Chapter 1
Overview of Land-Based Recirculating Aquaculture

Toshio Takeuchi

Abstract Land-based aquaculture systems can be divided into two types, those that use running water and those that recirculate water in a closed system. In Japan, recirculating aquaculture systems (RASs) that have a water exchange rate of below 5% in total volume are further specified as closed recirculating aquaculture systems (CRASs). This section gives an overview of the recent developments in research on land-based aquaculture, and on CRAS in particular, as a preparation for the case studies from Chap. 2 onward. In short, this section will describe the current state of CRAS, its features, advantages, and development history, as well as the challenges, economics, feasibility, and business opportunities for CRAS in the future.

Keywords Land-based aquaculture • Closed recirculating aquaculture system • History • Economics

1.1 Introduction

Conventional aquaculture has its own disadvantages, which led to the development of CRAS. Currently, most aquaculture fisheries, such as red sea bream *Pagrus major*, yellowtail *Seriola quinqueradiata*, and Pacific bluefin tuna *Thunnus orientalis*, are conducted as mariculture using net cages. Figure 1.1 illustrates a disadvantage of this net cage culture (Hall et al. 1992), using rainbow trout *Oncorhynchus mykiss* as an example species. Although rainbow trout is a freshwater fish, it is an appropriate example, because it is a well-studied fish culture that also can be kept in saltwater, where it is known as steelhead. In the past, fish in net cages were fed either raw fish or moist pellets, which combined raw fish and mash feed. Currently, fish are more often given only dry pellets. As soon as fish have reached a marketable size, they are harvested, and 27–28% of the nitrogen given as feed is redeemed as fish. Death accounts for 2–5% of nitrogen; however, the main disadvantage is that the rest is lost to the environment, as shown at the bottom of the

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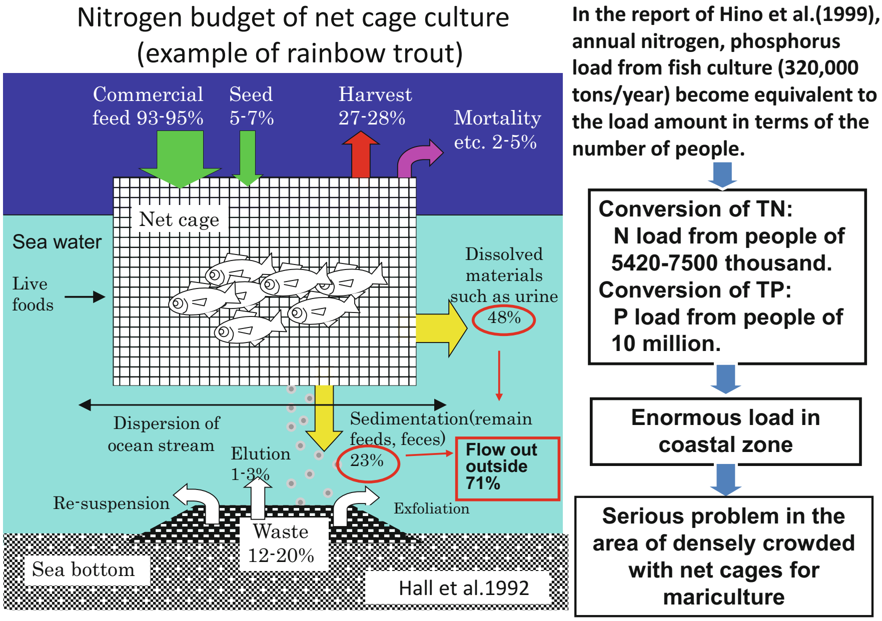

In the report of Hino et al.(1999), annual nitrogen, phosphorus load from fish culture (320,000 tons/year) become equivalent to the load amount in terms of the number of people.

Conversion of TN:
N load from people of 5420-7500 thousand.
Conversion of TP:
P load from people of 10 million.

