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The status of recirculating aquaculture systems in Africa: A review

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Abstract
Recirculating Aquaculture Systems (RAS) present a promising and sustainable approach to addressing Africa's aquaculture challenges by significantly reducing water consumption, minimizing land use, and mitigating environmental impacts. However, despite their potential, RAS adoption across the continent remains limited due to high initial investment costs, technical complexity, and the absence of supportive policy frameworks. This review synthesizes the current landscape of RAS in Africa by examining technological adoption trends, environmental and economic implications, and the status of regulatory frameworks. Drawing on peer-reviewed literature, regional data, and case studies from leading countries such as Egypt, South Africa, and Nigeria, the study highlights that RAS currently accounts for less than 4.5% of aquaculture production. Notably, RAS systems significantly reduce water usage and enable nutrient recycling, although their high energy demands (15-20 kWh/kg fish) pose a sustainability challenge. RAS systems need steady electricity supply, which represent important limited factors in most of African countries. Economically, while the upfront production costs range between $0.50 and $1.00 per kilogram of fish, these are offset over time by enhanced biosecurity and productivity. The lack of RAS-specific regulations in most African countries remains a major barrier to wider adoption. The review underscores the need for regionally coordinated efforts in areas like integration of renewable energy solutions to enhance scalability. Summative, RAS success depends on targeted investments in context-appropriate technologies, capacity building, and policy harmonization to address persistent financial, political and technical constraints.

Keywords: Recirculating aquaculture systems (RAS), Africa, sustainability, water efficiency, aquaculture policy

Introduction

Recirculating aquaculture systems (RAS) have attracted considerable interest in the last few decades largely due to its several advantages over traditional flow through plants. It reduces the use of water and space and also enhances the control over feeding, stock, and environment. In addition, RAS reduces energy use, effluents emission and also results in higher growth and survival rates in comparison to normal flow through culture systems (Blonç *et al.*, 2023) [26]. A review of farm records by Murray *et al.*, 2014 [79] found that although RAS technologies are responsible for just 6% of the world's fish production, this form of aquaculture is the dominant in experimental culture conditions (Dhinakaran *et al.*, 2023) [40]. Intensive farming has necessitated effective water quality management, particularly if high levels of productivity are to be achieved under controlled conditions. The application of RAS technologies can contribute towards sustainable intensification or moving towards an integrated multi-trophic aquaculture operation where species are selected to utilise different trophic resources more efficiently (Mathisen *et al.*, 2016) [70]. It is in this context that RAS soundly sits within the principles of sustainability as the environmental impact of production is minimised through better management of fish waste and effluent discharged into natural water bodies. It also reduces the rate at which fish consume external resources as the water is recirculated and re-used (Martins *et al.*, 2010) [69].

Biofilters in RAS remove nitrogen load and converts it to water insoluble nitrogen containing compounds like nitrate, by-products of this system are heat, carbon dioxide, and microorganisms (Espinal & Matulić, 2019) [44]. In RAS, nutrient composition of the culture water, a key value, is similar to what is in aquatic biological systems at natural latitude.

In other words, the nutrient ratio of total nitrogen and total phosphorous in the organic forms lies between 5:1 and 7:1, the inorganic ratio lies between 12 and 20; calcium and magnesium ratio lies in between 2:1 and 3:1, and the sodium and potassium ratio lies between 2:1 and 3:1 (Bergman *et al.*, 2020) [22]. Comparison of nutrient ratios of fish body and the culture water for both the recirculation line and the make-up water shows that operations leading to nutrient loss must be made in the RAS if the goal is to produce high-quality fish (Ebeling & Timmons, 2012) [43].

RAS are land-based, water recycling plants that culture fish in indoor rather than outdoor conditions (Bostock *et al.*, 2010) [29]. Yet despite such appealing characteristics very few RASs are operational across Africa. Most African fish farmers adopt basic RAS setup, avoiding sophisticated features like protein Schimmers (Figure 1). Some of the constraints are operational cost, skilled human resource, water cost and availability, and electricity cost and availability (Martins *et al.*, 2010) [69]. There are however prospects for RAS development in Africa.

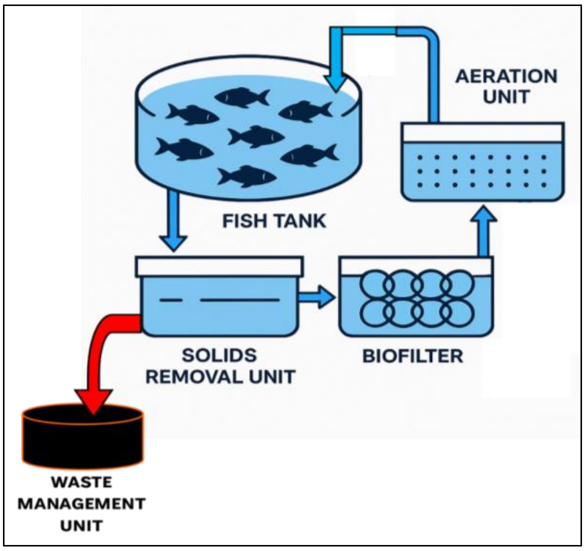

Fig 1: Schematic diagram showing basic parts of RASs commonly adopted in Africa

Despite the proven technical and environmental benefits of RAS globally, their uptake and integration in Africa remain minimal and poorly documented. While isolated initiatives exist across a few countries, there is limited consolidated evidence on their performance, scalability, and contextual challenges within the African setting. A continent-wide synthesis is urgently needed to assess the extent of RAS implementation, identify key barriers and enablers, and highlight opportunities for innovation, policy support, and investment. This review, therefore, aims to critically evaluate the current status of RAS in Africa, drawing attention to knowledge gaps, best practices, and future pathways for sustainable aquaculture development in the region.

Objectives of the Review Paper

The expansion of cage and pond aquaculture production is projected to exceed the limits of the resources required for its sustained growth in the near future (Blonç *et al.*, 2023) [26]. RAS produce high quality seafood with minimal environmental impacts and are an alternative to the open systems which predominate today. As global aquaculture production increases, there is a growing role for small intensively managed systems that are less dependent on land and water and can produce a high-quality and predictable seafood supply. They contain advanced features such as sophisticated water treatment technologies, automated waste collection, and data control systems, so there is a steep learning curve associated with development and operation in RAS enterprises, and these facilities generally require a high level of technical expertise and training of personnel (Achieng *et al.*, 2023) [2].

RAS, and RAS technology are being applied to varying degrees, scales of production, and aquaculture species in a growing number of countries including African countries. As of 2018, studies and RAS production and/or research are increasing in African countries, indicating at least some capacity for production or research in RAS (Hinrichsen *et al*, 2022) [52]. However, majority of these countries are still undertaking research in RAS related production. Sufficient knowledge is therefore needed to support the ongoing RAS experiments in African countries. This review therefore collects facts and status of RAS (research and production) in Africa to ease the ongoing investments of Ras research and production ventures.

Current State of Aquaculture in Africa

Africa has 54 countries with a population of over 1.53 billion people. In 2022, production of animal species from aquaculture in Africa increased by 0.8% compared to the production recorded in 2020 (FAO, 2024) [45]. Fish is a valuable nutritious, high-quality, low-fat protein food which is an important part of diets across Africa and is increasingly traded in domestic and export markets. Despite its potential, Africa contributes only 1.9 percent of global aquaculture production. If we consider all types of domestic animal proteins, 47% of it is fish, which indicates that consumption of fish in Africa is very substantial (Gupta *et al.*, 2024; Hinrichsen *et al.*, 2022; Dauda *et al.*, 2018) [49, 52, 38].

