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Conceptual design of a microalgae-based recirculating oyster and shrimp system

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Abstract

The need to reduce water consumption in aquaculture has long been recognized and a great deal of research effort has been directed toward the development of recirculating systems. Unfortunately, current research and development in aquaculture water re-use is largely devoted to bacteria-based systems, while microalgae-based water re-use system development has been neglected. That a large body of knowledge is available on bacteria-based wastewater treatment has no doubt contributed to this reality. However, a bacterial component in a water re-use system dedicates itself entirely to excessive nutrient removal and the required capital and operational expenses are cost items that contribute to the scarcity of commercial successes of such systems. In contrast, a microalgae-based water re-use system produces microalgae that can be used to produce a second crop, such as bivalve seed or *Artemia*, which can be sold to generate income. The main difficulty encountered in the development of a microalgae-based water re-use system has always been the inability to maintain the desired algal species in an open system. The University of Hawaii has solved this problem. The breakthrough in marine diatom production technology allows us to turn our attention to the development of a water re-use system where the 'effluent' becomes a valuable resource. An integrated shrimp/algae/oyster production system reduces water consumption and turns effluent 'waste' into a profit center while taking advantage of the antibacterial properties of the marine diatom to control bacterial diseases. The reduction of pathogenic bacteria is likely to also reduce the susceptibility of the shrimp to viral disease. This paper describes the design of a microalgae-based recirculating system that produces oyster and shrimp using the marine

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diatom *Chaetoceros* as the intermediary media to remove the excessive nutrients from the shrimp production and to serve as feed for the oysters.

1. Introduction

Within the last 30 years, US aquaculture production has grown from a farm gate value of around $100 million to a value approaching $1 billion (USDA, 1997). To maintain this growth rate, aquaculture must greatly reduce the amount of water required and the amount of effluent discharged per kilogram of biomass produced, and its production systems should also be expected to provide some degree of resistance to disease occurrence.

Penaeid shrimp, a major aquaculture product, requires about 20 000 l of water for every kilogram of shrimp produced (Timmons and Losordo, 1994). Shrimp aquaculture, an active actor on the world aquaculture stage, has suffered greatly from disease: Ecuador in 1992 and in 2000, Taiwan from 1988 to 1989, Thailand from 1995 to 1996, and China in 1993 and in 2001 (Ling et al., 2001). Flegel and Alday-Sanz (1998) estimated the losses due to yellow head virus and white spot syndrome virus (WSSV) from 1993 to 1999 in Asian countries to be several billion dollars. During the same period in the Americas, very severe losses resulted from Taura syndrome virus (Brock et al., 1997). Ecuador exported 147 400 MT of shrimp in 1998 when its production was unaffected by the WSSV, however, in 2000 the export was reduced to 51 400 MT (Globefish, 2002).

Realizing the importance of shrimp production to our own economy, the US Department of Agriculture (USDA) funded a multi-million dollar national shrimp project to improve marine shrimp culture. So far this program has contributed significantly toward the establishment of disease-free shrimp brood stock and the detection of shrimp diseases, however, it has made very little progress toward the control of disease occurrence in marine shrimp production.[2]

Current research and development on aquaculture water re-use are largely devoted to bacteria-based systems, while microalgae-based water re-use system development has been neglected. That a large body of knowledge is available on bacteria-based wastewater treatment has no doubt contributed to this reality. However, a bacterial component in a water re-use system dedicates itself entirely to excessive nutrient removal, and the required capital and operational expenses are cost items that contribute to the scarcity of commercial successes of such systems (Libey and Timmons, 1996). In contrast, a microalgae-based water re-use system produces microalgae that can be used to produce a second crop, such as bivalve seed or *Artemia*, which can be sold to generate income.

The main difficulty in the development of a microalgae-based water re-use system has always been the inability to maintain the desired algal species in an open system.

[2] Available from: http://www.oceanicinstitute.org/research/shrimp_proj_USMSF.html.

The University of Hawaii (UH) has solved this problem[3]. This breakthrough in marine diatom production technology allows us to turn our attention to the development of a water re-use system where the 'effluent' becomes a valuable resource. An integrated shrimp/algae/oyster production system reduces water consumption and turns effluent 'waste' into a profit center while taking advantage of the antibacterial properties of the marine diatom to control bacterial diseases. The reduction of pathogenic bacteria is likely to also reduce the susceptibility of shrimp to viral disease.

