Innovative Technologies to Promote Sustainable Recirculating Aquaculture in Eastern Africa—A Case Study of a Nile Tilapia (Oreochromis niloticus) Hatchery in Kisumu, Kenya

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This article is part of the special series “Improving Water Security in Africa.” The work is the culmination of 7 Horizon 2020 projects focused on the environmental and social challenges of improving water security in African countries.

ABSTRACT
Lake Victoria, regionally important both as a source of food and income, is under pressure due to overfishing and severe pollution. Currently, the vast majority of east African aquaculture is open-pond based. The adoption of modern and sustainable aquaculture technologies and practices—in this case study recirculating aquaculture systems (RAS)—will help the region increase food security and decrease its current reliance on imported fish and stressed wild stock. To this end, VicInAqua, a project under the EU Horizon 2020 program, has developed a pilot Nile Tilapia (Oreochromis niloticus) hatchery in Kisumu, Kenya using RAS adapted to local conditions. The hatchery is designed as a flexible, scalable, and modular system. An online monitoring system enables farmers to access farm data from both fish tanks and the supporting renewable energy systems, allowing around-the-clock monitoring and control. The hatchery is linked to a 14.3 kWp Photovoltaic (PV) system, including a 30 kWh Li-battery storage, to supply sustainable electricity. The water for the RAS, treated by a membrane bioreactor (MBR) and certified for use in aquaculture and agriculture, comes chiefly from Kisumu’s municipal sewage, which reduces the farms’ reliance on an expensive and occasionally intermittent potable water supply. Combining these technologies represents an industry first and offers a working example for larger-scale future developments. The purpose of the project is to demonstrate the possible technologies and practices in situ as well as provide a template for future development and investment. The hatchery is used by the Department of Livestock, Agriculture and Fisheries, Kisumu County, Kenya, as a training and demonstration facility to promote the aquaculture sector and increase the awareness, knowledge, and skills of fish farmers, as well as provide high quality fingerlings to cage farmers within the lake. Integr Environ Assess Manag 2020;16:934–941. © 2020 The Authors. Integrated Environmental Assessment and Management published by Wiley Periodicals LLC on behalf of Society of Environmental Toxicology & Chemistry (SETAC)

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INTRODUCTION
Fisheries are a vital industry in the Lake Victoria Basin, being a major source of income for the population and a driver for many regional economies (Njiru et al. 2008). However, the lake is under severe pressure due to overfishing and pollution (Ntiba et al. 2008). Promoting a shift from wild catch fisheries to sustainable aquaculture is vital (Bostock et al. 2010) for safeguarding the lake ecosystem and the provision of a reliable protein supply for the region’s ever-expanding population.

The Kenyan Government estimates that the nation produces 180 000 tons of fish annually, as opposed to a demand of 500 000 tons (Treasury 2019). Currently, this production gap is largely filled by imported frozen tilapia from China which has been found to be sold at 55% of the value required for local producers to break even (1 kg of imported fish is on average US$2.5 per kg, while the break-even selling price for...
local producers is US$4.5) (Obiero et al. 2019). Implementing modern aquaculture technologies and practices is crucial to closing this gap between supply and demand and enabling competition against foreign imports.

Recirculating Aquaculture Systems (RAS) incorporate water treatment and reuse 90–95% of the water requirement. RAS offer a variety of important advantages when compared to open pond culture, such as reduced water and land requirements, parameter control that allows the optimization of production conditions, strict waste management, and food safety benefits (Timmons and Ebeling 2013).

Adopting modern innovative technologies has contributed to global aquaculture growth, and, for the aquaculture sector around Lake Victoria to follow suit, implementing these technologies and practices is important. VicInAqua, a project under the EU Horizon 2020 program, has developed a tilapia hatchery in Kisumu, Kenya that operates using RAS. The hatchery can produce 25,000 fingerlings per month to supply pond aquaculture in the region. It is designed to be a flexible, scalable, and modular demonstration system which can be adapted to the needs of the operator and to be a tool for the dissemination of training and good practices in the local industry.

