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Building Climate Resilience in Aquaculture: A Framework for Strengthening Resilience in Kenya's Aquaculture Value Chain

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Abstract

Aquaculture is increasingly recognised as a key sector for achieving global development goals, including improving nutrition, ending hunger, poverty reduction, and economic growth. However, the sector remains highly vulnerable to climate change impacts. Addressing this requires integrated, cross-sectoral solutions involving collaboration across biological, technical, economic, and socio-cultural domains. This paper presents a framework for building a climate-resilient aquaculture value chain, using Kenya as a case study. Drawing on data collected through workshops, interviews and field observations, the study identifies the four key stages of the aquaculture value chain most affected by climate change: feed production, fish production, transportation and distribution, and post-harvest processing. It also maps relevant stakeholders and outlines specific adaptation pathways such as ecosystem-based approaches, policy reforms, and technical innovations that can be co-produced to enhance resilience at each stage. The framework emphasises the importance of multi-stakeholder collaboration and highlights the need for inclusive approaches that address gender and socio-economic inequalities within the sector. Findings suggest that, despite existing institutional and infrastructural challenges, there is a strong appetite among stakeholders in Kenya for collective action. While the proposed framework offers a practical tool for guiding resilience-building, efforts should be made to test the framework across different contexts.

Keywords: adaptation pathways; climate adaptation; fish production; gender equity; multi-stakeholder collaboration

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1. Introduction

Climate change is a major threat to food systems, including aquaculture, which is highly sensitive to climate variability and change [1,2]. The Intergovernmental Panel on Climate Change (IPCC 2022) [3] projects increasing strain on food production and access, especially in already vulnerable regions, while [4] estimates aquaculture production could decline by up to 16% by 2090, with broader implications for food security and livelihoods [5].

The aquaculture sector plays a critical role in the food security, employment, and economic development of many countries, particularly within the Global South. In numerous African nations, for example, aquaculture supports small-scale businesses that are integral to national economies and household livelihoods [6]. The sector not only serves as a primary source of animal protein but also supplements national fish supplies amidst the

ongoing decline in wild fish stocks [7]. In Kenya, aquaculture accounts for approximately 11% of total fish production and contributes around 0.3% to the national GDP, while in Nigeria, the sector contributes an estimated 3.24% to GDP [8].

Across the African continent, climate change is emerging as a significant constraint ton aquaculture development [9,10]. The escalating impacts of climate change present a growing concern for fish farmers, governmental bodies, regional institutions, and international organisations alike. These impacts pose a substantial threat to the sustainability and growth of aquaculture, affecting not only aquatic ecosystems but also the infrastructure that supports fish farming, ultimately influencing broader aspects of human wellbeing. The effects are multifaceted and manifest across various climate-related hazards, influencing both production systems and the broader aquaculture value chain [11]. Empirical evidence has documented how floods damage aquaculture facilities [12], such as fishponds, while droughts lower water availability [13], increasing the risk of disease outbreaks and placing additional stress on aquatic organisms [14,15]. Such environmental disruptions result in reduced fish yields, diminished food security, decreased income opportunities, and elevated levels of poverty, while simultaneously exerting pressure on national economies. These challenges are particularly acute for smallholder and community-based aquaculture producers, who often lack the capacity and resources necessary to adapt to climate-related shocks [16]. This context underscores the urgent need to develop and implement a system that enhances the resilience of aquaculture systems and supports the capacity of farmers to respond effectively to climate change.

Building resilience in aquaculture is complex because the sector spans diverse actors, production systems, species, and ecological interactions, with various climate vulnerabilities. Strengthening resilience therefore requires a systems approach that integrates technological, environmental, social, economic, cultural, and political dimensions. Because no single stakeholder can address these challenges alone, climate-resilient aquaculture depends on coordinated changes in both material capacities, such as infrastructure and technologies, and institutional capacities, such as knowledge, governance, and collaboration. This paper therefore asks:

What should a resilient aquaculture system look like in the context of climate change? Answering this question can help align interventions by farmers, policymakers, practitioners, and development organisations.