A commercial recirculating shrimp/algae/bivalve system, operated by the Kona Bay Marine Resources Company in Kailua-Kona, Hawaii, has demonstrated that an intensive shrimp/algae/bivalve-seed operation can be achieved with a minimum daily water exchange rate of only 5% (Yuan, 2001). Taylor Resources, a division of Taylor United located in Kailua-Kona, Hawaii, uses algae-based recirculating systems with a number of shrimp tanks, each of which has approximately 900 m^2 of surface area and is approximately 250 000 gallons in volume. The primary product of Taylor's system is bivalve seed. Since the shrimp production is low, the nutrient input is supplemented with fertilizer to maintain the production target of marine diatoms. The algae produced accounts for 75% of all the food fed to their bivalve seed. Seed production is currently about 250 million 3–5 mm clam seed and 100 million 4–6 mm oyster seed per year (Jakob, 2001). Aquaculture Technology Inc., supported by USDA Small Business Innovative Research (SBIR) grants, has shown that the continuous presence of a marine microalgae, *Chaetoceros*, can keep an aquaculture production system free of a large number of pathogenic bacteria, including *Vibrio vulnificus*. A shell fish harvesting permit was awarded in 1993 to ATI after 2 years of FDA-mandated monthly testing, the first and only time a land-based oyster producing facility had been so monitored. The results gave clear indication that such a system can meet the zero tolerance standard on vibrios and other pathogens in oyster meat. An open continuous microalgae culture system has been developed producing *Chaetoceros*, whose fast growth rate and ability to produce antibiotics[4] makes it an excellent candidate to be included in an integrated shrimp/algae/oyster recirculating system.

Another common difficulty in managing the production of biological materials is the universal tendency for individuals in a population to vary in growth rate. It is well known, for example, that the growth rate of bivalve spats, from a single spawn can vary greatly. It is not uncommon for the fast growing bivalves to have reached market size while the runts are still smaller than a fingernail.

It is clear that if we could stock only the fast growing oysters we could greatly improve the overall system production efficiency. But it is impossible for us to determine which oysters are fast growers until we have grown the oysters to a certain size. The staged production concept, when applied to oyster production, offers many

[3] Open continuous *Chaetoceros* sp. microalgae culture system (patent filed by the UH).

[4] Antibacterially active extracts from the marine algae *Chaetoceros* sp. and methods of use (US Patent #5 866 150. February 2, 1999).

opportunities to remove (cull) the runts from the production system. This means that a larger number of oyster spats and veligers must be produced, but this is affordable because the demand for production resources by spats and veligers is much less than by large oysters (juveniles and adults).

2. Biomass constancy and resource utilization efficiency

It is not a simple matter to integrate the production of shrimp, microalgae and bivalves under one umbrella. In an integrated, continuously operating, recirculating production system, in order to balance the demands for food and water among the three organisms, it is necessary that the resources required by the oysters, the algae and the shrimp remain constant. For example, the diatoms produced using the nutrient input that comes from the shrimp feed must equal to that which can be removed by the oysters in the system. It is therefore clear that the integrated continuous production system must be operated under a steady state; that is to say, the demand for resources and the discharge of waste must stay constant with respect to time.

The concept of the steady state is very important in the design of an integrated production system. It implies that if oysters, microalgae, and shrimp are to be produced by an integrated system, then the biomass of the two animals must remain relatively constant within the system.

By dividing the production process into stages, we can increase the constancy of the biomass in the system and improve the utilization efficiency of the physical facility.

3. System design example

We will attempt to design an integrated production system for shrimp/algae/bivalve seed. To do this, we must first make a number of assumptions.

First we need to make some assumptions regarding shrimp production:

Fig. 1 shows shrimp production data by Sandifer et al. (1988), Sturmer et al. (1992) and Sandifer et al. (1991). Fig. 2 is derived from growth data obtained by Aquaculture Technology at its Kailua-Kona, Hawaii pilot farm. Both figures indicate that the growth of penaeid shrimp can be approximated by a straight line beyond the nursery stage.

