INITIATIVE ON Low-Emission Food Systems

Promising Aquaculture Technologies and Innovations for Transforming Food Systems Toward Low Emission Pathways in Kenya: A Review

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INITIATIVE ON

Low-Emission Food Systems

Contents

List of abbreviations

ABDP	Aquaculture Business Development Programme
ADP	Aquaculture development pathways
AE	Agro-ecological practice
BFT	Biofloc technology
BMU	Beach Management Unit
BSF	Black soldiers fly
CH_4	Methane
CO_2	Carbon dioxide
CSA	Climate smart aquaculture
ESP	Economic Stimulus Programme
EU	European Union
FAO	Food and Agriculture Organization
FCR	Feed conversion ratio
GHGE	Greenhouse gas emissions
GIFT	Genetically Improved Farmed Tilapia
GWP	Global warming potential
HDPE	High-density polyethylene
IAA	Integrated agri-aquaculture
IMTA	Integrated multitrophic aquaculture
IPRS	In-pond raceway systems
KCSAP	Kenya Climate Smart Agriculture Project
KLDC	Kisumu Lakefront Development Corporation
KMFRI	Kenya Marine and Fisheries Research Institute
mt	Metric tonnes
PPT	Periphyton technology
RAS	Recirculating aquaculture system
SME	Small and medium-sized enterprises
SPRAS	Solar powered recirculating aquaculture systems
TAN	Total ammonia nitrogen
TIMP	Technology innovations and management practices
UN	United Nations

Definition of working terms

Technology: This is defined as an output of a research process that is beneficial to the target clientele (mainly farmers, pastoralists, agro-pastoralists, and fisher folk). Technology can be commercialized and can be patented under intellectual property rights (IPR) arrangements. Examples include research outputs such as tools, equipment, genetic materials, improved fish breeds, new vaccines, new equipment, laboratory techniques, etc.

Innovation: This is defined as a modification of existing technology for an entirely different use from the original intended use. It is also an application of new or existing knowledge/technology in a new way or context to do something better or different. An example is a narrow, deep-lined, or cemented pond for rearing catfish.

Management practices: A management practice is defined as recommendation(s) on practice(s) that is/are considered necessary for a technology to achieve its optimal output. These include, for example, different agronomic practices (e.g., seeding rates, fertilizer application rates, spatial arrangements, planting period, land preparation, and watering regimens) and protection methods for crops, as well as feed rations, management systems, and disease control methods, etc., for livestock breeds. This is therefore important information that is generated through research to accompany the parent technology before it is finally released to users, and the technology would be incomplete without this information.

Resource-use efficiency: This refers to the exploitation of the Earth's limited resources in an environmentally sustainable manner, leading to the creation of more output with less input.

Food systems: These are the interconnected systems and processes that influence nutrition, food, health, community development, and agriculture.

Emission pathways: An emission pathway is a transformational process that delivers long-term emissions reductions and sustainable development in collaboration with local communities, businesses, and other key actors.

1. Executive summary

Aquaculture has been the fastest-growing food-production sector globally for the past three decades. The sector can offer promising solutions to address global food security and sustainability challenges in the changing climate and rapid population growth. As the demand for animal protein continues to rise, particularly in developing countries, expanding traditional livestock production systems has been associated with significant environmental impacts, including greenhouse gas emissions (GHGE) and land and water system degradation. In contrast, aquaculture, as a nature-based solution, has the potential to provide a more sustainable source of animal protein, as it can be practiced in a variety of environments and can be more efficient in terms of resource use compared to terrestrial animal production. To fully realize the potential of aquaculture as a sustainable and equitable solution to global food security and environmental challenges, it is necessary to identify and promote technologies, innovations, and management practices (TIMPs) that can overcome these barriers and improve the efficiency and sustainability of aquaculture systems. This work aimed at (1) reviewing published documents and reports to identify TIMPs with the potential for scaling to reduce GHGE, (2) identifying the constraints and challenges faced by different value chain actors in scaling aquatic food system TIMPs from the angle of low emission development, (3) identifying potential social, economic, and environmental co-benefits and spillover effects from scaling the TIMPs, and (4) conducting a stakeholder consultation in Kisumu County, Kenya, to map out aquaculture value chains and identify sources of emissions, and identify promising TIMPs for scaling. Relevant search engines and systematic and iterative procedures were used to compile and study the available literature and data, evaluate the data, identify knowledge gaps where further research is needed in the future, and produce a comprehensive literature review.

There are several promising TIMPs in aquaculture that can contribute to reducing GHGE. The use of closed-system aquaculture, which uses tanks or ponds that are cut off from the natural environment, is a potential invention. Closed-system aquaculture allows for more precise control over water quality, feeding, and other factors, improving the efficiency and sustainability of the farming operation. The estimated quantities of GHGE measured in $kgCo_2e$/kg of fish produced emitted by specific technologies under closed or integrated systems include the in-pond raceway system (2.4), recirculating aquaculture system (RAS; 3.2–4.2), aquaponics (1.5–2.5), biofloc technology (BFT; 2.3–3.5), the integrated multitrophic aquaculture system (IMTA; 1.8–2.8), and the integrated agriculture-aquaculture (IAA) system (2.8-3.7). Other independent technologies include fish cages (3.7), offshore aquaculture (3.7–6.1), and periphyton technology (1.4–2.4). These technologies and innovations require tailor-made management practices for effective performance. The management practices that would drastically reduce the GHG emitted from various technologies and innovations include (1) the use of solar energy, (2) the application of precision farming procedures, (3) the use of genetically improved fish species, (4) the use of organic composts, (5) circular energy-cycling procedures, such as black soldier fly, to convert wastes into proteins, (6) application of biosecurity measures, (7) efficient feed management strategies, (8) use of financial tools, such as insurance, credit facilities, etc., and (9) spatial planning techniques for shared resources. However, it is difficult to provide specific information on the percentage by which GHGE may be reduced by adopting technologies and innovations, as this depends on specific characteristics and management practices of individual systems.

The use of advanced feed formulations and feeding strategies can improve the efficiency of feed utilization and reduce the environmental impacts of aquaculture. For example, using plant-based feeds and feed additives can reduce the reliance on wild-caught fish as feed, which can help conserve wild fish populations and reduce the overall environmental impact of aquaculture. Integrating aquaculture with other forms of agriculture, such as IMTA which involves the simultaneous cultivation of multiple species of aquatic organisms, such as fish, shellfish, and seaweed, can maximize the efficient use of resources and minimize the environmental impact. RAS improves the efficiency and sustainability of aquaculture operations, while also reducing the risk of disease transmission and the release of pollutants into the environment. Offshore aquaculture involves the cultivation of aquatic organisms in open-ocean environments, typically using floating structures or submerged cages. Offshore aquaculture has the potential to reduce the competition for land and water resources with other forms of agriculture and can also help minimize the impact of aquaculture on coastal ecosystems. Seaweed aquaculture has the potential to provide a variety of environmental benefits, such as the removal of excess nutrients from water bodies, the provision of habitat for marine life, and the sequestering of carbon dioxide from the atmosphere. Aquaponics systems use the waste produced by aquatic organisms as a source of nutrients for plants, creating a symbiotic relationship between the two. Aquaponics can be an efficient and sustainable way to produce both seafood and plant-based foods, while also reducing the use of synthetic fertilizers and pesticides. The use of advanced monitoring and control technologies, such as sensors, automation systems, and data analytics, can help optimize the efficiency and sustainability of aquaculture operations. These technologies can be used to monitor and control factors such as water quality, feeding, and disease management, and can help improve the overall performance and resilience of aquaculture systems. Genetic advancements in fish breeding and genetics can also play a role in the transformation of food systems toward low-emission pathways. Some potential applications of genetic advancement in fish include improved disease resistance, enhanced growth and feed efficiency, and increased tolerance to environmental stressors. Effective post-harvest

management and value-addition techniques can also contribute to the transformation of food systems toward low-emission pathways by improving the efficiency and sustainability of the seafood supply chain. Some promising post-harvest management and value-addition techniques in aquaculture include cold chain management, improved packaging, value-added processing, and sustainable fishing gear and methods. Overall, the adoption of these and other innovative technologies and practices in aquaculture can help to transform food systems toward low-emission pathways while also supporting the sustainable production of high-quality seafood for a growing global population.

There are challenges and constraints to the adoption and upscaling of these GHG reduction TIMPs in the Kenyan context. The challenges include the high initial cost of implementation, which may be difficult for small-scale farmers to afford, and the lack of technical expertise and infrastructure in place to support the use of these technologies. Despite these challenges, there are significant socio-economic and environmental co-benefits to the adoption of GHG reduction technologies in aquaculture. These technologies can reduce the environmental impact of aquaculture operations and improve the sustainability of the industry. In addition, the adoption of these technologies can create economic opportunities for farmers and communities, as well as contribute to food security. There may also be spillover effects from the adoption of GHG reduction technologies in aquaculture, such as the potential to be adopted in other sectors or to influence policy and regulations related to sustainability. To facilitate the adoption and upscaling of these technologies, it may be necessary to provide financial and technical assistance to farmers, as well as to invest in research and development to improve the effectiveness and efficiency of these technologies.

2. Introduction

2.1. Background Information

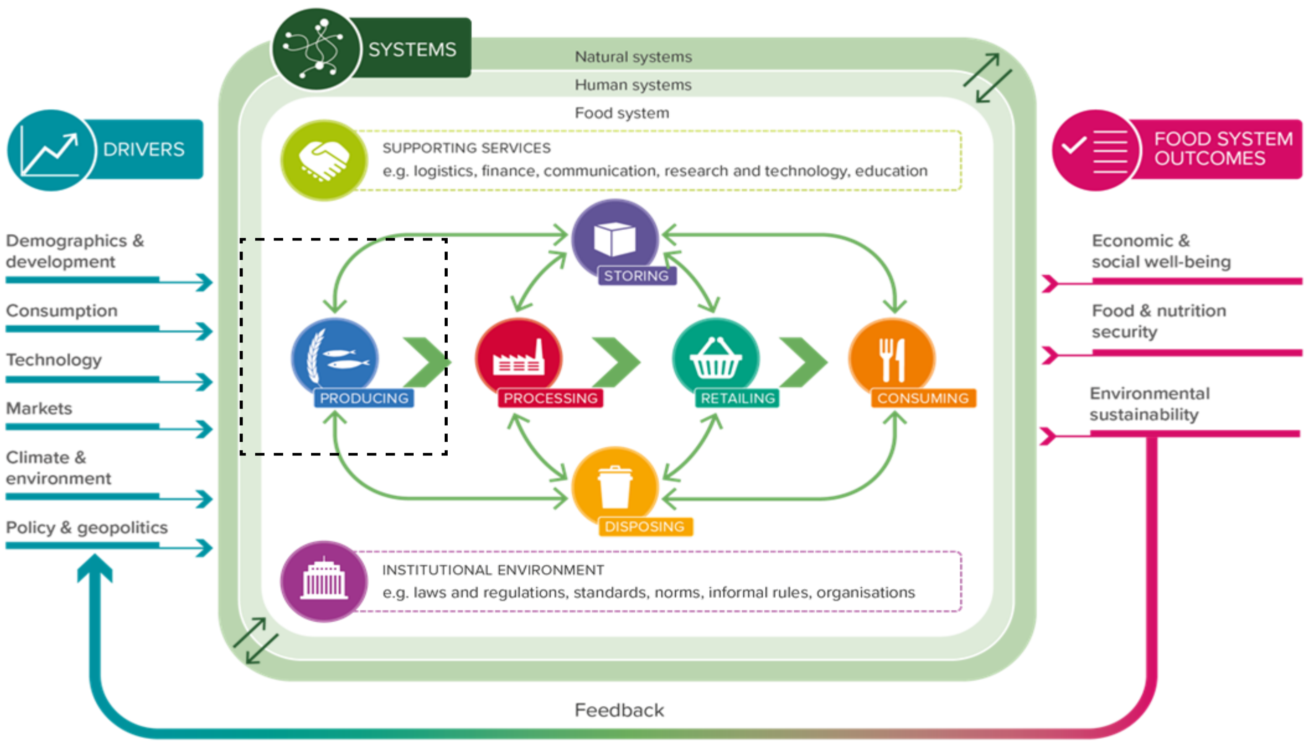
With the world's human population surging to 9.7 billion by 2050 (HLPE, 2014; United Nations, 2022), the food production sector and food systems are already under pressure to supply sufficient nutritional diets for the growing population. The pressure to produce enough food continues to strain natural resources, leading to challenges such as the emission of GHGs that fuel climate change. These challenges threaten food production systems, human welfare, and the environment. As a result, stakeholders in the food system sectors are negotiating critical balances between maintaining the human right to nutritious food, reaping increasing profits, and preserving environmental health (Henriksson et *al.*, 2021). The desire to solve food insecurity and environmental challenges has pushed scientists and policymakers to conceptualize and reimagine climate-smart, resource-use-efficient food production approaches that could maximize food production strategies. The strategies embrace some of the modern 'buzz' words such as "blue economy," "circular economy," "agroecology," "regenerative agriculture,'' and "integrated agriculture-aquaculture."

Aquaculture, which is the farming of aquatic animals and plants, is considered a resource-efficient and nature-based solution technology for providing relatively cheap protein to humans. Aquaculture is the world's fastest-growing agri-food sector, with an annual growth rate of 7.2 percent compared to 0.7 percent for capture fisheries since 1970 (FAO, 2022). Aquaculture accounts for 50 percent (about 91 million tonnes) of total annual global fish production (FAO, 2022). However, sustainable aquaculture production technologies are needed to enable production to reach the allowable environmental carrying capacity safely. Aquaculture's potential for the rapid production of fish has been widely reported, with clear evidence of enhanced livelihoods and economic growth for smallholder communities through its value chain linkages (Brummet & Williams, 2000; Brummet *et al.*, 2008; Beveridge *et al.*, 2013; Béné et al., 2016). With the increasing aquaculture production, scientists are beginning to reimagine the potential impact of aquaculture growth on GHGE. Within the context of food systems, aquaculture plays an important role in GHGE, just like other food value chains.

2.2. Food systems and GHGE

A food system is an interconnected web of activities linking agricultural production to consumption, mediated by post-harvest practices, marketing, and processing, contributing to food security, human development, economic growth, and environmental sustainability (von Braun et al., 2021). Many players are involved in the food system, including farmers, food processors, distributors, retailers, consumers, and disposers (Figure 1). Farmers are responsible for growing and harvesting crops and raising livestock and aquaculture crops or catching fish. They may operate small family farms or large commercial operations and use various methods including traditional, organic, or industrial practices. Food processors transform raw ingredients into finished food products. This may include activities such as cooking, preserving, packaging, and labeling. Food processors can range from small, local operations to large, multinational corporations.

Figure 1. Food system approach for food chain players, drivers, and outcomes for sustainability.



Source: *Woodhill et al. (2020)*

Distributors are responsible for getting food from producers to retailers and other points of sale. This may involve storage, transportation, and logistics. Distributors may be independent companies, or they may be owned by processors or retailers. Retailers are responsible for selling food to consumers. This may include grocery stores, supermarkets, convenience stores, and restaurants. Retailers may source their products from a variety of sources, including local farms, processors, and distributors. Consumers are the end users of the food system. They purchase and consume food for sustenance and enjoyment. Consumers may be individuals, households, or institutions such as schools, hospitals, and prisons. The estimated contribution of GHGE from the various food system players is summarized in Table 1.

Table 1. Estimated quantities of GHGE from food system players, which accommodate the aquaculture value chain.

Player	Sources of GHGE	Emissions estimates (kg CO_2e/kg food)	Source of data
Production	• Enteric fermentation (emissions from livestock digestion) • Manure management • Synthetic fertilizers • Rice cultivation	• 11-12 • 1-2 • 0.5-1 • 1-5	FAO, 2013
Food processing and transportation	• Fossil fuel use in food processing and transportation • Refrigeration and cooling • Packaging	• 0.1-1 • 0.1-0.2 • 0.1-0.5	IPCC, 2007
Retail and food service	• Fossil fuel use in transportation • Refrigeration and cooling • Packaging	• 0.1-0.5 • 0.1-0.2 • 0.1-0.5	IPCC, 2007
Consumption	• Food waste • Home cooking and food storage • Eating out and takeout	• 0.5-2 • 0.1-0.5 • 0.5-1	Mbow et al., 2019
Disposal	• Landfills • Incineration	• 0.2-0.5 • 0.5-1	Mbow et al., 2019

Source: *FAO (2013); Mbow et al. (2019); IPCC (2007)*

It is important to note that these values are rough estimates and may vary depending on the specific circumstances and practices of each food system player as well as the scope of measurement and estimation methods. Additionally, these estimates do not account for all sources of GHGE in the food system, and further research is needed to get a more comprehensive understanding of the full GHGE profile of the food system.

2.3. Role of aquaculture in GHG emissions

Aquaculture has the potential to play a significant role in providing reliable, affordable, and nutritious foods while reducing GHGE from food systems. According to the United Nations Food and Agriculture Organization (FAO), aquaculture currently provides approximately half of the world's seafood supply and is projected to provide even more in the future as wild fish populations continue to decline (FAO, 2023). One way aquaculture can contribute to GHG reduction is through the production of protein-rich foods with a lower carbon footprint compared to other protein sources, such as beef and pork. For example, a study by the World Wildlife Fund found that farmed salmon has a carbon footprint that is approximately 75% lower than beef and 50% lower than pork (WWF, 2018). Additionally, the production of seaweed, a type of aquatic plant that is commonly grown in aquaculture, has been shown to have a particularly low carbon footprint and can potentially be used as a source of feed for livestock, further reducing GHGE from the agriculture sector (FAO, 2018).

Aquaculture can also help to offset GHGE through the process of carbon sequestration. Seaweed and some types of shellfish, such as oysters and mussels, can absorb and store large amounts of carbon dioxide (CO_2) from the atmosphere as they grow (FAO, 2018). This process, known as ocean fertilization, can potentially help mitigate the impact of climate change by removing excess CO_2 from the atmosphere and sequestering it in the ocean. However, it is important to note that aquaculture also has the potential to contribute to GHGE if not properly managed. The growth of aquaculture has been limited in many regions due to a range of technical, economic, and social challenges (FAO, 2018). To fully realize the potential of aquaculture as a sustainable and equitable solution to global food security challenges, it is necessary to identify and promote TIMPs that can overcome these barriers and improve the efficiency and sustainability of aquaculture systems. Therefore, aquaculture practices must be sustainable and consider their potential environmental impact.

2.4. Aquaculture production in the African context

Today, aquaculture production in Africa continues to suffer from low technology adoption, poor infrastructure, insufficient government budgets and policies, unreliable supply, high cost of feed and other pond inputs, limited expertise, and diverse cultural and religious aspects (Brummet & Williams, 2000; Ogello & Munguti, 2016; Obiero et al., 2016; Ragasa et al., 2022). Consequently, aquaculture in Africa involves fewer cultivable fish species (mainly tilapia and catfish) cultured in less productive, small-scale systems operated using local inputs (Prein & Ahmed, 2000). With Africa's population projected to reach 2.5 billion by 2050 (United Nations 2022), achieving sustainable nutritional security is a looming challenge. Nonetheless, Africa's potential for aquaculture growth is prominent. About 23 percent of its surface area is suitable for aquaculture (Aguilar-Manjarrez and Nath 1998). Therefore, there is an urgent need to evolve predictable, cost-effective technologies and environmentally sustainable aquaculture development pathways to improve people's livelihoods in Africa.