In 2022, the primary sector of fisheries and aquaculture employed around 61.8 million people, compared to 62.8 million in 2020, with 54 percent engaged in fisheries and 36 percent in aquaculture (FAO, 2024; Hinrichsen *et al.*, 2022) [45, 52]. Until 2022, Egypt remains by far the leading country in aquaculture production in Africa producing approximately 62% of the continent's total aquaculture output, significantly outpacing its nearest competitor, Nigeria, which represented around 10% (FAO, 2024) [45]. With the sustained growth in the sector, the total aquaculture production in African continent now stands at more than 2.5 million metric tons, making the continent slightly less dependent on fish imports (FAO, 2024; Chan *et al.*, 2019) [45, 33]. More than 70 species of freshwater and marine warm and cold-water fish are farmed in various culture systems. Majority of the fish production comes from freshwater ponds of mixed farm where fish is cultured with other livestock, rice, vegetables, and other agri-businesses (Obiero *et al.*, 2019) [84]. The global share of African fish production from freshwater ecosystem is greater than 85% (Minich *et al.*, 2018) [73]. The main freshwater commercial species are Nile tilapia (*Oreochromis niloticus*), catfish (*Clarias gariepinus* and *Heterobranchus longifilis*) (Adeleke *et al.*, 2020; Dogah, 2020; Chan *et al.*, 2019) [3, 33]. Crustaceans culture is also growing with macrobrachium prawns, penaeid shrimps, and also river crabs (Valenti & Flickinger, 2020) [112]. There is rapid growth of seaweed farming in Mozambique and Tanzania. Sub Saharan Africa practices more than three thousand year's old extensive method of fish farming by trapping fish in natural or manmade water ponds partitions; the major species which is trapped are small barbs and mudfish (Msuya *et al.*, 2022) [77]. Fish production through this technique is often associated with rice and other agricultural production, in subsistence-based agriculture (Bergman *et al.*, 2020) [22].

Aquaculture in Africa comprises a diverse range of production systems, each varying in level of adoption, technological complexity, and suitability to local environmental and socio-economic contexts. While traditional methods such as pond culture remain the most prevalent due to their low cost and simplicity, other systems like cage culture and integrated aquaculture are gradually gaining ground, particularly in areas with favourable ecological conditions and growing market demand. However, advanced systems such as RASs are still in their early stages of adoption due to high capital and operational requirements. Table 1 summarizes the current adoption rates of the major aquaculture systems across the continent, providing insights into their distribution and associated characteristics.

Table 1: Adoption of Different Aquaculture production systems in Africa (Adeleke *et al.*, 2020; Boateng *et al.*, 2022; Kumar *et al.*, 2018) [3, 27, 62]

Aquaculture System	Adoption (%)	Details
Pond Culture	65-70%	Most common due to low cost and ease of construction, especially in rural areas.
Cage Culture	10-15%	Gaining popularity in large water bodies like lakes (e.g., Lake Victoria).
Recirculating Aquaculture Systems (RAS)	3-5%	Still emerging due to high capital and operational costs.
Flow-through Systems	5-7%	Used mainly in areas with abundant water resources.
Integrated Aquaculture (e.g., rice-fish systems)	5-8%	Practiced in some agroecological zones; promotes resource recycling.

RASs are increasingly being integrated into a variety of aquaculture farming systems to enhance water efficiency, environmental sustainability, and production control. The following are key farming systems where RAS technology can be effectively applied

Production systems in Africa: Aquaculture systems in Africa are increasingly integrating RAS components to improve water quality, boost productivity, and enhance biosecurity. Modern pond-based systems have evolved from relying on organic inputs to using formulated feeds, with adaptations like split ponds and in-pond raceways mimicking RAS principles. Biofloc technology, which cultivates microbial communities to recycle nutrients and reduce waste, aligns with RAS objectives and benefits species like tilapia and catfish. Intensive tank-based systems, highly compatible with full RAS setups, allow year-round, high-density production of species such as salmonids and African catfish under controlled conditions. In Integrated Multi-Trophic Aquaculture (IMTA), RAS enhances nutrient recovery by channelling waste from finfish to aquatic plants or algae. Hatcheries and nurseries increasingly use RAS to maintain optimal conditions for early-stage growth, while polyculture systems benefit from RAS-enhanced biosecurity, reducing disease risks through water treatment and selective species integration (Adeleke *et al.*, 2020; Hinrichsen *et al.*, 2022) [3, 52].

Over the past decade, the adoption of RAS technology has steadily increased, driven by factors such as the need for water conservation, improved biosecurity, and intensified production. An estimate of the contribution of RAS to overall aquaculture production in Africa, highlighting key trends and milestones in the technology's adoption across the continent is provided (Table 2).

Table 2: The contribution of RAS in aquaculture production in Africa (Verdegem *et al.*, 2023; Wambua *et al.*, 2021; Clough *et al.*, 2020; Adeleke *et al.*, 2020) [114, 116, 35, 3]

Year	Estimated Aquaculture Production (All Systems)	Estimated RAS Adoption (%)	Notes
2015	~1.8 million tonnes	~3%	Early adoption phase of RAS, mostly in South Africa, Nigeria, and Egypt.
2017	~2.0 million tonnes	~3.4%	Interest in RAS increased with donor-funded projects and university research.
2019	~2.3 million tonnes	~3.8%	More private farms began adopting RAS for tilapia and catfish.
2021	~2.4 million tonnes	~3.9%	COVID-19 disruptions accelerated the interest in local, closed-loop systems.
2022	~2.5 million tonnes	~4.2%	National and regional aquaculture policies began recognizing RAS explicitly.

Challenges Facing Traditional Aquaculture Systems in Africa: Traditionally, in Africa, aquaculture practices have been characterized by low stocking densities and the use of extensive feeding methods (Chan *et al.*, 2019) [33]. These systems primarily relied on organic manure and minerals sourced from terrestrial environments to sustain fish growth. A prevailing belief among traditional fish farmers has been that lower stocking densities promote faster growth rates in fish. Historically, water distribution velocities in traditional pond culture systems were reported to range between less than 1 cm/sec and up to 15 cm/sec (Akbarzadeh *et al.*, 2017) [9]. Moreover, fish stocking densities were often determined arbitrarily, typically ranging between 300 and 2,000 fish per hectare (Partelow *et al.*, 2023) [91]. These extensive systems do not maximize production potential and often result in slow growth rates and low yields.

Water quality and availability are essential components of successful aquaculture operations (Verma *et al.*, 2022) [115]. In traditional systems, there is often minimal or no regulation of water inflow and outflow, resulting in limited water exchange, low dissolved oxygen levels, and the accumulation of waste materials (Bhateria & Jain, 2016) [24]. Such inadequate water management practices contribute significantly to the rise in disease incidence and negatively impact overall fish health and productivity (Opiyo *et al.*, 2018) [89].

Many traditional fish farmers rely primarily on indigenous knowledge and have limited access to formal training in aquaculture best practices. This lack of technical education constrains their capacity to adopt improved production techniques, manage fish health, monitor water quality, and efficiently utilize available resources, ultimately affecting productivity and sustainability (Bernal-Higuita *et al.*, 2023; Hungevu *et al.*, 2025) [23, 54].