It takes approximately 16 weeks for shrimp to grow from 1.5 to 25 g. To produce 1000 kg of shrimp twice a week, or 2000 kg per week, and maintain a constant shrimp biomass in the system, we use 32 shrimp tanks. We harvest two tanks each week, on Tuesdays and Fridays, and we restock these two tanks with 1.5 g juveniles so that the shrimp can be harvested 16 weeks after they are stocked and weigh an average of 25 g. At the time of harvest, each tank should contain 4000 shrimp. Assuming a survival rate of 80%, the stocking rate should be 5000 shrimp per tank.

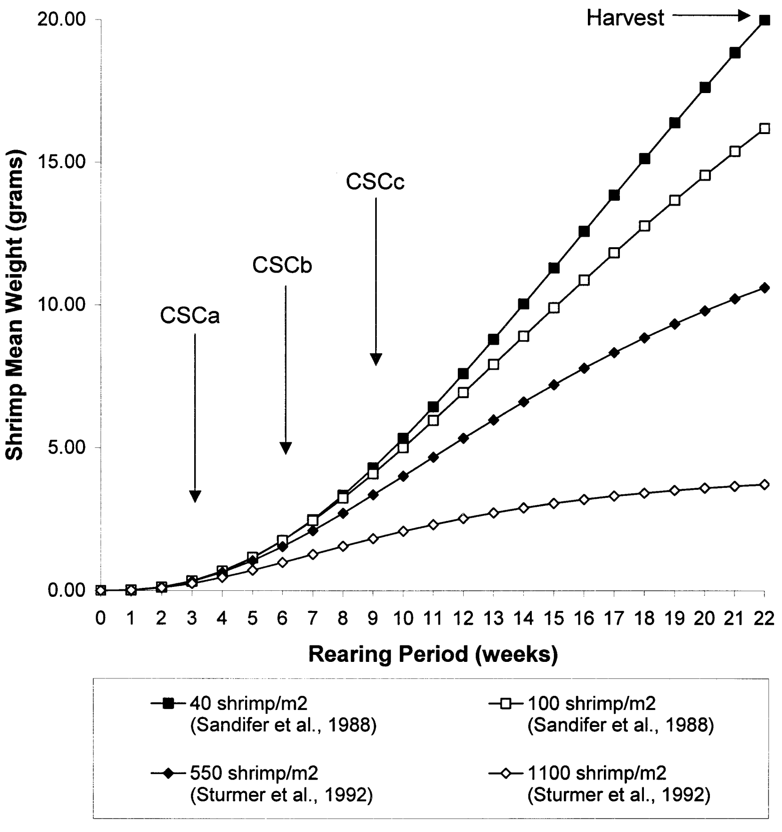

Fig. 1. Shrimp growth data

We use round tanks each with a surface area of 62 m^2 (4.43-m diameter) so the final stocking density is 65 shrimp/m^2.

Then we need to make some assumptions regarding the production of the diatom, *Chaetoceros* sp.

Protein, the major organic constituent of microalgae, varies from 12 to 35% of the algae, dry weight basis (Coutteau, 1996). The marine microalgae *Chaetoceros* contains about 20% protein (Coutteau, 1996). Vymazal (1994) indicated that the values of carbon concentration in marine algae vary from 25 to 36% dry weight basis, and the nitrogen concentration in marine algae varies from 1 to 6%, dry weight basis. Shrimp are fed 1.5% of their body weight per day. If we use shrimp feed that is 50% protein, 16% of which is nitrogen (Losordo, 1991), then a kilogram of shrimp feed has sufficient nitrogen for 1.6 kg of algae. Assuming that *Chaetoceros* sp. contains 5% of nitrogen, dry weight basis (Coutteau, 1996), and that about 50% of the nutrient input that comes from shrimp is not available for the production of algae, then 1.0 kg of shrimp feed produces about 0.8 kg of algae, dry weight basis.