Enormous load in coastal zone

Serious problem in the area of densely crowded with net cages for mariculture

Fig. 1.1 Problems of net cage mariculture (Modification of Hall et al. 1992 in left side and Hino et al. 1999 in right side)

figure. Effluents such as urine and soluble nitrogen account for 48% of the nitrogen, and fecal and feed scrap sediments account for 23%. These add up to 71% of nitrogen being wasted, which clearly contributes to marine pollution. According to calculations regarding aquaculture in Japan published in 1999 (Hino et al. 1999), the quantity of total nitrogen wastes derived from both inland water aquaculture and mariculture is equivalent to that produced by 5.42 to 7.5 million people, and total phosphorus waste is equivalent to that of 10 million people; these figures represent significant amounts of pollution. This would not pose as large of a concern if the effluent were spread around the whole coastline; however, aquaculture is conducted in a limited number of locations concentrated in coastal zones such as the Seto Inland Sea and Ise Bay. Essentially, mariculture will inevitably lead to massive self-pollution.

This section will introduce land-based aquaculture, especially CRAS, in order to further stimulate the global growth of aquaculture. It also provides an overview on the challenges regarding the popularization, economics, and feasibility of land-based aquaculture as well as the business opportunities that it can provide.

1.2 Current Status of CRAS

Due to the limited number of marine resources, the global production capacity of marine fisheries will inevitably be reached as the global demand for aquatic products continues to swell. It is therefore necessary to turn to aquaculture to meet this increasing demand. However, mariculture can be deployed at only a limited number of suitable locations. These limited conditions led to the fast development and industrialization of land-based aquaculture, such as CRAS, which does not require a location with specific conditions and has a higher productivity potential than offshore sea and inland water aquaculture.

Two factors have contributed to this fast development. The first factor is the effect of legal restrictions concerning pollution load, in the form of total effluent regulations and the Water Pollution Prevention Act. Until recently, aquaculturists regarded themselves as the victims of water pollution, as pollution in lakes, rivers, and enclosed bays has a negative impact on fish. With the discovery that the effluent from net cage mariculture causes self-pollution, as mentioned earlier, this opinion has changed. Now, aquaculturists are held responsible for the damages caused by eutrophication, and solutions are demanded of them, especially for reducing freshwater and saltwater levels of nitrogen and phosphorus (Takeuchi 2002; Takeuchi et al. 2002).

The second factor is the shifting trend of consumer awareness toward safety in aquaculture products. Consumers now demand transparent, completely regulated production systems that provide safe, responsible, and stable products as efficiently as possible. One result of this shifting awareness is the application of the hazard analysis critical control point (HACCP) system to the production processes of aquatic products. HACCP has already been implemented in other areas of food production, and between 1998 and 2000, Japan's national fishery agency tasked the Japan Fisheries Association with implementing HACCP in aquaculture. This first resulted in the HACCP manual for yellowtail, followed by the manual for seaweed *Porphyra tenera* and scallop *Patinopecten yessoensis* (Japan Fisheries Association 2000, 2001). Furthermore, the March 2007 meeting of the Japanese cabinet resulted in the introduction and standardization of the good aquaculture practice (GAP) methods in its basic fishery plan, and by March 2010, the handbook for the GAP method was created. The March 2011 great east Japan earthquake further increased consumers' concerns for safety. With the dispersal of radioactive substances, especially cesium-137, following the accident at the Fukushima Daiichi Nuclear Power Plant, assuring the safety of aquatic products from the Fukushima area has become even more difficult. These events led to a further realization that the best way to pursue the implementation of the GAP method is through CRASs for both freshwater and saltwater cultures.