One of the major challenges facing traditional aquaculture systems in Africa is the limited access to high-quality inputs and essential support services. Many small-scale fish farmers struggle to obtain reliable and genetically improved fingerlings, which are crucial for ensuring high survival rates, fast growth, and uniform harvests (Hungevu *et al.*, 2025) [54]. In many regions, hatcheries are few and far between, often lacking proper quality control measures, which results in the distribution of poorly bred or diseased stock. Furthermore, the availability of nutritionally balanced and affordable aquafeeds is a critical bottleneck. Most traditional farmers either rely on substandard commercial feeds or attempt to formulate their own using locally available ingredients, often without proper nutritional knowledge (Mabhaudhi *et al.*, 2018) [65]. This compromises fish health and growth performance, ultimately affecting yield and economic returns. Inadequate feeding practices can also lead to poor feed conversion ratios (FCRs), increased waste production, and deteriorated water quality (Mengistu *et al.*, 2020) [72]. Access to quality veterinary and extension services remains highly limited or non-existent in many rural aquaculture zones. Without proper support for disease diagnosis, health management, and biosecurity practices, fish mortalities can escalate rapidly, causing major financial losses (Opiyo *et al.*, 2020) [90]. The lack of extension support also prevents farmers from adopting modern husbandry practices or receiving timely advice during critical stages of production. Generally, the absence of standardized inputs and services not only affects fish growth and survival but also hinders the development of a consistent and competitive aquaculture value chain. According to Ababouch *et al.*, (2023) [1] and Mwaijande & Lugendo (2015) [80], there is an urgent need to establish reliable input supply chains, promote feed manufacturing standards, strengthen hatchery systems, and expand access to professional aquaculture services to enhance productivity and ensure aquaculture sustainability.

Poor infrastructure remains one of the most significant constraints limiting the growth and modernization of traditional aquaculture systems in Africa. Many traditional fish farms operate with rudimentary facilities that were not designed for efficiency, sustainability, or scalability. Ponds are often poorly constructed without proper lining, slope, or drainage systems, which leads to frequent water loss, pond leakage, and challenges in water quality management (Bergman *et al.*, 2020) [22]. The absence of critical components such as aeration systems results in suboptimal dissolved oxygen levels, especially during warm weather or at night, when oxygen depletion can lead to fish mortality (Mwaijande & Lugendo, 2015) [80]. Furthermore, the lack of mechanized or efficient harvesting tools means that harvesting is often labor-intensive, time-consuming, and stressful to fish, which can reduce product quality and increase post-harvest losses. Without proper infrastructure, these systems also limit the ability to adopt innovative technologies such as RAS, automated feeding machines, or water quality monitoring sensors (Gupta *et al.*, 2024) [49]. These modern technologies require a certain level of physical setup, electrical access, and structural stability that most traditional systems do not provide. The absence of cold storage, processing units, and reliable transport contributes to high post-harvest losses and limits farmers' access to larger or more distant markets (Sibanda & Workneh, 2020) [103]. As a result, producers are often confined to selling within local markets at lower prices, which diminishes profitability and disincentivizes investment in the sector.

Many traditional aquaculture practitioners in Africa operate in isolation from structured and formal market systems (Menezes *et al.*, 2024) [71]. This lack of integration severely limits their ability to access profitable and consistent markets for their fish products. Most smallholder fish farmers rely on informal sales channels and are heavily dependent on local intermediaries or middlemen, who often dictate prices based on opportunistic buying rather than transparent, demand-driven market dynamics (Steenbergen *et al.*, 2019) [105]. Due to their limited bargaining power and lack of access to real-time market information, traditional farmers frequently sell their produce at suboptimal prices, leading to low profit margins (Tripathi *et al.*, 2023) [110]. In many cases, farmers are unaware of prevailing market trends, consumer preferences, or quality standards required by larger buyers such as supermarkets, hotels, and processing companies. This restricts their ability to scale up production or improve the quality and uniformity of their harvests. Fish farmers are discouraged from improved production systems, as they are unsure whether they will receive adequate returns. Without stronger links to processors, exporters, and institutional buyers, traditional fish farmers remain vulnerable to price volatility and are often excluded from high-value market opportunities (Pradhan *et al.*, 2022) [94].

Potential of RAS in Addressing Aquaculture Challenges

RASs are quickly emerging as one of the most promising solutions for the future of aquaculture in Africa. Unlike traditional open systems, RAS are fully contained and highly controlled, making it possible to raise fish at high densities while maintaining water quality and reducing environmental impact (Holan *et al.*, 2020) [53]. These systems use sophisticated technologies to filter and recycle water, removing waste products like food remains, faeces, carbon dioxide and ammonia through automated scrubbers and biofiltration systems. Many of the most advanced RAS facilities are beginning to adopt creative solutions, such as incorporating mollusks for natural filtration, which would be impossible in more conventional, flow-through systems (Gupta *et al.*, 2024) [49]. These improvements align with international fish health standards, including those set by the World Organisation for Animal Health (OIE), making RAS a strong option for countries looking to strengthen their aquaculture sectors for both local food security and export readiness (Jolly *et al.*, 2023) [55].

In African contexts, where challenges like limited land and water availability, climate stress, and competition for agricultural resources are common, RAS offers a powerful alternative. Because they use significantly less water and can be set up in almost any location, RAS can operate even in areas where traditional aquaculture would not be feasible. This includes arid regions or urban zones where space is limited, water is expensive, or environmental regulations are tightening. However, fish farmers in Africa may face difficulties in importing industrial RAS components and therefore use locally available RAS setups (Mnyoro *et al.*, 2022) [75].

Many African aquaculture production farms remain vast or semi-intensive, with a heavy reliance on open ponds and low-tech procedures. These systems have a variety of challenges, including uncertain water quality, disease outbreaks, irregular yields, and restricted scalability (Jolly *et al.*, 2023) [55]. RAS, on the other hand, provides a more stable, high-efficiency solution. Although the initial setup expenses might be considerable, the long-term return on investment is typically higher, particularly when considering reduced water usage, quicker growth rates, and lower disease risks (Pasch & Palm, 2021) [92].

RAS presents an opportunity to create full-time jobs with decent wages and safe working conditions something that's not always guaranteed in traditional fish farming. As climate change intensifies and demand for fish continues to grow, adopting RAS is not just a good idea, it may be essential (Vasdravanidis *et al.*, 2022) [113]. Gupta *et al.*, (2024) [49] highlights how RAS helps maintain consistent production quality, supports rural economic development, and increases the resilience of inland aquaculture systems. Perhaps most importantly, RAS drastically reduces the amount of water needed for production, making it an ideal fit for regions facing freshwater shortages (Brown *et al.*, 2024) [122]. By investing in this technology, countries can enhance food security, create sustainable livelihoods, and protect vital natural resources. With the right support and policies in place, RAS could pave the way for a more resilient and prosperous aquaculture future across the continent.

RAS Technology Adoption in Africa

The limited published knowledge on the status of RAS in Africa presents a significant challenge in evaluating its adoption among commercial aquaculture producers. Findings in this review indicate that RAS adoption remains in its infancy in many regions of Africa, thereby limiting its contribution to the continent's aquaculture growth (Clough *et al.*, 2020; Brown *et al.*, 2024; Rege & Ochieng, 2022) [35, 97, 122]. To unlock the sector's potential, targeted investments are required in RAS-specific feed production and semi-commercial integrated farming systems. Such systems could, for example, align nutrient-rich RAS effluents with horticultural crop irrigation, optimizing resource utilization through integrated aquaculture-agriculture models (Clough *et al.*, 2020) [35]. Therefore, there is an urgent need for expanded research, technology validation, and extension services to establish financially viable RAS-based aquaculture production systems that are suitable for commercial expansion across diverse agro-ecological zones on the continent.