In Kenya, the inland aquaculture subsector is growing rapidly in response to declining capture fisheries and increasing national demand for fish. There is already a significant gap between projected demand and production, which is expected to increase to 360,000 MT by 2025, resulting in a continuous decline in per capita consumption and rising prices (3.0 kg/person/year compared to a global average of 20.3 kg/person/year) (FAO, 2023; KNA, 2021). The Government of the Republic of Kenya launched a large-scale aquaculture support program under the Economic Stimulus Programme (ESP) during the period 2009–2013 to promote small-scale aquaculture fish production through support to produce inputs, fish production, post-harvest, etc. While the ESP has had major achievements, the fact is that the aquaculture fisheries' value chains are not well articulated and have clear weaknesses concerning the availability of good quality fish feed and seeds, insufficient technical services providers, insufficient processing and value addition enterprises, and inefficient market access. The typical smallholder aquaculture producer, with small ponds comprising the largest concentrations of smallholder aquaculture enterprises, is operating low-input/low-output enterprises because of inadequate technical expertise of producers, input challenges (quality of fingerlings and feed or unaffordability of good quality ones) and inadequate marketing channels. These bottlenecks do not allow the aquaculture subsector to mature and fill the gap left by declining capture fisheries. Moreover, the magnitude of these bottlenecks is considerably higher for smallholder aquaculture farmers and affects their profitability and livelihoods.

Although aquaculture is becoming increasingly sustainable, the availability of inputs—land, freshwater, feed, and energy— is limited and will likely become even more so in the future. Given the increasing scarcity of water, land, and other aquaculture resources, the adoption and upscaling of climate-smart aquaculture technologies, innovations, and management practices (CSA-TIMPs) will be key to maintaining the required growth of aquaculture to meet the increasing demand for fish in Kenya and beyond. To maximize aquaculture growth while minimizing ecological impacts, it pays to identify emerging opportunities through sustainable aquaculture production pathways. Kenya has implemented some aquaculture development pathways (ADPs) that have contributed to increased fish production and improved livelihoods. The pathways include TIMPs that (1) improve production efficiencies, (2) reduce post-harvest losses, (3) mitigate the occurrence of diseases and parasites, (4) reduce or eliminate the use of antibiotics, (5) advance land-based recirculation technology, (6) focuses on novel feed ingredients, (7) reduces carbon footprints through improved energy efficiency or regeneration, and (8) promote social programs designed to improve local livelihoods (Hambrey, 2017). The ADPs include consolidated aquaculture ponds (aqua parks), fish cage technology, improvement of fish farming technologies and practices, improvement of culture species, feed management, post-harvest processing, and intensification of production systems. Others include IAA farming systems, non-fed aquaculture technologies (Little and Edwards, 2003), and improved trade, finance, and marketing systems.

Kisumu County is one of the 47 counties created by the Constitution of Kenya 2010 that introduced a devolved system of governance. The population was estimated at 1,155,574 (Kenya National Census Report, 2019). With increasing infrastructural development in Kisumu County, i.e., port expansion, cage fish culture in Lake Victoria, and road networks, the county continues to attract huge populations of people who require nutritious fish proteins. This requires clear spatial planning strategies to ensure smooth coastal and management systems integration. The county's strategic position is a gateway for Kenya into the rest of Africa's Great Lakes region. It is located on the shores of Lake Victoria and serves as the main commercial and transportation hub for the Western Region of Kenya and the East African region.

Kisumu County is one of the Lake Victoria riparian counties with enormous potential in fisheries and aquaculture development. The Kisumu Lakefront Development Corporation (KLDC) works with the Kenya Urban Roads Authority (KURA) to construct a 26-km promenade along Lake Victoria. The promenade is expected to open up the lakefront for development in the Lake Region Economic Block (LREB). The KLDC has been funded to start the project, which will act as a launchpad for a series of developments along the lake (KNA, 2020). Other areas of interest include the refurbished Port of Kisumu, where large passenger vessels and boats will dock, an ecotourism area around Hippo point, fish landing sites and fish processing plants, an 18-hole professional golf course, a public beach, and a port. The corporation has designated areas for luxury hotels along the lakefront. These hotels will boost the ecotourism sector and provide several employment opportunities for youth. The opportunities will create opportunities for tourism and guiding, (especially boat rides), handicraft production, and the catering and accommodation sectors, which are mainly handled by youthful populations.

This review aims to identify and assess promising aquaculture technologies and innovations that have the potential to transform food systems toward low-emission pathways in Kenya, a country where aquaculture has the potential to contribute significantly to food security and economic development (Fishnet Kenya, 2017). These technologies vary from simple and low-cost solutions to more complex and capital-intensive technologies. The report also focuses on case studies of aquaculture technologies and innovations that have been implemented in Kenya and that have the potential to transform food systems toward low-emission pathways.

2.5. Context of the study

This study reviews promising/potential technologies and innovations for the low-emission transformation of aquaculture value chains/food systems in Kenya, focusing on Kisumu County. In addition to a literature review, we also conducted a stakeholder consultation meeting in Kisumu County to map out aquaculture food systems and value chains and identify sources of emissions and promising technologies and innovations for scaling for low-emission transformation. The task will involve the following:

1. Compilation of relevant datasets and information from past and ongoing projects related to climate change assessments (adaptation, mitigation, GHG reduction);
2. Review of published documents and reports to identify technologies and innovations for scaling to reduce GHGE (low emission transformation);
3. Identification of constraints and challenges faced by different value chain actors in scaling aquatic food systems technologies and innovations from the angle of low-emission development in Kenya.
4. Identification of potential social, economic, and environmental co-benefits and spillover effects from scaling technologies and innovations in aquaculture value chains/food systems for reducing GHG/emissions.

2.6. Objectives of the study

2.6.1. General objective

To conduct a desk-based review to document promising/potential technologies and innovations for the low-emission transformation of aquaculture value chains/food systems in Kenya, focusing on Kisumu County.

2.6.2. Specific objectives

1. To review published documents and reports to identify technologies and innovations for scaling to reduce GHGE (low-emission transformation).
2. To identify the constraints and challenges faced by different value chain actors in scaling aquatic food systems technologies and innovations from the angle of low-emission development in Kenya.
3. To identify potential social, economic, and environmental co-benefits and spillover effects from scaling technologies and innovations in aquaculture value chains/food systems for reducing GHG/emissions.
4. To conduct a stakeholder consultation/meeting in Kisumu County to map out aquaculture food systems/value chains and identify sources of emissions and promising technologies and innovations for scaling for low-emission transformation.

3. Methodology

3.1. Literature review

This study involved a comprehensive, detailed literature search and review of published articles, policy documents, expert opinions, and media blogs. To understand the details of aquaculture innovations and technologies, a market systems approach focused on the core market functions, supporting functions, rules, and relationships that shape aquaculture behaviors and practices in Africa. The core market functions looked at drivers of aquaculture production that support the initiatives and flow of aquaculture products and services and food system outcomes for maximum profitability and social security. A systematic and thorough literature review was conducted to critically analyze information to understand the historical and current context of African aquaculture development pathways, innovations, and technologies.

3.2. Systematic literature review process

To generate a comprehensive literature review on potential aquaculture innovations in Kisumu County that addresses the key research questions, we used a systematic and iterative literature approach following three key steps (Figure 2). A comprehensive literature search was conducted using databases such as PubMed, Web of Science, and Google Scholar to identify relevant studies. The search included keywords such as "aquaculture," "low emission pathways," "food systems," "Kisumu County," and "Kenya." The identified studies were then screened for relevance based on the inclusion and exclusion criteria. The inclusion criteria included studies that focused on aquaculture technologies and innovations in Kisumu County, Kenya, and that addressed the research questions. The extracted data from the included studies were then synthesized and analyzed to identify trends and patterns. This involved comparing the different studies' findings and identifying gaps in the current literature.

Figure 2. The iterative process utilized to conduct the literature review.

1. Step 1 - REVIEW

Identification of documentation for incorporation

Used a three-step screening process: Identify potential documents for incorporation.

Examine strength of evidence according to selected review criteria: (1) conceptual framing, (2) transparency, (3) appropriateness, (4) validity, (5) reliability, and (6) cogency.

Final selection and analysis of documentation and secondary data.

Step 2: ASSESS and ANALYZE

Inclusion and analysis of relevant data

Three analytical questions were used to assess information relevance and strength:

(1) Are the articles and studies relating to the thematic objective the most current available?

(2) What gaps are there in the information?

(3) Is more information likely to be found and if not can the question be more adequately addressed through other data collection strategies?

The articles and documents assessed as being relevant and reliable were used to answer the consultancy objectives.

Step 3: IDENTIFY

Finalization of review and remaining gaps in literature

At this point, remaining literature gaps and questions raised were incorporated into the literature review document.

These questions were used to refine the actionable recommendations for further data collection, analysis and desk review in order to uncover the necessary information.

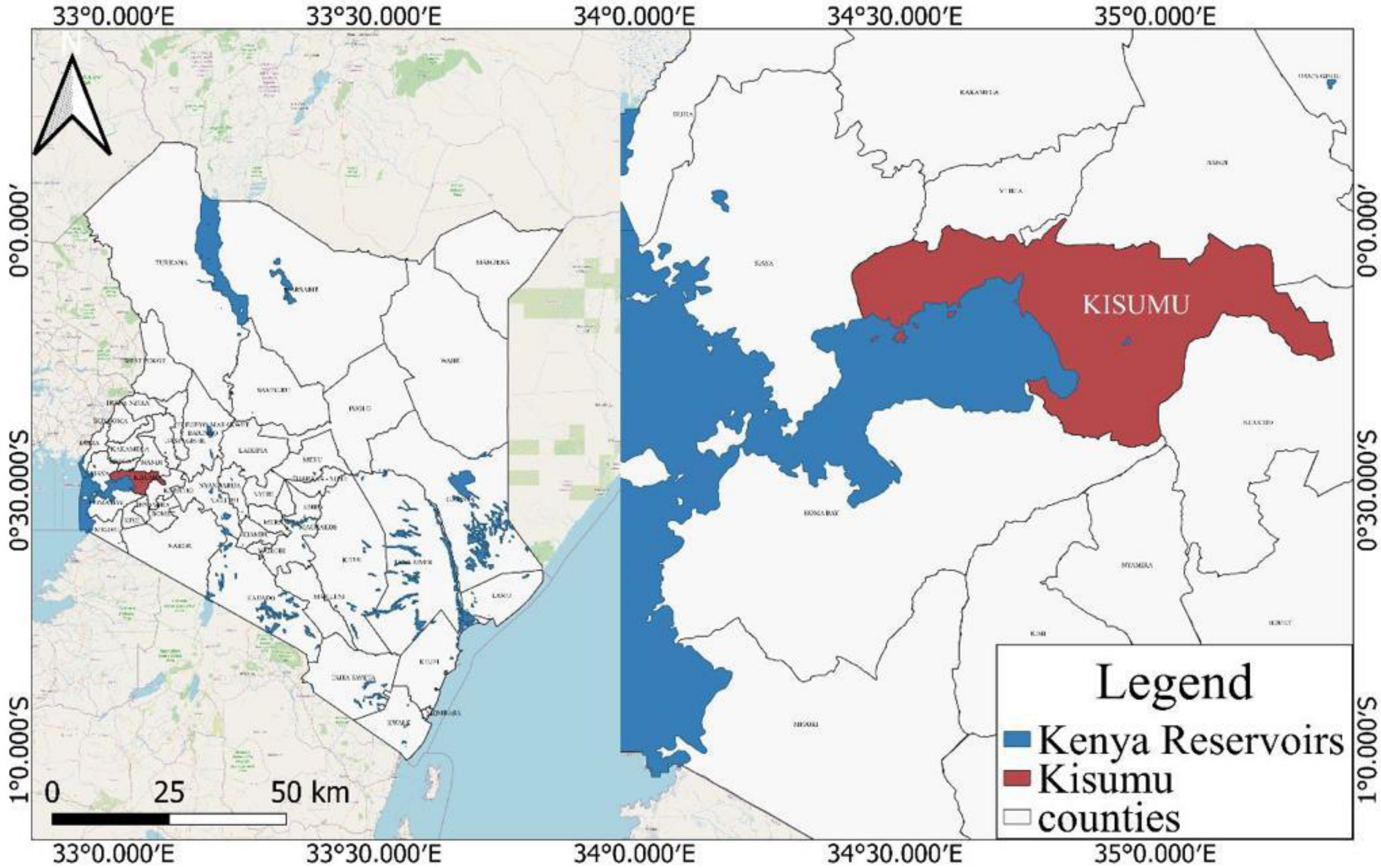
The research questions for the diagnostic study (see initial Terms of Reference) were regrouped into three general areas:

(1) understanding the context, (2) an analysis of barriers and opportunities, and (3) system intervention areas.

3.3. Study area

The review focused on the technologies that could be adopted and upscaled in Kisumu County. The county has been a fish-producing region, especially due to its proximity to Lake Victoria (Figure 3). Although most of the fish eaten around the county have been from the lake, fish farming in Kisumu County has expanded since the ESP was introduced, a new survey shows (The Standard, 2013). Kisumu County has great potential for aquaculture, as the region has a good climate that favors farming of various fish species, with Nile tilapia (*Oreochromis niloticus*) and African catfish being the dominant species in the region. Cage aquaculture has gained attention in the county, with over 10,000 fish cages currently in the lake within the county. This has significantly boosted fish production within the county.

Figure 3. Map of Kisumu County, where the study was focused.



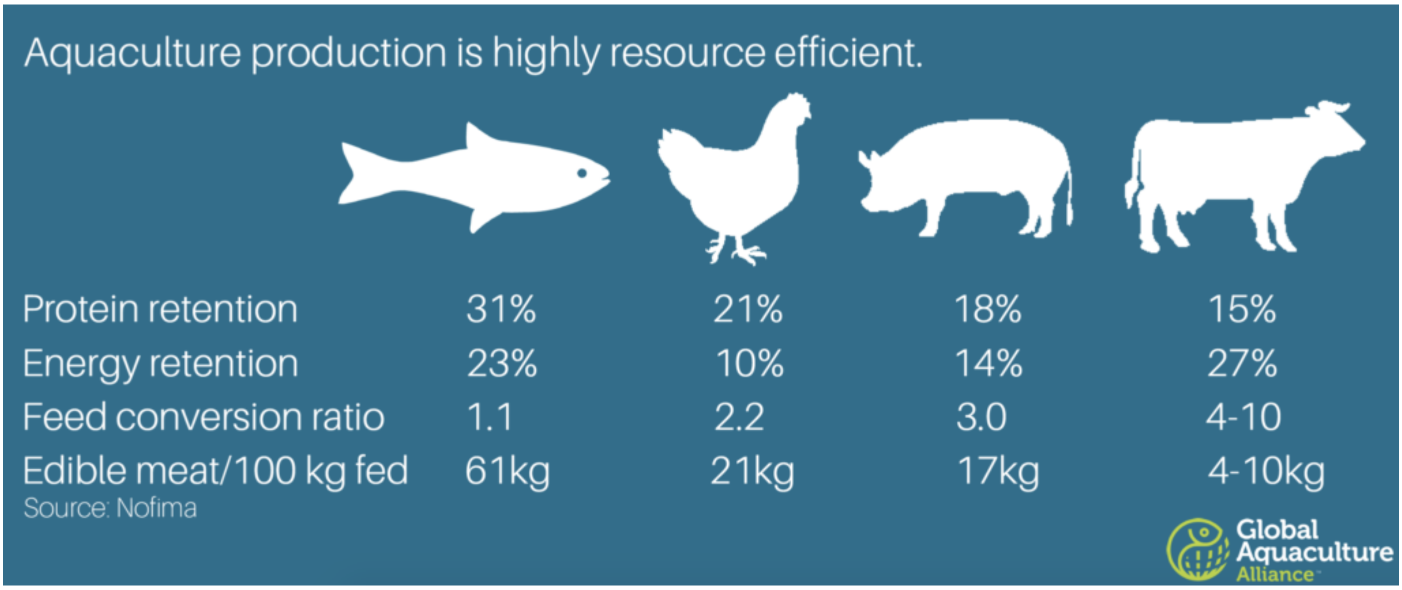
4. Study findings

4.1. Aquaculture as resource-efficient activity

One of the key ways in which aquaculture can be considered a resource-efficient activity is through its ability to produce high yields using relatively low inputs. Compared to other forms of animal agriculture, such as livestock and poultry farming, aquaculture requires smaller amounts of land, water, and feed to produce a given amount of protein (Verdegem et al., 2006). This is due in part to the fact that aquatic animals are more efficient at converting feed into body mass and because aquaculture systems can be designed to recycle and reuse resources such as water and nutrients (FAO, 2018).

In the Kenyan context, aquaculture has the potential to be an especially resource-efficient activity due to the country's abundant water resources and relatively underutilized land. According to FAO, Kenya has an estimated 1.7 million ha of inland water bodies suitable for aquaculture development, and only a small fraction of this potential is currently being utilized (FAO, 2016). By increasing production in these areas, Kenya could meet the growing demand for seafood within the country and potentially even become a major exporter of fish and other aquatic products. Fish is highly resource efficient. Compared to chicken, pork, and beef, it has the highest protein retention and a lower food conversion ratio (FCR) (Figure 4). Fish production requires much less water and land per kilogram of flesh.

Figure 4. Comparison of resource use efficiency of aquaculture and other value chains.



Source: *Global Aquaculture Alliance (2019)*

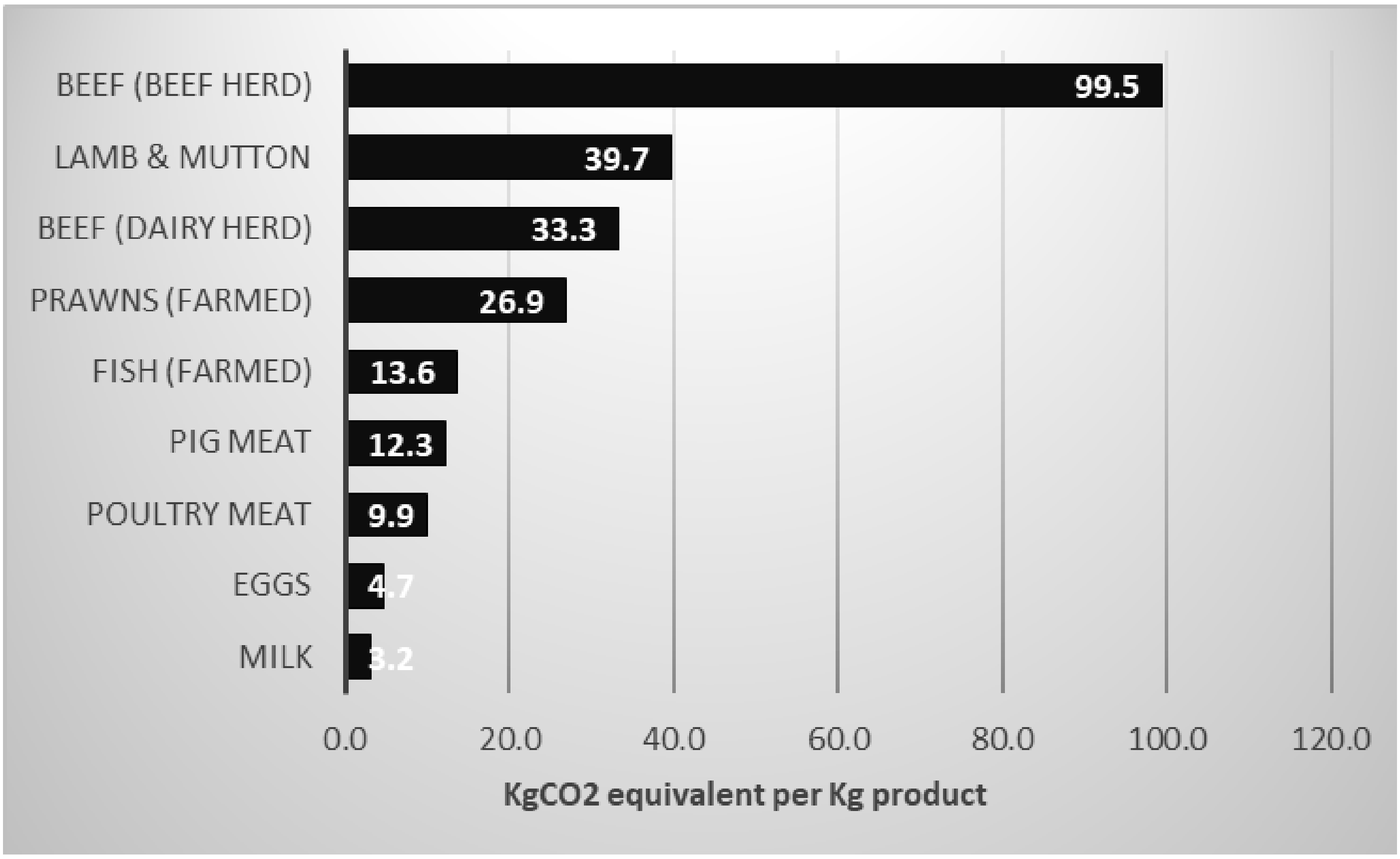
To maximize the resource efficiency and environmental sustainability of aquaculture in Kenya, it will be important for the sector to adopt best management practices and implement appropriate regulations and policies. This could include promoting the use of sustainable feed ingredients, minimizing the use of chemicals and antibiotics, and incorporating IMTA systems that incorporate a variety of species in a single system (FAO, 2018). In addition, aquaculture has the potential to be a resource-efficient and environmentally sustainable activity, particularly in the Kenyan context, where the sector is underdeveloped and has abundant water and land resources. However, the sector needs to adopt best management practices and appropriate regulations and policies to maximize its potential benefits and minimize negative impacts.

