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A Small-Scale Recirculating Aquaculture System for Global Aquaculture Education and Industry Development

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While global aquaculture is expanding rapidly, the United States (U.S.) and East Africa (EA) Great Lakes region have experienced slower growth. Aquaculture education is integral to overcoming existing limitations and accelerating production in these regions and worldwide. Toward this goal, an open access educational recirculating aquaculture system (ERAS) was designed to meet the differential objectives of aquaculture education in the U.S. and EA and trialed within educational institutions. Key ERAS design considerations were cost, operation, size, component availability, and construction. A secondary aspect of ERAS design was flexibility and application to different learning objectives. Over the trial period, two potential educational uses emerged: (1) to build student awareness of aquaculture and its importance in the food system, and (2) to teach practical aquaculture skills necessary for aquaculture careers. Construction and assembly guides for the educational ERAS will be offered open source through the University of Massachusetts Amherst aquaculture extension website.

KEYWORDS Hands-on learning, open source, Sub-Saharan Africa, sustainability

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INTRODUCTION

Aquaculture has been developing rapidly in response to increased global demand for seafood products (FAO 2012). However, not all regions are experiencing this accelerated growth, which limits global aquaculture production, national economic progress, and community food security (FAO 2012). The United States (U.S.) and Great Lakes region of East Africa (EA) are two examples of regions experiencing slower aquaculture development, although for differing reasons and despite great potential. While the United States has abundant raw feed materials, technology, skilled labor, infrastructure, and well-developed markets, strict regulations and high production costs hinder aquaculture development (Engle & Stone 2013). Conversely, while EA has abundant water resources, available labor, established markets, and a suitable climate, the lack of skilled labor, raw feed materials, access to technical information, and infrastructure complicates development (Brummett et al. 2008). The EA Great Lakes region, in contrast to arid North Africa, has high water availability, although its periodic nature often requires consideration of capture and storage strategies. There is also a large labor force due to accelerating population growth in the EA region. This explosive population growth lends itself to increasing demand for fisheries products in the already large domestic market, in addition to existing markets in the EU. Finally, countries in the EA Great Lakes region are located on or near the equator, creating tropical conditions ideal for year-round aquaculture production of warmwater fishes.

Educational solutions are key to accelerating aquaculture industry growth in the United States and East Africa. In the United States, education focused on increasing consumer awareness of aquaculture production is needed to increase demand and improve markets for domestically farmed fish (Gempesaw et al. 1995). In EA, the development of practical training in management of aquaculture processes is needed to strengthen the industry (Brummett 1994). Potential remedies in EA include the implementation of short-term technology transfer workshops and the development of long-term demonstration and teaching farms. Although the development of aquaculture education programs needs to be viewed as a long-term investment, the potential to positively influence both the U.S. and EA aquaculture industries is great.

Recirculating Aquaculture Systems (RAS) are highly controlled environments for intensive aquaculture production and offer a possible solution to growing global concerns over pollution from aquaculture effluent (Martins et al. 2010). RAS can also provide unique educational opportunities because they can be scaled down to small spaces and operated in areas of limited water availability. However, RAS require more specialized knowledge, which presents additional challenges, and there is a need for more communication and exchange between people working with RAS (Badiola et al.

2012). In the face of these challenges, educational RAS that are low cost and easily accessible benefit aquaculture education, but the relative lack of available programs using RAS still limits widespread aquaculture education and its positive effects.

In order to address these issues and promote accessible aquaculture education, we have developed a small-scale, low-cost, and multipurpose educational recirculating aquaculture system (ERAS) to be used as the centerpiece for aquaculture education. Our goal is to provide the ERAS construction instructions and management manual as an open source resource. To do so, we've created a public website (http://extension.umass.edu/aquaculture/) where interested users and stakeholders will be able to freely access ERAS construction and management instructions after inputting their names and contact information. Asking users for their contact information will enable us to understand our user community and help to connect users with each other. Furthermore, users will be able to give feedback on their experiences using the ERAS, which will also help us refine the ERAS design and understand user demand. If demand for the system is demonstrated, a host of additional services are planned for the website. Ultimately, we hope to build a community of global users and increase our education capacity collectively. The goal of this article is to briefly describe the ERAS design, raise awareness of its potential for aquaculture education, and begin to build a community of ERAS users.

