AFRICA ENVIRONMENTAL REVIEW Journal

ARTICLE

ISSN: 1727-8341
AER Journal Volume 4, Issue 2, pp.

123-138, Aug, 2021 **RESEARCH**

Available Online at *http://www.aer-journal.info*

Assessment of the Performance of Aquaponics and its Uptake for Integrated Fish and Plant Farming in Sub-Saharan Africa

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Abstract

Aquaponics is an innovative and sustainable fish and vegetable production system that has the potential to contribute to food security and livelihoods of many people in sub-Saharan African (SSA) countries that are experiencing pervasive droughts, declining crop yields, soil pollution, and climate change. Although an emerging innovation in many parts of the world, aquaponics has a huge potential for adoption in SSA countries. Aquaponics, as a technology, is based on the concept of efficient nutrient retention, reduction in water use, and waste discharge to the environment. Aquaponics is also expected to improve profitability by simultaneously producing two cash crops (mainly fish and vegetables). Several freshwaters, marine, and brackish water fishes can be reared in aquaponic systems. A variety of plants can also be grown in combination with fishes, ranging from green leafy vegetables and herbs to fruit plants. Plants utilize nutrients from fish excretion and egestion, and remnants of feeds, and in the process reduce the amount that would otherwise be released in wastewater. To achieve optimum fish and plant growth, maintaining optimal water quality conditions in aquaponic systems is a prerequisite. The amount of nutrients supplied in the system is directly related to the amount of feeds given to fish and the amount of waste produced by fish during excretion and egestion. This review shows that despite the huge potential of aquaponics to improve food security and livelihoods of people in SSA, its adoption is very limited. There is a need for investment in the research and training of farmers and practitioners on the practice and benefits of aquaponics as a sustainable food production system. This review highlights the performance and operation of aquaponics and assesses the constraints to its adoption in SSA countries, including Kenya. The review also identifies knowledge gaps that need to be addressed and gives recommendations on how to make aquaponics more sustainable as a food production system in SSA.

Keywords: Aquaponics, Fish Farming, Nutrient Cycling, Wastewater, Water Quality, Vegetables

INTRODUCTION

In the last five decades aquaculture in sub Saharan African (SSA) countries has steadily grown by over 20% (Smith, 2019; Tran *et al*., 2019). This growth has helped in combating food insecurity in many areas it has been adopted (Kara *et al.*, 2018). It is estimated that by the year 2025 more than 50% of fish production in SSA will be generated from aquaculture (FAOSTAT, 2016).

Despite the impressive growth figures, aquaculture is facing stiff competition from domestic, industrial, and agricultural uses of often limited supplies of fresh water. Innovative, cost-effcetive and sustainable methods for farming are highly sought to feed the ever-increasing human population. As aquaculture expands further, new technologies that intensify fish production, maximize water and nutrients re-use will continue to be sought after. Tyson *et al.* (2011) describes aquaponics as a system that integrates traditional recirculating aquaculture system (RAS) with hydroponics. As a technology, aquaponics has both sustainability and innovativeness aspects, and as a result it is gaining fast recognition in parts of the world (Hu *et al.*, 2012). The combination of recirculating aquaculture units with vegetable production has become a successful model for many players including environmental scientists and private entrepreneurs (Kledal & Thorarinsdottir, 2018).

Over the last thirty years, the integration of aquaculture into the hydroponic system has advanced, and this has seen several successful aquaponic system designs, working protocols, diverse plants, and aquatic animal species cultured to which we can refer to (Rakocy *et al.*, 2006). Today, aquaponics is primarily done in greenhouses or outdoor locations where the climate is favourable. In such environments, several methodologies borrowed from both the aquaculture and hydroponic sectors are used.

Design Considerations for Aquaponic Systems

Aquaponic systems are majorly composed of four compartments through which the water circulates (Figure 1):

(1) Fish production unit: this is the tanks where fish are reared. The tanks are designed to allow for the removal of as much fish waste as possible, directly from the tanks into a mechanical filter (Kwon & Kim, 2020).