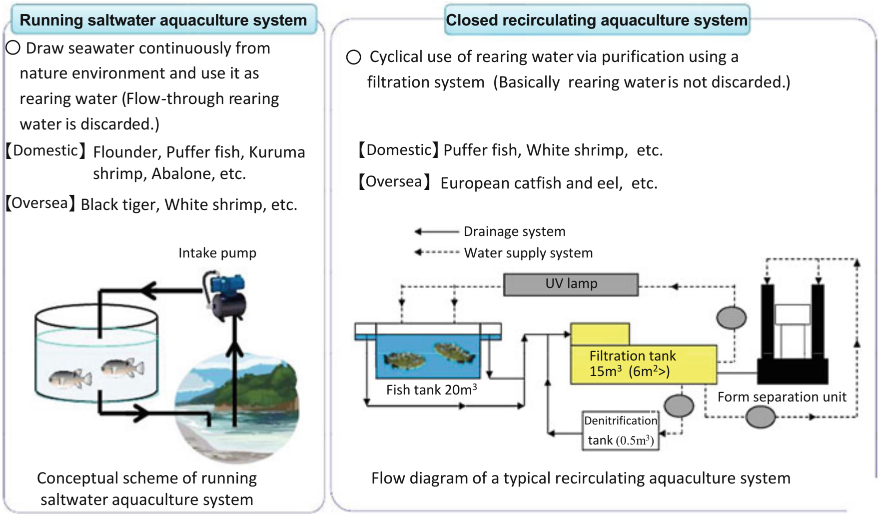

Fig. 1.2 What is land-based aquaculture (Modification of Fisheries Agency HP, http:www.jfa.maff.go.jp/j/saibai/yousyoku/arikata/pdf/4-3-1docu.pdf)

1.2.1 What Is Land-Based Aquaculture?

Figure 1.2 shows a diagram of land-based aquaculture, adapted from the homepage of the fishery agency (http://www.jfa.maff.go.jp/). Land-based aquaculture is the culture of aquatic products in an artificial environment constructed on land. There are two main approaches to land-based aquaculture, the running water system, which continuously pumps in rearing water from an external source and pumps out used water, and the closed recirculating system, which filters and recirculates the rearing water within a closed system.

In general, the running water aquaculture system involves setting up the culture tank or pond near the seashore or a river. The rearing water is drawn from the environment, and the used water is pumped back, thus polluting the environment with feed residue, feces, and urine. In Japan, this method is often employed for the culture of Japanese flounder *Paralichthys olivaceus* and kuruma shrimp *Marsupenaeus japonicus*, and in Southeast Asia, it is especially popular for the culturing of tiger shrimp *Penaeus monodon* and white shrimp *Litopenaeus vannamei*. In Thailand, a running water aquaculture system to culture white shrimp adapted for use in rice fields has caused a large harmful shifts in soil salinity.

In comparison, a RAS does not significantly expel effluents into the environment. In Europe, a system in which 10–50% of the rearing water is refreshed per day is designated a RAS. In Japan, a system that requires less than 5% of the rearing water to be refreshed and that has total water loss from normal evaporation and waste removal of less than 1% is defined as a CRAS.

1.2.2 The Current State of Land-Based Aquaculture

The total production volume of marine products (including fish, shellfish, crustaceans, and mollusks) from land-based aquaculture in Japan is estimated to be 6300 metric tons, equating to 66 million yen in profit. The majority of land-based aquaculture employs the running water system, and their production is limited to commercially profitable products such as Japanese flounder, tiger puffer *Takifugu rubripes*, kuruma shrimp, and abalone *Haliotis* spp. There are currently no statistics on the production from RAS aquaculture; however, it is estimated to be less than 100 metric tons. The reasons for the unpopularity of RAS are the high initial costs of facility construction and the high running costs due to factors such as electricity usage. These costs cause the price of the products to exceed the market price, making RAS an unfeasible system (this point will be discussed in more detail later). In addition, fish farmers' lack of experience with this system may result in massive deaths caused by inappropriate disinfection and oxygen supply, mismanagement of fish seed, and poor estimation of nitrifying capacity, all of which would force the facility to shut down. Other problems include the lack of backups (e.g., of materials) in case of emergencies.

1.2.3 A History of Land-Based Aquaculture

RAS was invented surprisingly early; the concept of a recirculating filter-equipped aquarium for freshwater and saltwater fish was developed in the late 1950s by Dr. Saeki, Faculty of Agriculture, University of Tokyo. The criteria for the setup were defined not from experience, but theoretically. In the 1960s, there were great advances in the study of the microbiology and sanitization of filtration tanks, and the RAS seemed near realization. These technologies were applied to aquariums, leading to dramatic improvements in fish culture. However, their implementation in aquaculture was very limited, and the technologies were only partly incorporated in the RAS for eel culture, which was developed later.