4.2. Low-emission aquaculture innovations and technologies

Currently, aquaculture provides around half of the fish for direct human consumption worldwide (FAO, 2023). The growth in the aquaculture sector has been due to the innovation and technological advancements in fish production, e.g., hybridization, genetic engineering, formulated diets, and the improvements in various culture systems, including ponds, cages, tanks, and recirculation systems (FAO, 2012). Nonetheless, aquaculture production will need to double between now and 2050 to meet the demands of a growing population. This has generated a greater need for finite resources (land and water) that are already under heavy stress (FAO, 2011). The only viable option is that the technical efficiencies of land, water, labor, capital, and energy must increase substantially—through sustainable intensification and integration approaches. Given the increasing scarcity of water, land, and other aquaculture resources, the adoption and upscaling of CSA-TIMPs will be the key to maintaining the required growth of aquaculture to meet the increasing demand for fish in Kenya. The adoption and use of the CSA-TIMPs are expected to contribute to increased productivity, strengthened resilience, and limit the emission of GHG, which poses climate change risks to targeted smallholder farmers and pastoral communities in the country. The low-emission aquaculture TIMPs are grouped into six categories representing sustainable intensification, namely (1) culture systems, (2) culture species and breeding, (3) feeds and feed management practices, (4) fish health management and biosecurity, (5) post-harvest loss reduction, value addition, and (6) fish marketing, trade, and supply channels.

Assuming the adoption of proper farm management practices, aquaculture has lower GHGE than other types of farming. For example, while cattle production produces 99.5 kg of CO_2 per kilogram of edible meat, aquaculture produces only 13.6 kg of CO_2/kg of edible meat. The FCRs are 8.0 and 1.3, respectively (Figure 5). Low GHGE from aquaculture, taken together with the high GHG emissions from agriculture, indicate that expanding aquaculture into agricultural landscapes could lower aggregate GHGE from agricultural ecosystems. Global agriculture is estimated to produce about 5 to 13.5 percent of annual GHGE (Poore and Nemecek, 2018). This figure covers only crop production and excludes other forms of agriculture.

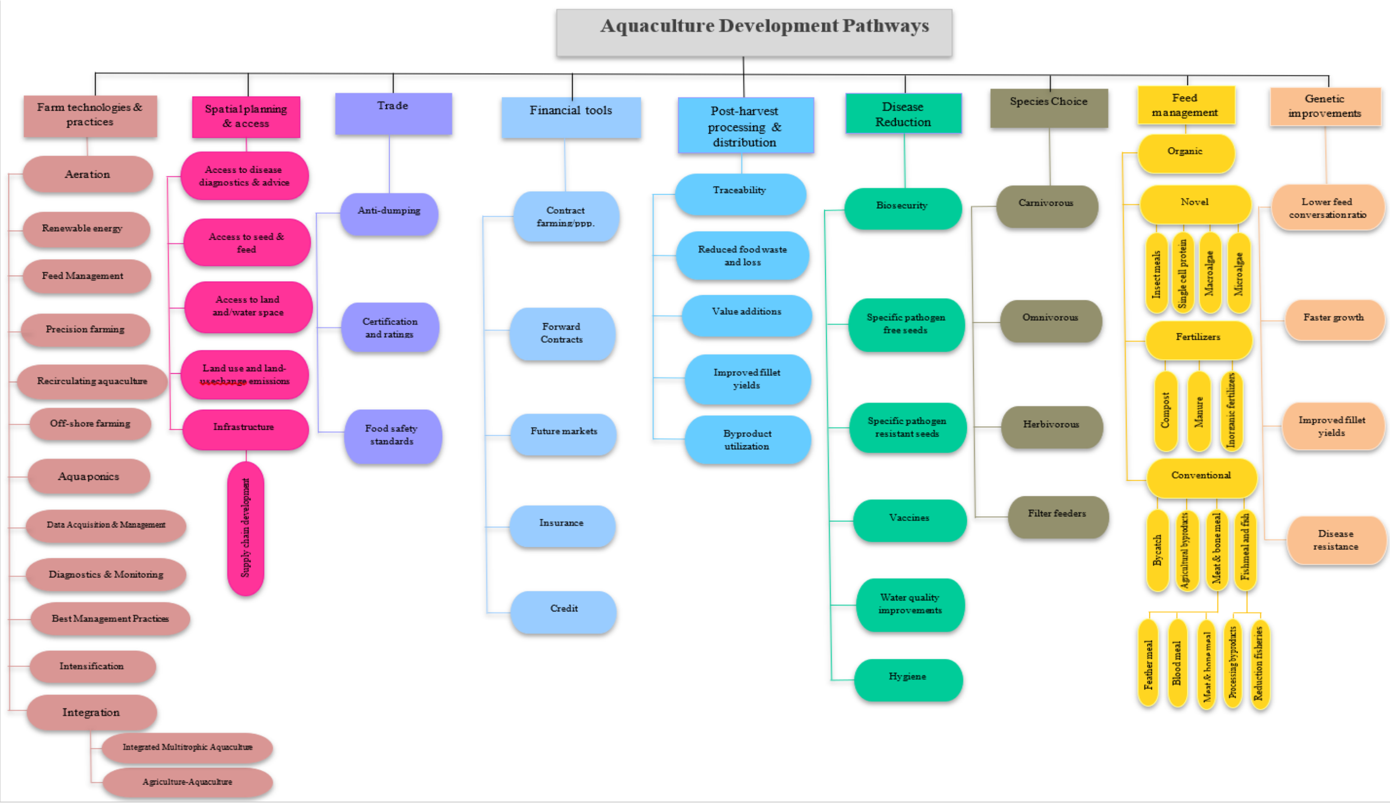
Figure 5. GHGE per kilogram of meat from different kinds of animal protein.



Source: *Poore and Nemecek (2018)*

This study analyzed potential low-emission aquaculture pathways that contribute to successful aquaculture production with low GHG emissions in Kenya. A matrix of the most promising aquaculture development pathways, for increased productivity and low GHGE, is presented in Figure 6.

Figure 6. Matrix of the most promising low-emission aquaculture development innovations and technologies for increasing fish production and food security.



Source: *Henriksson et al. (2021)*

4.3. Improved farming technologies and practices

TIMPs that may be implemented into current aquaculture systems and habitats to achieve the triple advantages of enhanced production, system resilience, and GHG emission reduction are examples of better agricultural practices. These TIMPs address current production concerns and reorient the sector toward resource efficiency and sustainable intensification (Munguti et al., 2022). Such improved farming technologies and practices in this context have been discussed in this chapter in terms of how they contribute to low emissions while providing optimal social benefits, including the potential to improve food and nutrition security as well as the spillover effects associated with the various technologies. Furthermore, the review suggests possible measures to mitigate these negative effects and the possible opportunities for adoption and upscaling, especially among the smallholder farmers within Kisumu County. The technologies and associated management practices are discussed in detail in the context of the Kenyan aquaculture sector, emphasizing Kisumu County. For those that cannot be directly adopted but still have a high potential for adoption, modifications to facilitate adoption and upscaling have been suggested.

4.3.1. Solar-Powered Recirculating Aquaculture Systems (SPRAS)

Solar-powered recirculating aquaculture systems (SPRAS) are an innovative technology that combines the production of aquatic animals with the use of solar energy, potentially reducing GHGE and providing socio-economic and environmental co-benefits. One of the key benefits of a SPRAS is its potential to reduce GHGE compared to traditional aquaculture systems. RAS can produce 3.2–4.2 kg CO_2 equivalent/kg of fish produced (Table 3). Solar energy is a renewable energy source that does not produce GHG during generation, and the use of SPRAS can, therefore help to reduce the carbon footprint of aquaculture operations (Liao et al., 2018). In addition, the closed-loop nature of SPRAS allows for the recycling and reuse of water and nutrients, reducing the need for inputs such as feed and chemicals and further decreasing the system's carbon footprint (FAO, 2018).

In the Kenyan context, SPRAS has the potential to contribute to the country's efforts to reduce greenhouse gas emissions and mitigate the impacts of climate change. Kenya aims to generate at least 100 MW of solar energy by 2020, and adopting SPRAS could help meet this target while increasing food security and promoting economic development in rural areas (GoK, 2018). However, scaling the technology in Kenya also presents several constraints, challenges, and trade-offs for different value chain actors. One major constraint is the initial cost of setting up a SPRAS, which can be high compared to traditional aquaculture systems (Liao et al., 2018). This can be a barrier for small-scale farmers and entrepreneurs, who may not have the capital or access to financing to invest in the technology. In addition, the lack of technical knowledge and expertise on SPRAS can be a challenge for farmers and entrepreneurs, particularly in remote and rural areas where access to training and extension services may be limited (Liao et al., 2018). This can make it difficult for farmers to operate and maintain the systems effectively, leading to reduced yields and profitability.

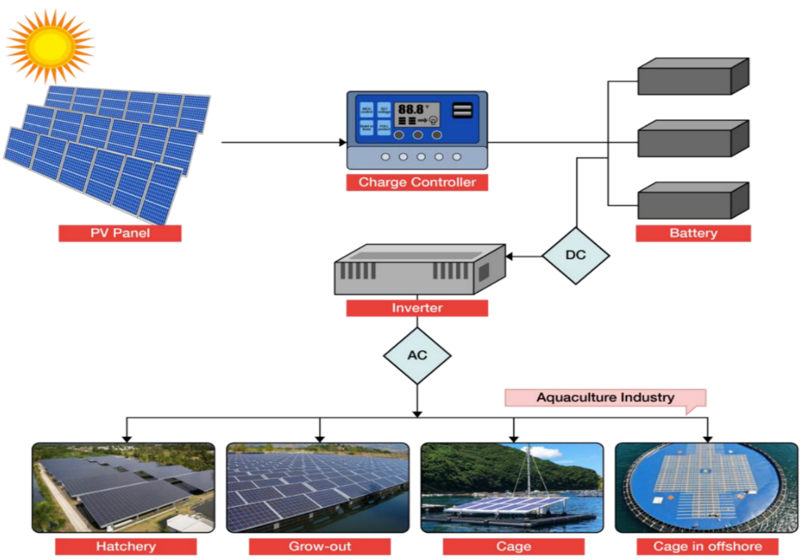
There are also potential trade-offs associated with the adoption of SPRAS, such as the need to allocate land and water resources for the technology, which could potentially compete with other uses (Liao et al., 2018). In addition, the use of solar energy for SPRAS may not be possible in all locations due to factors such as shading and access to the grid, which could limit the potential for adoption in some areas (FAO, 2018). Other constraints associated with scaling the technology include the initial cost of setup, and a lack of technical knowledge and expertise.

Despite these challenges, there are also potential spillover effects and co-benefits of SPRAS that could benefit different value chain actors. For example, the adoption of SPRAS could lead to increased income and employment opportunities for farmers and entrepreneurs, as well as improved food security and nutrition in the local community (Liao et al., 2018). In addition, the use of SPRAS could also lead to increased water productivity and the conservation of wild fish populations, as the systems can be designed to recycle and reuse water and nutrients (FAO, 2018).

In Kisumu County, Kenya, the VicInAqua youth group, which was funded by then EU Horizon 2020 project, has created a prototype Nile tilapia (*Oreochromis niloticus*) hatchery, employing RAS adapted to local circumstances and conditions (Clough et al., 2020). The facility uses waste water from sewage stabilization ponds that receive wastewater from the city of Kisumu. The water is then filtered through reverse osmosis and used in the production of tilapia fingerlings. The water from the fish tanks is used in the production of vegetables and fruits around the farm to maximize profit and reduce the cost of operations. The hatchery is intended to be a versatile, scalable, and modular system. It is now being used to disseminate training and best practices in the local sector. Farmers may access farm data from both fish tanks and the supporting renewable energy systems via an online monitoring system, allowing for round-the-clock monitoring and control. The hatchery can produce 25,000 fingerlings per month to support the region's pond aquaculture (Clough et al., 2020). The system's environmental benefits include its closed nature, which reduces waste discharged into the environment. Its use of wastewater also indicates its contribution to lowering GHGE into the atmosphere. Plants (vegetables and fruits) associated with the system also sequester CO_2 from the environment, helping to reduce GHGE to some extent.

Given these challenges, SPRAS has the potential to be an important part of the solution for the Kenyan aquaculture sector. The use of solar energy can help to reduce the sector's reliance on fossil fuels and reduce GHGE, while the closed-loop nature of the systems can help to conserve water and reduce the need for inputs such as feed and chemicals (FAO, 2018). In addition, the use of SPRAS could also help to improve the resilience of the sector to the impacts of climate change, as the systems can be designed to operate in a range of environmental conditions (FAO, 2018). Also, it will be important to consider the potential trade-offs and spillover effects of SPRAS, including the allocation of land and water resources and the potential for competition with other uses. To minimize these negative impacts and maximize the benefits of the technology, it will be important to adopt a holistic and integrated approach to the development and implementation of SPRAS in Kenya.

Figure 7. A schematic show of solar-driven aquaculture production system.



Source: *Vo et al. (2021)*

SPRAS has the potential to be a valuable part of the solution for the Kenyan aquaculture sector, helping to reduce GHGE, improve resource efficiency, and enhance the resilience of the sector to the impacts of climate change. However, it will be important to address the constraints, challenges, and trade-offs faced by different value chain actors to fully realize the potential of the technology.

4.3.2. Aquaponics systems

Aquaponics is a sustainable agriculture system that combines the production of fish and plants in a closed-loop system (Figure 8), with the potential to reduce GHGE and provide socio-economic and environmental co-benefits. Aquaponics can produce 1.5–2.5 Kg CO_2 equivalent/kg of fish produced (Table 3). One of the key benefits of aquaponics is its potential to reduce GHGE compared to traditional agriculture systems. Aquaponic systems can be powered by renewable energy sources such as solar or wind, which do not produce GHG during generation (FAO, 2018). In addition, the closed-loop nature of aquaponic systems allows for the recycling and reuse of water and nutrients, reducing the need for inputs such as fertilizers and pesticides and further decreasing the system's carbon footprint (Liao et al., 2018).

In the Kenyan context, aquaponics has the potential to contribute to the country's efforts to reduce GHGE and mitigate the impacts of climate change. Kenya aims to generate at least 100 MW of solar energy by 2020, and adopting aquaponics could help meet this target while increasing food security and promoting economic development in rural areas (GoK, 2018). However, scaling the technology in Kenya also presents some constraints, challenges, and trade-offs for different value chain actors. One major constraint is the initial cost of setting up an aquaponic system, which can be high compared to traditional agriculture systems (Liao et al., 2018). This can be a barrier for small-scale farmers and entrepreneurs, who may not have the capital or access to financing to invest in the technology. In addition, the lack of technical knowledge and expertise in aquaponics can challenge farmers and entrepreneurs, particularly in remote and rural areas where access to training and extension services may be limited (Liao et al., 2018). This can make it difficult for farmers to operate and maintain the systems effectively, reducing yields and profitability. There are also potential trade-offs associated with adopting aquaponics, such as the need to allocate land and water resources for the technology, which could compete with other uses (Liao et al., 2018). In addition, using renewable energy for aquaponics may not be possible in all locations due to factors such as shading and access to the grid, which could limit the potential for adoption in some areas (FAO, 2018). Despite these challenges, aquaponics also has potential spillover effects and co-benefits that could benefit different value chain actors. For example, adopting aquaponics could lead to increased income and employment opportunities for farmers and entrepreneurs and improved food security and nutrition in the local community (Liao et al., 2018). In addition, the use of aquaponics could also lead to increased water productivity and the conservation of wild fish populations, as the systems can be designed to recycle and reuse water and nutrients (FAO, 2018).

To fully realize the potential of aquaponics in the Kenyan context, it will be important to address the constraints and challenges faced by different value chain actors. This could include initiatives to increase access to financing and technical assistance for small-scale farmers and entrepreneurs, as well as efforts to improve infrastructure and technology in the sector. In addition, it will be important to consider the potential trade-offs and spillover effects of aquaponics, including the allocation of land and water resources and the potential for competition with other uses. To minimize these negative impacts and maximize the benefits of the technology, it will be important to adopt a holistic and integrated approach to the development and implementation of aquaponics in Kenya. One potential approach to scaling aquaponics in Kenya could be the establishment of community-based aquaponic systems, which could be owned and operated by groups of small-scale farmers and entrepreneurs. This model could help to reduce the initial cost of setup and increase access to technical assistance and support, while also promoting local economic development and food security (Liao et al., 2018).

Figure 8. Aquaponic system of tilapia and spinach production at a fish farm in Mwitoko.

Another example of a successful commercial aquaponics farm is the Kikaboni farm in Kenya. Increased awareness can promote the technology in other areas, such as Kisumu and Kakamega County. According to the survey's findings, there may be a demand for aquaponics products, and implementing the system might be a way to get over Kenya's climate-related seasonal production problems. The plants utilized in aquaponics are selected based on their capacities to recover nutrients for proper development, in addition to market value and consumer approval (Obirikorang et al., 2021). In the hydroponic portion of aquaponic systems, for the intense production of Nile tilapia, sweet wormwood, pigweed, and pumpkin can absorb about 74% of nitrate in effluents from fish production units (Gichana et al., 2018).

Aquaponics has the potential to be a valuable part of the solution for the Kenyan agriculture sector, helping to reduce GHGE, improve resource efficiency, and enhance the sector's resilience to climate change impacts. However, it will be important to address the constraints, challenges, and trade-offs faced by different value chain actors to fully realize the technology's potential.

4.3.3. High-Density Polyethylene (HDPE) fish cages

Cage aquaculture is where fish are raised in existing water bodies while confined in a net cage that enables water to flow freely. It is an aquaculture production system that can be installed in a reservoir, river, lake, or ocean and is made of a floating frame, net materials, and a mooring system (with rope, a buoy, anchor, etc.) (Olubiyi et al., 2021). Highly productive cage systems have developed and will continue to be an important driver of sustainable aquaculture growth if biosecurity, management practices, and environmental standards are promoted and enforced more effectively (Ragasa et al., 2022). Cage culture allows aquafarmers to use existing water resources, which are often restricted for other uses. Cage farms use natural currents, which provide fish with oxygenated water and remove the need for electricity-driven aeration, thus conserving energy and reducing emissions (Ignatius, 2016). Cage culture investment is relatively modest, requiring little/no land space, making it perfect for small-scale fish producers (Charo-Karisa et al., 2009). With proper siting and management, cages may be stocked at great densities while preventing waste material accumulation in the cage system. The high fish density and limited area for fish mobility lower the amount of energy available for muscular action, resulting in a rapid development rate (Juell, 1995).

The potential of high-density polyethylene (HDPE) cage culture in Kisumu is enormous, given Kenya's massive fish supply gap, which is anticipated to reach 553,000 MT by 2030 (Obiero *et al.*, 2019; Munguti *et al.*, 2021). This is coupled with the fact that Kisumu is a traditionally fish-eating region near Lake Victoria. Overfishing, habitat deterioration, environmental pollution, and the effects of climate change have all contributed to the decrease in Lake Victoria's capture fisheries during the past three decades (Yongo *et al.*, 2021). Fishermen in Lake Victoria are now turning to cage culture, which is anticipated to provide an alternative source of income to fishing, which has been the traditional source of fish around the lake (Musa *et al.*, 2022).