1.1. Frameworks for Resilient Aquaculture Sector

Building resilience has increasingly become a focus in critical sectors such as health and transportation [17,18]. In recent years, the aquaculture sector has also seen growing interest in resilience [19,20], particularly in light of several major climate-related events that have impacted operations globally [21,22]. These events, ranging from prolonged droughts to unprecedented floods, have led to significant investment losses, food insecurity, and economic setbacks. Despite this growing concern, there is still no clear consensus on what resilience in aquaculture should entail. Moreover, the sector lacks well-defined frameworks to guide value chain actors in investing in resilience-building measures.

While broader programs such as Climate Smart Agriculture [23] offer valuable strategies for addressing climate challenges, tailored approaches for aquaculture remain underdeveloped. This paper addresses this gap by presenting a case study conducted in four key counties in Kenya—Kakamega, Kajiado, Nairobi, and Kiambu—that are actively engaged in aquaculture. Through stakeholder engagement, the study identifies the major actors, their roles, and interactions within the aquaculture value chain in the context of climate resilience. It further outlines actionable steps that stakeholders can take to enhance resilience at each

stage of the value chain. In doing so, the paper contributes a much-needed framework for examining, prioritising, and strengthening climate resilience across the aquaculture sector.

1.2. Collaboration in the Aquaculture Sector

Aquaculture is an inherently complex sector involving a diverse array of stakeholders, disciplines, and institutions. This complexity has led many studies to emphasise the need for effective collaboration among actors across the sector [24–26]. While the importance of collaborative design and co-production in the sector is well recognized [27,28], progress in aquaculture has been slow, underscoring the need for urgent action. In the context of climate change, the urgency for collaboration becomes even more pressing. No single stakeholder or institution holds the complete knowledge, authority, or resources to independently drive the transformation required for climate-resilient aquaculture. Building resilience in the aquaculture system must therefore involve the mobilisation of knowledge, skills, and resources from a wide range of actors and disciplines (such as engineers, climate scientists, computer scientists, aquaculture experts, community extension workers, law enforcement agencies, and others). In addition, it requires active participation from academia, civil society, and private investors operating along different points of the aquaculture value chain.

While some studies have explored the need to adapt aquaculture infrastructure in response to climate change [29–31], there is currently no practical framework to guide the co-production of climate-resilient infrastructure. Co-production as an approach to building climate resilience is gaining momentum and is increasingly viewed as superior to conventional siloed strategies [32–34]. Engaging a broad coalition of stakeholders in the co-production of resilient aquaculture infrastructure not only fosters shared accountability but also strengthens governance and management outcomes. Moreover, collaboration builds trust among stakeholders, particularly around knowledge sharing and technology transfer, and can foster a supportive culture necessary for transformative sectoral change. Such trust and coordination can also help navigate political, regional, and cross-border challenges, including those related to genetic material exchange and technology dissemination.

Beyond resilience to the impact of climate change, cross-sector collaboration also promotes a deeper understanding of aquaculture's environmental impacts, aligning with growing global interest in sustainable technologies and innovations [35]. However, in many African countries, governance fragmentation and limited coordination among aquaculture stakeholders remain persistent barriers [36]. In Kenya, for instance, weak linkages across the aquaculture value chain have resulted in poorly coordinated operations and conflicting extension services [37].

Despite the strong theoretical support for co-production, the approach is not without critique. Critics argue that collaboration may slow innovation, and some contend that co-production is inherently politically driven by competing interests and often influenced by corporations that frame sustainability innovations primarily in technical or economic terms, rather than social or environmental ones [38,39]. Nevertheless, given the urgency of climate threats and the complexity of aquaculture systems, fostering inclusive, cross-sectoral collaboration remains a critical pathway for developing robust, climate-resilient aquaculture infrastructure.

