Article

Technology-Business-Management of Recirculating Aquaculture System (RAS) for Sustainable Urban Farming in Sub-Saharan Africa: A Review of Challenges and Opportunities

Emmanuel O. Benjamin [1,*], Oreoluwa Ola [2] and Gertrud R. Buchenrieder [3]

[1] Technical University of Munich (TUM), Germany and Aglobe Development Center, Nigeria; emmanuel.benjamin@tum.de
[2] Technical University of Munich (TUM), Germany; oreoluwa.ola@tum.de
[3] Universität der Bundeswehr München (UniBw M), RISK Research Center, Germany; gertrud.buchenrieder@unibw.de
* Correspondence: emmanuel.benjamin@tum.de

Abstract: The urban population in developing countries, especially sub-Saharan Africa, is rapidly increasing. As towns and cities grow, so does the demand for fish protein. While flow-through aquaculture can provide fresh, healthy and nutritious fish protein, it is plagued by extensive land requirement as well as effluent discharge, thus, unsuitable for city regions. Alternatively, small-scale Recirculating Aquaculture System (RAS) could improve food and nutritional security (FNS), livelihoods as well as reduce environmental degradation in urban areas despite land and water constraints. The question however remains - what are the key technical, business and managerial issues, surrounding small-scale RAS in urban farming? This study reviews the RAS prototype of the Sustainable Aquaponics for Nutritional and Food Security in Urban Sub-Saharan Africa (SANFU) II project based on mass balance and stock density, relevant for fish survival and/or availability as well as net cash-flow analyses. The results suggest that small-scale RAS are technically and financially viable only with family labor having proper aquaculture monitoring and management skills. Furthermore, access to adequate equipment and inputs as well as electricity for the recirculating system are crucial. Urban innovation actors will adopt RAS if operations are profitable given that family labor is employed.

Keywords: Food security; Urban farming; Fish protein; RAS; Land; Water; Sub-Sahara Africa

1. Introduction

The increasing population and spade of urbanization in sub-Saharan Africa is reaching unprecedented levels. In a number of instances, urbanization has passed the 50% threshold [28]. A number of factors ranging from high fertility rates to rural-urban migration drives population growth and urbanization [1, 41]. This implies that there will be a substantial increase in the demand for animal sourced foods (ASF), specifically fish protein, in cities and towns, which (rural) producers will be unable to meet [7]. Furthermore, prospective (rural) fish farmers, often young and agile, seek greener pastures in cities abandoning farming altogether. This exacerbates the fish supply deficit observed in sub-Saharan Africa, particularly Nigeria, where the fish consumption rate is less than 10 kilograms compared to the world average of 19 kilograms per person per year [11]. This is more severe among women and children resulting in malnutrition and one of the highest stunting rates among children under the age of five [42]. To compensate for this deficit, urban vulnerable groups often turn to backyard gardens and other micro- and small-scale agribusiness for subsistence as well as income generation [39]. Thus, one of the alternatives and viable options for ensuring food and nutrition security (FNS) and alleviating poverty in urban areas that has gained recognition over the years in sub-Saharan Africa is urban farming. The term urban farming implies cultivation of plants and the raising of

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animals for food in cities and towns (similar to the definition of urban agriculture by [15]). Urban farming has to embeded in urban planning and development as well as urban-rural interactions given its requirement for scarce resources such as land as well as the corresponding water, energy, food and ecosystem (WEFE) Nexus.

Conventional urban farming related to (flow-through) aquaculture has always been relevant for animal protein in and around cities and towns in developing countries, specifically, Lagos, Nigeria [1]. However, flow-through aquaculture involves the consistent exchange of fish wastewater for maintaining water quality levels and fish health. This leads to high discharge of effluents[1] into ground water as well as other water bodies resulting in eutrophication[2]. The spade of urbanization, particularly in sub-Saharan Africa raises questions about the ability of flow-through aquaculture to be viable given land and water constraints as well as environmental concerns. Climate change introduces additional challenges to flow-through aquaculture as the competition for scarce resources intensifies and non-circular food systems heighten the strained relationships between the WEFE Nexus. However, limited efforts in improving the productivity, efficiency, and reducing environmental pollution in conventional aquaculture in African cities has been made [14, 16, 20, 33, 34]. The ongoing COVID-19 pandemic, and more recently the Russian invasion of Ukraine, have had devastating effects on the FNS status of urban dwellers in sub-Saharan Africa [23]. Both external shocks disrupted regional and international supply and value chains and caused food and energy price inflation. This experience revealed the need to make local and regional food systems crisis proof, which means increasing system resilience while conserving resources and the environment.