DESIGN OF THE ERAS SYSTEM

The ERAS was designed to produce tilapia for approximately four adults, or two adults and two to four children. Tilapia were chosen because of their hardiness, widespread availability, and accelerating international demand. The U.S. Department of Agriculture nutritional guidelines recommend U.S. citizens eat diverse seafood products from a variety of sources, including marine fish and freshwater fish, for a total of about 12 kilograms of seafood annually (USDA, 2010). Given the requirement for diverse seafood products, tilapia consumption should total about 6 kilograms per person per year. To account for filleting loss, we estimated that the ERAS would need to produce 16 kilograms per person of whole tilapia per year. To meet the consumption goal for four people, the ERAS is designed to produce 68 kilograms of fish per year or about 150 fish based on a harvest size of 454 grams, with a few additional fish to account for mortality. The ERAS design cascade (Figure 1) describes the rationales behind the ERAS layout. A diagram of the ERAS is provided in Figure 2.

A production cycling scenario is ideal in order to operate the ERAS as the smallest, most efficient system possible (Masser et al. 1999). Depending on environmental conditions such as temperature and management initiatives

Production Goal [Produce 68 Kilograms of 1-Pound Tilapia Per Year]

- USDA suggests per capita seafood consumption of 12 kg.
- Assume half of consumption is tilapia produced in the ERAS.
- Assume a fillet yield of ~37%.
- Multiply by four for a family.
- Calculate number of fish to be stocked.

Production Cycle [Produce 2–3 Fish Per Week]

- Stock fry twice a year at 6-month intervals.
- Cultivate cohorts of fry for 6–12 months in four tanks.
- Grade and reallocate fish every 4–6 weeks.
- Maintain an average of 12–13 near-harvest fish in tank 4 at all times.
- Harvest 2–3 fish every week from tank 4.

Tank Size and Flow Rate [1,20l and 1,000 LPH Needed]

- Maximum tank biomass is 12–13 fish at 454 g or 6 kg.
- Stocking density of 50 kg/m^3 equates to 120L tanks.
- Two turnovers per hour equates to 240 LPH per tank.
- Four tanks equates to approximately 1,000 LPH for the systems.
- With a 1 meter lift, a 26 watt pump is sufficient.

Filtration [Two-Step Solids Separation, Trickling Biofilter]

- Employ a gravity settlement filter upstream of an exclusion filter.
- Simple, low-tech, and small footprint devices.
- 20L swirl separator and 500 cm^2 of Dacron matting.
- Employ a trickling biofilter with an expected TAN removal rate of 0.2 g TAN/m^2/day.
- Oversize for safety, aeration, and degassing.

Logistical Design Parameters

- Use predominantly recycled and readily available materials.
- Important components must meet international luggage requirements.
- Minimize power and specialized tool use.
- Keep capital costs to less than US$300.
- Factor in integration with hydroponics and/or alternative energy systems.

FIGURE 1 ERAS design cascade and considerations.