The few farms practicing RAS have demonstrated considerable viability for fish culture in water-scarce environments and offer substantial potential to address food insecurity and poverty in Africa (Bahnasawy *et al.*, 2009) [18]. In Africa, desire for RAS adoption is driven by its advantages and flexibility (Ayim *et al.*, 2020) [15]. The integration of RAS into fish farming holds promise for transforming aquaculture in Africa by enhancing productivity, promoting environmental sustainability, and supporting food security and rural livelihoods (Kim *et al.*, 2022; Bartelme *et al.*, 2019) [59, 19]. However, much of the existing research on RAS adoption particularly in countries like Nigeria and South Africa has been conducted in isolation, without a comprehensive analysis of the broader aquaculture ecosystem across the continent (Zhang *et al.*, 2022) [120]. There remains a pressing need for continent-wide studies that evaluate the systemic integration, socioeconomic impact, and scalability of RAS within diverse African aquaculture contexts.

Egypt, being Africa's leading aquaculture producer, started pioneering experiments with RAS as early as 1970s (Rurangwa *et al.*, 2015; Khater, 2006; Bahnasawy *et al.*, 2009) [100, 58, 18]. These early trials documented by researchers primarily focused on hatchery settings, where RAS offered fine environmental control during sensitive stages of fry and fingerling development. RAS in Egypt was utilized mainly for hatchery operations, an application that continues to define the technology's role. Hatchery systems ranging from hapa units in earthen ponds and greenhouses to more advanced heated greenhouse concrete tanks provide precise control over water quality, temperature, and biosecurity to maximize the survival and growth of tilapia fry (Bhujel, 2025) [25]. These RAS systems, particularly greenhouse setups, support earlier and more predictable spawning cycles a valuable advantage in hatchery management.

Major RAS farming systems in Africa consist of intermediate tech systems, based on only mechanical and biological filtration (Zimmermann *et al.*, 2023) [121]. Recommendations from these countries include investment in research and development; targeting specific investors in national RAS strategies; and possibly using regional development and facilities known in Europe as the Model Fish Farm (Ayim *et al.*, 2020) [15].

The first successful development of RAS in West Africa was recorded in Ghana toward the end of 1983 (Rurangwa *et al.*, 2015) [100]. This milestone marked the beginning of RAS deployment in the region, involving the establishment of two government-run and two privately owned fish farms that focused on the design, construction, and operation of both freshwater and marine RAS facilities (Tran *et al.*, 2022) [109]. In Nigeria, a marine RAS hatchery was later established in Lagos, further advancing the application of the technology. Following these initial efforts, several private aquaculture enterprises began emerging across Nigeria, adopting both small- and large-scale RAS installations directly on farms to enhance aquaculture productivity (Benjamin *et al.*, 2022) [21].

Wontesty Ventures, founded by Ing. Dr. Shadrack Kwadwo Amponsah in Ghana, exemplifies the growing adoption of RAS in West Africa. The company specializes in setting up RAS-based fishponds and provides services across the aquaculture value chain from production and processing to marketing. With a mission to make household-level fish farming accessible nationwide by 2040, Wontesty Ventures has expanded from 100 to over 500 RAS tanks, supporting more than 350 farmers who collectively produce around 350 tonnes of catfish annually. Through partnerships with institutions like GIZ and Bui Power Authority, the company has improved water-use efficiency and increased fish yields by up to 30%. Its "Pond to Plate" (P2P) model has also enabled product diversification, offering value-added catfish products such as fillets, nuggets, and canned recipes stimulating market demand and enhancing food security and employment across communities (Kwadwo *et al.*, 2025) [63].

Studies are confirming the potential of RAS in many African countries, e.g., in Zambia (Hasimuna *et al.*, 2019, Kenya (Wambua *et al.*, 2021) [50, 116], Uganda (Rutaisire *et al.* 2017) [101] and Nigeria (Benjamin & Buchenrieder, 2022) [21]. The demand for high value fish in urban markets in Africa has resulted in the growing acceptability of aquaculture over capture fisheries, with concomitant increase in number of aquaculture farms and livelihoods.

Environmental Impacts of RAS in Africa

The environmental impacts of RAS in Africa are influenced by multiple factors, including the quality of fish feed, the management of infectious diseases, and the efficiency of water resource use (Bartelme *et al.*, 2019) [19]. A comprehensive environmental evaluation using the Life Cycle Assessment (LCA) approach has revealed that the construction phase of RAS facilities contributes significantly to several environmental impact categories, primarily due to the intensive use of materials such as concrete and steel (Arashiro *et al.*, 2020) [13]. These construction-related impacts partially offset the benefits associated with operational efficiencies, such as reduced feed and electricity consumption. In addition to ongoing efforts to improve water management within RAS, there is growing interest in valorising by-products particularly nutrient-rich sludge as biofertilizers. Recognizing biofertilizer as a co-product of RAS systems offers a promising opportunity to mitigate environmental impacts while generating an additional revenue stream for RAS operators. This approach could enhance the overall sustainability and economic viability of RAS in Africa.

Energy Consumption and Efficiency in RAS

Generally, energy use in a RAS can mainly be found in various system components: pumping accounts for 11-50% of the total energy use, feeding takes up 10-60% and aeration can consume 17-24%. In RAS, pumps are usually the main energy consumer in the actual system (Wambua, 2021) [116]. The energy used in a RAS does not stop with the electrical energy used by the different devices and may in fact only be smallest part. The electricity demand to operate a RAS is associated with needs for cooling the water temperature, air conditioning for the indoor part, and gases for supply oxygen and carbon dioxide removal (Terjesen *et al.*, 2013) [107]. From these processes, about half of the energy can be reused by recovering the energy. Another significant way to minimize energy consumption is optimizing feeding regime. The physics behind this is clear, but the energy consumption often is not considered during the design and construction of these ponds and it is relevant to investigate this concept further in the African context (Bosma & Verdegem, 2011) [28].

The study and practice of RAS has increased significantly in many parts of the world to develop better systems for fish culture, while minimizing the environmental impact that is normally associated with high-load fish culture (Belward *et al.*, 2011) [20]. It is essential to understand the energy input in a RAS to evaluate if the significant energy investment in production of fish can be justified by the efficiency, compared with other production methods. Less than a decade ago, the RAS energy use in Africa was only roughly estimated (Belward *et al.*, 2011) [20]. Energy consumption in the RAS in African context is particularly high because of using of outdated equipment and optimization of the system design and system operation is vital in minimizing energy consumption. The peak flowrates of some RAS can be many times more than actual growth requirements (Ebeling & Timmons, 2012) [43]. This increases the energy cost per kg produced and consequently the cost of production as compared to other production systems (Table 3). Steady electricity supply is a critical limiting factor in Africa agricultural development (Manasseh *et al.*, 2025) [68]. Availability and reliability being the most critical issues. Complete RAS equipment may need an average of 380 volt /50 hrtz to operate efficiently, which is not possible in most African cases. Use of renewable energy could provide partial solution for this limitation.

Waste Management and Nutrient Recycling in RAS

Recycling of nutrients in the system could contribute as much as 80 - 90% of input demand and reduce the nutrient load into the environment. Research shows that RAS could play a significant role in minimizing environmental impact, through their ability to recycle and more efficiently and effectively manage nutrient waste in closed systems (Martins *et al.*, 2010) [69]. The major advantage of RAS waste management is the ability to contain most of the nutrient end products of fish, including BOD, making the subsequent land application less risky (Ebeling & Timmons, 2012) [43]. RAS exclude most of the pathogens; therefore, it poses a less risk to the environment, contrasting, for example, to the discharge of effluents from pond-based aquaculture (Tian & Dong, 2023) [108]. Rapid intensification has seen the development of specially developed components that play a crucial role in maintaining the stability of the system (Bartelme *et al.*, 2019) [19]. Processes involved in the management of waste removal and recycling involve the management of nitrogen in intensive RAS, more particularly, in recirculating systems with the highest stocking density. The removal processes include ammonia stripping and denitrification, biological processes (Dumont *et al.*, 2012) [42]. Chemical waste removal is also carried in RAS, through water exchange, which effectively removes wastes from RAS to prevent the accumulation of compounds in the system beyond their threshold levels (Rieder *et al.*, 2023) [98].