1.3. Aquaculture in Kenya

The history of fish farming in Kenya dates back to the early 1900s, when European settlers introduced species such as trout (*Oncorhynchus mykiss* and *Salmo trutta*), black bass (*Micropterus salmoides*), and common carp (*Cyprinus carpio*) for sport fishing purposes [40]. By 1926, the British colonial administration had established the Game Department to oversee

fisheries, and in 1954, the Department of Fisheries (DoF) was formally created [41]. Since then, Kenya's freshwater aquaculture sector has experienced two notable phases of growth: the first occurred in the 1960s with the launch of the "Eat More Fish" campaign by the colonial government, and the second in 2009, under the Economic Stimulus Programme (ESP) [42,43]. As illustrated in Figure 1, aquaculture production has shown fluctuations since the early 2000s, with significant declines in 2015 and 2017 attributed to key challenges such as limited access to quality fish feed, inadequate fingerling supply, poor infrastructure, and weak post-harvest handling [44].

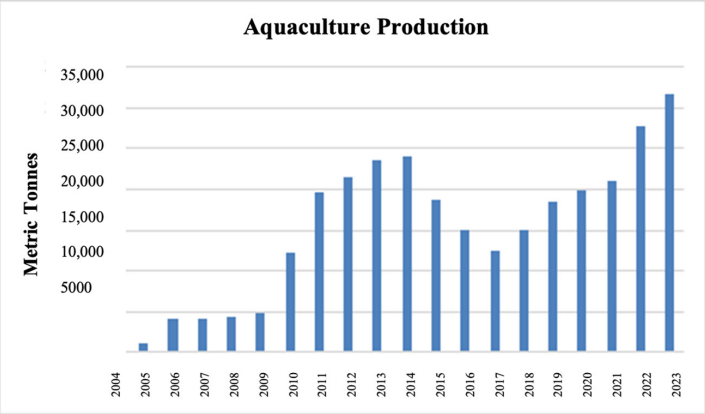

Figure 1. Aquaculture production in Kenya 2004–2023. Data source: Kenya Fisheries Services Annual Statistical Bulletin.

Recognising aquaculture's potential, the Kenyan government has made substantial investments in the sector, particularly through the ESP and Vision 2030 strategies. These initiatives have led to increased public financing, resulting in a production volume of approximately 21 million metric tonnes valued at over USD 50 million [45]. The ESP was specifically designed to alleviate poverty, stimulate economic growth, enhance public awareness of aquaculture, and support regional development [46]. It helped transform aquaculture from a largely stagnant sub-sector into one of the most promising in Africa by offering subsidies and promoting fish consumption [47,48].

Despite this progress, the sector faces mounting threats from climate-related hazards such as floods and prolonged droughts [16,31,49–51]. Moreover, aquaculture practices can contribute to environmental degradation through sludge discharge and excessive water abstraction [52]. These issues have prompted increasing calls for sustainable aquaculture and for integrating climate resilience into sector planning and infrastructure development [19,53].

Aquaculture production in Kenya is unevenly distributed spatially due to variations in environmental conditions such as soil type and water availability [54,55]. Leading counties in fish farming include Kakamega, Bungoma, Busia, Kisii, Meru, and Nyeri, while counties like Kitui, Lamu, and Elgeyo Marakwet lag behind [55]. The country's aquaculture systems span land-based freshwater aquaculture, cage culture, and mariculture [47]. Freshwater aquaculture, which includes both warm- and cold-water species [56], has evolved from static pond systems to more advanced models such as recirculating systems [57], raceways and more recently, cage systems [58]. Despite this technological progress, the sector still struggles to meet national fish demand due to high input costs and other structural barriers [43].

In 2021, Kenya imported 19,891 tons of fish at a cost of KES 2.5 billion to supplement domestic supply, an increase from previous years [59]. Imported fish remain critical in meeting the national demand of 500,000 tonnes annually, with local production standing at just 163,605 tonnes in 2021. This represented an 8% increase from 2020, according to the Kenya Fisheries Annual Statistical Bulletin [59].