Thus, to improve urban FNS and reduce the pressure on the environment, Davies et al. [14] and FAO [18] calls for the introduction of novel circular agri-food technologies and practices in the urban food systems, which simultaneously generate income through profitable businesses. A number of studies [6, 7, 9, 37] have also emphasized the need for innovative urban farming technologies that require limited resources (i.e., land and water). Examples of such innovative urban farming technologies include recirculating aquaculture systems (RAS). These technologies are suitable for African (peri-)urban settings because they do not require great access to land, water, or wealth. Moreover, they can spur job creation, especially for women and young adults. According to Fornshell and Hinshaw [20] (p. 11), "recirculating aquaculture systems consist of a culture unit connected to a set of water treatment units that allows some of the water leaving the culture unit to be reconditioned and reused in the same culture unit. Recirculating aquaculture systems minimally require water treatment processes to remove solids, remove or transform nitrogenous wastes, and add oxygen to the water." However, the rather high up-front costs of RAS and the operating costs related to electricity, which is essential to maintain the water circulation and aeration have limited its adoption among urban farmers [20]. Furthermore, Ahmed and Turchini [2] and Bodiola et al. [5] argue that the complex production design limits the adoption of RAS in developing countries especially in those of sub-Saharan Africa. Bodiola et al. [5] also attribute lack of skilled staff for water quality control and repair of mechanical faults on the slow adoption of RAS. Profitability was always an issue due to the relatively high up-front costs even though Aich et al. [3] argue that RAS has the potential to produce 30-50 times more fish per unit area compared to conventional fish farming. Yet, RAS has not witnessed broad adoption in urban farming in developing countries, only in developed countries [3]. Still, data that can provide insights on the challenges and opportunities of urban RAS adoption in sub-Saharan Africa are lacking. Aich et al. [3] also argue that this is a major challenge for RAS in urban food systems as economic viability of relevant parameters such as optimal and maximum density, market prices, energy cost etc. are often based on assumptions. This study revisits the design and technical details as well as costs and benefits of micro- and small-scale RAS. We explore

[1] Effluent is any form of liquid waste that discharged into body of water.

[2] Eutrophication is the prevalence of excessive nutrient in body of water.

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the results of the Sustainable Aquaponics for Nutritional and Food Security in Urban Sub-Saharan Africa II (SANFU II) project from March to June 2022.[3] The SANFU II RAS prototype is a simple micro- and small-scale RAS (600-liter fish tank, sorting and sump tanks with 148 African Catfish - *Clarias Garipinus*) undergoing testing in Lagos, Nigeria. The design, capacity and cost related to setting-up and managing the SANFU II RAS are presented. This type of circular agri-food innovation is found to be suitable for vulnerable population groups in urban environments where land, water, and wealth is limited.

The results suggest that the micro-and small-scale RAS can be stocked at a density twice its capacity of up to148 fish (grow out weight of >500 grams) but requires an efficient filtration system. This relative high stocking density requires certain management skills and entails risk of fish mortality. The monthly fixed and variable costs associated with running the RAS for a complete fish production cycle of four months was estimated at ₦36,733 (US$63) and ₦ 16,733 (US$29), respectively, assuming that the *latter* managed by an unpaid family member. In the case of the *latter*, the monthly cost per fish > 500 grams sold would thus come up to ₦111 (US$0.19) while revenue was ₦283 (US$0.49), resulting in a unit profit of ₦172 (US$0.30). The average price of fish > 500 grams in the local market varies between ₦1,000 (US$1.7) and ₦1,200 (US$2.1).

2. Materials and Methods

2.1. RAS technology – An overview

Compared to flow-through aquaculture, RAS is a more complex method of fish farming. RAS can be divided into several smaller sections or unit (treatment) processes that work as stand-alone unit or that are linked through a process stream. The basic concept of RAS is to have a solution (technology) and management in place for the envisaged scaled-up fish production that is effective in the sense of improving supply of fish protein as well as profitable within a specific region of the world. The process of a typical RAS (as illustrated in figure 1) ensures that the water flows from a fish tank and through units that remove solids (settleable, suspended, fine and dissolved), turns the ammonia to nitrate and adds oxygen before the cleansed water is returned back to the fish tank [17]. RAS also requires a monitoring and control system to be in place to avert fish mortality due to poor water quality, diseases, and other related risks.

[3] The food price inflation and fish feed chain disruptions caused by the Russian invasion were already reality during this time.

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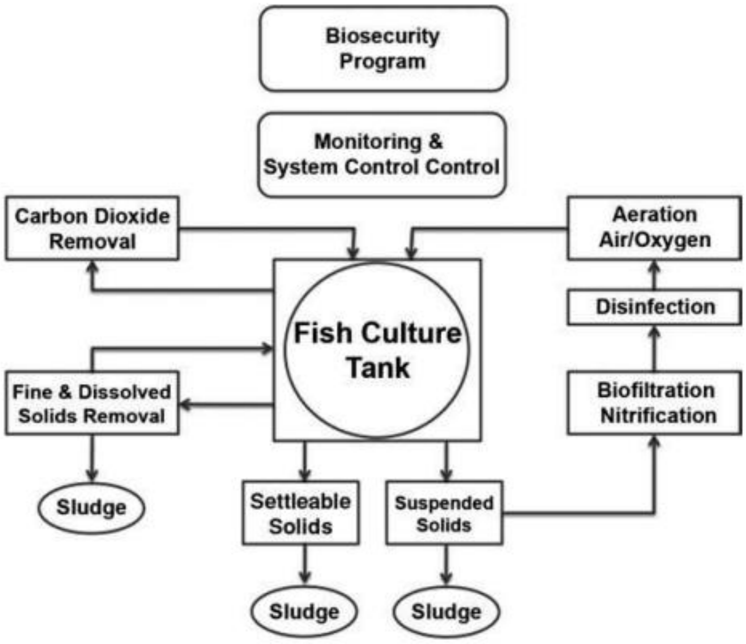

Figure 1. Unit processes used on a recirculating system

Scheme 17. (p. 248).

The SANFU II project was implemented on an area of 13.4 square meters with a partial open greenhouse in Lagos, Nigeria. Relevant data such as water quality, fish weight, system management, labor input, investment, and variable costs (e.g., costs of fish feed) were recorded. Market price information was collected from fish farmers and sellers in and around Lagos as well as through secondary sources. Other relevant data were collected using local knowledge if and when available. The duration of the SANFU II project data collection for this study was from March to June 2022.