Potential of Integrating Aquaponics into RAS in Africa

The symbiotic integration of aquaculture and hydroponics has emerged globally as a sustainable innovation in controlled environment food production. When integrated into RAS, aquaponics enhances nutrient recycling, reduces waste discharge, and increases overall productivity per unit area (Salia & Alda, 2008) [102]. In Africa, where arable land and freshwater resources are often limiting, the integration of aquaponics into RAS presents a transformative opportunity to boost fish and crop production in a resource-efficient, climate-resilient manner (König *et al*, 2018) [60].

Several African countries have pioneered small to medium-scale aquaponics/RAS hybrid systems, providing promising models for replication. In Kenya, urban vertical aquaponics systems in Nairobi and Kisumu have been piloted by NGOs and research institutions to improve food security. Notably, the *Mirror of Hope* aquaponics project integrates tilapia farming with leafy greens, demonstrating economic viability and minimal water use (Odero, 2023) [85]. In South Africa, the *Cape Town Urban Aquaponics Initiative* has utilized abandoned industrial rooftops to develop aquaponics systems that combine RAS-based tilapia farming with vegetable cultivation. These systems have proven popular for community-driven food projects and commercial startups (Lategan *et al.*, 2023) [64]. In Egypt, pilot systems developed at Ain Shams University and adopted by farmers in the Nile Delta have shown high water use efficiency and year-round vegetable production when coupled with warm-water fish species such as tilapia and catfish (Gammal *et al.*, 2024) [46]. These examples underscore the adaptability of aquaponics-integrated RAS to diverse African contexts. Aquaponics-integrated RAS may have slightly higher operational costs due to added components (grow beds, water circulation for plants), but it significantly increases overall system output and reduces per-unit water use a critical advantage in water-scarce regions (Table 3)

Table 3: Comparative analysis of the efficiency, output, and cost from published African studies and pilot projects (Odero, 2023; Lategan *et al.*, 2023; Gammal *et al.*, 2024) [28, 64, 46].

System Type	Water Use Efficiency (L/kg fish)	Crop Output (kg/m²/month)	Operational Cost (USD/m²/month)	Key Benefit
RAS-only	300-500	N/A	$3.50-$4.80	High fish yield, minimal water discharge
Aquaponics-integrated RAS	150-300	1.5-2.5	$4.00-$6.50	Dual yield: fish + crops; nutrient recovery
Traditional Pond Systems	1,000-3,000	N/A	$1.20-$2.00	Low-tech, but water-intensive and seasonal

Policy and Training Recommendations

To accelerate adoption of aquaponics-integrated RAS in Africa, policy support and capacity-building are strongly recommended through national aquaculture extension and incorporating aquaponics into agricultural vocational training. Improved university curricula, and youth empowerment programs (e.g., African Union's CAADP Youth Initiatives) can further enhance technical capacity and employment opportunities. Investment incentives and subsidies for integrated systems should also be considered, especially for smallholder and urban farmers (Mafwila *et al.*, 2019) [66].

Aquaponics as Climate-Smart Agriculture

The Food and Agriculture Organization (FAO) identifies climate-smart agriculture (CSA) as practices that increase productivity, enhance resilience, and reduce emissions (Pisano, 2017) [93]. Aquaponics RAS hybrids align closely with CSA principles by reduces methane and nitrous oxide emissions from traditional ponds, enables year-round food production under controlled microclimates and recovers nutrients, minimizes water loss, and supports circular economies. In drought-prone or peri-urban African regions, aquaponics can thus serve as a climate-adaptive food production model, enhancing both food security and ecological resilience (Kebeda *et al.*, 2019) [56].

Economic Feasibility of Recirculating Aquaculture Systems in Africa: The sustainable development goals (SDG) encompass multiple socio-economic variables, including poverty alleviation, food security, infrastructure, life in the ocean and employment (Niaz, 2022) [82]. The contribution of RAS to food security is evident as it is highly dependable in supplying the increasing global population with sufficient quantities of safe and nutritional sea foods by 2050. In particular, RASs contribution to sustainable intensification and promotion of sustainable management of food production systems has been recognized within sustainable development goals (Pretty & Bharucha, 2014) [95]. The importance of RAS to African agriculture and industrialization has also been noted under, aiming to construct resilient infrastructure, promote inclusive, sustainable industrialization and foster technological innovation (Atukunda *et al.*, 2021) [14].

Land-based RAS is potentially attractive in Africa. It reduces waste of clean water and provides an effective mechanism for effluent treatment in view of the water scarcity in several African countries (Teixeira *et al.*, 2021) [106]. Moreover, there are less spatial constraints when compared to offshore marine aquaculture (Atukunda *et al.*, 2021) [14]. Towards this, there has been an increased trend of young individuals, taking up RAS instead of agriculture (crop production) due to the associated potential benefits such as less energy consumption (depending on RAS configuration), and availability of water resources (Bartelme *et al.*, 2019) [19]. A significant benefit of the emerging growth of this sector is the potential for creation of jobs, which is a core mandate of the African Union Agenda 2063 (Okomoda *et al.*, 2022) [87].

Cost Analysis of RAS Implementation

Studies have reported upto 64.1% RAS operation cost being covered by feeds (Gupta *et al.*, 2024) [49]. The electricity consumption of a fully operational system ranges from 15 to 20 kWh kg^{-1} fish produced and the total electricity cost accounts for as high as 84% of the utility cost (Bujas *et al.*, 2022; Tyedmers, 2004) [32, 111]. Another simulated study from of RASs in Denmark reported 72.8% and 82.8% electricity consumption and operational costs respectively (Nistad, 2020) [83]. The administration and staffing costs were estimated to range from 11.6 and 18.8% of the total operational costs (Terjesen *et al.*, 2013) [107].

A Life Cycle Assessment (LCA) study on integrated aquaculture systems, including RAS, conducted in Taiwan reported consumer production costs from RAS to be approximately 5% higher than those from cage farming (Heyland *et al.*, 2021) [51]. However, the authors noted that this comparison inadequately accounted for the equipment and operational costs inherent to cage farming. A separate comparative study conducted in Lanyu, Taiwan, revealed that in 2014, operational costs accounted for a substantial 60.2% of the total annual RAS expenditure Heyland *et al.* (2021) [51]. This was largely attributed to the high utility costs, a finding consistent with the LCA study by Heyland *et al.* (2021) [51].

One of the most significant contributors to operational expenses in RAS is clearly evidenced to be electricity usage, which is notably higher than in traditional systems. In Greece, energy consumption was found to comprise 34% of the total production cost in RAS, with water pumping and aeration systems identified as the primary energy-consuming components (Tyedmers, 2004) [111]. Similarly, a pilot-scale study in Northern Australia reported that electricity costs accounted for around 10% of the total cost, primarily due to the demand for aeration (Bartelme *et al.*, 2019) [19].