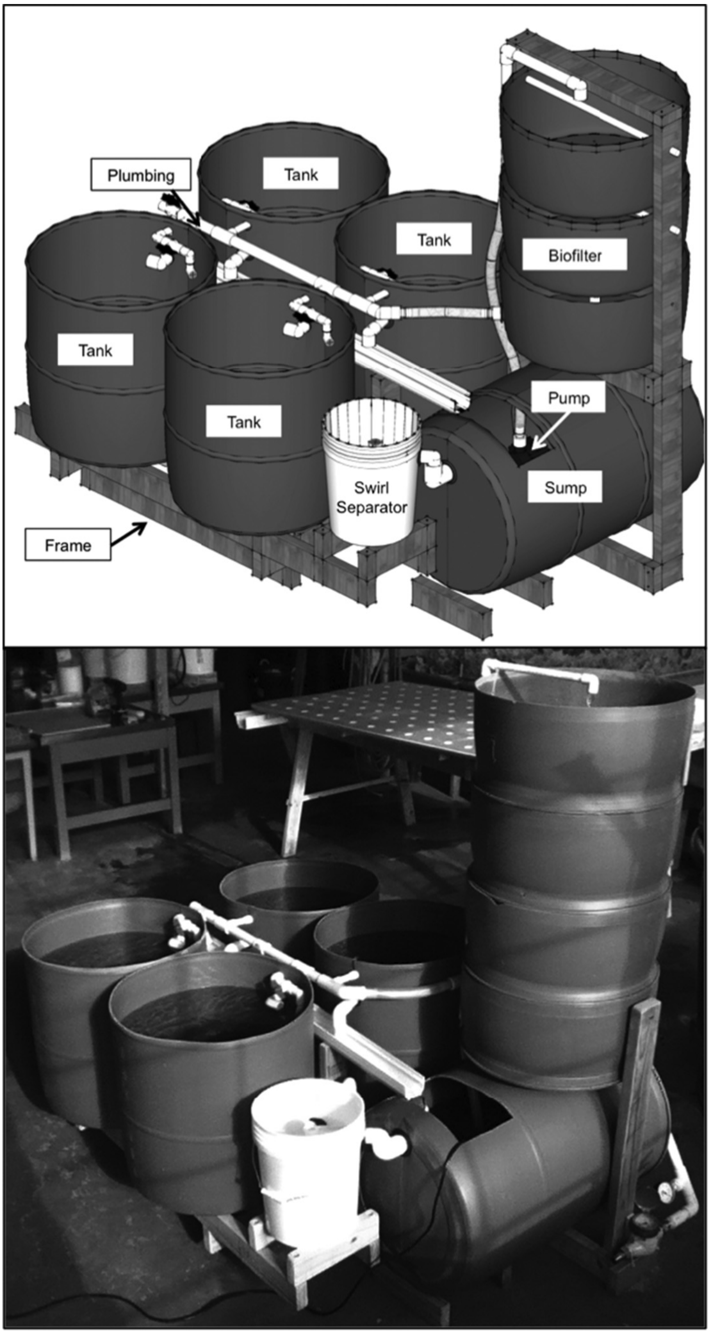

FIGURE 2 The ERAS is made up of the four tanks, the swirl separator, the sump, the pump, the biofilter, and the plumbing connecting all components.

such as feeding, tilapia grow from fry to 450 grams within 6–12 months. While the simplest production plan would involve stocking a tank with 150 fry and then harvesting a year later, this single production cycle leads to underutilization for the vast majority of the year. On the other hand, production cycling can take advantage of individual growth differences to not only reduce the frequency of fry acquisition and stocking but also to increase the frequency of harvesting. As a result, we incorporated production cycling into the development plan; the fastest-growing fish are moved to the next tank in the cycle at 4–6 week intervals. After 6 months, all fish will have been vacated from the preliminary stocking tanks, and room is made for a new cohort of fry. A production cycle incorporating four tanks, each having a maximum capacity of 12–13 fish at 454 grams each, will allow the user to remove 2–3 fish per week over the 6–12 months following stocking.

A high but achievable stocking density for recirculating systems is 120 kilograms per cubic meter (Suresh & Lin 1992). While tilapia can be grown quite effectively at these levels, such stocking densities require a source of pure oxygen, something not feasible for most educational settings. Consequently, the ERAS was developed based on what can be accomplished through aeration. With aeration only through adequate water flow, a recirculating system containing tilapia encounters anoxic conditions above 50 kilograms per cubic meter and often less for other species. Using these parameters as a guideline for producing the 12–13 fish at 454 grams, or an approximate total biomass of 6 kilograms, we need four tanks of approximately 0.12 cubic meters or 120 liters.