The SANFU II project is based on a simplified design and fabrication of RAS consisting of a fish and sump tank, a solid lifting outlet (SLO), a redial flow settler, mechanical and biological filtration that are all linked together as a process stream (see figure 2). The SLO pushes settleable and suspended solids into the redial flow settler, affixed with a stilling well that ensures settleable solids go to the bottom of the redial flow settler. This redial flow settler is an 80-liter barrel. This is different from the Cornell dual-drain system described by Ebeling and Timmons [17] (p. 250) which uses the culture tank itself as a swirl separator ('tea-cup' effect) and removes most of the settleable solids from a small percentage of discharge from the center drain. However, the results are similar in that only minimal water (10 to 25%) is used to displace settleable solids such as leftover feed and fish excrete [17]. Suspended solids are moved to the mechanical filtration system that uses a granular media filter consisting of granite rocks smaller than 1 cm in size as well as fishing nets, which intercepts the solids and hinder onward flow. The use of the biological filtration system aids the nitrification process were bacterial activities convert the ammonia to nitrite then nitrate based on surface area available for bacterial growth. The media used for surface areas in the biological filtration was the cap of waste plastic bottles (PEP: plastic engineered products) that were cut into four parts to act as floating beads. These floating beads further trap solids that were not intercepted in the mechanical filtration. As stated by Ebeling and Timmons [17] in the case of high levels of stocking density (> 45 kg/m^3), similar to that of the SANFU II prototype (148 fishes is equivalent to 74 kg/m^3), an aeration system is needed to provide adequate levels of oxygen. The requirements on monitoring rises with increasing stock density. To this end, regular measurement of pH and ammonia were conducted through external labor hired to oversee the biosecurity, monitoring and control procedure of the SANFU II RAS prototype. The

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SANFU II RAS system is equipped with a 3,000 liter/hour water pump and 600 liter/hour aeration system having a power consumption of 10 Watts per hour (see Figure 3).

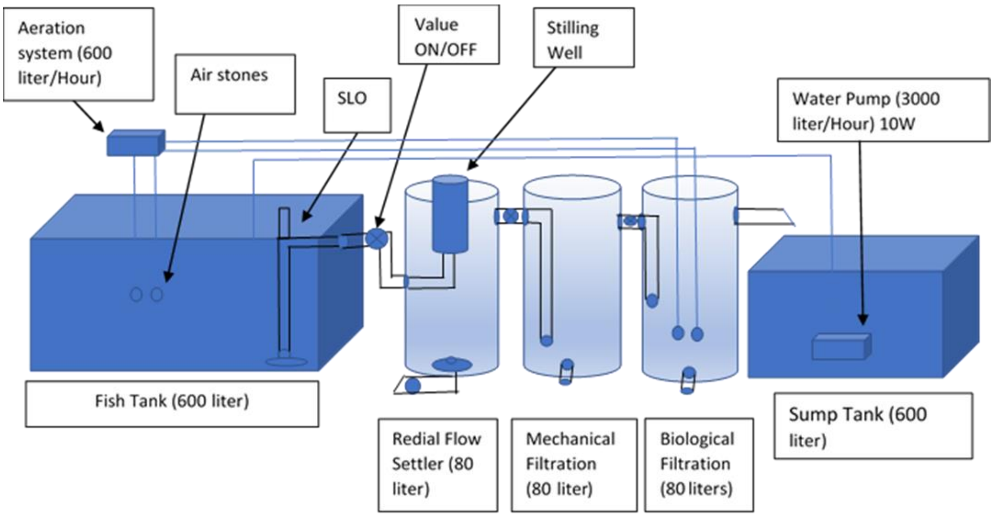

Figure 2. SANFU II micro- and small-scale RAS unit process design.

Notes: SLO = solid lifting outlet

Figure 3. SANFU II RAS prototype implementation.

2.2. Efficiency and Business-management indicators of RAS

As earlier mentioned, the technical and financial viability of RAS depends on a number of factors ranging from water quality based on filtration, stocking density, monitoring and management to cash flow. Thus, the quality of water will be estimated based on the mass balance, i.e. the volume of solids after filtration, which is also influenced by the stocking density. The mass balance approach makes it possible to track the amount and sustainability characteristics of circular and/or bio-based contents in the parts of the whole of the supply and value chain and attribute it based on verifiable records from the management and monitoring. The cash-flow analysis provide business viability estimates.

2.3. Mass balance

It is important to assess the technical viability of the RAS in developing countries before looking at the cost and benefit implications. Maintaining appropriate and good water quality is essential for successful management and operations of RAS. The quality of water can be estimated through the mass balance as well as the stocking density calculation [17]. The mass balance is denoted as:

$$Q\ X\ C_{in} + P_{solid} = Q\ X\ C_{out} \quad (1)$$

where C_{in} and C_{out} are concentrations of a vector of variables such as solids in and out of the fish tank (kg/m3), Q is recirculated water (liters per day) and P_{solid} is the production rate of total suspended solids (TSS) (mg per liter).

P_{solid} can be estimated using the mathematical formula: 0.25 × kg feed fed (dry matter basis4).