The substantial capital investment and energy requirements of RAS remain key challenges to its widespread commercialization for fish production (Chen *et al.*, 2019) [34]. The unit cost of fish production in RAS systems is estimated to range from US$0.50 to US$1.00 per kilogram (Bujas *et al.*, 2022) [32]. Nevertheless, reductions in production costs may be achievable through advancements in system design, improved recirculation efficiency, enhanced fish performance, and the ability to offset costs through increased productivity relative to conventional aquaculture systems (Heyland *et al.*, 2021) [51].

Socio-economic Benefits and Challenges of RAS Adoption

Adopting RAS technology in Africa presents numerous challenges. Among the most significant are the prohibitive setup costs, the technical complexity of operating and maintaining RAS, and the requirement for consistent access to clean water and efficient renewable energy systems, particularly for managing temperature and oxygen transfer (Bujas *et al.*, 2022) [32]. In many cases, systems are expected to operate continuously to maximize production, which becomes difficult under high-density stocking and intensive feeding regimes, requiring precise management. Moreover, a critical impediment to RAS business development across the continent is the time-intensive learning curve necessary to optimize these systems and build commercial-scale expertise for maintaining a healthy and stable aquatic environment (Blonç *et al.*, 2023) [26].

Despite these obstacles, land-based intensive production systems such as RAS are gaining traction due to their environmental and health benefits (Chen *et al.*, 2019) [34]. RAS technologies enable significant reductions in nutrient-rich waste discharge such as uneaten feed, faeces, and nitrogen through wastewater treatment and recirculation (Gupta *et al.*, 2024) [49]. In contrast to traditional open-water systems, closed containment systems provide enhanced biosecurity, significantly lowering the risk of parasitic and bacterial infections that typically affect conventional aquaculture operations (Brown *et al.*, 2024) [122]. These features make RAS a more sustainable and appealing option for aqua-farmers, particularly in areas where environmental regulations or biosecurity concerns are paramount (Bostock *et al.*, 2010) [29].

Adapting to the persistent challenges in seafood production particularly across Africa is both urgent and necessary. To address these issues, governments, stakeholders, and local communities must lead a coordinated transformation of the continent's aquaculture subsector. Innovative production systems, including but not limited to RAS, have been identified as promising pathways for enhancing and intensifying farmed fish production. The socio-economic benefits of a vibrant aquaculture industry in Africa are far-reaching. These include the creation and sustainability of employment, income generation, and increased revenue for governments. Additionally, aquaculture contributes to regional and international trade expansion, strengthening economic interconnectivity across borders (Kim *et al.*, 2022) [59].

Socio-Cultural Dimensions of RAS Adoption in Africa

The adoption of RAS in Africa is not solely influenced by technical or economic factors, but also by deeply rooted cultural norms, traditions, and community dynamics. In many regions, fish farming is closely tied to food customs and identity, with strong preferences for species like tilapia or catfish (Ayuya *et al.*, 2021) [16]. RAS-grown fish, especially those raised in enclosed systems with unfamiliar inputs, may be viewed as artificial or inferior. This perception is often reinforced by limited exposure to the technology and the deviation from traditional pond-based or riverine aquaculture methods.

Traditional aquaculture practices in Africa are often supported by indigenous knowledge, seasonal patterns, and communal labor structures. RAS, by contrast, demands technical precision, individual management, and consistent monitoring, which may alienate farmers who lack access to training or perceive the systems as incompatible with local realities. Gender roles also play a critical part, as women key contributors in traditional aquaculture may be excluded from the more technical aspects of RAS unless inclusive training and support are provided. Without such social integration, RAS risks becoming a top-down intervention with limited grassroots acceptance.

To address these challenges, a culturally informed approach to RAS is needed. This includes conducting cultural assessments, involving local communities in system design, and delivering training in local languages that respects existing knowledge. Promoting inclusive participation especially of women and youth and leveraging existing community networks can foster greater trust, sustainability, and uptake. Ultimately, recognizing and integrating these socio-cultural factors is essential for RAS to thrive as a sustainable aquaculture solution in Africa.

Policy and Regulatory Framework for RAS in Africa

Most African countries, such as Nigeria, Kenya, Egypt, Ghana, Tanzania, and South Africa, have national aquaculture development strategies or fishery acts. However, these frameworks often prioritize extensive or semi-intensive systems, and rarely address standards for RAS infrastructure and technology, Water reuse and waste management regulations tailored to RAS (Adeleke *et al.*, 2020) [3]. Several African policy tools do not provide clear information on incentives or support mechanisms specific to high-tech or intensive systems. For instance, Nigeria's National Aquaculture Strategy (2022) [113] supports aquaculture growth but lacks provisions specific to RAS (Hinrichsen *et al.*, 2022) [52].

The expansion of RAS in Africa faces multiple policy and regulatory obstacles that constrain innovation, investment, and scalability. Key barriers include land use and zoning laws, water and effluent management regulations, energy and infrastructure gaps, and biosecurity and licensing challenges.

Although RAS can be established in urban, peri-urban, and arid regions, existing land use and zoning policies often fail to recognize aquaculture as a viable land-use category in such non-traditional zones (Msoka, 2009) [76]. As a result, countries across the continent lack clear guidelines on permitting RAS installations in locations such as rooftops, warehouses, or industrial areas (Adeleke *et al.*, 2020) [3].

In terms of water governance, water abstraction rights and effluent discharge laws are frequently underdeveloped or misaligned with the needs of RAS. Despite the minimal nature of RAS effluents, they may still fall under stringent discharge regulations originally designed for open pond or flow-through systems, thereby creating unnecessary compliance burdens (Ayim *et al.*, 2020) [15].

Energy access and affordability pose additional challenges. RAS operations are highly energy-intensive, relying on continuous operation of pumps, aeration systems, and temperature regulation units. However, most African counties have repeatedly excluded aquaculture activities from national energy planning, and few countries offer support for renewable energy integration within RAS, despite its potential to significantly enhance system viability and sustainability (Brummett *et al.*, 2008) [31].

Lastly, most biosecurity regulations in Africa are tailored to traditional pond-based or open-water aquaculture systems (Das *et al.*, 2022) [37]. There is a notable absence of RAS-specific biosecurity protocols, particularly in the areas of pathogen control, disease monitoring, and closed-system biocontainment. This gap exposes RAS operators to legal uncertainty and potential disease risks without regulatory guidance or institutional support (Slette *et al.*, 2025) [104].

Regional and Continental Frameworks

The African Union Inter African Bureau for Animal Resources (AU-IBAR) plays a central role in promoting sustainable aquaculture through the Policy Framework and Reform Strategy for Fisheries and Aquaculture in Africa (PFRS) (AU, 2014) [5]. The PFRS encourages innovation, regional collaboration, and private sector engagement, thereby providing a foundation for modernizing aquaculture systems across the continent (Jolly *et al.*, 2023) [55]. However, despite its comprehensive outlook, the framework does not explicitly address RAS, which are increasingly recognized as critical for climate resilience, biosecurity, and water efficiency in fish production.

In parallel, the African Continental Free Trade Area (AfCFTA) presents a significant opportunity to facilitate cross-border exchange of RAS technology, inputs, expertise, and investment (Gogo, 2021) [47]. Nonetheless, the absence of harmonized standards, technical guidelines, and certification protocols for RAS across member states limits the full realization of these benefits (Ajewumi *et al.*, 2024) [8]. According to Olayiwola, (2020) [88], Establishing continental or regional technical standards for closed aquaculture systems, including RAS, would help streamline compliance, promote quality assurance, and support intra-African trade in aquaculture technologies and products.