(2) Fish waste processor: A solids filter used for the removal of suspended solids from the water that mainly consists of fish excretions and a small portion (typically <5% of uneaten feed (Pfeiffer *et al.*, 2008).

(3) A biofilter unit: essential for the oxidation of toxic ammonia secreted by the fish to less toxic nitrate, thus allowing recycling of the system water without continuous replacement (Van Rijn, 1996).

(4) Hydroponic unit: this is where the plants are grown.

Different types of aquaponic systems exist (Table 1), and they are categorized according to the growth-bed designs, hydroponics, and method of coupling (coupled or decoupled) (Kloas *et al.*, 2015). The first category includes the floating aquaponic raft system which is widely used to grow various leafy vegetables such as lettuce, spinach, coriander, amaranth, among many others (Rakocy *et al.*, 2006). The second category is the nutrient film technique (NFT) which is used widely to grow several crops such as garlic, tomatoes, cucumber, and strawberry (Edaroyati *et al.*, 2017). The last category is composed of a bed with growing media. Different materials are used as media, such as ballast, perlite, and peat moss (Rakocy *et al.*, 2006).

Figure 1: Schematic aquaponic systems (Adopted from Yogev *et al*. (2016)).

Table 1: Examples of aquaponic systems in the literature

Type of aquaponic <u>system</u> Combinations References

Floating raft system Tilapia + basil Rakocy *et al.* (2003) *Oreochromis niloticus* + lettuce
Palm *et al*. (2014)
Oreochromis niloticus + lettuce Ani *et al*. (2021)
Nutrient film technique (NFT) *crispum*) Pangas (*Pangasius* Mohapatra *et al.* (2020)
Grass Carp, *hypophthalmus*) + marigold
(*Ctenopharyngodon idella*) + (*Tagetes erecta)*
lettuce (*Lactuca sativa* L.), dill Lennard & Wards (2019)
(*Anethum graveolens* L.),
rocket (*Eruca sativa*),
coriander (*Coriandrum sativum*
L.), and parsley (*Petroselinum*
Climbing perch, *A. testudineus* + *B. alba* Anantharaja *et al.* (2017)
Media-based bed Nile tilapia + Common Knaus *et al*. (2017)
carp + Cucumbers + Tomato + Lettuce

Nile tilapia + spinach Rono *et al*. (2018)
Nile tilapia + Sweet Wormwood Gichana *et al*. (2019)
\+ Pumpkin, + Amaranth

Performance of Aquaponic Systems

Aquaponic systems substantially reduce water quality deterioration than either separate hydroponics or RAS. Aquaponic systems can maintain water quality at ranges suitable for fish culture with close to 30% water exchange in the fish holding tank (Shete *et al.*, 2013a). Effluents from the aquaculture component have both dissolved and particulate organic matter (DOM and POM, respectively), which come mainly from feeds given to cultured fish. Some of the feeds are digested and metabolized while

some are not eaten and remain as wastes in the water (Joyce *et al.*, 2019).

The main source of nitrogen in aquaponic systems is aqua-feeds, and it is an essential element composing of both proteins and nucleic acids (Joyce *et al.*, 2019; Maucieri *et al.*, 2020). Proteins, which represent up to 70% of fish production cost, are associated with nitrogen. Only 25% of this nitrogen is got via fish biomass whereas over 75% is excreted in the form of ammonia.

The microbial community (archaea, bacteria, viruses, and fungi) play a vital role in the processes of mineralization and denitrification hence improving the overall performance and productivity of the system (Joyce *et al.*, 2019). The microbial community is responsible for the breakdown of the uneaten food items resulting in the formation of nitrates which are absorbed by plants. The microbial community also influences the influencing nutrient fluxes and water quality in RAS and can be used as direct food sources for reared fish species (Blancheton *et al.*, 2013). This eventually allows for the removal of undesirable nutrients from the water making it possible for reuse. Through the process of nitrification, ammonia present in fish feeds and waste products is converted to nitrates for uptake by the plants (Nozzi *et al.*, 2018). Plants absorb nitrate and ionized and unionized ammonia. Nitrogen and nitrates are the essential nutrients required by plants. Therefore, proper management of an aquaponic system facilitates the thriving of beneficial nitrifying bacteria hence improving the sustainability of the aquaponics system.

