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Building Integrated Aquaculture

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Building Integrated Aquaculture

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Due to environmental degradation and declining capture fisheries, aquaculture now accounts for nearly 40% of the world's total fisheries production.[1] While per capita seafood consumption has already reached record levels in the U.S., recent USDA recommendations suggest more than twice this amount for a healthy lifestyle.[2] Achieving this goal represents a significant challenge considering approximately 85% of U.S. seafood is imported and nearly half of this comes from overseas aquaculture production. The reliance on imported, cultured seafood problematizes issues of food security, product quality, carbon emissions, and the growing costs of transport and globalization.

Building integrated aquaculture (BIAq) involves taking advantage of the interdependencies between a small-scale indoor recirculating aquaculture system (RAS) and the environment maintained by the building to maximize energy efficiency and optimize operations. In a BIAq approach, gained efficiencies have the potential to offset the energy intensity of recirculating aquaculture and ultimately make local-scale aquaculture more viable. From the twin perspectives of increasing food and energy security, as well as reducing greenhouse gas emissions and environmental waste, the benefits of applying green building principles to meet the needs of aquaculture facilities are clear. We identify areas where a BIAq approach might increase efficiency and reduce operating costs. Our focus is on processes and design decisions that have the greatest potential for energy conservation in the heavily populated temperate regions of the world.

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Aquaculture

To maintain a “water quality environment” suitable for the culture of fish and other aquatic organisms, traditional aquaculture systems such as ponds and net-pens rely on ambient outdoor temperatures and environmental services. This severely restricts the locations in which aquaculture can succeed. Because it has no such restrictions, an RAS provides an opportunity for commercial aquaculture within the urban and suburban environments where fish demand is greatest. To maintain a suitable water quality environment, an RAS uses an array of technology and equipment that provide thermal stability and oxygen, while simultaneously processing metabolic wastes, such as undigested solids, ammonia, and carbon dioxide, and limiting the proliferation of pathogenic organisms and disease (*Figure 1*). In an RAS, commercial success relies on balancing the costs of water treatment with the value of fish production. The high costs of operating water filtration and temperature control equipment requires culturing fish at exceedingly high densities (e.g., greater than 100 kg of fish per cubic meter [~1 pound per gallon] of water). Fish vary considerably in their tolerance to such conditions. Considering the majority of species amenable to an RAS require warm water, the success of local-scale BIAq in temperate climates relies largely on reducing the annual cost of heating water to levels below that of transporting processed fish from warm water production sites to temperate consumer markets.

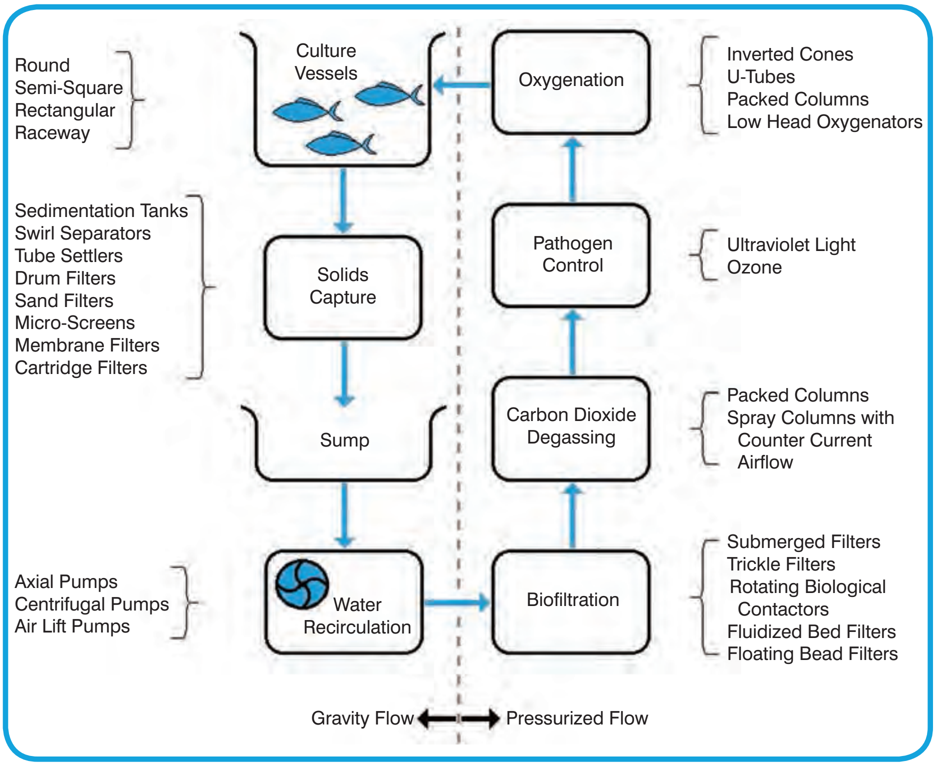

Figure 1: A recirculating aquaculture system (RAS) consists of culture vessels and various water treatment devices connected through flowing water.