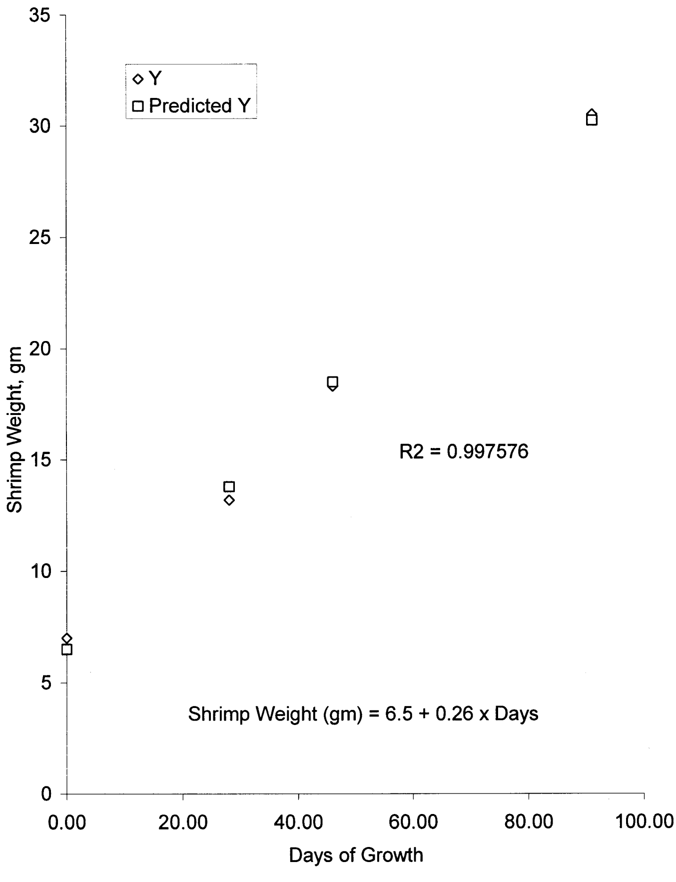

Fig. 2. Shrimp growth data, ATI, Kailua-Kona, Hawaii.

Table 1 shows that with 16 tanks and a total system shrimp biomass of 18 668 kg, daily feed of 280 kg is required. Based upon our assumptions, a daily algal production of 224 kg is estimated.

As a rough estimation, if we assume a food conversion of 2:1 between wet oyster meat and dried marine microalgae *Chaetoceros*, we can tentatively estimate that 224 kg of algae converts into 112 kg of live oyster meat per day. Assuming that meat is 16% of the oyster weight (Quayle and Newkirk, 1989), then we are producing 700 kg of oysters per day. Converting the live meat weight into number of oysters, at 100 g/oyster that works out to be 7000 pieces of oysters per day. The weekly production of oysters is then 49 000 pieces of 100 g oysters, or about 98 000 pieces of 50 g oysters.

Oyster production design is somewhat complicated. Basically, oyster production is divided into stages. Since the production of oyster spats is inexpensive and the consumption of microalgae by the veligers is minimal, the production strategy is to over-produce spats and select only the fastest growing 5–10% of juvenile oysters for cultivation.

Table 1
Estimated system production

Tank number	Number of shrimp	Average shrimp weight (g)	Shrimp biomass (kg)	Daily shrimp feed (kg)	Daily algae production (kg)
1	100 000	2	200	3	2.4
2	98 524	4	348	5	4
3	97 070	5	492	7	5.6
4	95 637	7	631	9	7.2
5	94 225	8	766	11	8.8
6	92 835	10	897	13	10.4
7	91 464	11	1024	15	12
8	90 114	13	1147	17	13.6
9	88 784	14	1266	19	15.2
10	87 474	16	1382	21	16.8
11	86 183	17	1494	22	17.6
12	84 911	19	1602	24	19.2
13	83 657	20	1706	26	20.8
14	82 423	22	1807	27	21.6
15	81 206	23	1905	29	23.2
16	80 007	25	2000	30	24
Sub-Total			18 668	280	224

Wang and Jakob (1991) gave a design example for an oyster production system that produces 126 000 pieces of 50 g oysters per week. The production of oysters is divided into three stages: from 1.2 to 7.4 g, from 7.4 to 26.3 g, and from 26.3 to 55 g. The ratio between stocked oyster juveniles to harvest oysters is 8.33%.