Ammonium (NH_4^+), which is derived from the fish component as a result of both fish urine and gill excretion, can build up to toxic levels if not removed from an aquaponic system. This is e done by the nitrifying autotrophic bacteria is principally composed of nitroso-bacteria (e.g., *Nitrosomonas* sp.) and nitro-bacteria (e.g., *Nitrospira* sp. and *Nitrobacter* sp.) (Delaide, 2017; Goddek, 2017). The *Nitrosomonas* sp converts ammonia into nitrite before the nitro-bacteria transforms it into nitrate (Keuter *et al.*, 2011; Goddek *et al.*, 2015). The nitrification process is an acid-forming process releasing hydrogen ions (Timmons *et al.*, 2002). The nitrifying bacteria (ammonia-oxidizing and nitrite-oxidizing) always determine the status of an aquaponic system. Their absence will make the system toxic resulting in mass fish mortality. A temperature range of between 15-30°C, pH ranges between 6.5 and 8.5 and DO levels above 3 mg L^{-1} provide an ideal environment for the bacteria to reproduce in the system (Gichana *et al.*, 2019a, b; Joyce *et al.*, 2019).

The nitrification process is aided by certain autotrophic bacteria (primarily *Nitrosomonas*) which oxidize ammonia to nitrite and others (primarily *Nitrobacter*) oxidize nitrite to nitrate. The overall reaction of nitrification can be summarized as follows (Haug & McCarty, 1972):

$$\textit{Nitrosomonas: } 55\ NH^{4+} + 5\ CO_2 + 76\ O_2 = C_5H_7NO_2 + 54\ NO_{2-} + 52\ H_2O + 109\ H^+$$

$$\textit{Nitrobacter: } 400\ NO^{2-} + 5\ CO_2 + NH^{4+} + 195\ O_2 + 2\ H_2O = C_5H_7NO_2 + 400\ NO^{3-} + H^+$$

Fish Species Reared in Aquaponics Systems

Fish species cultured in traditional aquaculture systems are also adaptable in aquaponics systems. Aquaponic systems can be established in freshwater, marine, and brackish water environments. Most cultured fish species can tolerate crowding a phenomenon that is good for aquaponic systems (Lennard & Goddek, 2019). As a result, there is a growing number of fish species that have been cultured in aquaponics systems, including Asian sea bass (barramundi), Nile tilapia (*Oreochromis niloticus*), Arctic char (*Salvelinus alpinus*), sturgeon (order Acipenseriformes), Murray cod, European lobster and pikeperch (*Stizostedion lucioperca*) (*Homarus gammarus*) (Rakocy *et al*., 2006; Rakocy, 2012).

Although there are diverse species of fish under both small-scale and large-scale (commercial) aquaponics, most of the data available for fish performance in aquaponics are based on tilapia production (Endut *et al*., 2016). Some studies have reported a significant growth in the culture of several fish species, such as Koi carp, Asian sea bass (barramundi), channel catfish, common carp, goldfish, Murray cod, and rainbow trout in trial aquaponics. However, the culture of fish in commercial aquaponics has been limited to Nile tilapia (*Oreochromis niloticus),* European eel (*Anguilla anguilla*), Atlantic salmon (*Salmo salar*) smolt, common carp (*Cyprinus carpio*), rainbow trout (*Oncorhynchus mykiss*), Koi carp (*Cyprinus rubrofuscus* among many others.

Most commercial systems have used different strains of tilapia (Shete *et al*., 2013a; Kloas *et al*., 2015; Rakocy *et al*., 2016; Makori *et al*., 2017; Fatima *et al*., 2018). Species of finfish and shellfishes that can do well in saltwater aquaponic systems include crustaceans, molluscs, echinoderms, shrimps, prawns, oysters, clams, abalone, flatfishes, pufferfish, and sea urchins among many others (Oliveira *et al*., 2020). Fish species like Nile tilapia of the red strain (a hybrid of *O. niloticus* x blue tilapia *O. aureus*) have been successfully raised in brackish water aquaponic system.