Studies on the economic and social implications of cage farming in Lake Victoria have found that, while present caging operations in the lake are in their early phases, the results indicate that it is a feasible economic activity (Musa *et al.*, 2022).

HDPE cages are a promising technology for GHGE reduction in the agricultural sector, particularly in the context of smallholder farms in Kenya. Although there are potential socio-economic and environmental co-benefits to be gained from using HDPE cages, trade-offs and challenges must be considered to scale the technology effectively. One of the main benefits of HDPE cages is their potential to reduce GHGE, with only 3.7 kg of CO_2 equivalent/kg of fish produced being emitted (Table 3). HDPE cages can help reduce N_2O emissions by providing a more controlled environment for plants to grow in, which can result in more efficient use of fertilizers and fewer emissions.

There are other potential socio-economic benefits of cage culture. Smallholder farmers in Kenya often struggle to access affordable and reliable sources of inputs, such as seeds, fertilizers, and water. HDPE cages can help reduce these inputs' costs by providing a more controlled and efficient growing environment. This can lead to increased productivity and profitability for smallholder farmers, which can, in turn, contribute to the overall socio-economic development of the region. Although there are clear benefits to be gained from using HDPE cages, there are also trade-offs and challenges that must be considered. One of the main challenges is the initial cost of purchasing and setting up cages, which can be prohibitively expensive for smallholder farmers. Additionally, there are concerns about the environmental impacts of the production and disposal of HDPE cages, as they are made from non-biodegradable plastic. Another challenge in scaling the use of HDPE cages is the need to develop appropriate financing mechanisms to support smallholder farmers. To make the technology more accessible, there needs to be a range of financing options available, such as grants, loans, and other forms of support. This will require the involvement of various stakeholders, including government agencies, development organizations, and private sector companies. Despite these challenges, there is potential for HDPE cages to significantly reduce GHGE and support the socio-economic development of smallholder farmers in Kenya. To effectively scale the use of HDPE cages, it will be necessary to address the constraints and challenges faced by different value chain actors, including smallholder farmers, input providers, and financing institutions. This will require developing innovative solutions and partnerships between these actors to ensure that the benefits of HDPE cages are realized in a sustainable and equitable way. To make the technology more environmentally friendly and reduce the potential spillover effects, especially on the environment, the technology can be modified into IMTA systems.

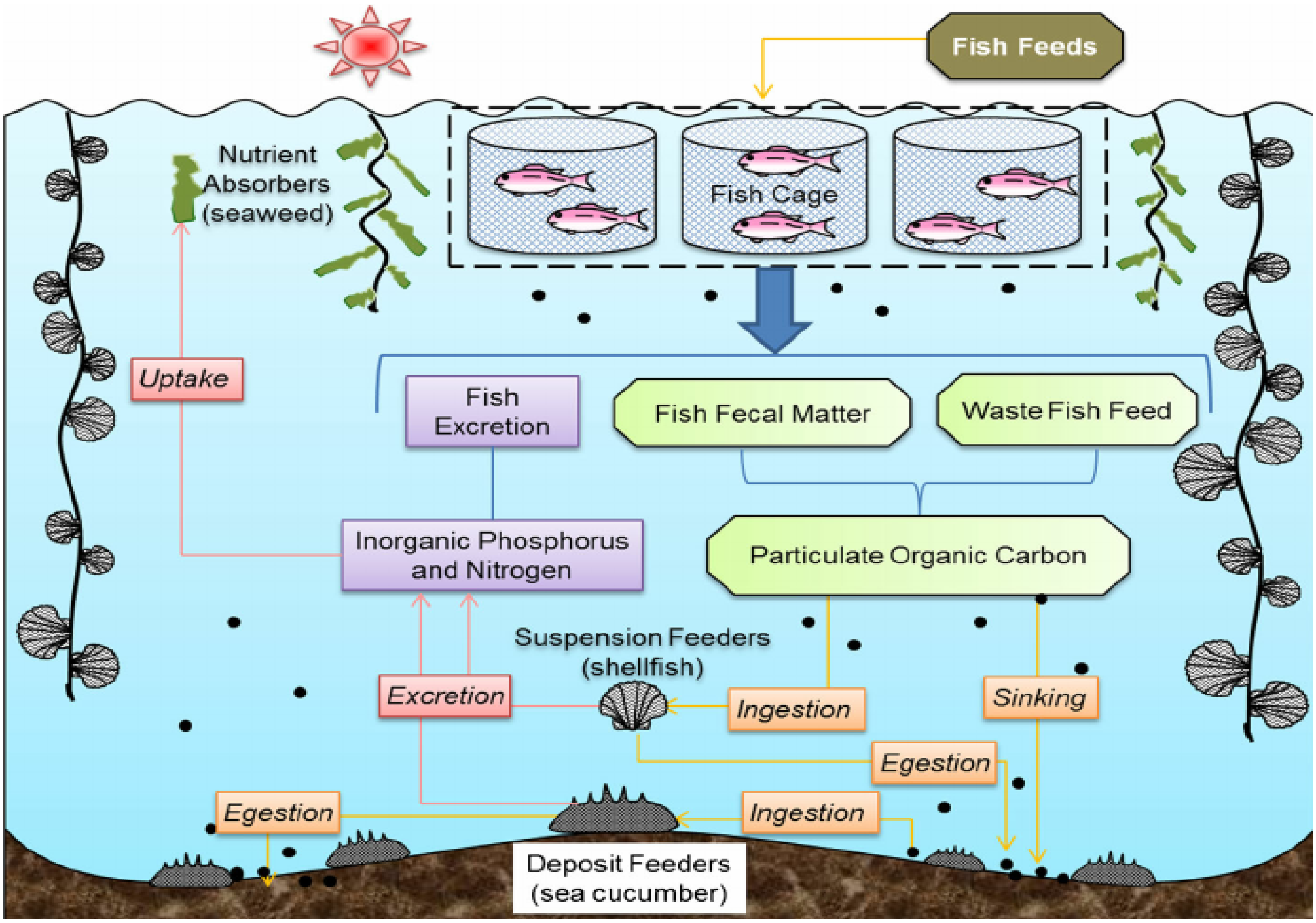
Figure 9. Locally fabricated 20 m-diameter HDPE cage in Lake Victoria, Kenya.

4.3.4. Integrated Multitrophic Aquaculture (IMTA)

IMTA is a system in which aquaculture species from various trophic positions are integrated into an agro-industrial system, increasing resource use efficiency (Chopin, 2013) (Figure 10). IMTA strives to minimize energy losses and environmental deterioration by integrating the production of aquaculture species from different trophic levels using a circular economy strategy. The technology is both resource-efficient and climate-smart in nature and has acquired societal acceptance in many countries over conventional monoculture systems.

Low fish production and productivity and environmental degradation connected with cage aquaculture systems in Lake Victoria, particularly from uneaten feeds and fish wastes, have been serious concerns. This justifies the use of IMTA since it enables the development of more sustainable production systems in which waste from fish production is viewed as a resource rather than a burden or pollution. This technology will help reduce the negative impacts associated with the conventional cage technology within the lake that has been seen to contribute to eutrophication and environmental degradation. For example, by-products of fish culture, such as fish feces, excreted nitrogen and phosphorus, and unconsumed fish feed, can serve as a source of nutrients for seaweed (inorganic processors) and shellfish (organic processors), reducing the accumulation of fish waste by converting it into fodder for another commercially valuable organism. This contributes to resource conservation, generating commercially viable by-products, and reducing environmental consequences (Soto, 2009). Billard et al. (1990) claimed that productivity in polyculture units can reach 30 kg ha-1 d-1 without feeding the fish. Such productivity is far more than traditional animal production on land (Birley & Lock, 1998). This helps with environmental sustainability and more effective resource usage and supports economic diversification (product variety, risk reduction, and social acceptability). To achieve the adoption of the technology within Kisumu and riparian counties, it is important to identify the aquatic plants and filter feeders that can be integrated into the production system. The possible ones are freshwater mollusks and reeds that can be planted in crates and anchored in cages. Some submerged aquatic plants are potential candidates for incorporation into this technology. The plants can then be used as fodder or for making artifacts, while the mollusks can be used in the formulation of animal feeds since they are rich in calcium.

Figure 10. IMTA system conceptual diagram.



Source: *Zhang et al. (2016)*

Note: *Boxes represent state variables and/or interaction processes. A brown arrow represents the carbon cycle, whereas a pink arrow represents the nutrition cycle.*

One example is the Mtwapa Creek Integrated Multi-Trophic Aquaculture Demonstration Project in Kenya, which was implemented by WorldFish and the Kenya Marine and Fisheries Research Institute (KMFRI) with support from the European Union and the Government of Kenya. This project demonstrated the technical and economic feasibility of IMTA in Kenya, and showed that the integration of nitrogen-fixing, nutrient-uptake, and biomass-producing species in a single system can significantly reduce the need for supplementary feed and fertilizer inputs and improve the utilization of nutrients in the system (Galloway et al., 2010). Although IMTA offers numerous benefits, including sustainability, environmental friendliness, and economic benefits, several barriers can prevent its wider adoption. These barriers include economic challenges, such as high initial capital costs and uncertain economic returns, and technical barriers, such as the lack of suitable sites and infrastructure and the technical expertise required to design and operate IMTA systems. Regulatory barriers, such as the lack of clear policies and regulations surrounding IMTA, can also create uncertainty and discourage potential investors and farmers from adopting the technology. Finally, a lack of knowledge and awareness about the potential benefits and challenges of IMTA among value chain actors and policymakers can also be a barrier to adoption. The scaling of IMTA in Kenya and other developing countries can also have spillover effects, both positive and negative, on the broader economy and society. Some of the positive spillover effects may include the development of new value chains and market opportunities, the transfer of knowledge and technology, and the establishing of partnerships and collaborations between different sectors. Negative spillover effects may include the potential for resource competition and conflict and negative impacts on traditional fishing communities and ecosystems if the technology is not properly planned and managed. IMTA produces about 1.8–2.8 kg of CO_2 equivalent/kg of fish produced being emitted (Table 3).

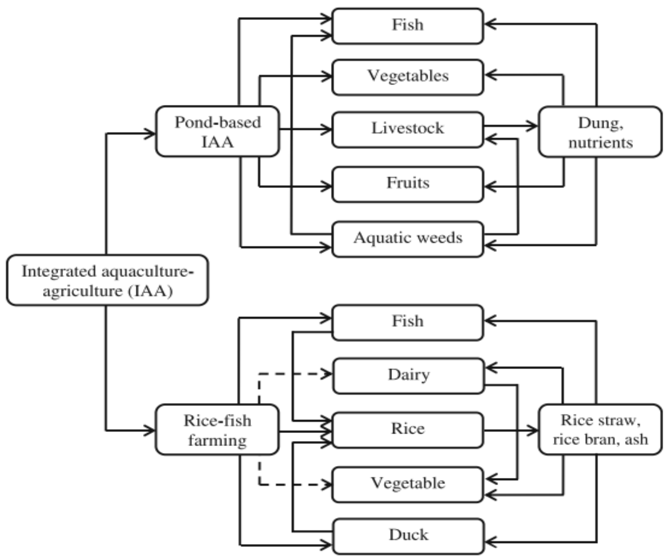
IMTA has the potential to significantly reduce GHGE in the aquaculture sector and provide a range of socio-economic and environmental co-benefits. However, the scaling of this technology in Kenya and other developing countries faces some constraints and challenges, including economic, technical, and regulatory barriers and a lack of knowledge and awareness. To maximize the potential benefits of IMTA and minimize negative spillover effects, it is important to carefully consider these constraints and challenges and develop appropriate policies and strategies to support the scaling of the technology.

4.3.5. Integrated Agri-aquaculture (IAA) culture systems

IAA culture systems, also known as polycultures, involve the simultaneous cultivation of aquatic animals (such as fish, shellfish, and seaweed) and crops in a way that is mutually beneficial and sustainable. This type of system has the potential to significantly reduce GHGE, as it can increase food production while minimizing the environmental impacts of traditional monoculture farming practices. The IAA system produces about 2–3.7 kg of CO_2 equivalent/kg of fish produced being emitted (Table 3). IAA is a promising agroecological (AE) practice that applies ecological and social principles to designing and managing food and agricultural systems. Spearheaded by FAO, AE is receiving increasing interest worldwide from different institutions as an effective answer to climate change and the interrelated challenges associated with food systems. The circular water-energy-nutrient systems of IAA are among the most promising AE practices in terms of addressing climate change and increasing the financial viability of smallholder farms (de Morais et al., 2022).

As depicted in Figure 11, IAA is a circular approach technique that lowers waste while increasing production by utilizing livestock manure and other agricultural and home by-products as fertilizer and fish/animal feed (Ogello et al., 2013; Tu Nguyen et al., 2022). Irrigation water from fish ponds may be used, and rice and fish can be grown together in trenches. IAA systems need fewer external inputs like fertilizer, insecticides, and animal feed, making them environmentally friendly (Raju, 2022). IAA can also be an effective climate change adaptation technique since it diversifies livelihoods and makes better use of precious water. It also delivers social and economic benefits to farmers, e.g., reduced dependency on external inputs and improved added value to agricultural by-products as feed components (Abisha et al., 2022). IAA systems can also help reduce GHGE by preventing methane and nitrous oxide emissions from decomposing animal waste, which is instead utilized for fish feed, as well as lowering the demand for fertilizer and animal feed and the emissions related to their production (Zajdband, 2011).

Figure 11. Types of IAA with the different components and inter-linkages.



Source: *Ahmed et al. (2014)*

However, several constraints and challenges must be addressed to effectively scale IAA culture systems in Kenya and other developing countries. One major constraint to the widespread adoption of IAA culture systems is the lack of knowledge and expertise among smallholder farmers and other value chain actors. This includes a lack of understanding of the technical aspects of polyculture farming and the economic and social factors that can affect its success. To overcome these barriers, it is necessary to invest in education and training programs that can help farmers and other value chain actors understand the benefits and challenges of IAA culture systems.

Another significant challenge is the lack of infrastructure and financing options for smallholder farmers. Many farmers do not have access to the necessary inputs (such as seedlings, feed, and equipment) to establish and maintain an IAA culture system, and they may not have the financial resources to invest in the initial setup costs. To overcome these barriers, it will be necessary to develop innovative financing mechanisms and invest in infrastructure development, such as the construction of ponds, irrigation systems, and storage facilities.

Despite these challenges, the adoption of IAA culture systems has the potential to provide numerous socio-economic and environmental co-benefits. For example, IAA culture systems can increase food security by providing a diverse range of crops and aquatic species, and they can also generate additional income for smallholder farmers by selling surplus produce. In addition, IAA culture systems can help to reduce the environmental impacts of traditional monoculture farming practices, such as soil degradation and water pollution, by using natural processes to maintain soil fertility and water quality. There is also evidence to suggest that the adoption of IAA culture systems can have positive spillover effects on the wider community. For example, a study conducted in India found that adopting IAA culture systems was associated with improved access to education and health care, as well as increased social cohesion and community empowerment (Sahoo et al., 2019). These findings suggest that adopting IAA culture systems can have far-reaching positive impacts on the social and economic development of rural communities.

IAA culture systems have the potential to significantly reduce GHGE and improve food security in Kenya and other developing countries. However, some constraints and challenges must be addressed to effectively scale this technology. These include a lack of knowledge and expertise among value chain actors, a lack of infrastructure and financing options, and the need to overcome cultural and social barriers to adoption. Despite these challenges, the adoption of IAA culture systems can provide numerous socio-economic and environmental co-benefits, as well as positive spillover effects on the wider community.

Rice-fish culture system

A rice-fish system is a rice field or rice field/pond complex in which fish are farmed alongside or alternately with rice (Obiero et al., 2022). Fish may be intentionally stocked (fish culture), may enter fields naturally when flooding occurs (rice field fisheries), or a combination of the two. Due to Kenya's limited land and water resources, rice-fish cultivation systems are expected to maximize land and water resources while maintaining ecological balance and economic advantage (Suloma & Ogata, 2014). Furthermore, dike farming allows farmers to meet the nutritional needs of their families by providing surplus food and a chance to earn extra money (fish and rice).

Research shows that rice-only fields require more fertilizer than rice-fish fields (Halwart & Gupta, 2004). Furthermore, methane emissions from rice-fish agriculture systems are 34.6 percent lower than those from rice monoculture cultivation systems (Yang et al., 2022). This is noteworthy since methane has a 25-fold higher global warming potential (GWP) than carbon dioxide. Aquatic organisms, particularly bottom feeders, disrupt the soil layers by moving or hunting for food, influencing the CH_4 generation processes. Aquatic organisms may enhance diluted oxygen in field water and soil, shifting anaerobic digestion to aerobic digestion and assisting in reducing CH_4 emissions (Dash & Mallikarjuna, 2022). Furthermore, herbivorous fish in rice fields devour weeds (absorb 30% of the weed biomass) and pests, thus lowering maintenance costs while reducing feed requirements and the use of pesticides. The remainder of the weeds is expelled and contributes to soil fertility by releasing nutrients that would otherwise be trapped in weeds (Halwart & Gupta, 2004).

Although this technique of rice cultivation requires a larger financial investment, fish production produces additional income while reducing labor and material costs. It also helps with on-farm water management and revenue diversification (Bosma et al., 2012). The approach may also boost rice and fish yields while reducing the requirement for fertilizer and pesticides, so eliminating related emissions. Fish yields from integration can range from 1.5 to 174 kg/ha/season, depending on the kind of rice-fish system, species present, and management used (Obiero et al., 2022). The ecological soundness of rice-fish systems, when combined with the beauty of the surrounding area, may also encourage eco-tourism, resulting in the diversification of local livelihoods (Koohafkan & Altieri, 2011).

Rice-fish culture has been experimented with at the Kabonyo Fisheries Station in Kisumu County. The experiment was conducted for 98 days to investigate the interactions between fish- and rice-growth performance in rice paddies (Rasowo et al., 2008). There was significantly less incidence of stem-borers in rice-fish polyculture compared to rice monoculture. Rice-fish polyculture had a significantly higher rice yield than rice monoculture. The rice-fish polyculture significantly improved the performance of rice compared to the rice monoculture (Rasowo et al., 2008). Although the rice-fish culture system has successfully been demonstrated, it has so far received a low adoption rate due to farmers' lack of awareness and technical knowledge. Many farmers are not aware of the potential benefits of integrated rice-fish culture. Experts need to transfer this knowledge to farmers and perform more on-farm trials in various regions to demonstrate the benefits of integrating rice systems with fish. For instance, the technology can be scaled in the area of Ahero, Kisumu County, which is well known for rice farming. The rice schemes in the area produce rice worth KES 1.4 billion per season (six months). Integration using herbivorous fish such as Nile tilapia can double the output, improving farmers' livelihoods. This may also reduce the high losses experienced, especially during floods. It, therefore, cushions farmers against possible losses associated with such events. This technology also provides a great opportunity for the youth and women within the county since it incorporates fish into the rice value chain, thus expanding it. With expansion come opportunities for various actors and players. The expansion also enhances both food and nutrition security by introducing fish (protein) into the food systems, thus increasing dietary diversity. This is supported by the fact that the community around the scheme are traditionally fish eaters, with some already practicing fish farming in conventional fishponds.

The technology can reduce emissions associated with conventional fish production systems, especially because the waste (if the fish are fed) is utilized by the rice plants within the fields. The climatic conditions around Kisumu County are conducive for fish and rice and will enhance the productivity of the systems.