The Fisheries Management and Development Act of 2016, which is the most recent regulatory framework, provides guidance on fisheries governance and aquaculture practices [60]. However, the Act lacks specific provisions addressing climate resilience in the sector, which remains a critical gap in policy [5]. Going forward, aligning national aquaculture strategies with climate adaptation objectives will be essential for safeguarding the sector's sustainability and long-term contribution to food security and economic development.

2. Material and Methods

This paper draws from a research project focused on adapting aquaculture infrastructure in Kenya to climate change, with particular attention to stakeholder knowledge and perceptions. Data was collected through two stakeholder workshops and semi-structured interviews conducted in four purposively selected counties—Kakamega, Kajiado, Nairobi, and Kiambu—chosen to reflect Kenya's diverse climatic zones (Figure 2).

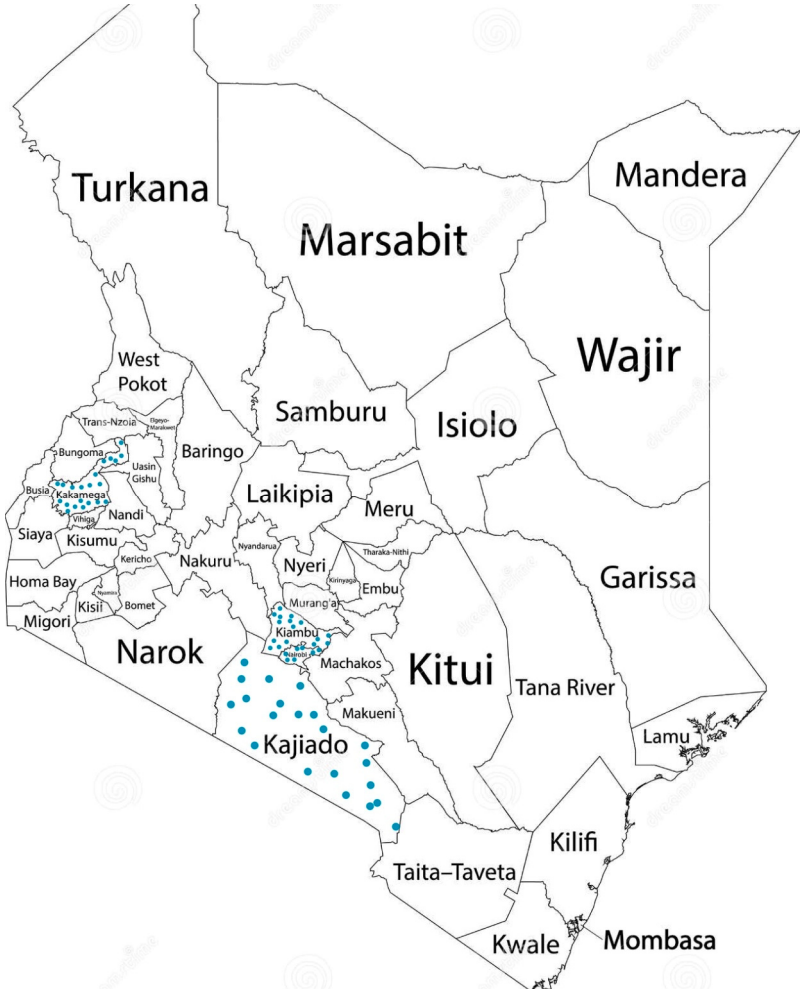

Figure 2. Map of Kenya showing the locations of the four study sites.

The stakeholder and validation workshops were held in Nairobi in June and October 2019, bringing together a broad range of participants from across the aquaculture value chain. These included fish farmers, aquaculture associations, private sector actors, researchers, government representatives, non-governmental organisations, and academics. Key institutional stakeholders represented in the workshops included the Kenya Marine and Fisheries Research Institute (KMFRI), the State Department for Fisheries and the Blue Economy (SDF&BE), the International Livestock Research Institute (ILRI), Kenyan uni-

versities, the Kenya Fish Processors and Exporters Association, the National Environment Management Authority (NEMA), and the Aquacultural Association of Kenya (AAK). Participants were purposively selected to ensure a balance of decision-making, operational, and knowledge-based roles across institutions. Across the two workshops, a total of 43 participants attended, with individuals attending either one or both sessions.