CHALLENGES FACING KENYAN AQUACULTURE

Currently, the aquaculture sector in Kenya, Tanzania, and Uganda mainly consists of small-scale farmers using earthen ponds to hatch and grow fish (Rutaisire et al. 2009; Opiyo et al. 2018). These are low labor, easily managed systems, but they only sustain low stocking densities. To compensate, they have a large footprint; the average pond in the region is 281 m² (Okewa and Getabu 1996). Fish hatcheries in the region use simple flow-through culture systems to ensure the high water quality that is necessary for egg incubation and larval rearing (Ngugi et al. 2007). From 2009 to 2013, the Kenyan government implemented the Economic Stimulus Program (ESP) and invested 22 billion Kenyan shillings (KSH) in the promotion of the aquaculture sector. However, in the 3 years following the end of the project, 73% of the farms built during the initiative have been abandoned, with 59% of surveyed farmers highlighting limited fingerling availability as a contributing factor (Musyoka and Mutia 2016), as well as other problems such as a lack of pond liner, limited feed availability, lack of finances, and inadequate water supplies. Limited training programs, stemming from a lack of resources and suitably trained personnel also inhibit the potential for growth in the sector (Shitote et al. 2013). Globally, farmed tilapia often undergo hormone sex reversal using 17α-methyltestosterone (MT)—a synthetic male androgen. Farmers prefer an all-male tilapia stock as their growth rate is greater than females, thereby reducing the time required to achieve market weight. A male-female mix leads to multiple fish sizes within the population, which causes difficulty at harvesting time, and unwanted spawning can cause stunting due to overpopulation within cages (Chakraborty and Banerjee 2010). Currently, only 9.6% of hatcheries within Kenya carry out sex reversal (Nyorje et al. 2019). For the local industry to compete with cheap imports, these practices must become common place.

Should the above issues be addressed effectively, there is great potential for growth, as currently only 0.014% of land suitable for aquaculture within Kenya is being used for this purpose (Munguti et al. 2014).

CHALLENGES WITH THE IMPLEMENTATION OF A RECIRCULATING AQUACULTURE SYSTEM IN THE REGION

A number of potential issues had to be overcome to implement a successful system in situ. First, RAS rely on a consistent energy supply to run effectively. Figure 2 shows the frequency and duration of power outages from December 2018 until May 2019 at the pilot site. A system error occurred on 23 December 2018, with the longest power cut lasting for approximately 12 hours. Without mitigating for these regular interruptions that are an issue across the whole of Kenya (Taneja 2017), stock death would become increasingly likely as oxygenated water cannot be delivered to the tanks and an increased pressure would be placed on expensive emergency oxygenation systems.

Since tilapia are very sensitive to the suboptimal water temperatures which seasonally occur in numerous areas of the region, RAS with an element of temperature control are especially relevant in hatcheries in this setting (Nasr-Allah et al. 2014).

Biosecurity is increasingly important in RAS due to the elevated stocking densities and reuse of water, and without due care infections can quickly devastate systems. This is of particular importance in hatcheries, as juvenile fish are the most susceptible to disease. Strict biosecurity procedures for staff and visitors and isolating the system from the surrounding environment are vital. Treated water is preferred for use in RAS, especially with the pollutant levels in Kenyan waterways increasing (Kithiia 2012), to ensure that the majority of contaminants and pathogens have been removed prior to system introduction, thereby reducing the likelihood of infection. However, supplies are prohibitively expensive, with 6 m³ of treated water delivered in a bowser costing approximately US$55.

Capital cost has remained a prohibitive issue in RAS development globally as the building of these systems requires a much higher initial investment when compared with simple pond or flow through systems. Also, ongoing system maintenance and upkeep as well as energy costs are all greater than that of a simple pond system.

The solutions developed through the course of the VicInAqua project to combat these challenges are discussed below.