Solving for C_{out} in kg/l will provide water quality concentration for the filtration device, i.e. left-over particles in a given filter device is estimated using the mass balance analysis and denoted as:

$$C_{out} = C_{in} + \frac{T}{100}(C_{best} - C_{in}) \quad (2)$$

where $\frac{T}{100}$ is the treatment (T) efficiency (%) of the filter and C_{best} is the optimal result obtainable by the filtration (e.g., no suspended solids).

2.4. Stocking density

When designing a RAS system, it is important to estimate the number of fishes that can be adequately and safely raised in the anticipated unit volume of the fish tanks. This should be done with the aim of moving the fish to the market once the table size weight, i.e., usually around or above 500 gram is achieved. This pre-defined fish weight of table size and the number of fishes in the tank are important for determining the feeding rate. Ebeling and Timmons [17] argue that the number of fishes that will be stocked for each unit volume ($Density$) is based on the species and size of fish at grow-out stage. Similar, to the approach of [17], this study uses the fish body length (L), when table size weight is achieved, to estimate the number of fishes that can be raised per unit volume of fish tank denoted as:

$$D_{Density} = \frac{L}{C_{Density}} \quad (3)$$

where $D_{Density}$ is total weight of fish that can be stocked (or harvested) per cubic meter measured in kg/m3, L is the length of fish in cm and $C_{Density}$ is a default value that is dependent on the species of fish (we use a $C_{Density}$ value for the African Catfish of 0.34, which is similar to that of trout species). It is however important to note that permissible fish stocking densities not only depend on the fish size and technical characteristics of the facility but also on operational and management skills [17].

2.5. System monitoring and management

To have a sustainable fish farming development through RAS, it is important to have an adequate management as well as a monitoring system for diseases and pathogens in place [3]. Even the small-scale RAS prototype of SANFU II requires a substantial level of monitoring and correctional measure, especially at a higher stocking density, to guarantee adequate fish wellbeing and yield. The monitoring and management tasks include filtration system cleansing and residual removal, disease control as well as controlled water

[4] The value of the dry matter basis ranges between 0.20 and 0.40.

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replenishment. One full-time staff, a facility manager, with on-site training in aquaculture management was saddled with this responsibility including data recording, working six hours a day seven days a week.

2.6. Cash-flow analysis

Cash flow analysis is used to estimate the movement of funds in and out of the company account within a given timeframe. This is based on current cash generated from operations as well as cost incurred (fixed and variable costs) due to running of the facility.

$$CF = R - (C_{fixed} + C_{variable}) \quad (4)$$

where CF is the cash flow, R is the revenue, and C_{fixed} and $C_{variable}$ are fixed and variable costs, respectively. While the up-front costs of the RAS components are not relevant for the cash-flow analysis, however, this study provided a rough estimate of the up-front costs to urban farming entrepreneurs. The units of all the values are in currency - Naira (₦) and US Dollars (US$).

3. Results

Mass Balance. The SANFU II RAS started out with 148 fingerlings. After 84 days into the four-month growth cycle, 22 African Catfish had achieved a marketable table size of ≥ 500 grams. Given that the African Catfish has reached its table size weight, sales activities started. Figure 4 shows the feeding pattern and decrease in stock density due to sales over time. The minimum and maximum daily feed quantity was 12 gram and 1.8 kg, respectively. The average amount of daily feed was approximately 0.78 kg with an average cost of ₦585 (US$1). The efficiency of each of the filtration systems was observed to be 98%, based on the volume of residuals of settleable solids observed in the fish tank. If the aforementioned values are computed for the concentrations of solids out, C_{out}, of the filtration system (eq. 2) it will result in a value of 0.015 kg/l.

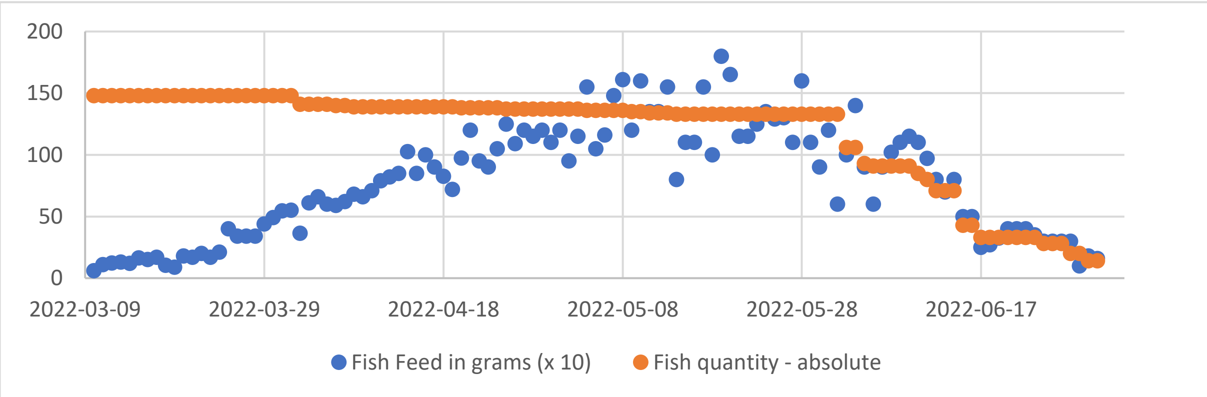

Figure 4. Quantity of fish and amount of fish feed in the SANFU II RAS in one cycle of 4 months.