A simple loop between active and passive water movement is the most elemental part of a recirculating aquaculture system; the pump is the heart of this loop. Calculations for ERAS water flow and pump sizing were centered on the tank size and fish density described. To grow tilapia to densities nearing 50 kilograms per cubic meter, a flow rate of one to two turnovers per hour is needed for adequate aeration. Selecting two turnovers per hour for safety reasons equates to an absolute flow rate of 240 liters per hour per tank. For all four tanks, a total of nearly 1,000 liters per hour is needed. Approximately 30 centimeters of lift would be sufficient if water was only recirculated between a sump and the tanks, but the ERAS employs a biofiltration unit that requires about 1 meter of lift. With the flow rate and head height in mind, a pump based on manufacturers' pump performance curves was selected. While several different pumps have this capacity, a model requiring about 26 watts of electricity was chosen. A pump of this size costs US$30–US$40 and has annual electricity costs about the same.

The ERAS employs self-cleaning round tanks and well-engineered plumbing to quickly remove solid fish wastes and transport them to removal devices. The system employs a single swirl separator collecting effluent from the bottom of all four tanks as a primary gravity settlement device. The swirl separator then empties onto coarse and fine layers of Dacron matting as a secondary size exclusion settlement device. The small size of the system means the swirl separator is only about 20 liters in volume. As such, the unit is incorporated into the system such that it can be easily isolated through a union valve and overflow connection. The entire unit can then be lifted out to discharge solids. Although seemingly low-tech, it is an effective combination when engineered and adjusted properly. Nonetheless, the low technology and lack of automation must be made up for in the labor associated with maintenance.

To remediate ammonia, remove carbon dioxide, and add oxygen, a trickling biofilter was selected. The ERAS employs a three-tray biofilter of approximately 100 liters in volume and packed with shredded plastic ribbon. The combination provides approximately 80 square meters of surface area, over twice what is needed to remediate ammonia produced from a fully stocked ERAS at a conservative Total Ammonia Nitrogen (TAN) removal rate of 0.2 grams of TAN per square meter per day. In addition to providing compensation for poor performance, oversizing enhances biofilter aeration and degassing capacities. As a design feature, the bottom tray of the biofilter will retain water in the event of a pump shutdown and facilitate bacterial recolonization should such an event occur.

Although RAS can easily reach into the hundreds of thousands of dollars, a RAS for educational use is limited by the constraints of educational budgets. As a result, ERAS design takes advantage of readily available parts commonly used in building and construction. The four tanks are cut from recycled, food-grade plastic barrels; the tops are removed and stacked to form the trickling biofilter; polyvinyl chloride (PVC) pipe is used for the plumbing and fittings; and the supporting frame is built of wood. Additional components include a standard-size 20-liter bucket swirl separator, filter media, and pump. Using these materials and recycled barrels, the total cost of an ERAS is approximately US$300. With conservative estimates, variable input costs (i.e., fingerlings, feed, electricity, and bicarbonate) for an ERAS are also under US$300 per year. For additional costs, an ERAS can be integrated with alternative energy systems, which may reduce lifetime energy costs, as well as with heaters/chillers or hydroponic plantbeds.

The ERAS requires minimal power tool use so that it can be built by individuals on a tight budget or in regions with limited access to electricity. For example, lumber for the supporting frame and barrels for the tanks can be cut with hand tools if needed. However, a basic power drill and bit set is necessary for plumbing the tanks, biofilter, and sump. The low tool requirement, combined with the use of common building supply materials, makes it possible to pack a small kit of necessary ERAS components into a single piece of international luggage.

Refinement and optimization of the ERAS design has been an ongoing process; seven systems have been built in educational settings in the United States and East Africa over 2 years. Preparing materials, collecting necessary components, traveling to educational sites, working with diverse stakeholders, and adapting to local conditions in order to build and run each ERAS has been a continual learning process. As a result, aspects of ERAS design have been modified for individual settings and for more efficient function in the future, although the fundamental principles underlying the ERAS have remained constant. For example, the trickling biofilter in the original design was found to be too precarious to handle strong winds and constant water weight over time; the design has been updated to include PVC pins attached to a wooden extension of the frame for added strength. Furthermore, drainage manifolds that were previously PVC are now vinyl tubing to allow for shifting and irregularities in construction. Our continued experiences in ERAS design, construction, and long-term maintenance allow us to develop and share more effective models at regular intervals.