Fish-poultry-livestock culture

Integrated poultry-fish farming is viewed as one of the ways to reduce fish feed costs and the cost of fertilizing fishponds (Ogello et al., 2013). The poultry industry naturally has an advantage over other animal sectors due to its minimal ability to cause global warming (Costa, 2009). Compared to other meat-producing animals, chickens create very little phosphate and carbon dioxide and no methane (FAO, 2010). Additionally, chicken is the most affordable domestic animal food, especially in Sub-Saharan Africa (FAO, 2010). Therefore, raising poultry for meat and eggs is the most environmentally benign way to produce animal protein (Mengesha, 2011). Broilers and layers can be combined with fish aquaculture by erecting poultry shelters above ponds, which minimizes transportation costs and increases land utilization. This eventually boosts economic benefits and reduces production costs/costs of inputs like fertilizer and feed (Gabriel et al., 2007). It has been demonstrated that fish raised in ponds fed with chicken excrement are more nutritionally rich than fish raised on pelleted feed (Hu & Yang, 1984).

Figure 12. Poultry-fish farming.

Currently, only state-owned organizations like the KMFRI in Sangoro and Sagana engage in the fish-poultry culture in Kenya. Nevertheless, farmers all around the nation have welcomed the technology even though they mostly utilize chicken excrement to fertilize ponds, with some areas recording spectacular results (Ogello et al., 2013).

Livestock by-products are used directly as fertilizers in fishponds in a livestock-fish integration system to promote the growth of natural food sources. In this integration, cattle may be allowed to graze on the pond banks and thus release their wastes on the banks, which may be collected or washed directly into the ponds (Schroeder, 1980), promoting the growth of natural fish feed materials while at the same time preventing emissions from animal waste degradation. The integration encourages environmental sustainability, labor cost reduction, and land conservation. Additionally, it boosts economic advantages, output, and food security (Prein et al., 1998: Ogello et al., 2013). According to an earlier study conducted by van Dam et al. (2006), on the Kenyan side of the Lake Victoria Basin, *O. Niloticus* fishponds fed with cow dung produce an average output of 200 kg ha^{-1} $year^{-1}$. This shows that livestock-fish integration is a viable technology that can be upscaled in the Lake Victoria region as a low-emission technology. The IAA system produces about 2.8–3.7 kg of CO_2 equivalent/kg of fish produced being emitted (Table 3).

Significant potential exists for boosting the production of high-value animal proteins, generating employment possibilities, and enhancing the socio-economic circumstances of rural smallholder farmers through the integration of fish, poultry, pig, and cattle cultures. An integrated farming system's output from one subsystem, which would otherwise go to waste, becomes an input for another subsystem, improving the efficiency of producing desired goods from the land and water under a farmer's control and increasing farmers' food and financial security. Many farmers in densely populated areas have employed integrated aquaculture systems as a better way to utilize available space and maximize farm profits.

IAA technologies have a high potential in Kisumu County, and the chances of adoption and upscaling are very high. This is especially because fish farming is already happening within the county, and many farmers are also raising other farm animals on their farms. The only modification required is integrating these farming systems into the fish production units to enhance resource use efficiency while increasing food and nutrition security and enhancing profitability. These are the greatest socio-economic benefits associated with technology. The technology has a high potential of reducing GHGE because the wastes from the animal production units are used in the fish production system thus reducing the possibilities of environmental pollution. The estimated quantities of GHGE from the different integrated aquaculture systems are summarized in Table 2.

Table 2. GHG and yield estimates from integrated aquaculture systems.

Form of Integrated Aquaculture	GHGE (kg CO_2e per kg of production)	Total Fish Yield (kg/ha/year)	Integration	Source
Land-based closed-system recirculating aquaculture	3.7–6.9	20,000–40,000	N/A	Muir & Tacon, 2012
Land-based pond aquaculture	2.3–3.3	5,000–20,000	N/A	Muir & Tacon, 2012
Offshore cage aquaculture	1.4–2.4	10,000–30,000	N/A	Muir & Tacon, 2012
Onshore pond aquaculture	1.2–2.2	5,000–20,000	N/A	Muir & Tacon, 2012
Coastal cage aquaculture	1.1–1.7	10,000–30,000	N/A	Muir & Tacon, 2012
IMTA	0.7–1.0	5,000–20,000	Seaweed, shellfish, fish	Muir & Tacon, 2012 Bartley et al., 2013
Integrated fish and crop production	Variable	Variable	Fish, crops (e.g. rice, maize)	Pathak et al., 2013 De Silva & Eddleston, 2002
Integrated fish and livestock production	Variable	Variable	Fish, pig, cattle, chicken	Pathak et al., 2013

Source: *Bartley et al. (2013); De Silva & Eddleston (2002); Muir & Tacon (2012); Pathak et al. (2013)*

4.3.6. In-pond raceway system

The in-pond raceway system (IPRS) is a promising aquaculture technology that has gained increasing attention in recent years for its potential to reduce GHGE, as well as its socio-economic and environmental co-benefits. In this essay, we will explore the constraints, challenges, and opportunities faced by different value chain actors in scaling the IPRS technology in Kenya, as well as its potential spillover effects.

First, it is important to understand the basics of IPRS technology and how it operates. The IPRS is a type of aquaculture system that involves the cultivation of fish in ponds, which are equipped with a series of interconnected raceways. These raceways allow water to flow continuously through the pond, providing oxygen and nutrients to the fish and maintaining the proper balance of the ecosystem. This system has several advantages over traditional pond-based aquaculture, including higher yields, better water quality, and more efficient use of resources (García-Lopez et al., 2014).

One of the key benefits of the IPRS is its potential to reduce GHGE. Aquaculture is a significant source of GHGE, mainly due to the use of feed, which is typically derived from crops that require energy-intensive production processes (Tacon & Metian, 2008). The IPRS can help to reduce GHGE by increasing the efficiency of feed utilization and reducing the amount of feed needed to produce a given quantity of fish (García-Lopez et al., 2014). Additionally, the continuous water flow in the IPRS helps minimize the release of GHGs such as methane and nitrous oxide, commonly emitted from pond-based aquaculture systems (Dharmaputra et al., 2016).

However, scaling the IPRS technology in Kenya presents some challenges and constraints that must be addressed. One of the main challenges is the lack of infrastructure and expertise. Many small-scale farmers in Kenya lack the necessary infrastructure and equipment to implement the IPRS, and there is a lack of trained personnel who can provide technical support and guidance (Mwangi et al., 2016). This makes it difficult for small-scale farmers to adopt and scale the technology. Another constraint is the high initial investment costs associated with the IPRS. The construction and maintenance of the raceways and other infrastructure required for the IPRS can be expensive, especially for small-scale farmers who may not have access to financing or capital (Mwangi et al., 2016). This can make it difficult for small-scale farmers to adopt the technology, even if it can potentially increase their yields and profits.

Despite these challenges, there are also some opportunities and co-benefits associated with scaling the IPRS in Kenya. One of the main benefits is the potential for increased food security and economic growth. The IPRS has the potential to increase fish production and improve the livelihoods of small-scale farmers, particularly in rural areas where aquaculture is a significant source of income and employment (Mwangi et al., 2016). Additionally, the IPRS can help to reduce the reliance on imported fish, which is a major contributor to the country's food insecurity (Mwangi et al., 2016).

There are also some environmental co-benefits associated with the IPRS. The continuous water flow in the raceways helps to maintain a healthy ecosystem, which can lead to reduced water pollution and improved water quality (García-Lopez et al., 2014). Additionally, the IPRS has the potential to reduce the demand for feed, which can help to reduce the negative environmental impacts associated with feed production, such as land and water use, and GHGE (Tacon & Metian, 2008).

Scaling the IPRS technology in Kenya also has the potential to create spillover effects in other sectors. For example, the increased demand for fish produced using the IPRS could lead to the development of a more robust and sustainable fish processing industry, which could create additional jobs and economic opportunities (Mwangi et al., 2016). Additionally, the success of the IPRS in Kenya could inspire other countries in the region to adopt the technology, leading to broader economic and environmental benefits. An in-pond raceway is being tested in a tilapia farm in Ruai, on the outskirts of Nairobi. Since the demonstration site's inception, fish farmers and government agencies have been eager to learn about its design, advantages, and anticipated harvest biomass.

Figure 13. In-pond raceways.

Source: *Brown et al. (2010)*

The IPRS can potentially reduce GHGE, improve food security and economic growth, and provide environmental co-benefits in Kenya. However, scaling the technology has challenges and constraints, including a lack of infrastructure and expertise, high initial investment costs, and limited access to financing. To overcome these challenges and realize the full potential of the IPRS, it will be important to develop policies and initiatives that support the adoption and scaling of the technology, particularly for small-scale farmers. Additionally, further research is needed to understand better the potential socio-economic and environmental impacts of the IPRS in different contexts and to identify best practices for its successful implementation.

4.3.7. Finger Pond technology

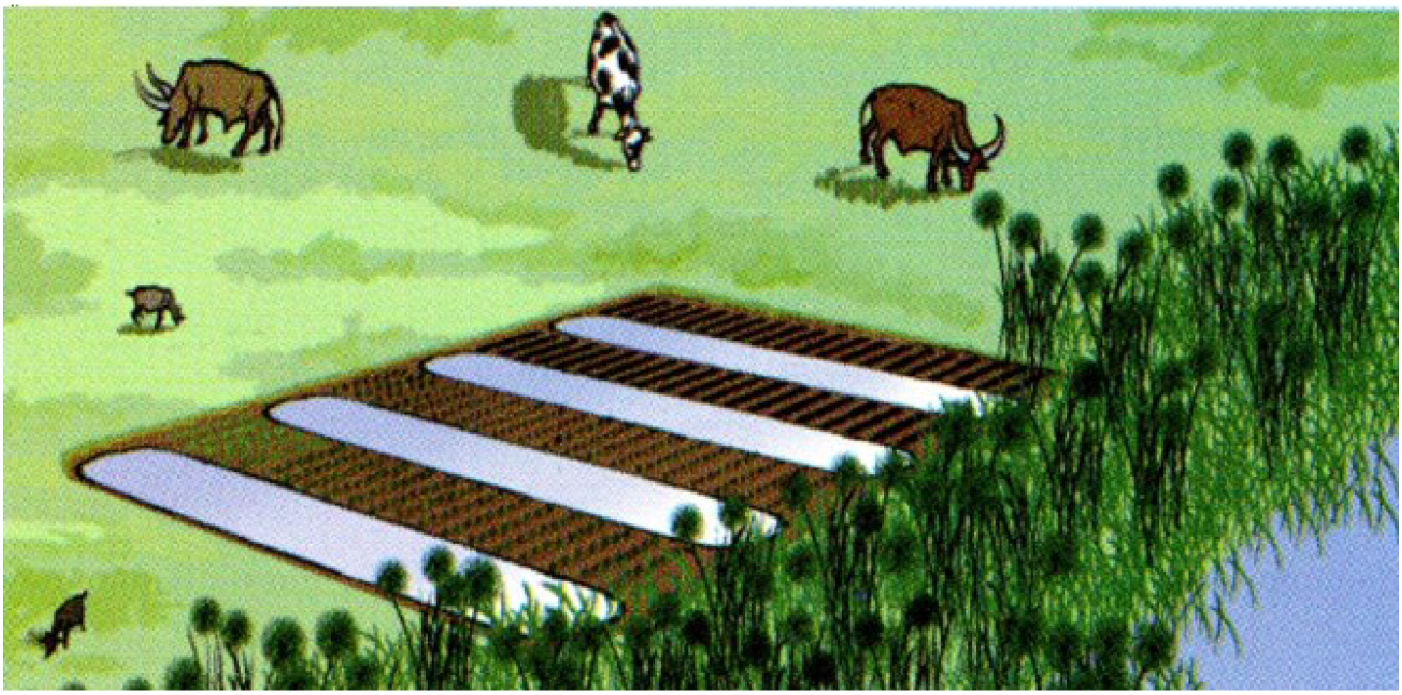
The Finger Pond technology is a low-cost, sustainable method for irrigation and water management that has the potential to reduce GHGE significantly in the agriculture sector. This technology involves the construction of small, shallow ponds that collect and store rainwater, which can then be used to irrigate crops and fish production during dry periods.

One of the main constraints value chain actors face in scaling the finger-pond technology is the lack of awareness and understanding among farmers and other stakeholders. Many farmers are not familiar with the benefits of the technology and may be hesitant to adopt it. In addition, there may be a lack of support from the government and other institutions in promoting the technology and limited access to financing and technical assistance for implementation. Another challenge is the need for adequate infrastructure and resources to support the construction and maintenance of the ponds. This includes access to materials such as clay, sand, and stones, as well as labor and equipment for construction. There may also be issues with land availability, as the ponds require a certain amount of space to be effective. Despite these constraints, the finger-pond technology has the potential to bring significant socio-economic and environmental co-benefits. One of the main advantages is reducing GHGE using more efficient irrigation practices. By using rainwater instead of fossil fuel-powered pumps, the technology can help reduce agriculture's carbon footprint. In addition, the ponds can serve as a water source for livestock, improving animal health and productivity.

There are also spillover effects from scaling the finger-pond technology, including improved soil health and fertility, increased crop yields, and increased farmer income. In addition, the technology can help to alleviate water scarcity and drought, which are major challenges in many parts of Kenya. To further understand the benefits and challenges of the finger-pond technology, it is helpful to examine specific case studies. For example, a study in Kiambu County found that implementing finger ponds resulted in a 50 percent reduction in water use for irrigation and increased crop yields and income for farmers (Mwangi et al., 2018). Another study in Machakos County found that finger ponds led to a percent reduction in GHGE, improved soil health, and increased crop yields (Mulinge et al., 2020).

The finger-pond technology has the potential to significantly reduce GHGE in the agriculture sector while also bringing a range of socio-economic and environmental co-benefits. However, some constraints and challenges must be addressed to scale the technology effectively. Further research and case studies are needed to understand the benefits and challenges of the finger-pond technology fully and to develop strategies for promoting its adoption in Kenya and other countries.

Figure 14. Layout of finger-pond technology in Siaya County, Kenya.



The technology can easily be adopted and upscaled in several areas of Kisumu County that are prone to flooding. Some of these include the areas at the mouths of rivers Nyando, Awach, and Sondu Miriu, especially in the plains of Kano and Nyakach. The self-stocking nature of the technology reduces the carbon emissions associated with the hatchery production of fingerlings. Additionally, since floodwater is the main water source in the ponds, the emissions associated with pumping are also reduced or eliminated. The socio-economic benefits of this technology are using the flood menace as a food production resource, enhancing food production within the communities. Planting vegetables in the finger gardens between ponds enhances dietary diversity and the venture's profitability. The possible spillover effect of the technology could be the possibility of endangered or threatened fish species coming into the ponds with the floodwater. This can have a negative effect on the associated aquatic habitats. This can also be true for other non-fish species like frogs, reptiles, and insects. This can be addressed by sensitizing the farmers on the importance of returning such species to the wild as a conservation measure. One of the hindrances to adoption is the unpredictability of flood events occasioned by climate change. This can make these systems unproductive and difficult to maintain. This can be overcome by redesigning the ponds into a multipurpose design that can be used both as finger ponds (during floods) and conventional fishponds (during dry seasons). This can ensure year-round fish production from these systems.

4.3.8. Precision farming

Precision farming in aquaculture uses advanced technologies and techniques to optimize production and resource use in aquaculture systems. This includes using sensors and other monitoring devices to collect data on water quality, temperature, and other key variables, as well as using precision feeding systems and automated feeding systems to optimize feed inputs and reduce waste. Precision farming in aquaculture has gained increasing attention in recent years as a means to enhance productivity, reduce GHGE, and minimize negative environmental impacts. Although precision farming has demonstrated promise in other agricultural sectors, its adoption in aquaculture has been more limited, particularly in the Kenyan context.

One of the main potential benefits of precision farming in aquaculture is its ability to reduce GHGE. Aquaculture is a significant source of GHGE, primarily due to the production of feed and the release of methane and nitrous oxide from manure and wastewater. Precision farming can potentially reduce GHGE by improving FCRs, reducing feed waste, and optimizing manure management practices. For example, a study conducted in Norway found that precision feeding systems could reduce GHGE from salmon aquaculture by up to 15% (Espe et al., 2015).

However, the adoption of precision farming in aquaculture has been limited in the Kenyan context, partly due to the high cost of technology and the lack of infrastructure and expertise. There is a need for greater investment in research and development to make precision farming technologies more accessible and affordable and to build capacity and knowledge among farmers and other stakeholders. In addition to the challenges and constraints in technology adoption and upscaling, there are also potential socio-economic and environmental co-benefits of precision farming in aquaculture. For example, precision farming can improve the efficiency and productivity of aquaculture operations, resulting in increased income and economic development for farmers and other stakeholders. Precision farming can also help minimize negative environmental impacts, such as water pollution and habitat destruction, through sustainable practices and technologies.

Precision farming in aquaculture also has potential spillover effects, including the potential to enhance food security and improve the quality and safety of seafood products. In the Kenyan context, precision farming in aquaculture has the potential to contribute to developing a sustainable and resilient seafood sector, which can provide significant economic, social, and environmental benefits. Overall, precision farming in aquaculture has the potential to reduce GHGE, enhance productivity and resource use efficiency, and minimize negative environmental impacts.

4.3.9. Fish post-harvest processing, value addition, and distribution

Post-harvest processing and distribution, which refers to the activities that occur after aquatic organisms are harvested from the farm, can have a significant impact on GHGE in the aquaculture sector. One of the main sources of GHGE in the aquaculture sector is the use of fossil fuels for transportation and refrigeration during post-harvest processing and distribution (Tacon & Median, 2008). In Kenya, most fish and other aquatic products are transported by road, which is energy-intensive and contributes to GHGE (FAO, 2018). To address this issue, there is potential to adopt and scale up technologies such as electric vehicles and renewable energy sources for transportation and refrigeration. However, there are several challenges and constraints to the adoption and scaling up of these technologies in the Kenyan context. One challenge is the high upfront costs of purchasing and installing these technologies, which may be a barrier for small and medium-sized enterprises (SMEs) in the aquaculture sector. In addition, the lack of infrastructure and access to finance may further hinder the adoption and scaling up of these technologies (FAO, 2018). Another constraint is the lack of technical expertise and capacity to operate and maintain these technologies, which may require training and capacity building for aquaculture stakeholders (Tacon & Metian, 2008).

Despite these challenges, there are potential socio-economic and environmental co-benefits of adopting and scaling up technologies that can reduce GHGE in post-harvest processing and distribution in the Kenyan aquaculture sector. For example, the use of electric vehicles and renewable energy sources can reduce the reliance on fossil fuels, which can lead to cost savings for aquaculture businesses and contribute to energy security in the country (FAO, 2018). In addition, the adoption of these technologies can also have positive spillover effects on the wider economy, including the creation of jobs and the development of a green energy industry (Tacon & Metian, 2008).

To address these challenges and facilitate the adoption and scaling up of GHG-reducing technologies in the Kenyan aquaculture sector, some policy interventions can be considered. One option is the development of financial incentives and subsidies, such as grants or low-interest loans, to support the adoption and scaling up of these technologies by SMEs in the sector. In addition, the provision of technical assistance and capacity-building programs can help to build the expertise and skills needed to operate and maintain these technologies effectively.

The potential environmental co-benefits of reducing GHGE in the aquaculture sector are also significant. In addition to mitigating climate change, the adoption of technologies that can reduce GHGE can also contribute to the conservation of natural resources and the improvement of air and water quality (Tacon & Metian, 2008). For example, the use of renewable energy sources can reduce air pollution and the negative impacts of extractive industries, while the reduction in transportation emissions can improve water quality in aquatic environments (FAO, 2018). Another option is the implementation of regulatory measures, such as emissions standards or incentives for the adoption of renewable energy sources, to encourage the transition to more sustainable practices in post-harvest processing and distribution. The establishment of partnerships and collaborations between government, industry, and other stakeholders can also facilitate the transfer of knowledge and technology and help to overcome barriers to adoption and scaling up (FAO, 2018). It is also important to consider the potential social and economic impacts of these policy interventions, particularly on small-scale and informal aquaculture businesses. To ensure that these interventions are effective and equitable, it is important to engage and consult with local communities and stakeholders to understand their needs and concerns and to design interventions that are appropriate and inclusive (FAO, 2018).