Stocking Density. The anticipated length of the African Catfish at the end of the four-month growth cycle is 40 cm. The $C_{Density}$ of 0.34 (default value uses for a certain species of fish) was used for the African Catfish to estimate the stock density (eq. 3) level of 118 kg/m³. Considering that the fish tank in use is 0.6 m³ implies a stocking density, $D_{Density}$, of 71 kg/m³. Ebeling and Timmons [17] recommend to start with half of the estimated stocking density, which would correspond to 35,5 kg/m³ given the fish tank measures 600 liter. This implies that 71 African Catfish with a table size of ≥ 500 grams should be farmed in the tank. Therefore, the SANFU II project with its initial 148 African Catfish stocking density is twice the recommended capacity based on [17].

The adequate aquaculture management put in place was able to prevent a high level of mortality. The mortality rate of the SANFU II RAS was 11% and below the 12% Catfish mortality rate often observed in aquaculture (see [40]). This is not to say there was no

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consequence for stocking at relatively high density as cannibalism was observed while 131 Catfishes survived. This resulted in the separation and sorting of the fishes after two and half months. African Catfish above 400 grams were transferred to a flow-through system and immediately sold to consumers while those below 400 grams were kept in the RAS. Figure 5 below shows the stocking density of the African Catfish in the micro- and small-scale RAS towards the end of the four months cycle.

Figure 5. African Catfish yield of the SANFU II RAS in one production cycle of 4 months.

System monitoring and management. The higher the high stocking density of a RAS the higher the demands on the monitoring and management. The twice as high stocking density as compared to the recommended capacity based on [17] in the SANFU II RAS was compensated with more intense monitoring and management. This entailed cleaning the immense settleable solids and other residues from the filtration system as well as observing fish health on a daily basis. A number of events such as system clogging, water treatment and fish health concerns led to complete removal and replenishment of the water in the fish tank over the four months growth cycle. Figure 5 illustrates the trend in water replenishment due to filtration cleaning and aforementioned occurrences. Figure 6 shows that 100% removal and replenishment of water took place less than 10 times in 114 days or one cycle, alongside the 10 percent water displacement attributed to filtration cleaning and effluent removal (also see [17]) associated with the micro- and small-scale RAS. Compared to conventional flow-through systems in which water is completely replenished every two days, depending on stocking density, the micro- and small-scale RAS prototype conserves water. Due to the presence of adequate monitoring and management as well as the expertise of the full-time staff member (see section 3.3) in aquaculture management, the SANFU II RAS prototype experienced a lower than average mortality rate. Fish mortality was predominantly due to bacterial infection. For instance, Amponsah and Guilherme [4] argue that bacterial infections account for the majority of mortality in aquaculture. As a way of minimizing bacterial and fungal infection, sea salt treatment and antibiotics were applied to the system once a sick fish was identified and separated. Occasionally, sea salt treatment was also applied as a precautionary measure.

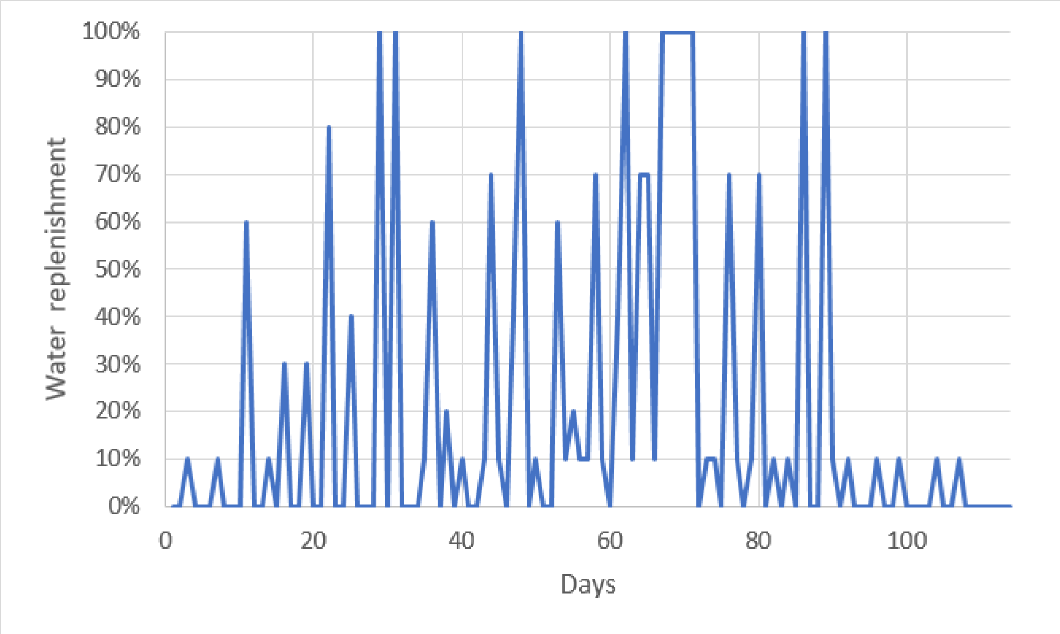

Figure 6. The filtration cleaning and water replenishment in the SANFU II RAS in one cycle.

Notes: Filtration cleaning was always taking place when the water replenishment was above 5 percent.