BIAq Parameters

Integrating Energy and Climate Control

Energy demands for space heating and cooling, water heating, humidity control, lighting, and electricity greatly influence overall building energy profiles. Studies have shown that in the U.S. over 75% of the total energy demands are due to building operations.[3] In aquaculture facilities, additional complexities must be addressed. The specific enthalpy of the indoor environment is high due to the evaporation of the water, which requires extensive dehumidification and air exchange. Relative humidity, air temperature, water temperature and air quality are all critical environmental control factors. In BIAq facilities, water heating and dehumidification costs are coupled. Given that a significant portion of annual energy costs originates from water surface evaporation losses, care must be taken to reduce the evaporation rate. The warmer the water used in indoor recirculating aquaculture facilities, the higher the evaporation rate. The lower the indoor environment’s dew point, the higher the evaporation rate. Energy and climate control in BIAq facilities must take into consideration humidity, airflow, and condensation risks.

Conventional aquaculture facilities do not typically control for humidity, and latent loads are simply allowed to “float” within the interior environment. While this may help to reduce the overall energy lost to evaporation, the greater than 80% relative humidity that inadvertently results poses a significant threat to the building’s envelope. Without proper humidity control, increased relative humidity can present a host of structural as well as occupational hazards. High relative humidity levels inside a building are well known for their destructive effects on building structure due to moisture intrusion and condensation within the building assembly. Condensation within the building assembly degrades the structure and thermal effectiveness of envelope materials. It rots wood, rusts steel, and causes freeze cracking of masonry. It also reduces the thermal resistance of insulation. Increased humidity and risk of condensation also promote the growth of mold and mildew, which can adversely impact the air quality. To ensure building durability as well as occupant comfort, the relative humidity in a typical indoor zone for human occupation should be maintained within a range of 50 to 60%.

In BIAq enterprises, controlling the moisture load requires using air-conditioning equipment, ventilation, and controls. Moisture must be removed from the space at the same rate it is generated to maintain stable space conditions. The most efficient means to do this in an indoor aquaculture facility is through the use of packaged mechanical refrigeration systems. In BIAq, both the cooling and heat rejection sides of the refrigeration cycle should be used to maximize energy conservation. The evaporator coil is cooled below the dewpoint of the ambient air, causing condensation and dehumidification.

Moisture (condensate) is a major byproduct of the evaporator process due to space air dehumidification. This condensate could be recovered and supplied as makeup water for the facility providing a significant water conservation strategy. Heat pumps that recover latent energy from the indoor air in order to moderate water and space temperatures can be applied. Moreover, the condenser can be designed as a heat exchanger for ventilation air (and/or makeup water), providing "free" heat to the space and water (*Figure 2*). This approach is the most energy-efficient means to control moisture-related issues within the facility.

Better building design and material selection can help to mitigate the significant energy loads present in an indoor aquaculture facility. First, the design and construction of the exterior envelope is critical. For high humidity indoor environments in cooler climates, the exterior walls are under the greatest threat. The placement and integrity of the vapor retarder to mitigate vapor diffusion and condensation within the wall or ceiling assembly is critical. Furthermore, proper design of an envelope system further reduces the risk of cold spots that lead to moisture condensation.

One example of an airtight and thermally sealed envelope system was used for the Kappen Aquatic Center, the first-ever LEED Platinum natatorium, which was designed using insulated concrete forms.[4] Other strategies to reduce condensation and/or energy loads include locating supply air ducts at ceiling level to allow supply air to "wash" building perimeter walls, particularly walls with glazing, this helps to dry out areas of moisture accumulation. And, the use of thermal blankets (commonly known as pool covers) to reduce evaporative water loss is a proven strategy in natatoriums that can be adapted for certain species in a BIAq enterprise.