The workshops consisted of expert presentations from invited speakers, followed by plenary discussions and focused breakout groups. These sessions explored the impacts of climate hazards on the aquaculture value chain, identified key vulnerable components, and examined which actors should support farmers in building resilience and defining roles and responsibilities. All sessions were audio-recorded and documented. In addition, informal interviews were conducted with twelve fish farmers, three from each case study site. These interviews allowed for more in-depth exploration of themes raised during the workshops, focusing on farmers' experiences with climate hazards and their perspectives on key actors and support mechanisms. The interview sample included farms of varying scales and ensured gender balance among respondents.

The research received institutional ethics approval, and all research activities were conducted in accordance with institutional ethical guidelines. Participants were provided with an informed consent statement at the outset of both workshops and interviews, and all consented to participate voluntarily. They were informed of their right to withdraw at any time.

Audio data from workshops and interviews were transcribed using Otteri software, then reviewed and cleaned by the research team. The transcripts were analysed using thematic analysis (TA), a method suited for identifying patterns of meaning within qualitative data [61]. TA helped uncover key themes and constellations of meaning that emerged from participants' narratives and discussions.

3. Results

The loss of fish attributed to climate change is already a significant concern among key stakeholders across Kenya, with stakeholders generally anticipating that these impacts will intensify due to increasingly severe and unpredictable climatic patterns. Despite these challenges, eight of the aquaculture farmers interviewed showed a strong commitment to continue fish farming activities, mainly because they do not have an alternative source of income to support themselves and their families. Although they acknowledged experiencing climate-related stressors, particularly flooding, extreme heat, and water scarcity, they did not explicitly associate these phenomena with climate change. Notably, one respondent remarked that their forebears had faced comparable environmental challenges and had managed to cope successfully. This belief in traditional resilience underscores a persistent gap in climate change awareness and highlights the need to better understand how fish farmers perceive and respond to environmental change. Nonetheless, all interviewed fish farmers recognised that the current situation has become sufficiently severe to justify external support and the implementation of new strategies to adapt and ensure the sustainability of aquaculture livelihoods.

3.1. Climate Vulnerability in the Aquaculture Value Chain

Building on issues raised during the stakeholder workshops and interviews, four critical segments of the aquaculture value chain were identified as particularly vulnerable to climate change: (i) feed production, (ii) fish production, (iii) transportation and distribution, and (iv) processing and storage. For each of these stages, the study mapped the relevant actors and their roles, and assessed opportunities for fostering co-production to enhance resilience. Examples of specific interventions and collaborative strategies are summarised in Table 1. Furthermore, we present a framework (see Section 3.6) that illustrates pathways for building resilience across the aquaculture value chain.

Table 1. Relevant stakeholders in promoting climate-resilient aquaculture in Kenya.