SYSTEM DESIGN

RAS description

The pilot hatchery consists of 3 separate RAS: 1 broodstock and egg incubation system, 1 system for larval rearing, and 1 nursery system (see Figure 1 for a plan view). The system
Figure 1. General plan view of the RAS showing the 3 systems, each with their independent water treatment areas. Additionally, ancillary buildings including the membrane bioreactor building and associated equipment are also shown.

Figure 2. Frequency and duration of power outages at the site from the start of December 2018 to the end of May 2019.
uses low pressure blowers releasing air into header tanks to oxygenate the water. Solids are removed from the tank wastewater by a self-cleaning drum filter. A 40 µm mesh collects particulate matter and a high-pressure pump washes this mesh periodically, removing detritus from the system.

While these types of filters are designed to use minimal amounts of water for backwashing, their efficiency was further improved by collecting effluent in a 2-tank settling system. This allowed feces and detritus to separate via gravity from the main body of water. This water is returned to the system, saving an estimated 600 L of water per day, and the solid waste is used as fertilizer spread on a 300 m² agricultural area surrounding the site. Crops grown in this area are sold locally, providing an additional revenue stream and ensuring minimal nutrient wastage from the site.

Particle-free water then flows to a biofilter. Ammonia, which is highly toxic to fish as it inhibits O uptake through the gills leading to suffocation (Randall and Tsui 2002), can quickly accumulate within a system. The median lethal concentration for tilapia larvae is determined as 1.0 mg/L (Çaglan et al. 2005), an amount which would be achieved in a matter of days in RAS without a functioning biofilter. A Moving Bed Biofilter (MBBR) hosts denitrifying bacteria species which convert the NH₃ first to NO₂⁻ and then to the much less harmful NO₃⁻. A single pump moves clean water from the MBBR sump to the aeration header tank and in turn, via gravity, to the tanks.

To reduce the risk of infections, water pumped to the egg incubation jars and circulated in the larvae system passes through UV-C sterilization lamps, destroying potentially harmful bacteria, since fish in their early life stages are most susceptible to disease.

To aid the removal of matter smaller than 40 µm, each system was equipped with a trickle tower protein skimmer. This creates foam that traps fish protein naturally secreted into the water as well as very small particles which would otherwise remain in the system. Also, the trickle tower, in which water falls via gravity through a tube filled with media creating a splashing effect, aids the removal of dissolved gases. This is important because without degassing, when stocking densities are increasing, the levels of dissolved CO₂ produced by fish during respiration can increase within the system. Fish feed, in the form of pellets, is produced and sourced locally within Kisumu; it is predominantly a mixture of maize flour and lake shrimp (Caridina nilotica).

Production of treated water and retention

In an industry first, the RAS were coupled directly with a membrane bioreactor. Crucial to the ongoing viability of the farm was a consistent clean water supply. Municipal water supplies proved to be intermittent, interrupted repeatedly by a construction site in the vicinity. Water for the RAS is originally sourced from raw municipal sewage delivered to the wastewater treatment plant adjacent to the site. From there it is pumped into the facility and into a Membrane Bioreactor (MBR). Gukelberger et al. (2020) discussed the process by which the sewage water is cleaned and sanitized in depth: a combination of aerobic biological treatment and ultrafiltration with nominal pore size of 35 nm treat the sewage and, combined with a UV disinfection light on the top up line immediately before the entry point to the systems, ensure that the water is pathogen free prior to its use in the RAS. Water from the MBR was tested and certified by Water Resources Management Authority, Kenya for usage in agriculture and aquaculture (for further details on the tested parameters and results, see Gukelberger et al. [2020]).