Cash-Flow Analysis. Although the cost of the RAS designed and fabricated under the SANFU II project is beyond the scope of this study, it is paramount to mention it and provide practitioners and policy-makers with a comprehensive cost overview. The up-front costs of the SANFU II RAS prototype, which consist of a 600-liter fish tank system (plus sorting and sump tanks), fingerlings, a 2.5 KVA solar system, 10W water pump and aeration device, was estimated at ₦ 700,000 (US$1,200). The cost of the 2.5 KVA solar system (incl. batteries) in Lagos, Nigeria ranges between ₦300,000 (US$517) and ₦850,000 (US$1,465). Thus, the cost of a complete solar powered micro- and small-scale RAS would range between ₦1,000,000 (US$1,724) and ₦2,000,000 (US$3,500) in Nigeria (see [6]). Alternatively, solar energy could be sourced from a local green energy provider such as MTN Solar Electricity. The SANFU II project deploys a mixed energy in powering the RAS by combining off- (solar) and on-grid electricity to account for electricity needed at night. The average daily running time of the 10W water pump and aeration device was 20 hours. The respective price per kilowatt-hour of solar and on-grid electricity in Lagos was ₦58 (US$0.10) and ₦45 (US$0.08), respectively [31]. The expected monthly expenditure on electricity (solar and on-grid) required to operate the RAS is estimated at ₦1,233 (US$2) while salary payable was at ₦20,000 ($34). This results in a monthly fixed cost of ₦21,233 (US$36). The monthly variable cost, comprising fish feed (foreign and locally sourced), medication, and other operational expenses, is estimated at ₦15,500 (US$27) bringing the total monthly fixed and variable cost of the SANFU II RAS prototype to ₦36,733 (US$63) but can be reduced to ₦16,733 (US$29) without external labor. A more detailed overview of the total monthly fixed and variable costs is presented in table 1. Fish feed and external labor make up 37 percent and 54 percent, respectively, of the total cost. The market price of one African Catfish at table size in Nigeria in 2022 was between ₦1,000 (US$1.7) and ₦1,200 (US$2.1). At the end of the four-month production cycle, 115 fishes weighing above 500 grams, were sold resulting in revenues of ₦130,140 (US$224). This implies a monthly

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revenue of ₦32,535 (US$56). If the average monthly expenses are compared with the revenues, the SANFU II RAS prototype still entails a deficit of ₦4,198 (US$7). In the short run, a profit will only be achievable if the paid full-time staff is substituted with family labor. We assume that family labor is without cost given that there is hidden unemployment in the family. In this case, the monthly profit would amount to ₦19,770 (US$34) or ₦172 (US$0.30) per fish sold.

Table 1. Overview of monthly fixed and variable cost of simplified RAS in Lagos, Nigeria.

Fixed Cost			
Description	Unit	Amount (₦)	Amount (US$)
Utilities			
Solar system	KWH	696	1.2
On-grids Electricity	KWH	537	0.9
Salary			
Facility manager	1	20,000	34.0
Total fixed costs		**21,233**	**36.1**
Variable Cost			
Fish feed	kg	13,500	23.2
Treatment of disease (antibiotics and sea salt)	kg	1,000	1.7
Miscellaneous (Repair, replacement etc.)	1	1,000	1.7
Total variable costs		**15,500**	**26.6**
Total costs		**36,733**	**62.7**

Notes: KWH = kilowatt hour. Exchange rate applied here was US$1 = ₦580, which was the average rate observed during the field work. 600-liter tank was stocked with 148 African Catfish.

3.1. Challenges of sustainable RAS in urban sub-Sahara Africa.

Electricity. According to Fornshell and Hinshaw [20] constant and stable electricity is essential for operating and managing RAS irrespective of location. One of the major challenges for micro-small-scale RAS in urban areas of sub-Saharan Africa is the issue of unstable electricity supply from the national grid. Bodiola et al. [5] identified power failure as a one of the major setbacks for RAS development across the globe. The SANFU II project piloted in Lagos, Nigeria, experience on average of 11 hours of on-grid power outage per day. The use of an alternative energy source, namely a 2.5 KVA solar system, made the aforementioned average pump running time of 20 hours possible. Figure 7 below illustrates the difference in the number of hours of available on-grid electricity and the running times of water pumps (see green arrows) supplemented by renewable energy. According to Aich et al. [3] such use of new energy sources will be vital in overcoming future challenges and attaining a sustainable blue economy.

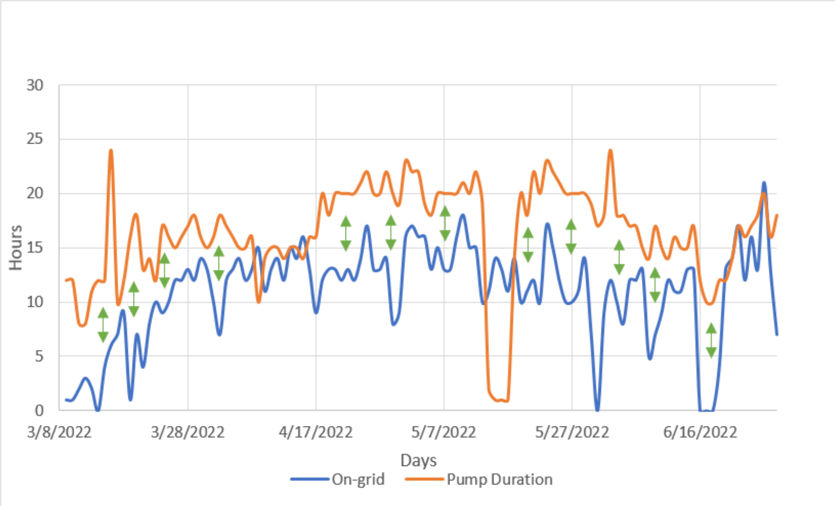

Figure 7. On-grid electricity supply and running time of water pump in hours per day.