Plants Grown in Aquaponics Systems The production of vegetables in aquaponics has been widely demonstrated (Rakocy, 2012; Knaus & Palm, 2017). The most commonly grown plants among many commercial producers include tomatoes (*S. lycopersicum)*, Lettuce (*L. sativa*), basil (*O. basilicum*), non-basil herbs, kale (*Brassica oleracea*, chard (*Beta vulgaris* subspecies *cicla*), bok choi (*Brassica rapa* subspecies *chinensis*), peppers (*Capsicum annuum*), and cucumbers (*C. sativus*) (Rakocy *et al*., 2004). Other crops grown include two varieties of garnish (Scallion and parsley (Pinho *et al*, 2018), lettuce (Jaeger *et al*., 2019), tomatoes Karimanzira *et al*., 2017), basil (Knaus and Palm, 2017), strawberries (Villarroel *et al*., 2011), cucumber (Tyson *et al*., 2008). Plants that can be used in saltwater aquaponic systems would include edible halophytes such as New Zealand spinach, ice plant (*Suada japonica makino*), glasswort, barley (*Hordeum spontaneum*), rice (PSBRc50 variety), Swiss chard, and seaweed (Palm *et al*., 2018; Oliveira *et al*., 2020). Crops like the chards (Swiss and ruby chards), beets, broccoli, basil, mint, and lettuce have also been grown in brackish water aquaponic systems.

The growth of plants in aquaponic systems can be very rapid and different cropping systems can be used, such as staggered, batch, and intercropping (Rakocy *et al.,* 2016). Comparatively, the biomass conversion ratio for crops is better than that of fish. For instance, as much as 9 kg of plants can be grown using fish manure from 1 kg of fish feed (Love *et al.,* 2015). There is some variation in crop properties based on the different types of aquaponic systems. Fruiting plants such as tomatoes are grown widely in media-based aquaponic systems, while herbs such as basil and thyme are grown widely in both raft and media-based systems (Schmautz *et al*., 2016).

The number of plants grown relative to the number of fish reared must be optimized to increase productivity using available nutrients (Baßmann *et al.,* 2020). Plant densities ranging from 16-44 plants $m^{-2}$are used mainly on floating aquaponic raft systems. These densities can produce various yields ranging from 1.4 to 6.5 kg m^{-2} per crop

(Dedium *et al*., 2012). When the crop is spaced widely (recommended range of 10-30 heads of lettuce per m^2(Licamele, 2009), it receives more sunlight, which in turn, improves the colour and nutrient content of the leaves. The amount of nutrients present in the plants is also dependent on growing conditions, such as temperature (Premuzic *et al*., 2004), irrigation, cultivation methods, and type of crop grown (Nozzi *et al*., 2018).

Plants that are grown in aquaponic systems also require macro-and micro-nutrients. These include three essential macronutrients; carbon (C), oxygen (O), and hydrogen (H), which are supplied by water (H_2O) and carbon dioxide gas (CO_2) (Rakocy *et al*., 2004). Other macronutrients like nitrogen (N), potassium (K), calcium (Ca), magnesium (Mg), phosphorus (P), and sulfur (S) are also supplied by water. Plants also need micronutrients (e.g., manganese (Mn), boron (B), iron (Fe), zinc (Zn), copper (Cu), chlorine (Cl), and molybdenum (Mo) needed in various quantities by the plants. These nutrients must be available for optimum plant growth, but when present at higher levels they make others unavailable (Nozzi *et al*., 2018). A good example is the excess potassium interferes with the absorption of both calcium and magnesium and their inclusion in excess will eventually affect the absorption of the two mentioned nutrients. Nozzi *et al.* (2018).