Initially, daily water exchanges were conducted to increase the MBR water proportion in a single system otherwise supplied with municipal water. For the purposes of these initial tests, the system was stocked with 20 broodstock as well as fingerlings and fry of varying sizes. Observations of fish behaviour and NH₃ and NH₄⁺ levels, which are used as the primary water quality indicator within the RAS, were checked daily. Water quality within this system was consistently excellent, with NH₃/NH₄⁺ values ranging between 0 and 0.25 mg/L at all times over the trial period of several months. Figure 3 shows the share of MBR water was gradually increased to 100% over 16 days in the larvae system. The broodstock and fry held there showed no signs of physical impairment or changes to their behavior and no mortalities were recorded. Also, no change occurred in the NH₃ levels within the systems both before and after the MBR water addition (P < 0.05).

The MBR currently produces 3 m³ of water in a 24 h period, which is enough to satisfy the majority of the demands of the 3 RAS where water losses equate to approximately 3.5 m³ a day—a 7.5% water exchange rate. The water from the MBR passed tests certifying that it is safe for usage in aquaculture, and the fish suffered no initial ill effects from its usage.

To act as a backup in case of MBR failure, a second 1 m³ header tank was installed. Municipal water storage before transfer to the RAS is essential to allow time for chlorine, a standard disinfectant in treated water, to evaporate. Concentrations of 0.2 mg/L will cause mortalities in even relatively tolerant species of fish (Brungs 1973). If water is...
required rapidly, the addition of Na$_2$S$_2$O$_3$ to the header tank will quickly neutralize the Cl present.

Couplings of MBR and RAS have a range of possible future applications, particularly in urbanized areas or regions with very low annual rainfall or minimal amounts of fresh water available. The low footprint of RAS, as compared to pond farming, combined with a ready supply of municipal sewage from an urbanized area (for example, Kisumu has a population of approximately 600,000) would allow aquaculture to develop in locations where it would have previously been precluded by environmental conditions or a lack of available land. Using this technology, fish can be consistently supplied locally and close to the place of consumption—the urban center. This reduces transport costs and logistics and the reliance on imports or wild stocks, and it ensures a fresher product arriving to the consumer.

**Sex reversal**

The techniques for conducting sex reversal are relatively straightforward and hopefully this hatchery will provide a platform for the dissemination of skills like this to local farmers. Hormone powder, containing MT, was used to create all-male fry populations. This powder is mixed with 98% C$_2$H$_5$OH and added to the fry feed. This feed is then dried and fed to the fry for 21 days post hatch, with 0.765 g of hormone needed for every 10 kg of feed.

The impact of untreated MT on the environment is currently unclear. However, it was reported to remain at elevated levels in soils for up to 3 months and in the water column for 2 weeks (Mialila et al. 2015). Performing this operation in the RAS allows all effluent to be controlled and treated before disposal, limiting the potential impact on the surrounding environment. This is particularly important in this pilot project because of the proximity of the RAS to Lake Victoria, with wastewater leading directly into the lake.

**REDUCTION OF RUNNING COSTS**

*Energy supply*

The hatchery is linked to a 14.3 kWp PV system to supply sustainable electricity, thereby guaranteeing an uninterrupted power supply as well as reducing energy costs. The PV system includes 52 PV modules and 12 Li-ion batteries with a total capacity of 30 kWh.

The electricity consumers on site are separated into emergency consumers and normal consumers. The consumers that are crucial for operations are connected as emergency consumers and are always kept powered. The more flexible equipment that can be switched off for some time without jeopardizing the immediate health of the systems is connected as normal consumers. The normal consumers are switched off in the event of energy scarcity to extend battery runtime. This happens during a grid outage and if the battery charge state falls below a predefined limit. The 14.3 kWp PV panels are mounted on a light Al structure fixed onto trapezoidal corrugated sheets.