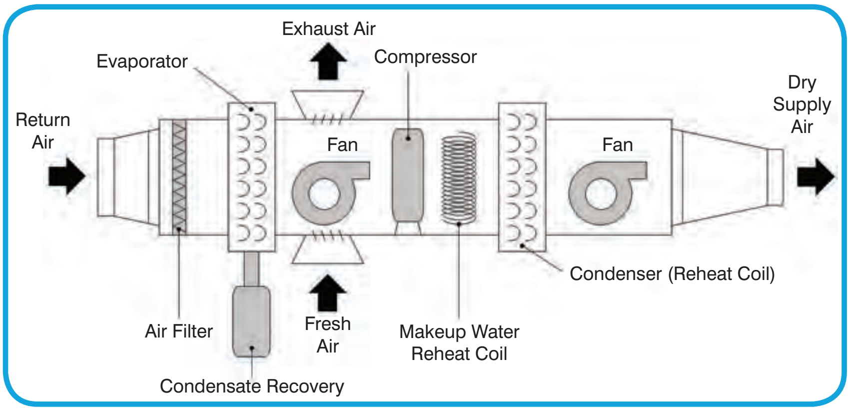

Figure 2: BIAq mechanical system (heat pump).

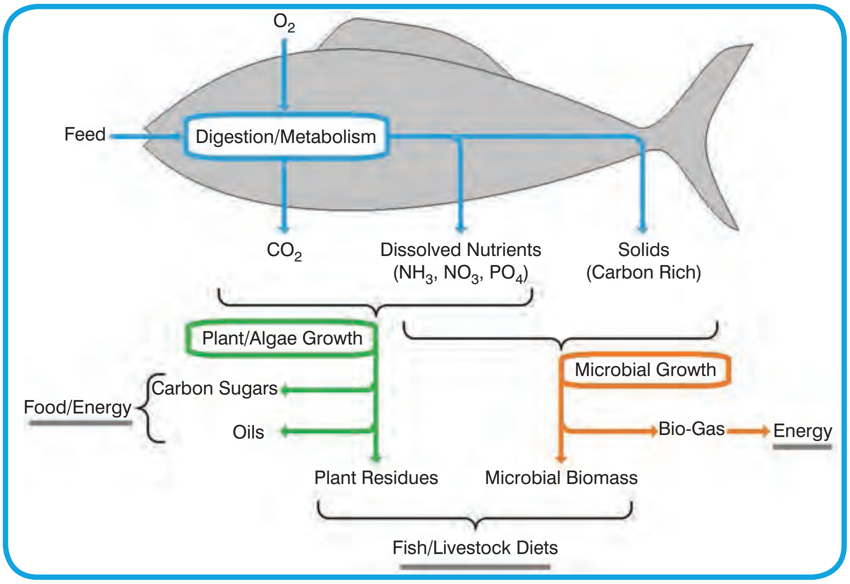

Figure 3: Opportunities for the integration of waste streams from recirculating aquaculture systems with other commercial enterprises.

Waste Stream Integration

Recirculating aquaculture systems operate by remediating, dispersing, and/or, removing the metabolic wastes of fish before they accumulate to toxic levels. Although no rigid definition exists, RAS requirements for new water are generally less than 10% of the total system volume per day. When municipal sources are used, new water is often preconditioned to remove residual chlorine and other potentially contaminating substances that might impact fish health. Requirements for new water are driven primarily by evaporation and the discharge of water associated with the purging and backwashing of filtration devices. Integration of these "waste streams" is particularly attractive because it can reduce or eliminate carbon, nitrogen, and phosphorus rich wastes that would otherwise be discharged into the environment. The ability to capture and use waste streams is a major advantage to the cultivation of fish in a freshwater RAS. Three wastes streams are of primary importance: undigested solids, dissolved nutrients, and dissolved carbon dioxide. Each of these waste streams offers ad-

ditional opportunities for the integration of BIAq with other forms of enterprise (*Figure 3*, Page 18).

Recirculating aquaculture systems concentrate wastes in an easily transportable liquid water medium. The most prominent example of integration has been the application of dissolved nutrient wastes from fish to hydroponic plant culture, commonly referred to as aquaponics. As waste, fish produce significant amounts of the same nitrogen and phosphate ions needed for plant for growth. Through such integration, the dissolved nutrient waste stream of fish culture can be converted into an additional food or energy crop. Additional energy might also be generated through microbial bio-gas production. Producing bio-gas from terrestrial animal manure has become an established enterprise for the conversion of solid wastes to a clean-burning fuel source. While the undigested solid waste stream of fish is a carbon-rich medium that could potentially serve as a substrate for cultivating methane-producing bacteria, even without bio-gas collection the waste heat generated from using bacterial digestion as a first step towards composting nutrient wastes might offset a portion of BIAq heating requirements.