Meanwhile in Europe and the United States, the research on RASs progressed from the 1970s, and its application in recirculating systems for fish culture was actively pursued through methods such as involving manufacturing companies and other industries. Japan lagged behind greatly in this practical phase. Research in Japan on CRAS for marine fish progressed in the late 1980s (Hirayama et al. 1988), influenced by the trends abroad. Especially significant contribution was made by the Central Research Institute of Electric Power Industry toward the creation of a system that was compatible for industrialization, which was designed for Japanese flounder (Hino et al. 1999). Following practical implementation trials with eels (Maruyama 2002), pejerrey *Odontesthes bonariensis* (Yoshino et al. 1999), and tiger puffer (Marino-Forum 21 1999–2003), full-scale facilities have been set up for species such as white shrimp (Nohara 2012) and production has begun. See Pet III and Chap. 10 for details on the current filtration system used in tanks and on CRAS for various aquatic products.

1.2.4 Advantages of CRAS

The advantages of CRAS include (1) artificially controllable culture environment (less impact from meteorological phenomena such as global warming and typhoons); (2) promoting the brand of the products, such as by raising their quality and avoiding the use of chemicals; (3) the location of facilities can be more freely decided, as there are no restrictions on placement posed by the fishery act such as the demarcated private fishery areas; (4) possibilities for the employments of a greater range of workers, such as the elderly, because the work can be performed on land; and (5) contribution to a better environment by not releasing effluents. Taken together, these advantages allow CRAS to avoid the impacts of natural hazards such as red tides and typhoons, and high-density production and uniform product size can be achieved all year round, as water temperature can be controlled. This type of system will also enable the production of aquatic products in an environmentally friendly, safe, stable, and efficient manner. Absolute product traceability would be possible, as would the introduction and branding of new breeds, avoidance of aquaculture chemicals that prevent disease outbreaks, avoidance of contamination by heavy metals and dioxins in the environment, and reduction of the environmental impact of nitrogen and phosphorus pollution. Additionally, we have reported possibilities for even further-enhanced productivity through the adjustment of culture conditions. For instance, changing the photoperiod and changing the salinity of culture water in a previous study led to enhanced growth of fish and regulated reproduction (Takeuchi and Endo 2004).

1.2.5 Features of Representative Systems

Table 1.1 shows features of representative RASs and CRASs in Europe, the United States, and Japan (Hino et al. 1999). It is worth noting that the table has taken into consideration various factors, such as the kind of system implemented at the facility, type of fish (freshwater or saltwater), method of solid waste removal and (de)nitrification, water exchange rate, and final culture density. This means that a single, uniform system is not sufficient, as different systems are intermingled. The reality is that trial and error in optimizing the system is inevitable.

Table 1.1 Characteristics of certain land-based aquaculture systems (Hino et al. 1999)

Item	Certain European system	Central Research Institute of Electric Power system	Israel system	Fully equipped system	Miyazaki university system
Purpose	Full scale	Experimental	Experimental	Experimental	Experimental
Target fish	Seabass etc. (saltwater)	Japanese flounder (saltwater)	Carp (freshwater)	Pejerrey (0.7% brackish water)	Eel (freshwater)
Rearing period	1–2 years	About 1 year	About 80 days	About 1 year	About 8 months
Scale of the system	Variously	10 kL	50 kL	2.1 kL	1.1 kL
Filtration	Mesh filter	Settling tank and drum filter	Settling tank	Drum filter with foam separation unit	Foam separation unit
Nitrification	Biofilter	Immersed filtration	Trickling filtration	Rotary disk fluid bed	Upward flow-type immersed filtration
Ammonia-N	<2 mg-N/L	<1.05 ± 1.22 mg-N/L	<2 mg-N/L	<0.2 mg-N/L	<Av. 1 mg-N/L
Nitrite-N	<2 mg-N/L	<1.53 ± 1.24 mg-N/L	0–0.4 mg-N/L	<0.1 mg-N/L	<Av. 0.1 mg-N/L
Denitrification	Non	Non	Anaerobiotic fluid bed (sand, sludge product)	Immersed filtration (fiber type filter, methanol)	Upward flow type (cylinder type filter, methanol)
Nitrate-N	–	–	Max 40 mg-N/L → 0–15 mg-N/L	900 mg-N/L → 150 mg-N/L	150 mg-N/L → 40–50 mg-N/L
Oxygen supply	Oxygen-generating and oxygen-dissolving device	Oxygen-generating and oxygen-dissolving device/aeration	Trickling and aeration	Oxygen-generating and oxygen-dissolving device	Foam separation apparatus
Saturation degree/DO density	>90%	>10–130%	6–7 mg/L	Av. 103%	Av. 80%
Water temp.	16–24 °C	20–25 °C	22–27 °C	20 °C	28 °C
pH	6.5–8.3	7–7.5	7–7.8	7–8.2	7.5–8