The Aspect of Aquaculture Value Chain	Relevant Stakeholder	Examples of Actions Needed
Feed Production	Commercial Fish feed operators (manufacturers and importers)	To ensure quality feeds which meet the growth requirements of the target species
	National Environment Management Authority (NEMA)	To ensure sustainable environment and that practices do not undermine crop-based ingredients for fish feed production
	Ministry of Agriculture, Livestock, Fisheries and Cooperatives	To promote revival of plant-based fish feed ingredients such as soy, sunflower and cotton
	State Department of Fisheries and Blue Economy	Create awareness on role of quality feeds, formulations and their impact on aquaculture production and the environment
	Kenya Marine and Fisheries Research Institute	Conducts research on the available market fish feeds and informs the sector on their quality and effects on the fish and the environment
	Kenya Bureau of Standards (KEBS)	To ensure quality of fish feed production and recommend Best Management Practices of feeds and their application
	Africa organisation for Standards (ARSO)	To harmonise the feed standards into African standards through the Eco Mark Africa label that promotes Mitigation of climate change and adaptation to its impacts will be vital for Kenya and the African continent.
Fish Production	Local aquaculture artisan community	To ensure environmentally resilient technologies and innovations
	Kenya Fisheries Service (KeFS)	To ensure aquaculture policy regulation enforcement for environmental and investment safeguards
	Kenya Marine and Fisheries Research Institute	Assess existing technologies and innovations for aquaculture production, test novel climate-resilient innovations and promote their adoption and management
	Kenya Meteorological Department (KMD)	Provide localized climate information products and services to inform aquaculture investment
	Kenya Veterinary Department	To support adequate management of fish disease at production, transportation and markets
	National Commission for Science Technology and Innovation (NACOSTI)	To support fabrication and investment in production of aquaculture infrastructure
	Water Resources Management Authority (WARMA)	Ensure sustainable water use including that abstractions are done responsibly.
	Non-Government Organisations (e.g., Aquaculture Association of Kenya)	Support farmer education and capacity building
Fish Transportation and Distribution	Non-Government Organisations (e.g., Aquaculture Association of Kenya)	Network the aquaculture value chain members
	National Commission for Science Technology and Innovation	To support fabrication and investment in affordable and climate-smart fish transportation and preservation technologies and innovations
	Kenya Meteorological Department	Provide weather information including early warning
	Kenya National Highway Authority	Ensure good roads that support movement of produce in different climatic seasons
	Businesses and Financial Institutions	To promote investment in the aquaculture value chain operations and create loaning packages for aquaculture
Fish Post-harvesting, Preservation and Storage	State Department of Fisheries	To sensitize aquaculture value chain actors on aquaculture Best Management Practices and provide common fish storage infrastructure for aquaculture formal groups
	Kenya Marine and Fisheries Research Institute	Conducts research on resilient fish handling, processing and transportation technologies and innovations, informs sector actors on their resilience and sustainability for adoption
	Businesses and Financial Institutions	To promote investment in the aquaculture value chain operations and create loaning packages for aquaculture
	Kenya Meteorological Department	Provide weather information including early warning
	Fish Market Authority	To sensitize aquaculture value chain actors on the export standards for the aquaculture produce to ensure quality production and handling environmental standards, avoid post-harvest losses and overall investment losses

3.2. Aquaculture Feed Systems and Vulnerabilities to Climate Change

One of the key challenges identified during the study was the difficulty in acquiring sufficient and appropriate aquaculture feed. In Kenya, aquaculture feeds are largely composed of both plant- and animal-based ingredients, including fishmeal, fish oil, maize, soy, and other agricultural by-products, which are processed into dried pellets. According to a representative from a government agency, over 70% of the ingredients used in aquaculture feed production in Kenya are plant-derived, mainly from maize germ, soybeans, and corn. As such, feed production is intricately linked to the broader agricultural sector and is inherently sensitive to climatic variability. Any disruption in the availability of these agricultural raw materials caused by droughts, floods, or changing growing conditions can therefore significantly affect feed availability and the broader aquaculture sector.

Furthermore, stakeholder discussions revealed that aquaculture feed production in Kenya can be broadly classified into three categories: (i) small-scale or on-farm production; (ii) medium-scale or community/cottage-level production; and (iii) large-scale commercial production, either domestically produced or imported. Both the small-scale and large-scale sectors account for approximately 30% of feed production each, while the remaining 40% is produced at the community or cottage level, often by farmer groups or cooperatives. This distribution suggests a high reliance on locally formulated feeds, many of which are developed without adequate understanding of fish nutritional requirements or environmental sustainability. Based on participant discussions, we found that poor feed quality in Kenya is frequently attributed to knowledge gaps among producers. Despite the need to enhance the resilience and quality of locally produced feeds, workshop participants and interviewees also highlighted a growing reliance on imported feeds. This reliance exposes the aquaculture sector to external supply chain disruptions such as delays or price fluctuations as were seen during the COVID−19 pandemic when international feed supply chains were significantly interrupted.