UTILIZING THE ERAS

The ERAS can be used for multiple aquaculture-related educational activities; this reflects the interdisciplinary nature of aquaculture and the flexibility of ERAS design. Two broad areas of education have emerged: (1) food systems and sustainability education, and (2) practical aquaculture education. Although exceptions exist, demand for the former has been more prominent in the United States, while demand for the latter has come from East Africa.

A key educational use of the ERAS is illustrating to consumers that cultivating fish is a necessary component of modern food production because of increasing seafood consumption and overfishing of wild stocks. Due to public concern surrounding aquaculture, such educational directives are a high priority (Schlag & Ystgaard 2013). With an ERAS as a tangible example, students are guided in discussions of resource use and food production by addressing critical issues in feed nutrient inputs, water consumption, land use, and energy footprints. For example, through the calculation of ERAS feed and electrical requirements, students begin to address complex topics forming the underpinnings of bioenergetics and life cycle analysis. In the analysis of feed requirements and extrapolation to larger scales, students confront issues such as the large volume of fishmeal currently consumed by the aquaculture industry and think about possible alternatives (Naylor et al. 2000). In the measurement of electrical consumption and extrapolation, students can be urged to discuss why the majority of aquaculture producers currently cultivate fish in open water cages as opposed to land-based recirculating systems (Ayer & Tyedmers 2009). Both of these issues lie at the core of aquaculture's negative public perception in the United States. The next generation must more critically examine these important issues in fish production and call attention to the need for more sustainable aquaculture practices.

The modular design of the ERAS also allows for the addition of hydroponic plant beds to become an aquaponics system, where plants and fish are cultivated in a symbiotic relationship (Bernstein 2011). Aquaponics is gaining attention in North America as a tool for sustainability and science education (Hart et al. 2013), which demonstrates a growing cultural awareness of food production and agriculture (Kearney 2010). While the addition of plants expands the energy footprint through a second pump, it also increases the educational opportunities of the system. For example, an ERAS aquaponics system illustrates the potential in closing aquaculture waste streams by integrating other agricultural systems, a core concept of sustainable food initiatives and sustainability education (Lightfoot 1990). Students can conduct experiments to measure fish wastes such as ammonia and nitrate while also exploring their conversion to plant matter. Similarly, advanced studies might include the application of solid fish wastes to biogas production and subsequent conversion to energy (Hoque et al. 2012). With the combined goals of maximizing production, minimizing resource use, and eliminating wastes, an ERAS aquaponics system can provide tangible examples of lessons integral to food systems and sustainability education.

In EA projects, the central goal of ERAS education has been practical aquaculture training and skill development to promote aquaculture industry growth in the EA Great Lakes region. Students using an ERAS in this capacity are involved in hands-on activities that mirror the technical skills needed to successfully run a commercial aquaculture system: fish handling, feeding and growth assessment, water-quality monitoring, and fish health and disease treatment. For example, managing an ERAS provides students with an opportunity to learn the technical intricacies of water chemistry and gain real-world experience in ameliorating pH, ammonia, and alkalinity levels (Badiola et al. 2012). Undoubtedly, students will also get exposure to emergency situations such as responding to disease outbreaks, equipment failures, or extremes in water chemistry, all of which are integral to achieving a working knowledge of aquaculture production. In this way, an ERAS can provide the essential hands-on component for small, poorly funded aquaculture training programs directed at advancement of the EA industry.

The ERAS has also become a component of agribusiness and entrepreneurship programs in EA projects. As a small-scale tangible example of an agribusiness venture, students can explore topics related to accounting, finance, marketing, and the application of new technologies to industry (Badiola et al. 2012). With an ERAS, students have the opportunity to calculate the cost of feed inputs and fish outputs relative to differing feed ingredients, feed conversion ratios, and accessible fish markets. Students can also learn how to compute capital costs and amortize them over their working life and manage operating costs related to fingerlings, feeds, energy, and labor. By emphasizing cost/benefit analysis in relation to after-harvest profits, students can compare recirculating technology with other aquaculture production methods (e.g., ponds and cages) to strategically apply more costly recirculating technology to enhance overall industry output. Collectively, the practical business experience gained through an ERAS can provide students with a realistic understanding of commercial aquaculture and the ability to solve problems in new business ventures.

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