of resources and the reduction of feed waste and nutrient discharge. One of the limits of aquaculture expansion is likely to be the availability of feeds derived from fish meal or fish oil resources. Concerns about contamination and possible risk to humans such as level of dioxins in fish have been expressed. Future studies aimed at gaining an understanding of the physiological basis of observed growth in terms of anabolic and catabolic processes will enable informed decisions to be made on the modification of diets and feeding regimes. Research is still needed to improve feed quality and usage in aquaculture, which will result in better fish growth and survival. Feeds should be designed to contain high digestibility, low rates of N excretion and less dietary protein to minimize nutrient discharges from aquaculture to the environment and ensure the sustainability of the aquaculture.

3.3.2 Integrated aquaculture system

Rapid development of intensive aquaculture in China has raised increasing concerns on environmental impacts of such often mono-specific practices (Zhou et al. 2006). The negative economic and environmental features of mono-specific operations are being realized and their sustainability questioned (Zhou et al. 2006). In recent years, there has been increasing emphasis on developing sustainable integrated cultures (with macroalgae, filter-feeders and deposit-feeders). It is ideal to accommodate two or more ecologically compatible species in one system; they can co-inhabit an environment with no conflict in foods and space.

By integrating fed mariculture (fish and shrimp) with inorganic and organic extractive mariculture (seaweed and filterfeeding bivalve), the wastes of one resource consumer become a resource (fertilizer or food) for others in the system. Such a balanced ecosystem approach provides nutrient bioremediation capacity, mutual benefits to co-cultured organisms, and economic diversification by producing other value-added profitable products (Chopin et al. 2001). Modern integrated mariculture systems, seaweed-based in particular, are bound to play a major role in sustainable development in coastal aquaculture (Neori et al. 2004). Fish effluents produced by open-water systems are more difficult to treat than those from land-based systems. Integration with seaweeds and/or filter feeders is often proved to be the only economically feasible alternative for waste treatment in open-water systems (Troell et al. 2003).Various strategies for integrating seaweed into fish culture have been proposed. Buschmann et al. (1994) finds that the effluents from intensive tank culture of salmon in Chile favor the production of *G. chilensis* in tank culture. Also, Haglund and Pedersen (1993) find that *Gracilaria tenuistipitata* grows well in co-cultivation with rainbow trout, particularly in warm months of the year. The selection for the best seaweed species suited for an integrated aquaculture may differ depending on the type of culture operation (Nelson et al. 2001). The filtering rates of the oyster *Crassostrea gigas* and the scallop *Patipectin yessoensis* may be up to 101 and 951 d^{-1} individual^{-1}, respectively (Wu 1995). The use of mussel/oyster to control phytoplankton growth and eutrophication has also been suggested (Wu 1995).

Chopin et al. (2001) has suggested that integrating seaweed into fish aquaculture in coastal waters can alleviate the seasonal nutrient depletion by using constant nutrient supply from fish farm, which is then valued (wastes become fertilizers) and managed (competition for nutrients between desirable algal crops and problem species associated with severe disturbance). The co-culture provides mutual benefits for involving organisms: seaweeds capture the nutrients required for their growth, while contributing to water quality improvement around fish for their health enhancement (Chopin et al. 2001, Neori et al. 2004). Cultivation of seaweeds in the proximity of fish cages not only counterbalances nutrient inputs but also other metabolic aspects, such as dissolved oxygen, acidity and CO_2 levels, in one step. Consequently, as legislative controls on discharge of inorganic nutrients into coastal waters become more stringent and the 'polluter pays' principle will be implemented in the soon future, bioremediation via the production of seaweed will aid the fed fish mariculture industry to avoid non-compliance (Zhou et al. 2006). One of the primary benefits derived from this system will be its contribution to the reduction of inorganic nutrient discharge into waters, decreasing the potential for outbreaks of devastating and costly hypertrophic events. An additional benefit, to operators of finfish aquaculture, is that the currently discharged (unassimilated and/or excreted) P and N, which represent a loss of money in real terms, will be captured and converted into the production of saleable macroalgae. Finally, economic development and job diversification would be achieved by developing this sustainable and environmentally system to optimize the efficiency of aquaculture operations, while maintaining the health of waters (Chopin et al.1999).