Even in fish densities of up to 1 pound per gallon, the dissolved carbon dioxide waste stream of an RAS may present the greatest challenge to indoor aquaculture production. Due to its high solubility, the removal of carbon dioxide requires increasing the water surface area maximally while simultaneously exposing it to sufficient quantities of carbon dioxide-free air. In practice, this is generally accomplished by passing water through packed-media or spray columns using counter-current air at flow rates five to ten times that of the water. To maximize degasification and prevent potentially toxic levels of indoor carbon dioxide, fresh air is generally used in counter-current exchangers and then vented outside. Considering the entire water volume of the operation might pass through a degasification column every hour, carbon dioxide removal represents a putatively significant source of heat loss (*Figure 4*).

BIAq operations might use systems to recapture the waste heat associated with carbon dioxide removal and apply it towards the fresh air intake of degasification columns. While this addresses the problem from the perspective of building design and construction, additional solutions might come through integration. In greenhouses supporting terrestrial agriculture, carbon dioxide is often added to the interior environment to enhance crop production. In turn, plants sequester this carbon dioxide through photosynthesis and pro-

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duce the carbon sugars and oxygen on which human and animal life depends. Considering both fish carbon dioxide production and plant carbon dioxide consumption peak in daylight hours, the potential for integrating BIAq with greenhouses operating on year-round schedules exists. With proper design, integration of BIAq and greenhouse crop production could reduce the individual heating costs of each operation, bolster crop production, and offset a fraction of the total BIAq carbon footprint.

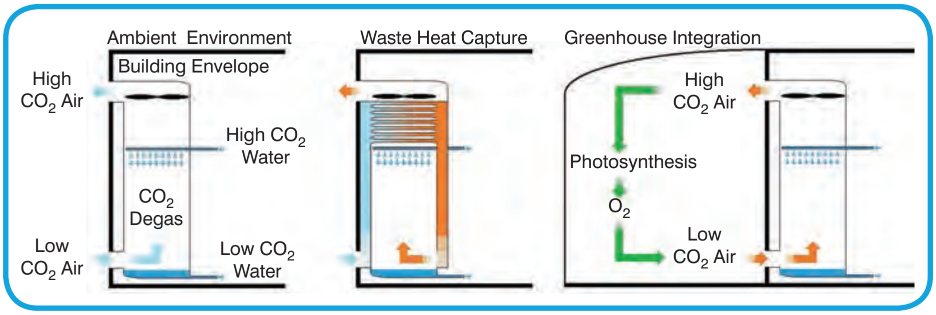

Figure 4: Warm-water aquaculture in temperate regions creates great potential for heat loss during carbon dioxide degassing (left). Heat loss can be minimized through design and engineering (center), or possibly through integration with year-round greenhouse crop cultivation (right).

Using Passive and Renewable Energy

Operational energy costs associated with recirculating aquaculture facilities could potentially be reduced by integrating renewable energy systems and capitalizing on passive energy gains. Energy demands associated with water and air heating/cooling, humidity control, lighting and pumping could all be reduced with the use of passive systems. For example, passive solar thermal heating could be used to help regulate the water temperature, control the indoor air humidity, or meet the electrical requirements of a BIAq enterprise.

Currently, warm water fish species necessitate heating water with heater/chiller units positioned outside the building envelope (*Figure 5*). Using the same design logic, a passive solar thermal water heater could be incorporated into the

RAS upstream of the heater/chiller unit. Passive heating can be used when insolation is sufficient, and the heater/chiller unit retained for periods of insufficient insolation. A major drawback of this design is the inability to store solar thermal energy during times of sufficient insolation since water exiting the solar collector must be maintained within the thermal limits of the species being cultured. In BIAq, thermal energy might be stored in a separate hot water storage tank. Since fish will not be kept in the storage tank, no restrictions on maximum water temperature exist and the unit can collect as much thermal energy as possible. Heating of the RAS is then accomplished through a heat exchanger contained within the new water storage tank. A downstream heater/chiller provides redundancy for periods of low insolation when the temperature of the new water storage tank falls below that of the RAS. This design has other potential benefits to BIAq. For example, the additional water within the building envelope contributes to thermal stability. Furthermore, the additional water also acts as a readily available reserve for the RAS. However, considering the water temperature may be greater than thermal tolerance of the cultured species, mixing with unconditioned, ambient temperature water may be necessary.