(continued)

Table 1.1 (continued)

Item	Certain European system	Central Research Institute of Electric Power system	Israel system	Fully equipped system	Miyazaki university system
Sterilization of rearing water	UV irradiation	UV irradiation	None	UV irradiation	None
Exchange water rate	100%/day	150%/year	6%/day	8.5 L/day (0.4%/day)	None
Survival rate	–	95%	69%	92%	91%
Final culture density	>100 kg/m^3	39 kg/m^3	15 kg/m^3	18 kg/m^3	33 kg/m^3

1.3 Challenges in the Popularization of Land-Based Aquaculture

1.3.1 Comparisons of Mariculture and Land-Based Aquaculture

The advantages of CRAS are especially obvious in the category of issues involving the environment. Recent changes in climate leading to increased saltwater temperature and the subsequent alteration in the quantity and type of catch, the prevalence of red tides, the aging of the fisherman population, population decline in fishery regions, and regional radioactive contamination are all problems that mariculture must face. In addition, contact with external water creates a high risk of disease in mariculture and in running water systems. Running water systems for kuruma shrimp culture have suffered considerable damages from infections of penaeid acute viremia, *Vibrio*, and *Fusarium*, among others. As in a CRAS, the concentration of probiotics can be stabilized; it is possible to suppress the proliferation of *Vibrio* bacteria in culture water as well as in shrimp guts. This also has the extra advantages of strengthening the shrimps' immune system and enhancing their growth (Mochizuki and Takeuchi 2008). This is just one example of the ability of CRASs to improve productivity, viability, safety, and marketability of aquatic products. This is the so-called "sixth sector (1 × 2 × 3) industrialization" policy. For the reasons listed above, the superiority of CRAS in realizing these policies is immeasurable.

The difference between CRAS and mariculture is also apparent in the quality of their products. In the case of tiger puffer, those grown in CRASs have less damage in regions such as the caudal fin and score higher in taste tests (more translucent and firmer meat, thicker skin, etc.), compared to their counterparts grown in net cage cultures (Japan Aqua Tec Co. Ltd: Marino-Forum 21). A minor, unforeseen benefit is that tiger puffers grown in CRAS from fish seed and given a formulated diet are free of tetrodotoxin, as under natural conditions this neurotoxin is the product of bioaccumulation in the fish's organs. This means that CRAS-reared tiger puffer can be consumed without the risk of poisoning.

1.3.2 Development of New Fish Culture for RASs

In 2010, the US Food and Drug Administration declared the genetically modified Atlantic salmon *Salmo salar* containing a king salmon growth hormone gene and eelpout gene safe to eat. In 2012, they reported that the same genetically modified organism would not endanger the fish species in nature, as the female fish are triploid and therefore sterile. Currently, approval for the genetically modified Atlantic salmon is pending, having reached the final stage of public comment. This strain looks similar to ordinary Atlantic salmon, but grows twice as fast as its counterpart and can be grown more efficiently with less feed. Such a fish is ideal for culturing in CRAS, as it would have reduced production time and burden on components such as the filtration and denitrification tanks, resulting in a higher efficiency of the overall system.

Similarly, we have successfully inserted a growth hormone gene of medaka *Oryzias latipes* in tilapia *Oreochromis niloticus*, a freshwater fish. This quadrupled the growth rate, increased the feed efficiency 1.6-fold, halved the nitrogen excretion, and led to a 40% reduction in phosphorus excretion (Fig. 1.3) (Lu et al. 2009). Marine fish such as Japanese flounder, tiger puffer, and red sea bream cannot grow when given feed containing only plant-derived lipids and require polyunsaturated fatty acids such as fish-derived eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which increases the cost of fish feed. Genetically modified fish have been developed that can circumvent this dietary limitation by internally converting linolenic acid, the plant-derived precursor, to EPA and DHA (Alimuddin et al. 2008; Yamamoto et al. 2010). The use of such fish will decrease the feed cost and is therefore favorable to CRAS; however, consumers generally express a strong resistance to genetically modified organisms. This resistance is causing a prolonged approval time in the case of Atlantic salmon, and thus the trend of opposition to genetically modified organisms must be followed closely. In November 2013, Environment Canada approved the use of genetically modified salmon egg, with the condition that they only be produced within CRAS.