Post-harvest processing and distribution in the Kenyan aquaculture sector have the potential to contribute significantly to GHGE, but there are also opportunities to adopt and scale up technologies that can reduce these emissions and provide co-benefits. To facilitate the adoption and scaling up of these technologies, policy interventions such as financial incentives, capacity-building programs, regulatory measures, and partnerships and collaborations can be considered. It is also important to engage with and consult with local communities and stakeholders to ensure that these interventions are effective, equitable, and inclusive.

Improved Fish smoking Kiln

Traditional kilns have many drawbacks, such as poor capacity and inefficient fuel utilization (firewood), which contribute to forest loss. Furthermore, the health risk posed by its operation due to smoke damages the operator's eyes and lungs. Fingers are burned as a result of excessive exposure to direct heat. Furthermore, the technique is time-consuming, and low-quality items were generated. Molds thrive in poor-quality smoked fish due to inadequate fish smoking. This involves the development of enhanced ovens and kilns for the effective and efficient exploitation of the various fish species in our bodies of water.

The smoking kiln is developed and built using readily available materials. It is rectangular and has stainless steel inside lining. The stainless-steel sheet is lagged with fiberglass and coated with another stainless-steel coating. The double wall construction with insulating material is supplied to preserve heat energy by limiting heat loss, providing a comfortable working environment for the user, and improving the overall performance of the kiln. The kiln includes four six-tray shelves constructed of stainless wire gauge and appropriately completed edge fine wire mesh to prevent dried fish items from dropping through and to allow them to be hauled out without tilting and to simply slide in and out. The drying capacity of fish varies according to species and thickness. The kiln includes a double-wing door that is easily opened and closed. When closed, the door glides effortlessly. This improves air and heat circulation within the kiln chamber as well as moisture removal from the dry product. The kiln has a chimney at the top that serves as an outflow for the moisture-laden air. For smoking and drying, the kiln can use sawdust, charcoal, or firewood.

Figure 15. Improved fish smoking kiln (courtesy of Dr. Domitila Kyule of the KMFRI).

4.3.10. Disease reduction strategies

Biosecurity

Biosecurity techniques are those that reduce the danger of introducing and transmitting infectious illnesses in a facility (Mugimba et al., 2021). Internal (people, equipment, and fish husbandry) and external biosecurity risks are significant (water supply, egg, fish, feed, pests, deliveries, and visitors). Through proper husbandry, pathogen management, and personnel management, biosecurity attempts to get healthy stocks and optimize their health and immunity (Ragasa et al., 2022). The "prevention first" philosophy in fish health management and practices aids in the reduction of illness occurrence and severity in aquaculture (Yang et al., 2020). This is mostly accomplished by developing early warning indicators and reaction processes to prevent the spread of fish infections.

Even though aquaculture is the fastest-growing food production sector, it is vulnerable to disease outbreaks, which can have significant economic and environmental impacts. Biosecurity measures include a range of physical, biological, and chemical interventions, such as using disease-free seed stock, implementing quarantine procedures, and disinfection equipment. Biosecurity aims to protect the health of farmed aquatic organisms and reduce the risk of disease outbreaks, which can have significant economic and environmental impacts. One key strategy for improving aquaculture biosecurity is using closed-loop systems, which recycle water and nutrients and reduce the risk of disease transmission. These systems can also improve water quality and reduce the environmental impact of aquaculture, which can have a range of co-benefits. For example, the use of closed-loop systems can reduce the reliance on fresh water and the associated GHGE and improve aquaculture's economic viability by reducing water treatment costs.

Another important strategy for improving aquaculture biosecurity is using disease-resistant species. For example, introducing tilapia species resistant to common diseases can significantly reduce the risk of outbreaks. In addition, the use of genetically improved strains can also improve the resistance of species to disease. However, adopting these strategies can be constrained by some factors, including the availability of funding, the capacity of small-scale farmers to adopt new technologies, and the lack of infrastructure to support closed-loop systems. In addition, there may be social and cultural barriers to adopting new technologies, particularly in the Kenyan context, where traditional farming practices may be deeply entrenched.

To address these challenges and facilitate the adoption of closed-loop systems and disease-resistant species, targeted interventions may be needed, such as training programs, extension services, and financial incentives. These interventions can help small-scale farmers to adopt new technologies and improve their capacity to manage disease outbreaks. In addition to reducing disease risk, adopting closed-loop systems and disease-resistant species can also have a range of co-benefits. For example, using closed-loop systems can improve water quality and reduce the environmental impact of aquaculture, which can have positive spillover effects on other sectors, such as tourism and fishing. In addition, using disease-resistant species can improve the economic viability of aquaculture by reducing the cost of disease management.

Biosecurity is a critical aspect of aquaculture that requires the implementation of effective strategies to reduce the risk of disease outbreaks. Adopting closed-loop systems and disease-resistant species can have a range of co-benefits, including GHG reduction, improved economic viability, and improved environmental impacts. However, implementing these strategies may be constrained by various factors, including funding, capacity, and social and cultural barriers. To overcome these challenges and facilitate the adoption of biosecurity measures in the Kenyan context, targeted interventions may be needed to support small-scale farmers and improve their capacity to manage disease outbreaks.

Vaccines

Vaccines have played a crucial role in controlling infectious diseases in aquaculture, leading to increased production and profitability. In addition, the use of vaccines in aquaculture has the potential to reduce GHGE and provide socio-economic and environmental co-benefits. However, adopting vaccine technology in aquaculture faces several challenges and constraints, including issues related to upscaling and spillover effects. The main benefit of using vaccines in aquaculture is the potential to reduce GHGE. Vaccines can help reduce these GHGE by reducing the need for antimicrobials, which are often used in aquaculture to control diseases (FAO, 2018). This is because vaccines stimulate the immune system to produce antibodies that protect against diseases, reducing the need for antimicrobials and the associated GHGE.

Despite the potential benefits of using vaccines in aquaculture, several challenges and constraints hinder their adoption. A major challenge is the high cost of vaccines, which can be a barrier for small-scale farmers and limit the widespread adoption of vaccine technology (Wang et al., 2017). In addition, the lack of infrastructure and trained personnel to administer vaccines can also be a barrier to adoption (FAO, 2018). Another challenge is the lack of data on the effectiveness of vaccines in different aquaculture systems and species, which makes it difficult for farmers to make informed decisions about vaccine use (Wang et al., 2017). There is also a lack of understanding about the long-term effects of vaccine use on fish health and the environment, which can concern farmers and consumers (FAO, 2018).

Despite these challenges, several case studies demonstrate the potential of vaccines to provide socio-economic and environmental co-benefits in the Kenyan context. For example, a study in Lake Victoria found that the use of vaccines reduced the incidence of diseases in tilapia, leading to increased production and profitability for farmers (Oketch et al., 2010). In addition, the use of vaccines can help reduce the negative environmental impacts of aquaculture, such as the release of untreated waste and the overuse of antimicrobials, which can negatively impact the surrounding ecosystem (FAO, 2018).

It is important to consider the potential spillover effects of vaccine use in aquaculture, particularly in the context of Kenya, where there is a high degree of interaction between wild and farmed fish (FAO, 2018). There is a risk that vaccines used in aquaculture could spill over into wild fish populations, potentially affecting their health and the wider ecosystem. This risk can be mitigated by developing targeted vaccines specific to farmed species and implementing measures to prevent the release of vaccinated fish into the wild (FAO, 2018).

To address these challenges and facilitate the adoption of vaccine technology in aquaculture, it will be important to invest in research to improve our understanding of the effectiveness and long-term impacts of vaccines in different aquaculture systems and species. This could include studies on the best practices for vaccine administration and the development of targeted vaccines that are specific to farmed species. In addition, it will be important to invest in infrastructure and training programs to support the widespread adoption of vaccines in the aquaculture sector. By addressing the challenges and constraints to vaccine adoption, it is possible to support the sustainable development of the aquaculture sector in Kenya and contribute to the global effort to address climate change.

4.3.11. Species choice and diversification

The choice of species for aquaculture and the diversification of species can have significant implications for the success and sustainability of the industry. One of the key considerations in species choice and diversification for aquaculture is the GHGE associated with different species and production systems. For example, a study conducted in Norway found that the GHGE per unit of production were significantly lower for shellfish aquaculture compared to finfish aquaculture (Bøhn et al., 2014). In addition, the use of feed derived from alternative protein sources, such as insects or microalgae, can further reduce GHGE in aquaculture (Tacon & Metian, 2008).

In Kenya, the most commonly cultured species are tilapia and catfish, with a smaller industry for shrimp and other species (FAO, 2021). However, there is potential for the diversification of species in aquaculture in Kenya, including the cultivation of indigenous species that may have lower GHGE and be more adapted to local conditions (Mishra et al., 2018). For example, the African catfish (*Clarias gariepinus*) has been shown to have a lower FCR and GHGE per unit of production compared to other commonly cultured species, making it a potentially more sustainable option for aquaculture in Kenya (Odong et al., 2014).

One of the major challenges to the adoption of new technologies and species in aquaculture in Kenya is the lack of infrastructure and technical capacity. Many small-scale aquaculture operations in Kenya are reliant on traditional and low-tech production systems, which can limit the potential for GHG reduction and other benefits (FAO, 2021). In addition, the high costs and lack of access to credit can be barriers to the adoption of more sustainable technologies and production systems (Mishra et al., 2018). In addition, well-managed aquaculture can have a positive impact on the environment, including the restoration of degraded habitats and the provision of ecosystem services (Mishra et al., 2018). However, it is important to consider the potential spillover effects of aquaculture on other sectors and the environment. For example, the expansion of aquaculture can lead to the displacement of traditional fishing communities and the competition for resources such as water and land

(Mishra et al., 2018). In addition, the introduction of non-native species for aquaculture can have negative impacts on native biodiversity and ecosystem functioning (FAO, 2021).

The choice of species and the diversification of species in aquaculture in Kenya has the potential to contribute to GHG reduction and provide socio-economic and environmental co-benefits. However, there are several challenges and constraints to the adoption of new technologies and the expansion of aquaculture in Kenya, including the lack of infrastructure and technical capacity, as well as potential spillover effects on other sectors and the environment. By carefully evaluating the potential impacts of different species and production systems and taking a holistic approach to the development of the industry, it may be possible to achieve significant GHG reductions and other benefits through aquaculture in Kenya.

4.3.12. Fish feeds and feed management

Fish feeds and feed management in aquaculture play a crucial role in the growth and health of farmed fish, as well as in the sustainability of the aquaculture industry. In the Kenyan context, where aquaculture is a significant contributor to food security and economic development, understanding the challenges and constraints in adopting sustainable fish feed technologies, and the potential co-benefits and spillover effects of such adoption is essential for reducing GHGE and minimizing negative impacts on the environment. One of the major challenges in adopting sustainable fish feed technologies in Kenya is the high cost and limited availability of raw materials for feed production. Most fish feeds in Kenya are currently produced using imported raw materials, such as soybean meal and fishmeal, which can be expensive and subject to price fluctuations. In addition, the availability of these raw materials is often constrained by factors such as trade policies and global demand.

To address these challenges and reduce GHGE in the aquaculture industry, there is a need to shift toward using locally available alternative protein sources in fish feed formulation. For example, research has shown that using plant-based protein sources, such as legumes and oilseeds, can significantly reduce GHGE in fish feed production (Stadtlander et al., 2021). In Kenya, there is potential to utilize locally grown crops, such as pigeon peas and groundnuts, as alternative protein sources for fish feed (Muchemi et al., 2015). However, the adoption of these alternative protein sources is often constrained by a lack of knowledge and expertise among feed manufacturers and farmers and the need for suitable processing technologies and infrastructure.

In addition to technological challenges, socio-economic and environmental co-benefits, and spillover effects to consider in adopting sustainable fish feed technologies in Kenya. For example, using locally grown protein sources can increase the demand for smallholder crops, leading to economic benefits for local farmers and communities (Naraine, 2022). At the same time, adopting sustainable fish feed technologies can also have positive environmental impacts, such as reduced water pollution and improved soil fertility (Bashir et al., 2020).

Despite these challenges and constraints, there are ongoing efforts in Kenya to promote the adoption of sustainable fish feed technologies and practices. For instance, the KMFRI has been working with feed manufacturers and farmers to develop and test alternative protein sources for fish feed and improve feed production and management practices (Muchemi et al., 2015). In addition, the GoK has implemented policies and programs, such as the Livestock Sector Development Strategy, which aims to promote adopting sustainable practices in the aquaculture industry (Government of Kenya, 2017). Adopting sustainable fish feed technologies and practices in the Kenyan aquaculture industry is essential for reducing GHGE, minimizing negative environmental impacts, and maximizing socio-economic benefits.

4.3.13. Novel fish feed alternatives

Biofloc Technology

Biofloc aquaculture technology is a method of cultivating aquatic animals, such as fish, shrimp, and other species, using a system of interconnected tanks or ponds that are fed with organic waste material. This waste material is converted into biofloc, a dense, nutrient-rich biomass that provides a food source for aquatic animals and helps to maintain water quality. One of the primary benefits of biofloc aquaculture technology is its ability to reduce GHGE, including carbon dioxide (CO_2). This is because biofloc systems can effectively recycle organic waste material, which would otherwise decompose and release GHGs into the atmosphere (Ogello et al., 2021). One study found that a biofloc system produces about 1.5–2.5 kg of CO_2 equivalent/kg of fish produced being emitted (Table 3) and can reduce GHGE by as much as 70% compared to traditional aquaculture systems (Ekasari, 2014). This reduction is due in part to the fact that biofloc systems do not require the use of synthetic fertilizers, which are a significant source of GHGE in traditional agriculture (FAO, 2006). Additionally, biofloc systems can help to reduce the amount of organic waste material that is disposed of in landfills, which also contributes to GHGE (Marín-Beltrán et al., 2022).

In addition to reducing GHGE, biofloc aquaculture technology has several other environmental benefits. For example, it can help to reduce the impact of aquaculture on wild fish populations by using the locally sourced feed, rather than relying on fishmeal and fish oil (FAO, 2011). Biofloc systems can also be used to treat and recycle wastewater, helping to reduce water pollution and improve water quality (Martinez-Cordova et al., 2022). Several case studies demonstrate the effectiveness of biofloc aquaculture technology in reducing GHGE and improving environmental sustainability. In Thailand, the Biofloc Training Center is promoting the adoption of biofloc systems. The center has trained over 1,000 farmers in the use of biofloc systems and has helped to reduce GHGE and improve the environmental sustainability of aquaculture in the region (FAO, 2011).

In recent years, there has been increasing interest in the use of biofloc technology (BFT) in aquaculture as a means of reducing GHGE and improving the sustainability of the sector (Morais et al., 2017). Despite the potential benefits of BFT in aquaculture, there are several challenges and constraints to its adoption and upscaling (Ndirangu et al., 2019). One significant constraint is the lack of technical expertise and knowledge on the implementation and management of BFT systems, which can hinder the uptake of this technology in the sector (Morais et al., 2017). There is also a lack of research on the economic feasibility of BFT in aquaculture, particularly in the Kenyan context, which can discourage potential adopters (Ndirangu et al., 2019). In addition, the initial investment required to set up a BFT system can be prohibitively expensive for many farmers, particularly smallholder farmers who make up a significant portion of the aquaculture sector in Kenya (Ogello et al., 2021).

In addition to the technical and economic challenges, there are also socio-cultural constraints to the adoption of BFT in aquaculture (Ndirangu et al., 2019). For example, traditional beliefs and practices may discourage the adoption of new technologies, particularly in the conservative Kenyan fishing communities (Ogello et al., 2021). There is also a lack of awareness and understanding of BFT among many farmers, which can hinder its adoption (Ndirangu et al., 2019).

Despite these challenges, there are also significant potential socio-economic and environmental co-benefits and spillover effects associated with the adoption of BFT in aquaculture in Kenya (Ndirangu et al., 2019). For example, BFT systems can improve the efficiency of fish production, resulting in increased profits for farmers and contributing to economic development in the sector (Morais et al., 2017). BFT systems can also help to reduce the environmental impacts of aquaculture, such as water pollution and the overuse of natural resources, through the effective recycling of nutrients within the system (Kumar et al., 2016). In addition, the adoption of BFT can contribute to the development of a more sustainable and resilient food system in Kenya, particularly in the face of the increasing challenges of climate change (Ndirangu et al., 2019).

The use of BFT in aquaculture has the potential to significantly reduce GHGE and improve the sustainability of the sector (Morais et al., 2017; Kumar et al., 2016). However, the adoption of BFT in Kenya is constrained by a lack of technical expertise, economic feasibility, and socio-cultural factors. To overcome these challenges and realize the potential benefits of BFT in the Kenyan context, there is a need for greater research and knowledge sharing on the implementation and management of BFT systems (Morais et al., 2017), as well as the development of policies and incentives to support the adoption of this technology.

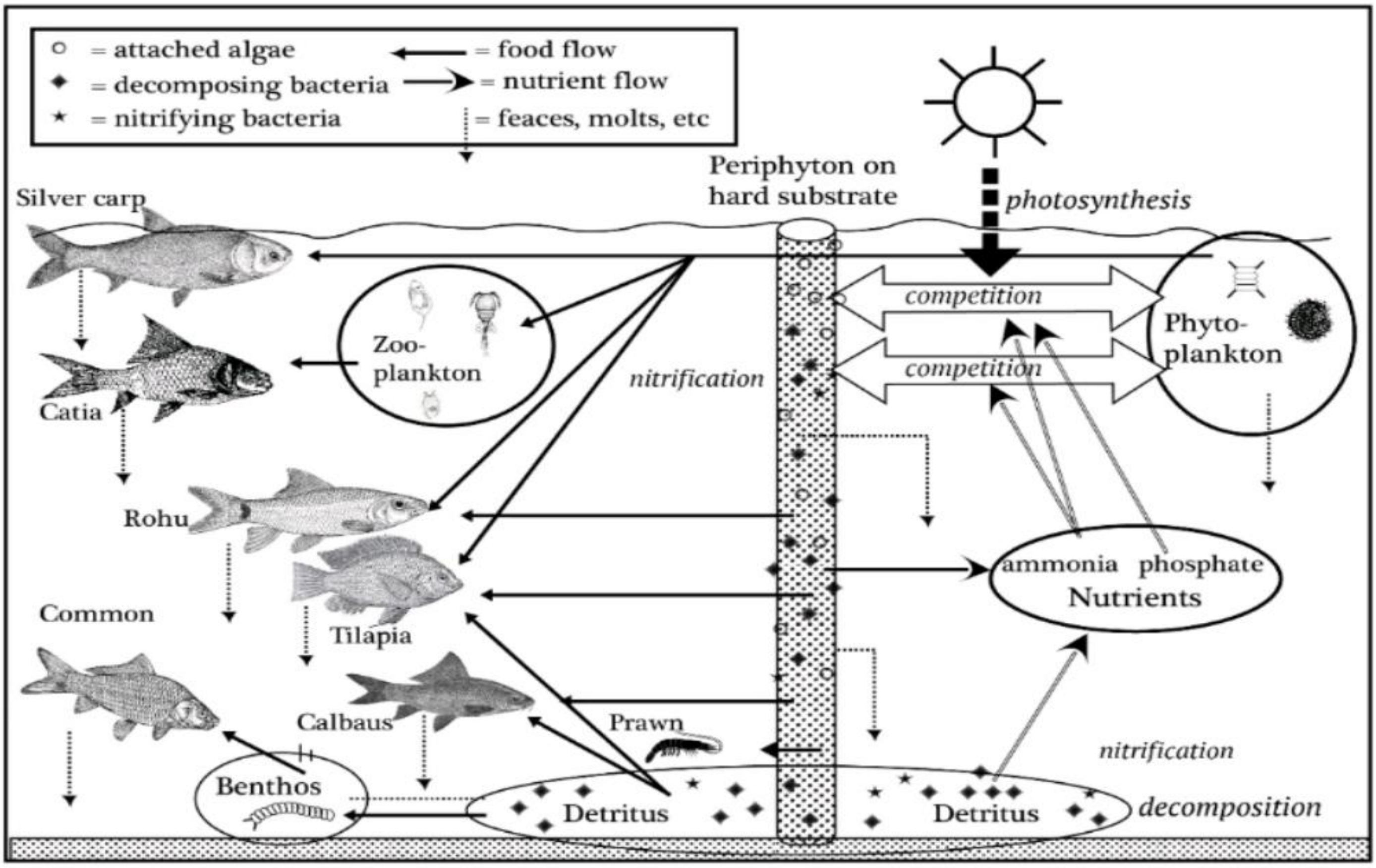
This technology can be adopted as either pond- or tank-based depending on the level of capital investment available to the farmer or investor. Under the Kenya Climate Smart Agriculture Project (KCSAP) the technology was validated and proved to be viable in Kisumu and Busia counties. The tank-based biofloc unit is at Maseno University while the pond-based units are at the Bukani Aquapark in Busia County.