The conventional strategy for reducing space air humidity in aquaculture facilities involves the use of mechanical cooling equipment (refrigeration systems) and/or high ventilation rates, which require a high capital investment and are energy intensive. As an alternative or supplement to refrigerant coils, the application of desiccant or enthalpy wheels, which are air-to-air heat exchangers with rotating disks embedded with a desiccant, is promising. Of particular interest are systems using a passive approach, exploiting renewable solar energy. One approach involves a cooling and dehumidification system with solar desiccants.[5] Another passive dehumidification mechanism is based on materials with controlled pore size and sufficient pore volume to facilitate moisture condensation. For certain porous materials, water vapor will condense within the pores due to capillary condensation. Materials with engineered pore structures can passively remove humidity from the ambient air at a specific humidity level.[6]

Given the electrical demands of water pumps, aerators, and lighting, the use of photovoltaic panels, small-scale CHP and wind turbines can be integrated into the system design to reduce operational costs. BIAq systems should also include redundancy in the form of backup generators, which could conceivably run on biofuels made in fish wastewater. Another electricity saving measure is the use of translucent roofing materials to provide ambient light within a BIAq facility; however, the lower insulation properties of such materials must be taken into consideration, especially in northern regions.

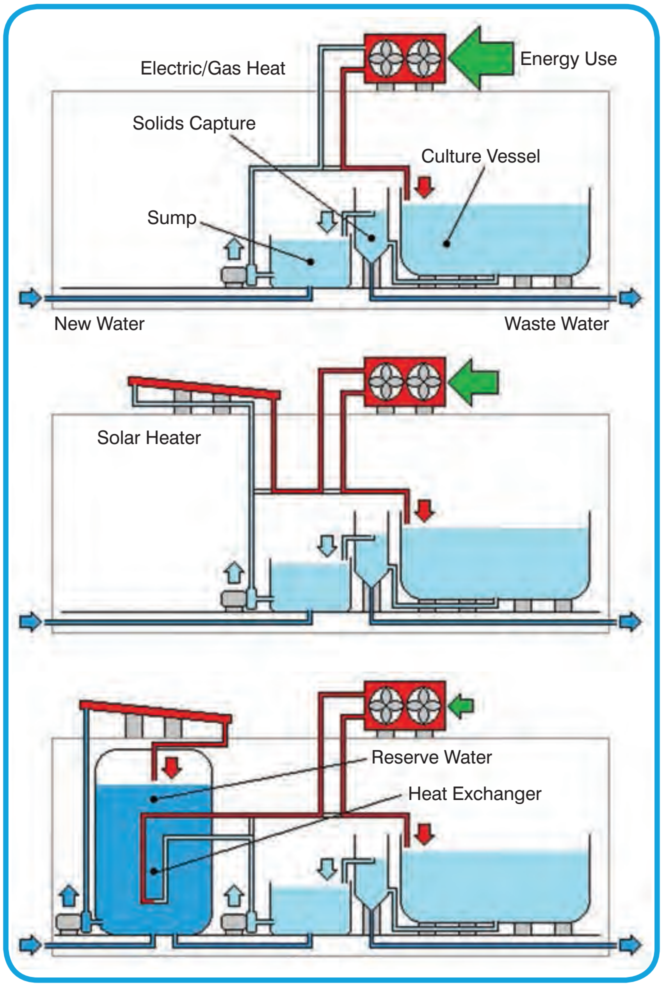

Figure 5: Solar heating of water for BIAq. In recirculating aquaculture systems (RAS), water temperature is usually increased using electric or gas heat (top). Because the temperature can only be increased to the thermal maximum of the cultured species, incorporating solar heaters using the same strategy is an inefficient use of the technology (middle). Using solar to heat incoming reserve water enables the capture of greater heat energy (bottom). This heat can then be transferred to a RAS through a heat exchanger or new water exchange.

Discussion

The success and sustainability of a BIAq enterprise relies heavily on balancing operating costs, maximizing production, and a positive work environment that fosters long-term institutional capacity. As aquaculture moves into the built environment, the health, comfort, and safety of personnel in these unique indoor environments must be considered. The combination of warm temperatures and water not only has the potential to create humid and uncomfortable conditions, but also to promote the growth and proliferation of potentially hazardous microbial pathogens. Unlike indoor swimming pools and water features that are often chlorinated, BIAq water must also be managed for the health of the fish and bacterial populations encompassed within the system. Noise, spatial organization, and the close proximity of water and electricity must be considered when adopting a more holistic BIAq approach.

BIAq presents a sustainable approach to indoor aquaculture production. Framing the development of RAS facilities as a holistic and synergistic systems-based endeavor enables a robust analysis of the environmental, social, and economic benefits that would make fish production more sustainable. Climate control is a major challenge for indoor recirculating aquaculture systems, and continuing to ignore the design of the building envelope will result in inefficiencies and higher costs. While complete systems integration that minimizes environmental impacts may not be financially or physically feasible due to high capital and/or operating costs, prioritizing and evaluating sustainable options that incrementally reduce operating costs of fish production will likely increase the long-term success of indoor aquaculture enterprises.

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