Quite recently, the targeting-induced local lesion in genome (TILLING) method was applied to fish. This method has been widely used for the selective breeding of plants. Using the TILLING method, Dr. Yasutoshi Yoshiura developed the "double

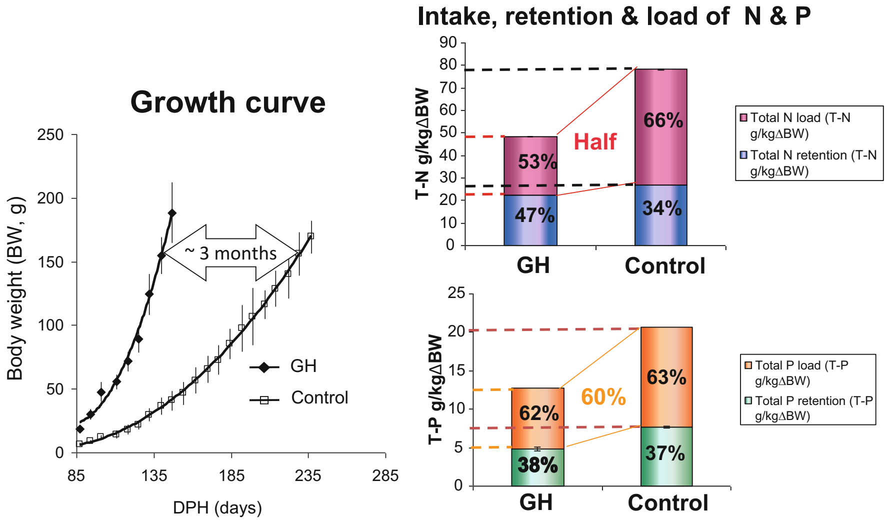

Fig. 1.3 Efficient productivity and lowered nitrogen and phosphorus discharge load from growth hormone (GH)-transgenic tilapia under visual satiation feeding (Drawing figures from Lu et al. 2009)

muscle medaka," which is 1.3-fold heavier and has twice the muscle volume of an ordinary medaka (from a grant from the National Agriculture and Food Research Organization, Enterprise for the Stimulation of Innovative Creation in Fundamental Research). The technique involved in the strain's creation was the identification of myostatin, a muscle-regulating protein, from the Belgian Blue breed of cattle, which arose in the nineteenth century by spontaneous mutation and is heavily muscled (referred to as "double muscling"). Using the TILLING method, a medaka containing the same myostatin mutation as a Belgian Blue was developed.

The TILLING method differs from genetic modification in that this technique artificially induces a mutation that might otherwise have occurred naturally. The technique has already been applied for the creation of novel variants of rice, wheat, soy, corn, tomato, potato, melon, and other species. The application in medaka is the first example in fish, and efforts are being made for its further application in tiger puffer for aquaculture purposes. This is the first step toward the creation of "domesticated fish," and its acceptance by consumers will contribute to the further advancement of CRAS industrialization.

1.4 Economics and Feasibility of Land-Based Aquaculture

1.4.1 Economics-Based Approach Toward Planning, Facility Design, and Profitability

To successfully establish land-based aquaculture as an enterprise, it is necessary to develop a competitive culture technique and propose a business model. In doing so, the following aspects become of importance: reduction of initial costs and variable costs such as feed and energy, establishing a stable and safe production technology, and choice of location for maximum geographic advantage.

The facility of saltwater fish in Japan must be able to hold an aquarium of at least 1000 metric tons for it to be profitable, even after the six-tenth factor rule and 20% reduction in the initial costs have been applied by employing common units, simple facilities, and uniform design. The final culture density in the aquarium, which must be at least 5%, is also important for profitability. It is preferable to obtain specific pathogen-free fish seed. To maximize profitability and productivity, the time period between the introduction of fish seed and the shipment of the product should be as short as possible, and the facility should be prepared for a daily shipping of uniformly sized fish, which will aid marketability, including in online vending. Transparency in the implementing body and the establishment of a consortium would also contribute to the stability of the enterprise.