Stakeholders suggested that enhancing the resilience of aquaculture feed systems should prioritise the promotion of local feed production by strengthening the value chains for plant and animal-based feed ingredients. Evidence of progress in this area includes community-level initiatives such as the Bidii Fish Farmers Self Help Group and the Matayos Aquafeed Self Help Group in Busia County. It was also confirmed that these groups have begun producing slow-sinking pellet feeds and currently supply fish farmers in their localities. Women, in particular, were identified during group discussions as playing a critical role in managing farms and sourcing agricultural by-products used in local feed production. Participants highlighted the importance of commercial feed imports to the aquaculture sector's growth. They suggested that the long-term strategy should focus on localising feed production by leveraging novel, climate-resilient feed ingredients such as aquatic macrophytes that have already been identified as promising alternatives. Incorporating such local resources can reduce dependency on imports, improve feed system sustainability, and build climate resilience.

Another critical issue mentioned by participants relating to feed production sustainability is the environmental degradation associated with fish farming, particularly through effluent discharge. Workshop participants highlighted that untreated waste from fish farms in Kenya is often released directly into rivers and other water bodies. They explained that this can cause excessive nutrient build-up, encourage algal growth, reduce oxygen levels in the water and damage aquatic ecosystems. Participants also noted that the build-up of waste can block waterways, increase the risk of flooding, and affect the availability of raw materials used to produce fish feed. They emphasised

that problems at one stage of the system can have knock-on effects across the wider supply chain.

3.3. Vulnerabilities in Fish Production

The fish production stage of the aquaculture value chain was consistently identified by participants as the most vulnerable to climate impacts, largely due to disruptions in the availability of key inputs and environmental instability. All respondents expressed concern about the increasing unpredictability of prolonged rains and droughts, which were reported as the most prominent climate hazards affecting production. These climate-related challenges are said to be increasingly affecting fish farming. They highlighted that these conditions can lead to fish illness and disease outbreaks, damage to fish-farming infrastructure and the loss of fish during floods when they escape into natural water bodies.

A recurring issue identified in the discussions was the vulnerability of earthen fishponds, typically constructed from clay soil, to climate extremes. Most small- to medium-scale aquaculture operations in Kenya utilise such ponds, which are highly susceptible to both drying and flooding depending on their location and construction quality. Poor site selection and inadequate design were emphasised as major risk factors, often resulting in fish loss during floods or complete drying of ponds during drought. Participants agreed that improving pond site selection and upgrading pond design are crucial steps toward enhancing climate resilience. Specific recommendations included the construction of elevated or reinforced production units, such as wooden liner ponds or concrete raised ponds (Figures 3 and 4), which have proven effective in flood-prone and water-scarce areas.



Figure 3. Raised wooden liner ponds.



Figure 4. Raised concrete ponds.

Another key finding was the limited access to timely and reliable climate information, which hinders farmers' ability to make informed decisions during the production process. Farmers expressed awareness of the need to build climate resilience but noted their dependence on external authorities for weather updates and early warning systems, which are often delayed or unavailable. This lack of climate information services undermines farmers' ability to prepare for climate shocks and implement adaptive measures. Participants underscored the need to strengthen climate information dissemination, extension services, and farmer capacity building to support adaptive planning at the farm level.

Despite these challenges, several locally driven adaptation efforts to enhance the production process were noted. In counties such as Kajiado and Kakamega, fish farmers are collaborating with county fisheries officers, NGOs, and research institutions to develop climate-resilient aquaculture solutions. These include the use of raised ponds, integrated recirculating aquaculture systems (RAS) (Figure 5), and improved site selection practices. In other places, increased flooding has prompted a shift toward backyard aquaculture using elevated wooden or concrete ponds. However, many of these systems are fabricated with basic local materials and lack standardization. While these efforts are commendable, further support is needed to enhance their effectiveness, particularly through the integration of renewable energy technologies (e.g., solar-powered aerators) and closed-loop systems such as aquaponics. Field observations revealed notable disparities in farmers' ability to adopt these technologies, largely tied to socio-economic status. While some farmers could afford advanced systems, others lacked the financial means, indicating the need for targeted support mechanisms to ensure equity in climate adaptation.