Input market. There is an immense input market gap (for instance with regard to fish feed, fingerlings and equipment) for RAS if the technology and practices should be adopted as part of urban farming, across sub-Saharan Africa. The situation would have been worse but for the availability of some virtual marketing platform as well as local plumbing and hardware stores. However, substitutes and alternative equipment at plumbing and hardware stores do not necessary conform to aquaculture standards. According to Lutz [25], the use of less-standardized inputs can reduce yield and thus profit while making quality control more difficult. Thus, for micro- and small-scale RAS to thrive in urban sub-Saharan Africa, input supplier must be in close proximity, have quality products, be reliable and trustworthy.

4. Discussion

External shocks such as the COVID-19 pandemic, climate extremes as well as other similar events in the future will exacerbate global food insecurity and poverty for urbanites [12, 38, 27, 44]. The disruption to food systems due to these external shocks has again raised the debate on local food production and supply and value chains. However, dietary diversification through home gardens and small livestock could help improving FNS, especially among vulnerable groups such as women and the youth [8, 29]. Due to its modest requirements regarding land and water, RAS can be perceived as a longer-term adaptive strategy for food accessibility and nutritional provision among families and communities in urban areas of developing countries [24, 26]. The existence of local ASF systems in cities and towns is relevant for a stable protein supply [24]. Producing fish protein in RAS bears the benefits of improving the animal sourced protein supply while improving food system resilience to shocks and reducing the pressure on the environment, thus, improving the WEFE Nexus. However, adoption of innovative aquaculture technologies such as RAS in urban sub-Saharan Africa has been slow due to a more complex food production system, rather high up-front costs, and profitability challenges.

This study aims to shed more light on these challenges by investigating the fish production cycle and cost-benefit characteristics of a mixed energy small-scale RAS implemented under the SANFU II project in Lagos, Nigeria, from March to June 2022. The technical design of a stable RAS system should have a filtration system able to provide adequate water quality with little or no solid residue in ensuring fish health and survival [17]. The estimated water quality concentration, which is expressed in the left-over particles in a given filter device in kg/l (C_{out}) for the micro- and small-scale RAS of the SANFU II project was of 0.015 kg/l. This modest value attest to the efficiency of the filtration units used for fish wastewater recycling under the SANFU II project, as the value is similar to that of [17]. This has minimized the complete removal and replenishment of water in the

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RAS to less than 10 times during the production cycle compared to over 60 times in a conventional flow-through system for the same stocking density and duration.

The appropriate stocking density estimated for African Catfish in the SANFU II project was 35 kg/m^3. Similarly, Dai et al. [13] found that stocking African Catfish at a density between 35 kg/m^3 and 65 kg/m^3 provides high welfare standards with higher stocking density hindering certain welfare indicators, such as hematological and biochemical indices. However, van de Nieuwegiessen et al. [43] argue that African Catfish can adapt to higher stocking densities between 100 kg/m3 and 300 kg/m3 in intensive recirculating systems. Hengsawat et al [21] also found that high stocking density will result in increased catfish harvests. As such, the SANFU II project opted for a density of between 50 and 100 kg/m^3 with the purchase of 148 African Catfish fingerlings. This stocking density was done with the intention of replicating the conditions in a typical micro-scale commercial flow-through system. The grow out weight of the African Catfish at this stocking density at the end of the four months period was above 500 grams and a length above 40 cm. Benjamin et al. [6, 7] also found that after four months a length of 40 cm as well as a weight of over 500 grams was achievable in African Catfish. Brummet [10] argue that for aquaculture to develop in Africa and provide diverse benefits to society, a business approach that focuses on small and medium scale enterprises must be adopted. This will enable practitioners, especially vulnerable groups in urban areas to rear fish for subsistence consumption as well as revenue generation through selling them. Amponsah and Guilherme [4] argue that fish farming using tanks in RAS requires high initial investment and reliable electricity but is easy to construct on limited space, e.g., in backyard gardens or courtyards. The cash-flow/profitability analysis conducted for the SANFU II project follows this line of reasoning in exploring the cost-benefit of RAS in an urban farming context.

In terms of scaling the project to reach more households, an important question to ask concerns the high initial investment and operating costs. As mentioned earlier, the costs of fabricating RAS equipment is beyond this study's scope, however, from our results, we can pinpoint areas where urban farm households or start-ups can reduce their operating costs.[5] The small-scale RAS under consideration in this study can become financially viable if households utilize family labor and if the family labor has the appropriate aquaculture management skills.

By replacing an external facility manager with family labor, the monthly operating expenses estimated at ₦20,000 (US$34) of the micro-and small-scale RAS could be reduced to ₦6,000 (US$10). This will also enhance acquisition of new skills and learning on the job. The use of family labor in urban farming, specifically RAS, may not only improve FNS due to improved subsistence consumption but also make it a profitable and thus viable venture. When family labor replaces external labor and aquaculture management skills are accessible, a monthly revenue of ₦32,535 (US$56) and net cash-flow (profit before taxes) of ₦9,802 (US$17) could be realized. This is still below the daily poverty ceiling of US$1.90 a day but a net benefit if the assumption that the family member has hidden unemployment because then this profit actually increases average family income. These numbers bodes well for efforts to improve FNS in urban and peri-urban sub-Saharan Africa.