Figure 4 highlights the system configuration. The main inverter distinguishes between “normal” and “emergency operation mode.” Due to the effectiveness of the emergency dosing system in the RAS, the only pieces of equipment designated as emergency consumers are the MBR aeration blowers. By analyzing the frequency and duration of power cuts, the extent to which the battery can be discharged at night (state of charge limit) was calculated to ensure enough power for the emergency consumers until sunrise in the event of a power outage. Considering a mean value of time without radiation of 14 hours, the system can be supplied for 14 hours in emergency mode (1.5 kWh), which is greater than the longest recorded outage. Discharging the battery from 100% to 70% after sunset allows for approximately 2.5 hours of normal operation while still retaining enough power to cover for the event of a long outage. Therefore, this was the set state of charge limit. From November 2018 to June 2019 a total of 113,000 KSH of has been saved through the use of solar power, which is equivalent to US$1080.

The systems autarchy (degree of independence from the national grid) was calculated for the months of April, May, and June 2019:

\[
\text{Degree of Autarchy} = \frac{\sum E_{PV, \text{month}}}{\sum E_{\text{Total, month}}} \times 100
\]

\[
= \frac{(1266 + 1299 + 1312) \text{kWh}}{(2868 + 2987 + 3254) \text{kWh}} \times 100
\]

\[
= 42\%
\]

*Monitoring system*

A real-time monitoring and alarm system, developed and manufactured by OxyGuard International A/S, is used throughout this facility, both in the RAS and the MBR units. This allows for the automatic recording of key system parameters: dissolved oxygen (DO) and pH. There are individual DO probes in each tank and one pH probe per system.

Every tank has an emergency O line—an air stone in the tank which connects, though a dosing cabinet containing a pressure regulator and flow meters, to a bottled O supply. If a low DO event is detected through the probe in one tank, then a solenoid valve within the dosing cabinet is opened and O$_2$ is released directly into the tank. Therefore, the default position of the solenoid valves is open, so that, in the event of power loss to the site, O$_2$ is delivered to all tanks, keeping the fish alive through a period without pumps or aeration.

To increase the efficiency of this emergency dosing, a proportional-integral-derivative (PID) controller was implemented. In a standard operation, if the measured DO drops below a predetermined value, then emergency O$_2$ is delivered until the DO level is restored to above the value (with a given degree of hysteresis). Due to delays between O$_2$ dosing and an increased DO level being detected by the probe, a system like this leads to inefficiencies, as the
The amount of O₂ released will be greater than the minimum amount required. Using the PID, this wastage is minimized as the dosing response is proportional to the magnitude of the DO deficiency—the lower the detected DO, the greater the amount of time the solenoid valve is open in a defined time period. For example, when detected DO is only marginally lower than the set point, the emergency system will only dose for a short period of time within a period (e.g., for 5 s in every 30 s). This allows for a gradual increase in the DO value and in turn minimizes waste.

**RAS housing and green water**

RAS hatcheries typically use heat pumps and heat exchangers to maintain a consistent temperature throughout the year and to control spawning cycles. Kisumu is located directly on the equator with an average annual temperature variation of only 2 °C consistently around 24 °C, which is at the lower limit for *O. niloticus* fry’s optimum growth (El-Sayed and Kawanna 2008). Rather than use heat pumps, which have high capital, energy, and maintenance costs, the RAS was housed within a greenhouse, maintaining increased water temperatures and decreased diurnal variations. The broodstock’s system average temperature was 27.5 °C (SD = 1.3 °C) and the larvae system average temperature was 28.0 °C (SD = 1.9 °C). Figure 5 shows the diurnal variations in temperature and DO over the course of a week.

Due to the elevated temperature, increased nutrient load in the water, and high light levels, conditions were ideal for algal growth. Therefore, the system runs with green water consisting of algal matter suspended within the water column. Issues were identified when the density of algae became too great. Photosynthesis caused large daily variations in DO and pH levels. Biofilter activity can be impacted by changes in pH, potentially influencing water quality, although this was not observed during the first 4 months of operation.