Role of Water Quality on Performance of Aquaponic Systems

Aquaculture ecosystems consist of physical, chemical and biological components that interact collectively or individually to influence the performance of the cultured species. According to Sidoruk and Cymes (2018), fish produce ammonia through gills and urine, including any undigested feeds and fish egesta and excreta that alter water quality considerably. Fish growth is adversely affected when fish wastes are continuously released in water causing ammonia to build up (Boyd *et al*., 2012).

The key water quality variables related to the culture of fishes are temperature (range from 24°C to 26°C for tropical fish), dissolved oxygen (DO) (4.86-10.53 mg L^{-1}), and hydrogen-ion concentration (pH) (range from 6.1 to 8.3). Temperature affects the growth performance of plants grown in aquaponic systems. The ideal temperature range is from 15-24 ^{o}C but temperatures above 26^{o} C results in bolting and bitter leaves (FAO, 2014). However, other parameters such as ammonia (ranging from 0.003 to 0.25 mg L^{-1}), nitrates (ranging from 10 to 50.7 mg L^{-1}), phosphates, alkalinity, and hardness also have significant impacts within aquaculture ecosystems (Makori *et al*., 2017).

According to Lennard & Goddek (2019) and Rakocy *et al.* (2006), the DO levels must be managed well since it is essential for the fish, plant roots, and microflora and must be maintained in aquaponic systems. DO levels that are below 3 mg L^{-1}are good for the plants and microflora, whereas most fish require above 5 mg L^{-1}. Therefore, having DO levels ranging from 3 - 5 mg L^{-1}ensures that DO requirements of the plants fish and microflora are met. This ensures optimal plant and fish growth (Lennard & Goddek, 2019).

The recommended pH level for most aquaponic systems should be close to neutral (Tempero *et al*., 2002). An increase in pH increases NH_3 toxicity, but at low pH increases NO_2 toxicity (Luo *et al*., 2015). High and low pH levels also decrease nitrification processes. The respiration of fish, bacteria, and plant roots contribute to an increase in carbon dioxide (CO_2) concentrations in water, which form weak carbonic acid and decrease water pH. Carbon dioxide rarely causes harmful effects on fish, but higher concentrations prevent the supply of oxygen by lowering the pH of the blood at the gills (Alatorre-Jacome *et al*., 2012). However, high CO_2 levels do not cause harmful effects when there is sufficient oxygen supply in the water. Free CO2 concentration should be maintained below 3 mg L^{-1}for improved fish growth (Summerfelt *et al*., 2015).

Nutrient Removal in Aquaponic Systems

The amount of nutrients produced by fish in aquaponic systems is directly proportional to the amount of feeds consumed, which also corresponds to the amount of waste (organic matter) released. The fish feeding ratio is often used to determine the number of plants that can be grown (Rakocy, 2007). When fish are fed daily, a continuous supply of nutrients for plant growth is produced. This allows the plants to grow optimally preventing any nutrient build-up in the fish growing unit. Each square meter of hydroponic growing area in a tilapia-lettuce aquaponic system removes about 0.83 g of total N and 0.17 g of total P per day, hence reducing their discharge into the environment (Akter *et al*., 2018).

The feeding rate and stocking density influence the nutrient load (Doughty & McPhail, 1995). Endut *et al.* (2009) reported removal of biological oxygen demand (BOD), total suspended solids (TSS), total ammonium nitrate (TAN), nitrite-nitrogen, total phosphorus, and nitrate-nitrogen by 47-65%, 67-83%, 64-78%, 68-89%, 43-53%, and 42-65%, respectively when the water flow rate ranged between 0.8- 4 L min^{-1}. Endut *et al.* (2016) also reported a reduction of TAN concentration in a spinach-based aquaponics system by 88.7% from 0.85 to 0.09 mg L^{-1}. The same authours reported a reduction in TAN concentration in a mustard green aquaponics system by 78.2% to 0.18 mg L^{-1}.