Accompanying the use of family labor is access to appropriate aquaculture monitoring and management skills. Monitoring helps to identify fish diseases and to engage in counter measures, thus reducing losses and costs. The SANFU II project trained and retained a young adult from the host community as a facility manager responsible for water quality and fish health management. The facility manager undertakes filtration maintenance as well as data collection including recording of fish growth, pH and ammonia of the RAS. The filtration maintenance was observed to be more frequent as fish growth pro-

[5] Badiola et al. (2018) outline a series of activities needed to optimise the design of RAS technology while reducing production costs.

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gressed, among others, due to the high stocking density and treatment of bacterial infection. Authors should discuss the results and how they can be interpreted from the perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

4.1. Policy Implication

For RAS to be financially viable, acquiring the proper aquaculture management skills is important. Despite the importance of these skills as well as the growing recognition of the role that aquaculture could play in fostering FNS, reduce environmental pressure due to ASF production, aquaculture management skills remain mostly unavailable when consulting the list of extension services provided by extension workers in sub-Saharan Africa [30, 32]. Getting aquaculture management skills on the radar of public extension workers is therefore essential, especially for households who might be unable to afford private extension services.

Other areas where policymakers could improve the viability of RAS concerns how to reduce energy costs. Governments should work on optimizing the already existing energy infrastructure to improve its efficiency. Otherwise, investing in renewable energy sources [see 35] to ease power availability concerns and energy costs of operating RAS systems represents a cost-effective approach. Governments in sub-Saharan Africa could invest in renewable energy to increase availability of green electricity and make them accessible to the public. Incentives such as subsidy provision, reducing regulatory constraints to encourage private investments, developing a stable regulatory framework that reduces environmental pollution, e.g., introducing a carbon tax can help to mobilize massive private sector investments in renewable energy sources [36].

Finally, technology has an important role to play in further enhancing the availability of RAS equipment and inputs. For instance, online platforms that could improve access to aquaculture inputs and RAS technology. Another useful area is in linking RAS technology developers to potential users to facilitate dialogue between individuals who design and use the technology respectively to create a feedback network. This represents a cost-effective way for users to gain needed expertise to operate the technology and feedback from users to developers could provide insights on how to further optimize the functionality of RAS technology. An example is the linkage of RAS practitioners and stakeholders to digital innovation hubs (DIHs) such as the SmartAgriHubs.eu or DigitalAgriHubs.eu. This will provide them with access to digital decision support and risk analysis tools as well as access to investors. Public and private policymakers should create supportive frameworks to encourage the development of these platforms. This could be done by providing funding to develop and sustain the platforms, leveraging already existing networks e.g., extension agencies, to promote and market the platforms to a wider audience, and building strong public-private sector partnerships to attract more investors for RAS systems.

5. Conclusions

African (peri-)urban areas still suffer from high levels of undernourishment and malnutrition due to deficiency of protein, among others [11]. An important animal sourced food (ASF) is fish, accounting for up to 50% of protein intake in some African countries [19]. Up to now, the majority of fish is produced on the basis of flow-through aquaculture in sub-Saharan Africa. Flow-through aquaculture is, however, usually unsustainable in city region food systems because it requires substantial land and water resources and pressures the environment through effluents.

Sustainable (i.e., circular and resilient) and equitable city region food systems with strong production and market connections are a critical foundation for thriving communities and businesses [22]. This can be achieved by transforming linear production and midstream components of the city region food system into circular ones [45]. Circularity in a food system context implies reducing the amount of waste generated and changing diets towards more diverse and resource efficient food patterns. RAS are circular and suitable for the unique context of African cities because they do not require great access to land, water, or wealth. RAS has the potential to produce 30-50 times more fish per unit area compared to conventional fish farming. Yet, RAS has not witnessed broad adoption in urban farming in developing countries. This is attributed to the rather high up-front costs, the costs associated to the dependence on electricity to maintain water circulation and aeration, and the managerial requirements with regard to water quality control, fish health, and maintenance of the RAS equipment.

This study assessed the technical and financial viability of a small-scale RAS prototype in Lagos, Nigeria of the SANFU II project from March to June 2022. The small-scale RAS prototype consisted of a 600-liter fish tank system (plus sorting and sump tanks), fingerlings, a 2.5 KVA solar system, 10W water pump and aeration device. It was stocked with 148 African Catfish, which was twice the recommended stocking density of [17]. Yet, the fish mortality rate was even lower than the average, which can be attributed to adequate monitoring and management of the SANFU II RAS for which a full-time facility manager was employed. The highest cost factor was external labor with 54 percent of total costs, followed by fish feed with 37 percent. Electricity costs at the time were rather modest with 3.3 percent of total costs. Due to the paid manager, the RAS operations were not profitable, however. Assuming that the monitoring and management is taken over by a qualified but unpaid family member, the monthly cost per table size fish would amount to ₦111 (US$0.19) and with an average price in the local market of ₦1,139, unit profit of ₦172 (US$0.30) can be achieved. Alternatively, the produced fish could be consumed by the family, thus reducing the purchasing costs for fish protein and contributing to improved FNS.

These results imply that small-scale RAS are technically and financially viable if labor costs are moderate, e.g. through employing family labor, and if the facility manager has the proper aquaculture monitoring and management skills. Furthermore, access to adequate equipment and inputs as well as electricity for the recirculating system are crucial. Given these supply market conditions are in place, it is plausible to assume that urban innovation actors will adopt RAS because operations are profitable given that family labor is employed.

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