Opportunities for Strengthening the RAS Policy Landscape: Development of infrastructure and energy efficiency standards, water quality and waste management protocols, and health and biosecurity regulations specific to closed-loop aquaculture systems are important opportunities for strengthening aquaculture policies in African countries (Ajewumi *et al.*, 2024) [8]. Financial incentives such as tax breaks, grants, and subsidized loans should be provided to attract investment, alongside the establishment of public-private partnerships (PPPs) to develop demonstration units that showcase scalable models (Demianyshyn & Shuliuk, 2023) [39]. Furthermore, most African countries have plenty of renewable energy sources, therefore aligning RAS with green energy policies can enhance environmental sustainability and reduce operational costs (Ajewumi *et al.*, 2024) [8].

Equally important is the investment in human capacity and knowledge systems to support the long-term viability of RAS. Training programs targeting regulators, extension officers, and youth can build technical expertise and foster innovation (Ajewumi *et al.*, 2024) [8]. According to Compagnucci & Spigarelli, (2024) [36], establishment of regional centers of excellence for RAS research and technology transfer would strengthen institutional support and accelerate knowledge dissemination. Integrating RAS modules into academic curricula can further prepare the next generation of aquaculture professionals (Compagnucci & Spigarelli, 2024) [36]. Additionally, regional harmonization of licensing procedures, health protocols, and certification systems led by economic communities such as ECOWAS, EAC, and SADC would enable smoother cross-border investments and facilitate trade in aquaculture products (AU, 2014) [5]. Collectively, these interventions can create an enabling environment for the scalable and sustainable adoption of RAS across Africa.

Capacity Building and Knowledge Transfer for RAS in Africa: Strong capacity building and efficient information transfer tools are very essential for the successful growth and sustainability of RASs in Africa. RAS technology involves the continuous treatment and reuse of water within fish production systems and this is technically demanding and requires specialized skills in water chemistry, system design, disease management, and energy efficiency (Aich *et al.*, 2020) [7]. Therefore, building a workforce that is knowledgeable, skilled, and adaptive to emerging technologies is critical.

Training initiatives that target many stakeholders including regulators, extension staff, farmers, and young people is one key area of emphasis. For instance, in Kenya, the Kenya Marine and Fisheries Research Institute (KMFRI) has introduced training initiatives on RAS technologies for small- and medium-scale farmers (KMFRI, 2021) [57]. These programs cover technical aspects such as system maintenance, water quality management, and biosecurity protocols. Similarly, South Africa has made strides in formal training through institutions like Stellenbosch University, which offers aquaculture courses with RAS components, preparing students to operate and innovate within advanced aquaculture systems (Britz *et al.*, 2020) [30].

Established regional centers of excellence also play a vital role in strengthening RAS knowledge dissemination. The WorldFish Center, operating in Egypt, has incorporated RAS research into its regional aquaculture programs, providing practical training for farmers from across North and Sub-Saharan Africa (Majumdar *et al.*, 2022) [67]. These centers serve not only as research hubs but also as demonstration and learning sites where farmers, technicians, and policymakers can observe and engage with operational RAS units. Moreover, Nigeria's African Center of Excellence for Aquatic Resources Management and Food Security (CERAF) at the University of Ibadan has incorporated RAS research and capacity building into its academic and outreach programs (Adewumi, 2018) [123]. In Tanzania, the Modal Farm of Sokoine University of Agriculture has designed a simplified RAS for research as well as public demonstrations (Mnyoro *et al.*, 2022; Mnyoro *et al.*, 2024) [75, 74].

Another critical component is the integration of RAS education into formal curricula. In most African universities, and agricultural colleges RAS modules have been incorporating into fisheries and aquaculture programs, ensuring that the next generation of aquaculture practitioners is equipped with modern, sustainable farming techniques (Amponsah, 2021) [12]. This academic integration is essential for ensuring that RAS knowledge is institutionalized and evolves with technological advancements.

Knowledge transfer initiatives are further strengthened through international collaboration and partnerships (Amponsah, 2021) [12]. For example, European-African partnerships under programs such as the Horizon Europe projects (e.g., AquaBioTech and its affiliates) have provided technical expertise and co-funded RAS research and capacity development programs in African countries (Amponsah, 2021) [12]. Such collaborations enable African institutions to access global best practices and tailor them to local environmental and economic conditions.

Despite the continental efforts for RAS knowledge transfer, challenges remain, including limited funding, inadequate infrastructure for practical training, and a shortage of trained trainers (Ras *et al.*, 2021) [95]. Addressing these gaps requires increased investment from African governments, donor agencies, and private sector stakeholders to expand RAS-focused training centers, support scholarship programs, and develop digital learning platforms for remote capacity building.

Collaboration and Networking Opportunities for RAS Development: The advancement RAS in Africa depends heavily on strategic collaboration and networking among governments, private sector players, research institutions, and international development partners (Kotecha *et al.*, 2011) [61]. These partnerships can help overcome technical, financial, and institutional barriers while fostering knowledge exchange and innovation tailored to the African context. One key collaboration opportunity lies in the partnership between African research institutions and global aquaculture technology leaders. For instance, in South Africa, the Stellenbosch University collaborates with private RAS technology providers to improve system designs that are adapted to local climatic and resource conditions (Roux, 2021) [99]. Such partnerships enable the transfer of cutting-edge technologies and skills, enhancing the competitiveness of local producers.

At the regional level, initiatives by organizations like the African Union's Inter-African Bureau for Animal Resources (AU-IBAR) promote cross-border collaboration in aquaculture research and development (AU, 2014) [5]. Through its aquaculture strategy, AU-IBAR encourages member states to develop harmonized standards and regional centers of excellence, which could also focus on RAS-specific technologies (AU, 2014) [5]. For example, the Lake Victoria Basin countries (Kenya, Uganda, and Tanzania) have collaborated through regional aquaculture programs to address shared challenges in fish farming, offering a model that could be expanded to include RAS development (Roux, 2021) [99].

Public-private partnerships (PPPs) also offer significant networking opportunities. In Kenya, for instance, the collaboration between Victory Farms a private aquaculture company and various research and development organizations such as Kenya Fisheries Research Institute (KFRI), has paved the way for innovations in sustainable aquaculture practices, including semi-closed systems that resemble aspects of RAS (Obiero *et al.*, 2019) [84]. Additionally, international development agencies such as the FAO and the World Fish Center are active in promoting sustainable aquaculture through funding, capacity building, and technology transfer initiatives worldwide. For example, the FAO's support for sustainable aquaculture projects in Nigeria has emphasized the importance of modern systems like RAS for urban fish farming, enhancing productivity while conserving water (Benjamin *et al.*, 2022) [21].

Established hubs can act as catalysts for RAS adoption across different African regions by providing technical training, business development support, and exposure to investors. Moreover, South-South cooperation between African countries and emerging aquaculture leaders like China and Vietnam is expanding (Naylor *et al.*, 2023) [81]. Countries like Ghana and Côte d'Ivoire have engaged in bilateral partnerships with Chinese aquaculture experts to improve hatchery and system management skills, and there is potential to extend these collaborations to RAS technology development (Zhang *et al.*, 2021) [119].

Future Prospects and challenges for RAS adoption in Africa: RAS offer a highly practical method for optimizing the use of facilities in aquaculture, particularly in regions facing challenges such as water scarcity, land limitations, and environmental degradation. Investment in RAS in Africa can therefore be strategically justified under the overarching themes of food safety, environmental sustainability, and poverty reduction (Benjamin *et al.*, 2022; Obiero *et al.*, 2019) [21, 84]. The continent holds immense promise for aquaculture expansion, supported by rising demand for fish protein, favorable climatic conditions, and the increasing recognition of aquaculture's role in food and nutrition security. Consequently, there is significant capacity to expand RAS technologies across Africa. However, the current presence of large-scale RAS operations remains limited, often concentrated in a few countries with relatively advanced aquaculture industries (Roux, 2021) [99].