Figure 16. Tank-based and pond-based biofloc technologies, Kisumu and Busia counties.

Periphyton Technology

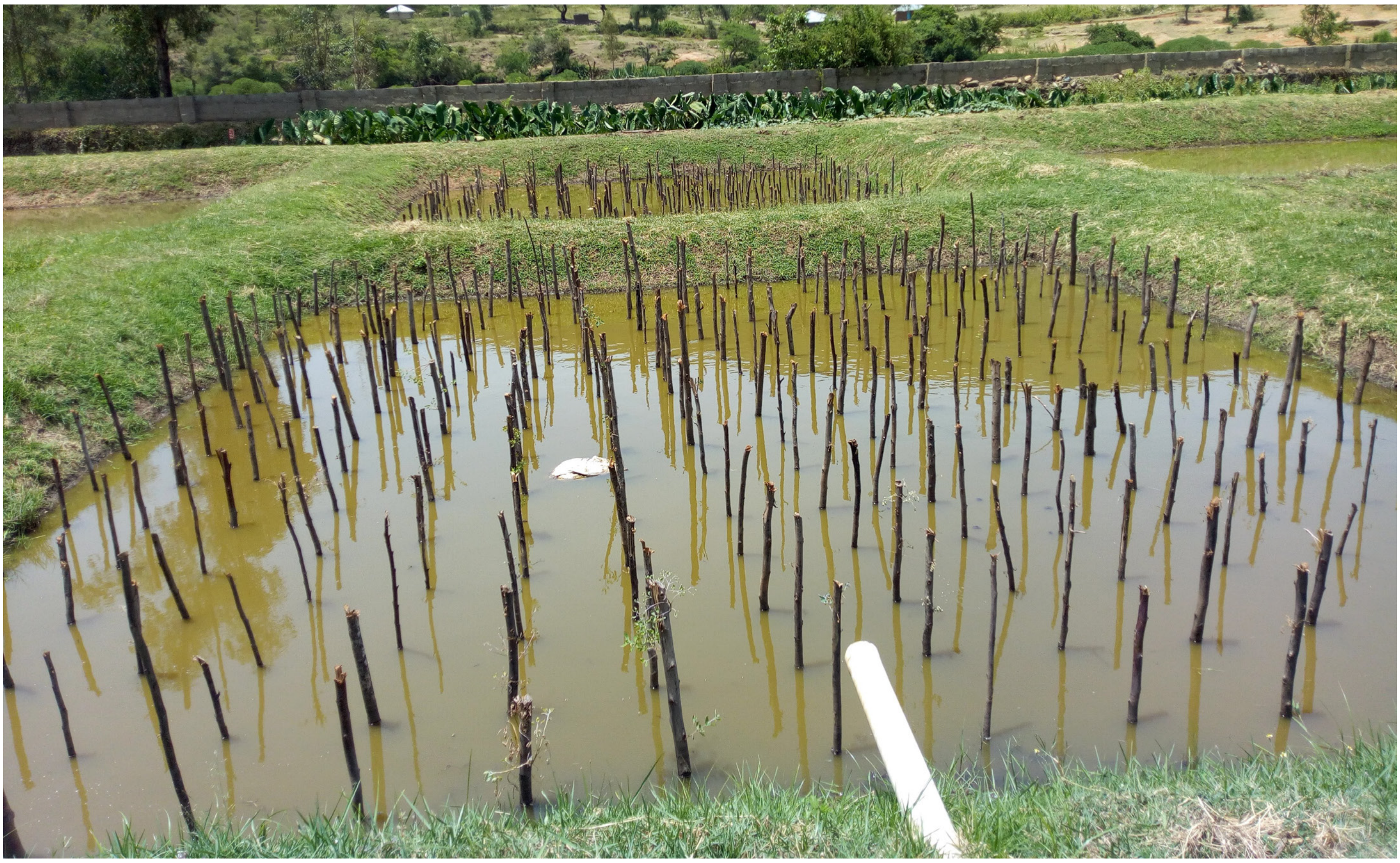
Culture systems such as periphyton technology (PPT) are considered sustainable and regenerative systems due to the generation of highly nutritious natural food materials within the system (Muthoka et al., 2021). Periphyton technology is a concept derived from traditional fishing methods in West Africa and was recently improved in Bangladesh and India by introducing substrates in the polyculture of Indian carp (Yadav et al., 2017). The principle of PPT involves using underwater substrates, e.g., bamboo sticks on which a community of bacteria, fungi, protozoa, snails, chironomids, mayflies, oligochaetes, and crustaceans colonize (Azim et al., 2002; Abwao et al., 2014). The substrates provide sufficient surface area for the growth of periphyton communities, which are direct food sources for cultured fish (Miao et al., 2021) and facilitate good water quality (Beveridge et al., 1998; Li et al., 2019). The growth of the microbial community is enhanced by maintaining a higher carbon-nitrogen ratio of about 10–15 (Ogello et al., 2018), which is best achieved through the addition of carbohydrate (molasses) or a low-protein supplemental diet (Avnimelech, 1999; Tinh et al., 2021). The periphyton community also converts total ammonia nitrogen (TAN) generated in the system to bacterial biomass by heterotrophic bacteria (Aisyah et al., 2021) or converts it into nitrite in the presence of oxygen and later into nitrate by nitrifying bacteria, allowing other microorganisms to form less harmful molecules.

Figure 17. A cross section of single bamboo stick underwater showing the food web and flow of energy and ecological interactions of microscopic flora, decomposing matter, zooplankton, and fish communities under the water mass in a periphyton aquaculture system.



Source: *Yadav et al. (2017)*

Figure 18. PPT pond for culturing Nile tilapia in the KMFRI, Sangoro, Kisumu.



PPT has the potential to reduce GHGE in aquaculture through several mechanisms. First, periphyton can be used as a natural feed source for farmed fish, reducing the need for manufactured feed that requires energy and GHG-intensive inputs. Periphyton can also be used to remove excess nutrients from the water, reducing the risk of eutrophication and associated GHGE. Finally, periphyton can be used to produce biofuel, which could potentially replace fossil fuels and reduce GHGE in the aquaculture industry. The technology produces about 1.4–2.4 kg of CO_2 equivalent/kg of fish produced (Table 3).

Despite the potential benefits of PPT, there are also several challenges and constraints to its adoption in the Kenyan context. One major challenge is the lack of knowledge and expertise in periphyton cultivation among aquaculture farmers. Training and capacity building will be necessary to help farmers understand how to cultivate and manage periphyton effectively. Additionally, there may be constraints on the availability of suitable equipment and infrastructure for periphyton cultivation, particularly in rural areas. Another challenge to adopting PPT is the lack of reliable data and research on its effectiveness in the Kenyan context. Although there have been several studies on using periphyton in aquaculture in other countries, more research is needed to understand how it can be effectively implemented in the Kenyan context. This includes studies on the most suitable periphyton species for cultivation, the optimal conditions for periphyton growth, and the potential impacts on water quality and the environment.

Despite these challenges, there is also significant potential for upscaling and spillover effects from adopting PPT in the Kenyan aquaculture industry. For example, using periphyton as a natural feed source could reduce the demand for manufactured feed, lowering costs for farmers and increasing profitability. Cultivating periphyton could create new job opportunities, particularly in rural areas, and contribute to developing local economies. PPT has the potential to significantly reduce GHGE in the Kenyan aquaculture industry while also providing socio-economic and environmental co-benefits. However, there are also challenges and constraints to its adoption, including a lack of knowledge and expertise among farmers and a lack of reliable data and research on its effectiveness in the Kenyan context.

Insect-based diets: Case of Black Soldier Fly Larvae

Black soldier fly (BSF) is an emerging technology in the field of aquaculture that has gained significant attention in recent years due to its potential to improve the sustainability of fish and other aquatic animal production. BSF refers to the use of the larvae of the *Hermetia illucens* fly, which are capable of efficiently converting organic waste into high-quality protein feed for fish and other animals.

BSF is an effective tool for mitigating GHGE in aquaculture in the context of GHG reduction. This is because the BSF larvae consume organic waste and convert it into protein feed, which can significantly reduce the amount of feed that needs to be produced using traditional methods such as plant-based feed or fishmeal. Additionally, BSF can help reduce the amount of organic waste produced in aquaculture operations, which can help offset the carbon emissions associated with the decomposition of this waste.

Despite the potential benefits of BSF in aquaculture, there are several challenges and constraints to its adoption and upscaling. One of the main challenges is the high initial cost of setting up and maintaining a BSF system, which can be a barrier for small-scale farmers and aquaculture operations. In addition, farmers and other stakeholders may lack knowledge and expertise about how to effectively use and maintain BSF systems, which can hinder their adoption and use.

Another constraint to the adoption and upscaling of BSF in aquaculture is the lack of regulatory frameworks and policies to support and encourage its use. In many countries, including Kenya, few incentives or regulations are in place to encourage the use of BSF or other sustainable practices in aquaculture. This can make it difficult for farmers and other stakeholders to invest in and adopt these technologies, even if they are interested in doing so.

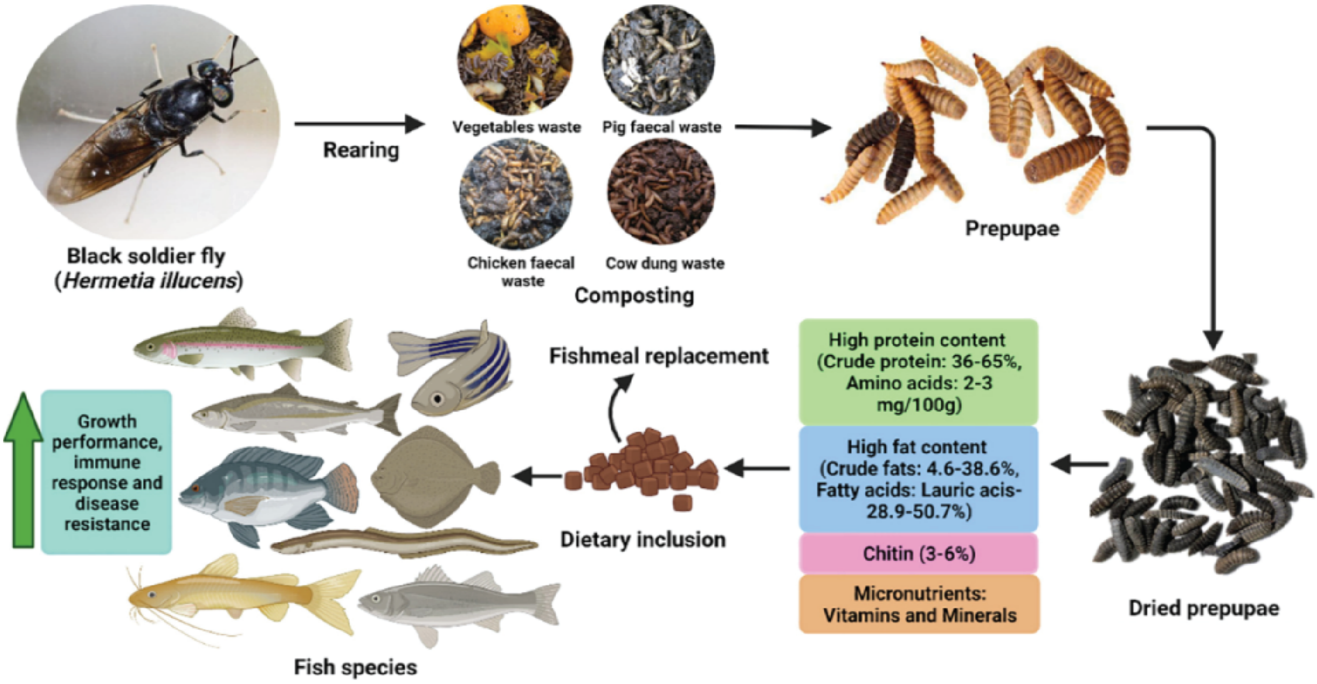
Despite these challenges, several socio-economic and environmental co-benefits exist to adopt and upscale BSF in aquaculture. For example, BSF can help improve the health and productivity of fish and other aquatic animals, increasing the profitability of aquaculture operations. In addition, BSF can help reduce the risk of diseases and other health problems among fish and other aquatic animals, improving the overall sustainability of aquaculture operations. There are also spillover effects of BSF in the Kenyan context, including the potential to improve waste management practices in the country. BSF can help reduce the amount of organic waste that is produced in aquaculture operations, which can help reduce the environmental impacts of waste management and improve public health.

BSF is a promising tool for improving the sustainability and environmental performance of aquaculture operations in Kenya and worldwide. Although there are challenges and constraints to its adoption and upscaling, there are also significant socio-economic and environmental co-benefits to be gained from its use. To realize these benefits, it will be important for governments, industry, and other stakeholders to work together to create the necessary regulatory frameworks and policies to support and encourage the use of BSF in aquaculture.

Researchers discovered that BSF larvae may eat and reduce the amount of substrate (and hence garbage) by up to 50%–70% while generating less GHG than conventional composting processes (Dzepe et al., 2021). The BSF-feed has an FCR ranging from 1.7 to 3.6 depending on the kind of substrate (De Marco et al., 2015) and a high protein efficiency (Razak et al., 2012), with 1 kg of substrate creating 0.4 kg of BSF biomass (Anton et al., 2020). Scaling up BSF production is an exciting opportunity for organic waste reduction, environmental cleanliness, and food waste valorization into usable goods. These include (1) protein powder for animal feed (pet food, cattle feed, and aquaculture feed) and even alternative protein for human consumption, (2) frass for fertilizer production, (3) oil for biodiesel, cosmetics, or medicines, and (4) insect chitin for biomaterial inputs.

Figure 19. Developing a circular food economy using BSF as a bioreactor.

Figure 20. Schematic demonstration of BSF.



Source: *Mohan et al. (2022)*

Except for a few firms that have produced and exploited culturing and processing procedures for flies and crickets on an industrial scale, protocols for insect culturing and processing (i.e., for houseflies, black army flies, and crickets) are still at a laboratory stage in Africa (Kenis et al., 2014).

The adoption of BSF technology has several good environmental effects and can help to reduce GHGE in a variety of ways. Organic waste degradation and conversion into biomass that can be utilized as feed or feed ingredients decreases GHGE into the environment associated with decomposition. It also minimizes the requirement to raise plants and animals for protein sources in aquafeed composition. Organic manure produced by the BSF from the breakdown of organic materials minimizes the requirement for inorganic fertilizer in crops. Technology provides several opportunities for women, youth, and persons with disabilities, and it has the potential to offer numerous job opportunities. This technology is already in use in Kisumu and can be quickly scaled up with minimal difficulty. Some of the potential impediments to adoption and upscaling relate to most farmers' lack of expertise. This can be addressed by providing them with technology training and capacity building.

4.3.14. Genetic Improvement

Genetic improvement in aquaculture has the potential to significantly reduce GHGE, increase productivity, and improve the sustainability of this important industry. Genetic advancements in fish breeding and genetics can also play a role in the transformation of food systems toward low-emission pathways. Through selective breeding or genetic engineering, for example, fish can be developed that are more resistant to diseases that commonly affect aquaculture operations. This can improve the sustainability and efficiency of aquaculture by reducing the need for costly treatments and lost production due to disease outbreaks. Fish with improved growth and feed efficiency can be produced through selective breeding or genetic engineering, allowing for more efficient use of resources, and reduced environmental impacts. For example, genetically modified fish that can convert feed into body mass more efficiently can be produced, reducing the amount of feed required to produce a given number of fish.

In the Kenyan context, some challenges and constraints must be considered in the adoption of this technology, including socio-economic factors, environmental co-benefits, and spillover effects. One of the main challenges in the adoption of genetic improvement technologies in aquaculture is the high upfront costs associated with research and development, as well as the costs of implementing new breeding programs. This can be a barrier for small-scale farmers in Kenya, who may not have the financial resources to invest in these technologies. Additionally, there may be a lack of technical expertise and infrastructure in place to support the adoption and implementation of these technologies.

Despite these challenges, there are several potential socio-economic and environmental co-benefits of genetic improvement in aquaculture in the Kenyan context. For example, the use of genetically improved fish breeds could result in higher productivity and efficiency, leading to increased profits for farmers. In addition, the adoption of these technologies could lead to the development of more resilient and disease-resistant fish breeds, which could reduce the need for chemical treatments and improve the overall sustainability of the industry. There are also potential spillover effects of genetic improvement in aquaculture in Kenya, including the potential for increased exports and the development of new value chains. This could lead to economic growth and development in the sector, as well as the creation of new jobs.

Despite the potential benefits of genetic improvement in aquaculture, it is important to carefully consider this technology's risks and unintended consequences. For example, there is a risk of negative impacts on wild fish populations if genetically improved fish breeds escape into natural systems. It is also important to ensure that adopting these technologies does not disproportionately benefit large-scale farmers at the expense of small-scale farmers.

Genetic improvement in aquaculture can significantly reduce GHGE and improve the industry's sustainability in the Kenyan context. However, several challenges and constraints must be considered in adopting these technologies, including the high upfront costs, the lack of technical expertise and infrastructure, and the potential risks and unintended consequences. To maximize the benefits and minimize the risks of genetic improvement in aquaculture, it is important to consider the socio-economic and environmental co-benefits and spillover effects carefully and to ensure that the technology is adopted in an inclusive and sustainable way.

Selective Breeding of Tilapia in Kenya

Through the KMFRI, Kenya has developed an F-9 generation of Nile tilapia strain through selective breeding programs. The F-9 tilapia grows faster than wild stocks, consumes less feed, has a greater flesh-to-bone ratio, and has a higher survival rate. It was created to address some of the challenges that aquaculture faces, such as a lack of certified quality fish seed and breed in small-scale aquaculture enterprises, which is associated with stunted growth and a low survival rate, resulting in poor yields and low uptake of fish farming throughout the country. Nile tilapia is indigenous to Africa. The F-9 Kenyan tilapia strain is comparable to the Genetically Improved Farmed Tilapia (GIFT) developed by WorldFish. When compared to conventional, non-genetically enhanced tilapia strains, GIFT had a beneficial influence on net profit margins (Ibrahim et al., 2019). Kenya continues to lag in the implementation of aquaculture breeding programs. The application of genetic principles to aquatic species in aquaculture is very new, and it has not yet fully utilized existing technology to boost yields (Abwao et al., 2021). Today, the most pressing issue is creating breeding programs to aid in conserving aquatic genetic resources while protecting biological variety. Furthermore, GIFT encounters opposition in some locations due to fears that alien species would impact native strain conservation. To reap the benefits of GIFT in Kenya, research is needed to assess the suitability of GIFT in production systems, as well as to develop and implement cost-effective monitoring and conservation measures to ensure the genetic diversity of farmed tilapia is maintained, allowing farmers to respond to ever-changing consumer demands and environmental conditions (Ragasa et al., 2022). Within 7 months, the enhanced seed performed best in Kilifi and Homa Bay counties, with an average fish weight of 400–600 g. For distribution, a technical report and a poster were created and released. Farmers that have used this method have had a consistent source of revenue and livelihood.

In terms of growth rate, GIFT is considerably superior to native African tilapia strains (Ansah et al., 2014), with studies revealing growth rates of 27% and 36% in monoculture and polyculture settings, respectively (Tran et al., 2021). In areas where the use of hormones is prohibited, the GIFT strain may be utilized as an alternative to boost tilapia output. Fast-growing, hardier GIFT has several advantages for small-scale and resource-limited farmers. They provide farmers with a higher return on investment, and, in certain countries, GIFT has increased national tilapia output. Because of its high survivability and greater use efficiency of natural food, particularly periphyton and benthos, only supplementary feed is supplied during the culture phase (Haque et al., 2016). This reduces both the culture period and the food applied and by extension the carbon footprints of the associated culture systems.