Effect of Stocking Density on the Performance of Aquaponics

Stocking density is among the major factors affecting fish growth under culture conditions (Makori *et al*., 2017). Different stocking densities have been considered for different fish species in aquaponic systems (Table 2). Stocking density directly affects potential feed loss and limits access to feeds by the fish. Some studies have evaluated the effects of stocking density on food consumption, fish growth (Lambert & Dutil, 2001), and survival (Fatima *et al*., 2018). Several studies have also demonstrated the effect of stocking density on the welfare of cultured fish (Ellis *et al*., 2002; Liu *et al*., 2019). In conventional aquaculture, stocking density affects fish growth either negatively or positively depending on the fish species reared (Rahman, 2015). Stocking densities of 106-177 fish m^{-3}(even higher densities of up to 500 fish m^{-3}) have been used for tilapia, 300-600 fish m^{-3} for goldfish, and 140-280 fish $m^{-3}$for Koi carp (Rahmatullah, *et al*., 2010; Shete *et al*., 2013a; Hussain *et al*., 2014).

Most studies on the effects of stocking density on fish performance and survival in aquaponic systems have used tilapia more than other fish species (Yep & Zeng, 2019; Mchunu *et al*., 2020). Based on extensive studies, most of the stocking densities for raising tilapia are affected by the age of the fish at stocking (Endut *et al*., 2009; Sace & Fitzsimmons, 2013). When raising fingerlings, the stocking densities that have been used range from 1,000 fingerlings m^{-3} to 10,000 fingerlings m^{-3} grown up to table size (250-400 g) in ultra-intensive systems with a lot of mechanical aerations.

There is an inverse relationship between stocking density used and growth performance of fish (Knaus & Palm, 2017; Rayhan *et al*., 2018). Although the relationship between the survival of fish and stocking density keeps varying (El-Sayed, 2002), densities chosen are influenced by both the experience and intuition of the farmer. Stocking density also affects water quality, which indirectly plays a vital role in the growth and survival of fish (Makori *et al*., 2017).

Table 2: Stocking densities of different fish species in aquaponic systems

Fish + plant species combinations	**Optimal fish stocking density**	**Growth period**	**References**
Oreochromis niloticus + lettuce	300 fish m^{-3}	8 weeks	Ani *et al*., 2021
European Carp+ catalogna chicory, lettuce + Swiss Chard	2.5 kg m^{-3}	20 weeks	Maucieri *et al*., 2020
Gift tilapia+ morning glory, *Ipomoea reptans,* and taro, *Colocasia esculenta*	106 fish/m³	15 weeks	Rahmatullah *et al*., 2010
Rainbow trout+ Lettuce	3.81 kg m^{-3}	16.7 weeks	Birolo *et al*., 2020
Goldfish (*Carassius auratus*) + spinach (*Spinacea oleracea*)	500 fish m^{-3}	8.6 weeks	Shete *et al*., 2013b
Koi carp + gotukola (*Centella asiatica*)	2.1 kg m^{-3}	8.6 weeks	Nuwansi *et al*.,2021
Tilapia + Indian spinach (*Basella alba*)	167 fish m^{-3}	8 weeks	Rayhan *et al*., 2018
Koi Carp + spinach (*Beta vulgaris var. bengalensis).*	1.4 kg m^{-3}	8.6 weeks	Hussain *et al*., 2014

Economic Analysis of Aquaponics

Aquaponics is a capital- and knowledge intensive food production technology. Adequate capital and operational costs are a prerequisite when establishing and running an aquaponic system. The amount of money needed may vary with the level of intensification or the size of the system to be developed (Engle, 2015). Items to be considered when making estimates for setting up an aquaponics system include greenhouse structure and materials, the tanks, feeds, fish, PVC pipes and accessories, submersible pumps, and filtration systems (Rieger *et al*., 2015; Johnson, 2016). Importantly, it is not profitable to run an aquaponic system basing on the fish production unit only because the cost of fish reared may be less than the market price. Hence, the profitability of the system is due to the inclusion of the vegetable portion (Bailey *et al*., 1997; Rakocy, 2012; Tokunaga *et al*., 2015). The plant which is incorporated in the system also absorbs most of the nutrients derived from the fish component at no cost, thereby improving the system's profitability rather than using commercialized inorganic fertilizers which are very expensive (Timmons & Ebeling, 2010).