As for the quality aspects of the fish, factors such as the development of novel feeds that improves the flavor of the fish, the choice of brandable fish, and the promotion of the fish's traceability so as to create an image of safe (e.g., chemical and heavy metal-free, radioactive contamination-free) product become of importance.

The location must be carefully considered. An ideal location should be close to consumers and have easy access to an energy source such as thermal energy. For example, we have established a CRAS facility for the experimental validation of tiger puffer culture in a farm in the Obihiro region of Hokkaido, which is far from the usual production area of tiger puffer. This location has the advantages of having an uncompetitive market for the selected product and access to high-purity bio-methane from cow manure, which contributes to a reduction in operating costs (see Chap. 14 for details). Such reductions in operating costs from optimal use of the facilities surrounding the location are essential and can be achieved by the use of thermal energy and exhaust heat from other facilities for the heating of culture water, by utilization of the cold water generated from the heat pump for processing, by harnessing renewable energy sources such as offshore wind power, and other such methods. The organic linking of mechanical elements, such as heat retention, filtration, and waste disposal, to the surrounding facilities can enable the construction of a low-cost system with optimal technology and equipment, which is crucial to successful implementation.

1.4.2 Costs Involved in Land-Based Aquaculture

Figure 1.4 shows the trial balance of tiger puffer production from CRAS. It is clear that the bulk of the costs are incurred by the facility and the costs of the electricity required for temperature regulation and power supply. The production cost of tiger puffer in the current trial balance is 3300 yen/kg, which is far from the market value of about 2500 yen/kg. This deficit underscores the infeasibility of the enterprise; therefore, methods of cost reduction are required. First, the installation of aquarium larger than 1000 metric tons becomes necessary. To reduce electrical power consumption, power-saver settings and the incorporation of renewable energy will be essential. Another trial calculation predicts a 10% increase in the internal rate of return by increasing the final culture density from 3% to 5%. A final necessary measure is the education of future technicians who would be able to keep the fish at high growth and survival rates at high culture density. However, if subsidies can be obtained from instructions such as the government for the initial costs of construction, feasibility would improve sufficiently even if the final culture density remained at 3%.

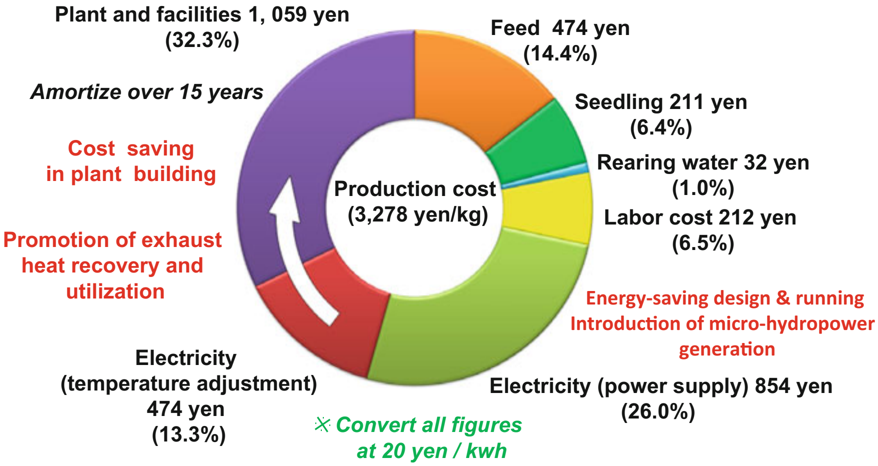

Fig. 1.4 Trial balance of tiger puffer production from closed recirculating aquaculture system

1.5 Possible Business Opportunities

Currently, the Japanese government is promoting the implementation of the "sixth sector industrialization" policy. This policy, which is aimed at revitalizing remote regions and stimulating employment, would also provide business opportunities for CRAS. Provided that traceability and quality control of the products are satisfactory, export of CRAS products would also become possible. The opportunity to export the CRAS technology itself, for instance, to desert regions, should also be considered. To this end, the creation of a consortium of industry, academia, and government would be effective. Figure 1.5 presents the industrialization scheme of CRAS and biomass energy (Takeuchi et al. 2013), as a reference for future directions.