The efficient deployment of RAS technologies across African countries would yield simultaneous benefits, including enhanced food safety, improved water use efficiency, and expanded employment opportunities within the aquaculture sector (Yogev *et al.*, 2020) [118]. To realize this potential, African nations must prioritize the development of indigenous and widely accessible RAS technologies tailored to their local conditions. Each country has the opportunity to succeed by leveraging its unique natural, human, and technological resources. Strengthening local innovation in RAS, such as through the use of dams, submerged hatcheries, and locally adapted rearing systems for smolt, fingerlings, and juveniles, would further enhance food security. Moreover, engineering and technological advancements aimed at adapting and improving RAS facilities can enable African aquaculture producers to maintain competitive production costs while ensuring environmental sustainability and resilience to climate variability.

Despite the promising prospects for aquaculture development, the expansion of RAS technology in Africa remains limited, largely due to low levels of knowledge, awareness, and technical capacity (Atukunda *et al.*, 2021) [14]. Ethnic and habitat variations, coupled with vulnerability to aquatic hazards such as floods, have historically marginalized the culture and utilization of marshes, wetlands, and other inland water bodies (Atukunda *et al.*, 2021) [14]. Consequently, these aquatic ecosystems have been under-assessed and underutilized for aquaculture development. Only a few wild African fish species and their genetic pools have been employed globally to improve local domesticated stocks (Bartelme *et al.*, 2019) [19]. However, their native status and inherent adaptability present strong opportunities for acclimatization to RAS environments, maximizing their genetic potential for sustainable aquaculture. Another major challenge facing the continent is the projected population growth, which is expected to drive increased demands for nutrition and water resources, potentially exacerbating overfishing pressures (Okomoda *et al.*, 2022) [87]. Nevertheless, Africa possesses the necessary natural resources, infrastructure, and indigenous fish species that can serve as driving forces for sustainable aquaculture growth if harnessed effectively (Teixeira *et al.*, 2021) [106].

In regions where aquaculture is still in its emerging phase such as much of Africa RAS offers an opportunity to increase fish production sustainably, meet the growing aquatic food demand, and mitigate the risks of overfishing (Dumont *et al.*, 2012) [42]. Africa waters are home of rich fish genetic diversity, offering a comparative advantage for aquaculture development Badiola *et al.*, 2012 [17]. While the continent currently produces a substantial share of global aquaculture products, per capita fish consumption remains below the global average, underscoring the urgent need to expand domestic production (Compagnucci & Spigarelli, 2024) [36]. However, the rising contribution of aquaculture to total fish production in Africa signals strong potential. The strategic application of RAS technology, alongside the farming of both indigenous and selected exotic fish species, can significantly enhance food security, foster rural development, and aid in the conservation of endangered aquatic species (Achieng *et al.*, 2023) [2].

Research and Development Priorities for RAS in Africa

One of the foremost priorities revealed by this review is the adaptation and localization of RAS technologies to suit African agro-ecological zones and socio-economic realities. Many existing RAS designs are developed in temperate regions and do not consider local variables such as high ambient temperatures, erratic electricity supply, or limited technical expertise (Yogev *et al.*, 2020) [118]. Research should therefore focus on designing energy-efficient, modular systems that integrate solar or hybrid energy solutions to offset the high energy demands of RAS, which can range from 15 to 20 kWh per kilogram of fish produced (Compagnucci & Spigarelli, 2024) [36]. Furthermore, innovations in water treatment, such as the use of biofloc technology or low-cost biofilters, are necessary to enhance water reuse efficiency and reduce operational costs.

A second critical area is economic viability and cost optimization. RAS are capital-intensive, with significant upfront investments in infrastructure, water purification, aeration, and temperature control systems (Badiola *et al.*, 2012) [17]. Targeted RAS research and development should explore locally sourced materials and frugal innovations to reduce construction and operational costs (Mnyoro *et al.*, 2022; Mnyoro *et al.*, 2024) [75, 74]. Comparative studies assessing cost-benefit scenarios of RAS versus conventional pond or cage systems in African countries would help determine scalable models appropriate for small- and medium-scale farmers (Gumbo, 2011) [48]. Additionally, research into market access, consumer preferences, and price competitiveness is needed to ensure economic sustainability.

Species selection and culture system optimization constitute another high-impact research priority. Most African RAS initiatives have focused on tilapia and African catfish, which are well-suited to intensive production. However, further studies are needed to determine optimal stocking densities, feeding regimes, and growth performance under recirculating conditions for both indigenous and high-value species (Ofori-Mensah *et al.*, 2018) [86]. Research should also examine polyculture possibilities and the integration of aquaponics to improve nutrient recycling and diversify income streams.

Capacity building and human resource development are equally essential. The technical complexity of RAS necessitates well-trained personnel in system management, water quality monitoring, fish health, and biosecurity. R&D initiatives should be accompanied by the establishment of demonstration centers, training programs, and vocational curricula to bridge the knowledge gap among farmers, extension workers, and technicians (Benjamin *et al.*, 2022) [21]. Moreover, digital tools such as remote monitoring systems and mobile-based advisory services should be developed and tested to improve operational efficiency and real-time decision-making (Albahri *et al.*, 2018) [10].

At the policy level, RAS development must be supported by research-informed regulatory frameworks. Most African countries lack specific guidelines on RAS licensing, environmental standards, or waste management (Munguti *et al.*, 2025) [78]. Legal and policy research is therefore required to create enabling environments that balance innovation, investment, and environmental protection (Almahdi *et al.*, 2019) [11]. In parallel, socio-economic research should investigate gender, youth, and equity dimensions of RAS to ensure inclusive development.

Climate resilience and sustainability assessments should also be emphasized in African research and development strategies. With increasing climate variability, RAS offers a climate-smart alternative to open water systems, but its environmental footprint especially in terms of energy use and waste discharge must be critically examined (Yogev *et al.*, 2020) [118]. Life cycle assessments (LCAs), carbon footprint analyses, and studies on the integration of RAS with renewable energy and circular economy approaches are necessary to guide sustainable development pathways (Almahdi *et al.*, 2019) [11].

Conclusion

RAS offer a forward-looking solution to many of Africa's pressing aquaculture challenges, particularly in the face of escalating water scarcity, limited arable land, and environmental degradation. This review has demonstrated that, while RAS has the potential to revolutionize fish farming across the continent through efficient resource use, enhanced biosecurity, and reduced environmental impacts, its Spread to Africa is hampered by high capital costs, technological demands, and policy gaps. The current uptake of RAS in Africa remains modest, driven primarily by urban market dynamics and the need for water-efficient production systems. Nevertheless, the long-term benefits of RAS such as water savings of up to 90%, nutrient recycling, and improved productivity make it a compelling option for sustainable aquaculture development.

To fully harness the potential of RAS, there is a critical need for context-specific innovations, especially those that reduce energy dependence through renewable energy integration. Additionally, national and regional stakeholders must prioritize the development of enabling regulatory frameworks and invest in capacity building to overcome the technical and operational challenges associated with RAS. Policy harmonization, access to financing, and public-private partnerships will be essential to scaling up these systems in a sustainable and inclusive manner. Ultimately, the future success of RAS in Africa depends on a coordinated, multidisciplinary effort that aligns technological advancement with economic viability, environmental stewardship, and institutional support.

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