When large fish and correct vegetables are sold profitability is assured (Engle, 2015; Rakocy, 2012). The price of vegetables will largely whether a farmer makes a profit or not (Bailey & Ferrarezi, 2017). Other factors that affect the profitability are the low prices of fish, high inputs of energy, poor water quality management, poor monitoring and cycling of nutrients, diseases or parasite infestation, high labour costs, and the location of the farm. Aquaponic systems established in urban settings are more profitable than those in rural and semi-urban settings due to the availability of a ready market (Stadler *et al*., 2017). Tokunaga *et al*. (2015) estimate labour at 46% of the total operational costs which also takes at least 40% of total annual costs.

Rakocy *et al*. (2006) recommend that profitability is assured when both plants and fish are grown continuously. Fish can be reared at different sizes whereas plants can be staggered to allow continuous harvest throughout the growing season. When making an aquaponic business plan it is prudent to underestimate the anticipated production and slightly overestimate the costs (Engle, 2015). This will act as a buffer against unforeseen circumstances that may shrink projected profits.

Gaps in Aquaponics Research and Practice

Aquaponic systems are highly reliant on microbial communities. Hence, slight contamination with potentially harmful pathogens can affect the process of nitrification. There is therefore a need to identify and classify the composition of these pathogens in aquaponic systems (Goddek *et al*., 2015).

Heavy metal contamination is common in both capture and culture fisheries sectors. According to Wu *et al*. (2019), the amount of mercury farmed and wild fish are nearly very close. This indicates that there is a possibility of heavy metal contamination in aquaponic systems, a phenomenon worth investigating to come up with relevant conclusions that can guide farmers and policymakers.

Pest infestation is another major challenge in aquaponic systems, especially under greenhouse conditions (Goddek *et al*., 2019). Common pests such as aphids, spider mites, whiteflies, and many others, have been reported to cause severe damages to plants reducing the yields thereof (Rakocy *et al*. 2012; Goddek *et al*., 2019), which eventually increases the cost of controlling this infestation of pests. The current methods used to control pests and diseases are still limited and toxic to the fish. The costs of non-toxic pesticides are also very high and not easily available to farmers (Goddek *et al*., 2015; Wu *et al*., 2019).

There is a shift towards the use of integrated pest and disease management (IPDM) principles instead of pesticides to control pests and pathogens in agriculture (Schnelle & Rebek, 2013). In hydroponics, IPDM principles are done chronologically. The steps followed include prevention, pest identification, monitoring the activities of the pests and choosing a control method, and lastly evaluating the choice made. These steps can also be used in aquaponics but with caution since the choice can have detrimental effects on the fish because of the toxicity of most of the pesticides in the market (Rakocy, 2012; Goddek *et al.,* 2015).

The high stocking densities used in aquaponic systems and RAS are usually associated with the emergence of both fungal and bacterial diseases in the cultured fish species. Attempts to treat infected fish with commercially available antibiotics end up contaminating the system. Despite this challenge, several treatment options such as the use of UV radiation, ozone, organic acids, temperature, and chlorine, can be used. A gap exists in determining the optimal or recommended levels that can be safely and easily used in the aquaponic systems (Wu *et al.,* 2019).

Adoption of Aquaponics in Sub-Saharan Africa

As an efficient food production system aquaponics has gained attention worldwide (Love *et al*., 2015), including in mosts SSA countries. However, several factors hinder the adoption and development of aquaponics for sustainable food production. Disposal of wastewater is a major concern in aquaculture, Recirculating aquaculture systems are therefore seen as means of reducing the huge volumes of discharged wastewater. Even though the volume of discharge is reduced in RAS, the pollution load (in terms of organic matter and dissolved nutrients per unit of discharge is higher. This may pose a danger to the environment, and as far as RAS is concerned, an additional expense of treating the water may be incurred (Li *et al*., 2019). The introduction of a hydroponic component to recirculating systems is intended to reduce the discharge of aquaculture effluents into the environment, and hence extending water use as well as its conservation.