For the production of oysters, the fluidized technology is used[5]. Fluidization is a well-known phenomenon even though it is not yet properly understood. As described by Couderc (1985), fluidization is observed when a bed of solid particles comes into contact with a vertical upward fluid flow in an intermediate range of flow rates. At low flow velocities, the solid particles lie on one another and on the porous bottom of the column, and are said to be in a fixed state. At high flow velocities, the solid particles are conveyed out of the column, a process known as hydraulic transport. For intermediate values in a range large enough for practical purposes, each particle becomes individually suspended in the fluid flow, while on the whole the bed remains motionless relative to the column walls. In this state the bed is said to be fluidized.

Ver and Wang (1995) reported on the development of a fluidized bed oyster nursery. Under fluidization, oysters are suspended in high density in a fluid, each oyster separated from the others so that cohesion between the oysters is prevented. While suspended, each oyster remains motionless relative to the column walls. Food and dissolved oxygen (DO) are evenly distributed to the oysters and their feces, carried away by the fluid. Thus, the labor requirements for maintenance are reduced and the high flow rate required for fluidization insures that the oysters receive adequate oxygen and algal food for fast growth. The technique was used to culture clutchless oyster seed from 2 to 25 mm in size suspended in upflowing commercial shrimp pond effluent.[6] Fluidized bed data for large oysters are available from the author.

4. Discussion

In an integrated shrimp and oyster production system, the excessive nutrient from shrimp feed is used to produce a crop of marine diatoms, the diatoms are fed to the oysters by passing the diatom-laden water through the fluidized oyster columns, and the water is then returned to the shrimp tank (Wang and Jakob, 1991). With proper control the algae produced should be mostly *Chaetoceros* sp., which is an excellent food for *C. virginica* and other bivalves. In such an integrated system, the continuous harvesting of the algae by the oysters is a key factor in maintaining the diatom production. In addition, the reduction of algal density during the night has a positive

[5] Fluidized bed production of oysters and other filter feeding bivalve mollusks using shrimp pond water (US Patent #5 692 455, December 2, 1977).

[6] A fluidized nursery is different from an upflow nursery. The 'upflow nursery systems' originally developed by C. Budge in 1969 (Claus, 1981) has been widely accepted in Europe, but has attracted only limited attention in the US (Manzi et al., 1986). In an 'upflow' system the fluid velocity remains quite low and bed fluidization is not attained.

effect on the DO content of the system water while the carbon dioxide production during the day by the oysters has a positive effect on the pH value of the shrimp tank water. In a pilot system developed at Aquaculture Technology Inc., fluidized beds are used to produce market size *C. virginica* in 6–12 months. The UH has obtained a basic patent on the application of the fluidized technology to bivalve production[7], and has applied for a patent regarding the production of *Chaetoceros* sp. and other diatoms under an open system without inoculation[8]. It should be noted that the diatom *Chaetoceros* sp. has been shown to produce novel antibiotics[3] and the ability to maintain a high concentration of this marine diatom will eliminate *V. vulnificus* and other pathogenic bacteria which contribute to the propagation of viruses in the shrimp production environment.

It is not a simple matter to integrate the shrimp and the bivalve production components. In such an integrated continuously operating recirculating production system, it is necessary that the demands for resources by both the oysters and the shrimp stay constant and equal. For example, the diatoms produced using the nutrient input that comes from the shrimp feed must equal to that which can be removed by the oysters in the system. It is therefore clear that the integrated, continuous production system must be operated under steady state; that is to say, the demand for resources and the discharge of waste must stay constant.

The concept of the steady state is very important in the design of an integrated production system. It implies that if oysters and shrimp are to be produced by an integrated system, then the biomass of these two animals must remain relatively constant within that system.

Two commercial systems using the integrated production concept have come into being in recent years. The pilot production system developed by Aquaculture Technology Inc. under USDA SBIR grants has evolved into a commercial system to produce shrimp and clam seeds, operated by Kona Bay Marine Resources. Another facility, which produces shrimp brood stock and clam seeds, is operated by Taylor Resources, a unit of Taylor United. Both units are located in Kailua-Kona, on the island of Hawaii.

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[7] Fluidized bed production of oysters and other filter feeding bivalve mollusks using shrimp pond water (US Patent #5 692 455, December 2, 1997).

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