Finally, the use of the nitrogen and phosphorus wastes from CRAS deserves mention, as environmentally friendly waste disposal is one of many future challenges for implementing CRASs. Aquaponics, the system of CRAS combined with hydroponics, would provide a way to effectively utilize these organic materials. To date, the United States has chiefly led the industrialization of aquaponics through advancements in freshwater systems. As in Japan, the main aquaculture product is marine fish; the development of a saltwater system is necessary for the application of aquaponics. Some candidate plants include ice plant, glasswort, and tetragon, to be grown with Japanese flounder, tiger puffer, and some kinds of grouper, respectively.

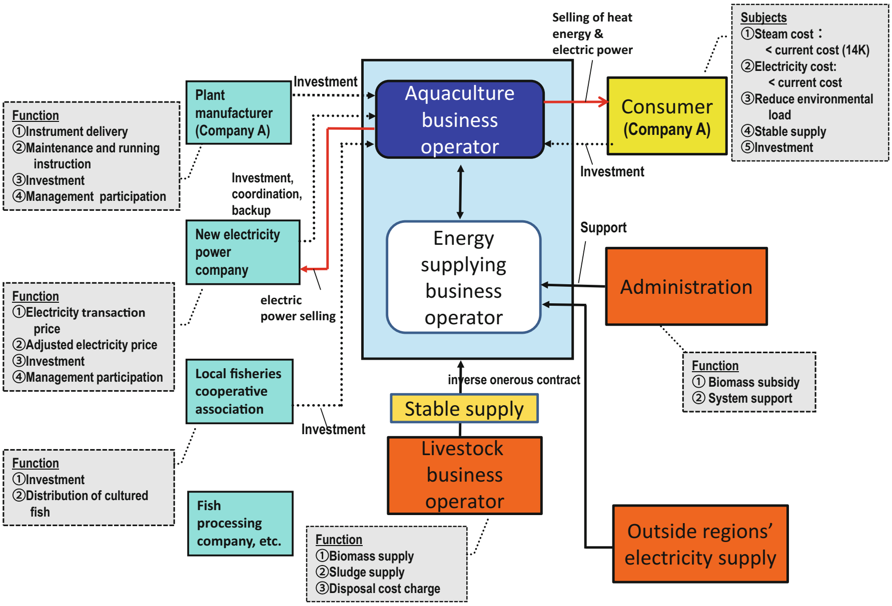

Fig. 1.5 Proposal of the industrialization scheme of the closed recirculating aquaculture and biomass energy

1.6 Conclusions

According to the Food and Agriculture Organization, the world's total fishery production was 150 million metric tons in 2004 and is predicted to reach 172 million metric tons in 2015. Given such data, the realization sets in that there is a limit to the productivity of our oceans. This issue will ignite serious discussion on how we can continue to effectively use our marine resources in the future.

Until now, there was little exchange of information between aquaculturists and industries, which operated independently of each other. As the development of the individual equipment and machinery for the setup of a complete aquaculture system is almost complete, the time has come for these entrepreneurs to confer and proceed together in joint efforts toward establishing a total aquaculture system that includes marketing.

Japan is currently in possession of advanced key technologies that can be applied to our existing RAS. Through further technological advance and development, especially in the field of clean energy, the industrialization of CRAS would become highly plausible. The additional development of "domesticated fish" adapted to CRAS conditions (and in fact, only suitable for use in CRAS, as their use in open systems would disturb existing gene pools) and a reduction of fish-derived components in feed will improve the feed conversion efficiency and growth rate, increasing the system's profitability. Similarly, the development of a novel feed that prevents the leaching of feces would also aid the successful implementation of CRAS. Lastly, collective support of further development by a consortium of academics, industry, and the government is crucial.

One of CRAS' recent slogans is "aiming for the creation of sustainable society through eco-engineering." This includes the developments of aquaponics (see Chap. 11) and a closed (controlled) ecological life support system (CELSS) to be used in space. CRAS may lead to the development of a closed ecological recirculating aquaculture system (CERAS; see Chap. 13), a type of CELSS. In this way, CRAS represents a system that can help to sustainably improve current fishery output and to serve as a foundation for future technological developments in aquaculture.

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