At night, DO can drop dramatically to a recorded minimum of 3.2 mg/L as algal photosynthetic activity ceases (Figure 5). As there is no direct injection of O₂ into the systems and the aeration blowers run at a single speed, a limited number of options are available to the system operator to boost DO. Initially, the emergency dosing system was used to maintain DO at a minimum of 4.5 mg/L through the night. However, the cost of bottled O₂ means that this is not a practical solution. Instead, O₂ was allowed to drop to as low as 3.4 mg/L before activating the emergency dosing system with no negative impacts on the fish being discerned.

While Feed Conversion Ratio (FCR) has not yet been measured at this stage, it is anticipated to be higher than in a clear system and growth rates in juvenile fish are anticipated to be greater, as the tilapia were observed grazing on the algal growth within the tanks, a result that has been reported previously and quantified (Azim and Little 2008).
To control the algal load in the systems and maintain it at advantageous levels, regular and rigorous cleaning and siphoning of tanks is required. Shade netting was installed over the broodstock tanks to limit photosynthesis, and tank turnover was increased. During recirculation, 100% of the water circulating through the larvae system passes through a UV-C disinfection lamp. This had a visually observable effect (although unquantified) in inhibiting algal growth.

**SYSTEM PERFORMANCE**

Successful reproduction cycles have been completed multiple times to date within the pilot system with fish transferred to local farmers for stocking cages in the lake. The broodstock system is currently housing 560 Nile Tilapia, with a 3:1 female-to-male ratio. During a harvest, 19,500 eggs were collected over 5 days. Of these, 84% of hatched eggs achieved a marketable size. Fingerlings are typically sold at between 1.3 g and 2 g for approximately 3 KSH per fish, with a premium for larger fingerlings. Therefore, a collection of 19,500 eggs will yield approximately 50,000 KSH, or US$470. These fingerlings were all sold as monosex males.

The RAS design displays the possibilities for RAS in the region with low mortalities, the successful production of fingerlings, and functioning equipment. Also, with the regular sale of fingerlings to local farmers, future predictions provided by the managing partner on site, the Department of Agriculture, Livestock and Fisheries, Kisumu County, suggest that all costs associated with the site will be met through fingerling production.

A hurdle that must be cleared to permit wider usage is perception. The question of whether people would be willing to eat fish that have been partially reared in recovered wastewater is important for any large-scale farm to answer. Initial indications from this pilot are good; local farmers showed no reluctance to buying the fish to stock their cages. Indeed, approximately 3 months after the RAS started up, requests for fingerlings stood at 250,000 fry/month, which is 10 times the amount the system was designed to produce.

**CONCLUSION**

The pilot can be considered a success. It is likely that, given the demand for the fingerlings, this will continue to be self-sustaining in the future and will hopefully establish a lasting legacy of knowledge and technology dissemination in the region. Furthermore, the rationale and designs can act as a template for future investment and advancement of the industry. Hopefully having a working pilot operational in situ with a clear demand for its products will encourage external parties to invest in RAS in the region, thereby allowing the sector to continue to expand.

Future research should focus on an investigation into any longer-term impacts of using the MBR treated water on the fish. It would be instructive to analyze the final product, fingerlings from the RAS that have been sold to local cage farmers and grown to market size, to confirm that there are no negative impacts from using MBR water in this setting. Thus far, as the coupling of MBR and RAS has only been operational for a relatively short period of time, no opportunities have appeared to take fish samples for testing.

Additionally, it will be important to assess the full lifecycle of the RAS system. The environment it is situated in, with consistent high humidity and temperatures, is unforgiving for the operation of equipment. Procuring specialist spare parts in regions such as this is challenging. Therefore, it is essential to ensure that all equipment installed here is sufficiently rigorous to allow long-term usage in this setting. Collecting this information is important given the intention for this pilot to act as a template for other projects to follow.

![Figure 5. Graph showing diurnal variations in the temperature and DO levels in one tank in the larvae system.](image-url)
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Data Availability Statement—All data discussed in the paper are available on request from the corresponding author Jan Hoinkis (Jan.Hoinkis@hs-karlsruhe.de). Additional background data and metadata are unavailable, as parts of the VICINAQUA project are confidential.

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