3.3.3 Waste management

In order to reduce the negative impact of aquaculture waste, production of waste products in aquafarms should be studied and water quality standards of the environment where effluents are discharged should be set. But to our knowledge, in China, no studies have characterized waters receiving aquafarm effluent and waters used by the farms, or have related water quality to farming activity. Past, obsolete technologies and incomplete arrangement of waste management systems are still used in aquaculture, which might cause a great economic loss, destroy the aquatic biodiversity, and to some extent, hinder the sustainable development in aquaculture. Thus, imperative treatment of aquaculture waste should be spread and strengthened. Closed and semi-closed water systems that recycle water through a series of reservoirs, treatment ponds (with fish, bivalves and algae) and canals back to production ponds serve to reduce the amount of discharged wastes and minimize the entry of disease organisms from natural waters. Pond sludge may be reduced through the application of probiotics, or by the tilling and drying of the pond bottom. Alternatively, sludge may be collected and stored near the farm for mangrove planting or subsequent transfer to agricultural or forest land. Mangroves can be used to treat shrimp pond effluents with high levels of solids, organic matter and nutrients.

3.3.4 Governmental regulation

Misuse of the antibiotics may result in antibiotics residues in the aquaculture products, which leads to not only the decrease in the immunity of the aquaculture products, but also the decrease in the disease resistance of consumers and the increase in the possibility of infecting the disease. The European Union prohibited the import of shrimps from the mainland of China, Vietnam and Indonesia after finding the prohibited chloramphenical remained in the imported shrimps (Xie & Yu 2007). Aquaculture products can accumulate the heavy metals from the pesticides, algaecides and some organic organisms used in the farming through biologic accumulation, which may lead to food safety problem. Thus, legislative control on chemicals used in aquaculture should be strengthened. Further research should be focus on finding alternatives for present chemicals. Rational stocking density within the capacity of ecosystem is recommended for disease prevention.

In recent decade, some regulations in aquaculture management have also been attempted by Chinese government. For example, 'Water Quality Standard for Fisheries' (GB11607-89) was issued and enforced on 1 March 1990 (Xie & Yu 2007). The Ministry of Agriculture issued 'Regulations for Fishery Loss Calculation of Accidents of Waters Pollution' and 'Regulations and Procedures for Investigating and Handling Pollution Accidents in Fishery Waters' in 1997, thus bringing the investigation and handling of pollution accidents in aquaculture onto a legal track. Ministry of Agriculture and local fishery administrations began to reinforce construction of infrastructures of fishery environment monitoring stations in 1999. However, more specific regulations and standards for developing environmental friendly aquaculture should be shaped.

4 Conclusions

China's aquaculture will continue to play an important role in the global supply of fish in the future. Negative effects of waste from aquaculture to aquatic environment are increasingly recognized, though they were just a small proportion to land-based pollutants. Properly planned use of aquaculture waste alleviates water pollution problems and not only conserves valuable water resources but also takes advantage of the nutrients contained in effluent. It is highly demanding to develop sustainable aquaculture which keeps stocking density and pollution loadings under environmental capacity.

5 Recommendations and Perspectives

The treatments of aquaculture waste and wastewater in China is still in its preliminary stages and there is no quantitative data to show how much of the polluted areas are treated or not. Additionally, the insufficient detection system of aquatic environment and wastewater discharge standards for aquaculture promote the pollution caused by the direct waste discharge. It is, therefore, necessary that proper policies and practical management systems for regulating aquaculture waste be adopted. Different stages of waste management in aquaculture should be integrated so that the overall rate of pollutant removal and reuse is optimized. Such stages will comprise feed quality manipulation, feeding management, waste pretreatment, primary separation, secondary thickening, sludge stabilization and sludge reuse or disposal. It would probably be more efficient and beneficial to combine two approaches more in the future. The traditional procedures for aquaculture waste treatment, mainly based on physical and chemical means, should be overcome by more site-specific approaches, taking into account the characteristics and resistibility of the aquatic environment. Further research needs to improve or optimize the current methods of wastewater treatment and reuse. Proposed new treatment technology should be evaluated for their feasibility at a larger scale for practical application.

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