The ultimate aim of any fish production system is to increase and/or maintain high levels of overall fish growth performance, survival, and good water quality. These will ultimately translate to high yield, improved economic benefits, and maintenance of ideal environmental conditions within the fish culture system. The open aquaculture systems that are commonly practised in many sub-Saharan African countries, including Kenya, often result in low fish growth performance, low economic benefits, and sometimes deterioration of water quality in recipient water bodies (Minoo *et al*., 2016).

To solve the problem of low production, there have been suggestions of increasing stocking density. Increased stocking density without changing the culture unit size will result in an increased critical standing crop that cannot be supported by the culture operation (Opiyo *et al*., 2014). This will result in the deterioration of water quality and impaired fish growth performance. An aquaponic system, which entails recirculating water within the production unit, has been proposed to address these challenges. However, being a new technology in many SSA countries, studies on several aspects of the culture system are limited, and not many species of fish are grown. Many studies are also carried only at the experimental level (van Gorcum *et al*., 2019). A knowledge gap on the appropriate fish stocking density to achieve optimal outputs has hindered the adoption of aquaponics and generally retrogressed development of aquaculture in many SSA countries.

Aquaponics is a capital- and knowledge intensive food production technology. Adequate capital and operational funds are a prerequisite when establishing and running aquaponics system. Even though most SSA countries have placed a lot of investment on food production, and specifically on aquaculture, the requisite investment in research on new methods of food production, including aquaponics, is very limited. Thus, there is scarce information and data about many fish species that are needed to maximize production in aquaponics operations. Limited investment in research also extends to limited investment in new methods of food production by farmers. Several studies have deemed profitability in aquaponic systems to be marginal (Tokunaga *et al*., 2015), or being a net loss on the fish but a net gain on when vegetables are incorporated (Love *et al*., 2015). This tends to discourage farmers but with the right choice of valuable crops, profitability is assured.

CONCLUSION

Although some studies have been carried out in recirculating systems in aquaculture, there has been limited research on the growth performance data of fish species like *O. niloticus* and *C. gariepinus* in an aquaponic system in Sub-Saharan Africa (SSA). Certainly, less information is available for other fish species, despite Africa having one of the most diverse fishes in the world. For aquaponics to grow as a sector of sustainable food production, there is a need for investment in the technology and knowledge base of the farmers. Specifically, there is a need to come with cost-effective technologies that can lower the initial cost of setting up the system and its operational costs. Several designs can be adopted or modified using locally available materials, and associated challenges can always have sustainable remedies. Aquaponic systems can easily be powered by solar energy and this will reduce electricity bills and risks especially during blackouts and power surges.

Available data show that aquaponics in many SSA countries is still done at small-scale levels, and this is done by few people with the most reported studies being experimental. Nonetheless, aquaponics can contribute to food security and address nutritional challenges facing many SSA countries. Policies aimed at overall food production and food security need to add more weight to the growth of new technologies for food production under the blue economy mantra. Incentives and knowledge on the concept of aquaponics need to be disseminated among starting practitioners. Moreover, creating the right conditions that better support aquaponics entrepreneurs are needed to attract investors and practitioners.

To foster the adoption and growth of aquaponics in SSA countries, this study recommends the following:

1. Agricultural policies in many SSA countries do not include aquaponics. There is a need for verifiable aquaponics studies to inform policy by goverements. This will guide the sector in terms of funding, credit and extension support, targeting both new and experienced aquaponics entrepreneurs (Mchunu *et al.*, 2018).
2. There is a need for investment in research to study all components of an aquaponic system, particularly in relation to the various tropical fish and plant species.
3. There is also a great need to establish pest and disease management protocols that are accommodative and non-toxic to fish reared in different aquaponic systems regardless of design and type used.
4. There is a need to adopt optimal stocking densities to ensure high productivity in both the fish and plant components of the aquaponic system
5. Lastly, the issue of profitability needs to be addressed by focusing, not only on the economic profitability of the system but also on the environmental benefitis too (Greenfeld *et al.*, 2019). Furthermore, profitability can be achieved when the right crops are incorporated. The growing of these crops can be staggered or different varieties included.

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