This is a significant concern in aquaculture, especially when fish feed costs more than 60% of the total cost of production. Accurate assessment of fundamental nutritional demands throughout the culture period, as well as best practices in feeding regimens and technology, are thus critical in attaining a considerable reduction in production FCR values (White, 2013). In terms of turning feed into harvestable biomass, the GIFT strain outperforms red tilapia. Based on nutrition, the FCR of GIFT is found to be 15% to 33% higher than that of red tilapia (Ng & Hanim, 2007). This minimizes the quantity of feed required, lowering operational costs while improving yield.

Fillet yield, or the proportion of edible meat in a given number of fish, is a highly desirable feature for species marketed as fillets or where fillets are favored. Fillet and weight are particularly important economic characteristics because marketing systems in major fish-producing nations are transitioning from payment based on whole-fish live weight to payment based on fillet weight (Nguyen et al., 2010). Small variations in yield% can have a significant impact on an operation's profitability. When compared to other strains, the GIFT strain yields almost 3.6% more fillets. The high fillet percentage in GIFT is due to weight selection, and so there is a significant link between growth rate and fillet percentage (Rutten et al., 2002). Because it reduces production costs while increasing yield, the method is very resource efficient. Tilapia has the lowest fillet output of around 33%, whereas genetically enhanced fillet yield has the highest fillet yield of more than 60%.

Disease resistance is frequently used to describe the host's capacity to restrict infection or the consequences of infection by reducing pathogen proliferation (Bishop & Woolliams, 2014). Diseases such as viral, fungal, bacterial, and parasitic infections have long been a source of worry in aquaculture. Developing disease-resistant fish strains to provide stock with better resistance to major infections is one strategy to minimize disease frequency. GIFT was initially oriented on growth rates, but disease resistance is now critical for long-term tilapia output increase. GIFT increases resistance to infections, particularly *Streptococcus agalactiae*, which is one of the most common illnesses in farmed tilapia and causes significant economic losses. Because the GIFT requires fewer medicinal treatments, production costs are reduced (Lu et al., 2020).

Table 3. Summary of GHGE from promising aquaculture technologies.

Aquaculture System	GHGE Level (kg CO_2e/kg fish produced)	GHGE	Source
IPRS	2.4	Carbon dioxide (1.6–2.2), Nitrogen oxides (0.2–0.6), Methane (0.1–0.4)	MacLeod et al., 2019
Cage	3.7	Carbon dioxide (2.4–3.3), Nitrogen oxides (0.4–0.8), Methane (0.2–0.6)	MacLeod et al., 2019
Integrated	2.8–3.7	Carbon dioxide (1.8–2.7), Nitrogen oxides (0.4–0.8), Methane (0.2–0.6)	MacLeod et al., 2019; de Silva et al., 2020
RAS	3.2–4.2	Carbon dioxide (2.1–2.9), Nitrogen oxides (0.5–0.9), Methane (0.2–0.7)	MacLeod et al., 2019
Offshore	3.7–6.1	Carbon dioxide (2.4–3.9), Nitrogen oxides (0.5–1.0), Methane (0.2–0.7)	MacLeod et al., 2019
Aquaponics	1.5–2.5	Carbon dioxide (1.0–1.6), Nitrogen oxides (0.2–0.6)	Li et al., 2018
Biofloc	2.3–3.5	Carbon dioxide (1.5–2.4), Nitrogen oxides (0.4–0.8)	Kim et al., 2020
Periphyton	1.4–2.4	Carbon dioxide (0.9–1.6), Nitrogen oxides (0.2–0.6)	Wang et al., 2022
IMTA	1.8–2.8	Carbon dioxide (1.2–1.9), Nitrogen oxides (0.3–0.7)	McLeod et al., 2019

Source: *de Silva et al. (2020); Kim et al. (2020); Li et al. (2018); McLeod et al. (2019); Wang et al. (2022)*

5. Supporting management tools and practices

For the technologies to be adopted and upscaled and their impacts felt within the communities, there need to be certain management tools and practices to support them. These could be financial, policy, social, or technological tools and practices. These will provide an enabling environment for adopting and upscaling the technologies.

5.1. The concept of Aquapark and aquaculture villages

In Kenya, a community-based coordination and support framework is used to construct and administer the aquapark idea, which consists of aggregated smallholder aquaparks and links them to nearby smallholder aquaculture production clusters (Odende et al., 2022). As a one-stop shop for all nodes throughout the fish value chain, the aquapark idea is a novel fish farming model for smallholder fish farmers to promote socioeconomic progress in rural regions. It improves fish output while incorporating environmental preservation strategies, including nutrient cycling, water conservation, waste minimization, and stakeholder integration (Otachi et al., 2022). Fish farmers' cooperatives primarily run and own the production nodes (fishponds and cages), which are supported by the input supply nodes and produce fish (fish feed processors and suppliers, fish hatcheries). The market connections, cold storage facilities, seafood merchants, processors, and value-adding are all included in the processing node (Mwirigi & Theuri, 2012). BSF, which is employed as a protein source in fish feed formulation, biologically degrades wastes and by-products produced by these systems and the environment (Joly and Nikiema, 2019). BSF's by-products, including high-quality organic manure and pond effluents, are then used for crop cultivation. This bio-circular economy approach lowers environmental degradation by repurposing trash into valuable goods.

The Aquapark concept presents a chance for recent graduates to start up management service providers. Due to the backward and forward connections and the multiplier effect, which makes the aggregated production regions into drivers of economic growth, the high output volumes in the pilot aquaparks are stimulating growth. The model has shown that compared to production from single ponds, producing fish in aggregated production units is both more affordable and capable of realizing a significant profit (Odende et al., 2022). Additionally, as seeds and feeds are offered at discounted costs in bulk and delivered in bulk by the firms straight to the aqua park, one benefits from economies of scale. This is mostly because when farmers act as a consolidated entity rather than as individual producers, their negotiating strength is increased and transportation of inputs is limited, hence minimizing GHGE. Buyers visit the aqua park during harvest to make large purchases, which lowers the price of transporting fish to markets. Here, fish is gathered and sold whole. In contrast, fragmented farming necessitates travel to get inputs and sell mature fish to the market, which occasionally sees low sales and substantial post-harvest losses. As a result, the strategy lowers post-harvest losses, increasing farmers' profits from the fish farming industry.

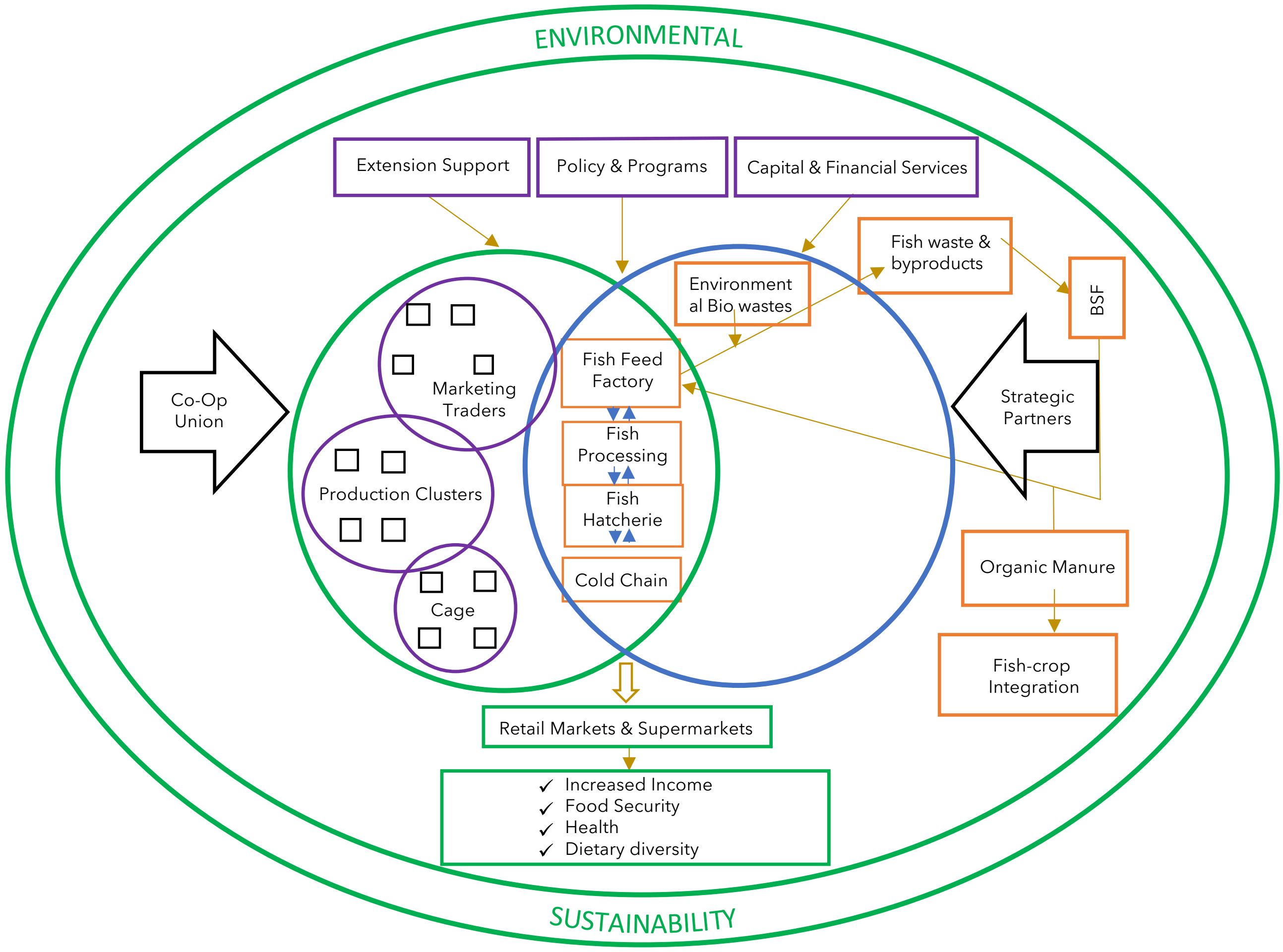
The aquapark farming approach has also shown to be a viable method of involving the rural poor in an active role in economic development. The concept makes it possible to significantly lower management and operating costs and has made it easier to provide competitive items to the market. For instance, the Busia Beach Management Unit (BMU) education scholarship program was established because of the seascape fish farming concept that was implemented in 2020. The BMU network owns 91 cages that offer educational support to the community's students enrolling in secondary school, helping the government's 100% transition to a secondary school program. It is now acknowledged that the aquapark concept has enhanced aquaculture production in Busia County and has the potential to be replicated in other counties throughout the nation (Odende et al., 2022).

Figure 21. Aggregated fish farms (aquapark) in Busia County, Kenya.

Source: *Odende et al. (2022)*

The adoption and expansion of the management tools and practices within the aquaculture sector make it possible for the adoption and upscaling of the technologies. This can be beneficial to the entire aquaculture sector within the country – not only in Kisumu County.

Figure 22. Conceptual framework and schematic flow of an ideal Aquapark unit showing all components of food production and value chain linkages.



Source: *Odende et al. 2022.*

5.2. Financial tools, trade, and marketing

Financial tools, trade, and marketing play a critical role in the development and sustainability of the aquaculture industry in the Kenyan context. These factors can impact the adoption of technologies that aim to reduce GHGE and improve the industry's sustainability.

One of the main challenges in adopting GHG-reducing technologies in aquaculture is the high upfront costs associated with research and development and the costs of implementing new production systems. To overcome this barrier, financial tools such as grants, loans, and subsidies can be used to support small-scale farmers' adoption of these technologies. For example, the Kenyan government's Agricultural Sector Development Strategy provides grants and subsidies to support adopting sustainable aquaculture practices, including using GHG-reducing technologies.

In addition to financial tools, trade and marketing strategies can also play a role in adopting and scaling GHG-reducing technologies in aquaculture. For example, developing value chains and marketing networks can provide a market for sustainably produced fish, incentivizing farmers to adopt these technologies. This can be supported by establishing standards and certification programs that verify the sustainability of aquaculture production systems.

There are also several potential socio-economic and environmental co-benefits of adopting GHG-reducing technologies in aquaculture in the Kenyan context. For example, these technologies can lead to increased efficiency and productivity, resulting in higher profits for farmers. In addition, the adoption of these technologies can reduce the environmental impacts of aquaculture, including GHGE and water pollution.

However, there are also potential risks and unintended consequences of adopting these technologies. For example, adopting GHG-reducing technologies may lead to increased competition and displacement of small-scale farmers if they cannot compete with larger, more technologically advanced operations. It is therefore important to ensure that the adoption of these technologies is inclusive and sustainable and that small-scale farmers can access the financial, trade, and marketing support they need to compete in the market. Financial tools, trade, and marketing play a critical role in adopting and scaling GHG-reducing technologies in aquaculture in the Kenyan context. These factors can support small-scale farmers' adoption of these technologies and provide a market for sustainably produced fish. However, it is important to carefully consider these technologies' potential risks and unintended consequences and ensure that their adoption is inclusive and sustainable.

Table 4. Summary of GHGE from promising aquaculture management practices.

Area	GHG /CO_2 Emission Level	Source	Notes
Value addition	High	FAO, 2018	GHGE may be higher due to energy use and transportation of inputs and products
Solar energy	Low	Hu et al., 2018	Can significantly reduce GHG and CO_2 emissions by replacing fossil fuel energy sources
Precision farming	Moderate	Aquaculture Alliance, n.d.	Can help to optimize inputs and reduce GHGE through targeted application of resources
Black soldier fly	Low	Bosch et al., 2019	Can significantly reduce GHGE compared to traditional feed sources due to their efficient conversion of organic waste into protein-rich feed
Organic or compost fertilizers	Low	Bekchanov & Mirzabaev, 2018	Organic or compost fertilizers can help to reduce GHGE compared to synthetic fertilizers by improving soil health and reducing the need for synthetic fertilizers
Species choice	High	MacLeod et al., 2019	Some species, such as carnivorous fish, have higher GHG emissions due to the higher carbon footprint of their feed.
Biosecurity	Low	Palić and Scarfe, 2019.	Good biosecurity practices can help prevent the spread of diseases, which can lead to reduced GHGE from treatment and disposal of infected animals.
Disease resistance	Low	Palić and Scarfe, 2019.	Disease-resistant strains of fish may have lower GHGE due to reduced treatment and disposal needs.
Feed management	High	Mohammad and Doris, 2017	Inefficient feed management can lead to higher GHGE due to wasted feed and the carbon footprint of producing the feed.
Genetic improvement	Low	Sae-Lim et al., 2017	Selective breeding for traits such as growth rate and disease resistance can lead to reduced GHGE due to increased efficiency and reduced treatment and disposal needs.
Financial tools	Low	Hammer et al., 2022	Financial tools such as carbon pricing and subsidies can incentivize the adoption of low-GHG practices in aquaculture.
Spatial planning	Low	Gentry et al., 2016	Spatial planning can help ensure that aquaculture operations are sited in areas with low GHGE and do not conflict with other uses.

Table 5. Classification of promising aquaculture technologies, innovations, and management practices for low GHGE in regards to category and readiness for upscaling.

Climate-smart TIMPs	TIMPs Category	Status of TIMPs Readiness
SPRAS	Technology	Ready for upscaling
Aquaponics/hydroponics systems	Technology	Ready for upscaling
HDPE fish cage	Technology	Ready for upscaling
Integrated culture systems IMTA Rice-fish culture systems Crop-livestock-fish systems	 Innovation Innovation Technology	 Requires further research Require validation Ready for upscaling
IPRS	Innovation	Requires validation
Finger-ponds	Technology	Ready for upscaling
Precision farming	Management practice/innovation	Requires further research
Post-harvest technology and value addition	Technology	Ready for upscaling
Biosecurity practices, e.g., predator control, disinfection practices, quarantine, and surveillance systems, and pathogen-free seed	Management practices	Ready for upscaling
Disease reduction strategies	Management practice	Ready for upscaling
Improved Smoking Kiln	Technology	Ready for upscaling
Species choice and diversification	Management practice	Ready for upscaling / new species requires further research
Feed Management Practices	Management practices	Ready for upscaling
Novel Animal-based Feeds, e.g., BSF larvae BFT PPT	 Innovation Technology Technology	 Ready for upscaling Require validation Require validation
Genetic Improvement (selective breeding techniques)	Technology	Ready for upscaling
Aquapark and aquaculture villages	Management practice/tool	Ready for upscaling

6. Conclusions and recommendations

In conclusion, aquaculture has the potential to provide a sustainable and efficient source of animal protein as a nature-based solution to global food security and environmental challenges. There are various promising technologies and innovations in aquaculture that can contribute to low GHGE, including closed-system aquaculture, precision farming, and the use of solar energy. However, it is difficult to quantify the percentage by which GHGE may be reduced through adopting these technologies and innovations, as it depends on the specific characteristics and management practices of individual systems. To fully realize the potential of aquaculture as a sustainable solution, it is necessary to identify and promote these technologies and innovations, as well as effective management practices, and address the challenges and constraints faced by different value chain actors. The case study in Kisumu County highlights the importance of conducting stakeholder consultations to map out aquaculture value chains, identify sources of emissions, and identify promising technologies and innovations for scaling. Further research is needed to address knowledge gaps and identify ways to improve the efficiency and sustainability of aquaculture systems.

Scaling aquatic food systems technologies and innovations in Kenya's aquaculture value chains for low-emission development can be constrained and challenged by various factors. These may include limited access to finance and other resources, inadequate infrastructure and technical support, regulatory barriers, and social and cultural factors. However, significant potential co-benefits and spillover effects can also accrue from scaling these technologies and innovations. These may include improved economic opportunities and livelihoods for value chain actors, increased food security and nutrition, and reduced GHGE. To effectively scale these technologies and innovations, it will be important to address these constraints and challenges while also considering and maximizing the potential co-benefits and spillover effects. This may require various policy and supportive interventions, including targeted financing and technical assistance, regulatory reform, and capacity building. Overall, scaling aquatic food systems technologies and innovations in Kenya's aquaculture value chains has the potential to contribute significantly to the country's low-emission development goals while also generating a range of social, economic, and environmental benefits.

This study identified six key recommendations to reduce GHGE from the various TIMPs:

1. Adopt closed-system aquaculture technologies, such as IPRS, RAS, aquaponics, BFT, IMTA systems, and IAA systems, to reduce GHGE and improve the sustainability and efficiency of aquaculture systems.

2. Consider using advanced feed formulations, such as plant-based feed and feed made from single-cell proteins, to reduce GHGE further and improve the sustainability of aquaculture systems.

3. Implement management practices that can help to reduce GHGE and improve the efficiency and sustainability of aquaculture systems, including the use of solar energy, precision farming, genetically improved fish species, organic composts, circular energy-cycling, biosecurity measures, efficient feed management, financial tools, and spatial planning techniques.

4. Consider the social, economic, and environmental co-benefits and spillover effects of scaling aquaculture TIMPs, as well as the constraints and challenges faced by different value chain actors in adopting them.

5. Conduct further research to identify and address knowledge gaps in the field of aquaculture and to identify new TIMPs that have the potential to improve the efficiency and sustainability of aquaculture systems.

6. Invest in training and capacity building programs to ensure that aquaculture practitioners and value chain actors have the necessary skills and knowledge to effectively adopt and implement TIMPs. This could include training on the proper use and maintenance of closed-system aquaculture technologies, advanced feed formulations, and management practices that can reduce GHGE and improve the sustainability of aquaculture systems. Additionally, training programs could focus on topics such as financial management, marketing, and business development to help value chain actors succeed in the aquaculture industry. Ensuring that practitioners and value chain actors have the necessary skills and knowledge will be key to realizing the full potential of aquaculture as a sustainable and equitable solution to global food security and environmental challenges.

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