Figure 5. A recirculation system.

Participants identified water shortages as a major challenge affecting fish production in Kenya. They explained that this is caused by recurring droughts, poor management of water resources, increasing water pollution and growing demand for water as the population increases. Participants also suggested that climate change is making these pressures worse, further limiting the availability of water for fish farming. Furthermore, they highlighted the vulnerability of freshwater aquaculture to diminishing water resources and suggested both technological and institutional responses. While improved aquaculture system design (e.g., water-saving technologies) was seen as a potential solution, there were calls for policy-level reforms, particularly regarding the regulation of underground water abstraction. The unregulated proliferation of boreholes poses a risk to aquifer stability and long-term water security. Effluent management also emerged as a critical issue. The release of waste feed, faecal matter, and pharmaceuticals into surrounding water bodies not only degrades water quality but also threatens fish health and productivity. Participants emphasised the need for stronger environmental guidelines, farmer training on effluent management, and broader adoption of best practices in water use efficiency.

3.4. Climate-Related Vulnerabilities in Fish Transportation and Distribution

Participants identified transportation and distribution as a critical stage in the aquaculture value chain that is increasingly vulnerable to climate change impacts. The majority of aquaculture operations in Kenya are located in rural areas, and harvested fish must often be transported over long distances to reach markets and consumers in urban centers. Participants reported that elevated ambient temperatures during transport, attributed to climate variability, have led to increased fish spoilage. The most common issues cited were tissue decomposition, rancidity, and microbial contamination, particularly during extended transit times without adequate cold chain infrastructure. Compounding these risks is the poor quality of rural road infrastructure. Climate-induced flooding events were reported to cause severe road inaccessibility, significantly delaying deliveries and leading to post-

harvest losses. Participants emphasized that these losses are likely to increase in frequency and scale as climate variability intensifies, unless resilience measures are introduced into the transportation system.

A specific challenge affecting the transport of sensitive aquaculture products, such as fish fingerlings, is the decline in the use of polyethylene bags, a common packaging method involving water and medical oxygen. The enforcement of Kenya's plastic bag ban [62] has complicated traditional transport methods, leading many farmers to revert to less accessible or costlier alternatives such as mobile-aerated tanks. However, the adoption of these alternatives is constrained by limited availability and technical expertise, particularly among smallholder operators.

Participants called for improved monitoring and management of hazard-critical control points, including those related to flooding and heat extremes, through enhanced forecasting and transportation planning. Access to timely and localised weather information was identified as essential for helping farmers schedule transport more effectively and reduce climate-related losses. A notable initiative to reduce transport-related losses was one by the Aquacultural Association of Kenya, in partnership with the State Department of Fisheries, Aquaculture and the Blue Economy. This initiative involved the distribution of motorbikes fitted with cooler boxes to smallholder farmers as a means of maintaining fish freshness during transport. While this intervention was initially successful in reducing spoilage, participants noted that only about half of these motorbikes remained in active use, citing maintenance issues, operating costs, and limited program scale. Nevertheless, this model was viewed as a promising entry point for climate adaptation and considered a scalable solution with appropriate support and investment.

The study also revealed important gender dynamics within the fish distribution node of the value chain. Traditionally, women have played a central role in post-harvest processing and local fish trade, often traveling long distances to reach markets. However, increased climate-induced constraints such as extreme heat and poor road conditions have disproportionately impacted women's ability to participate in fish transportation and trade. In contrast, men and youth, who have greater access to mechanized transport (e.g., motorbikes), are increasingly dominating this aspect of the value chain. This shift was said to be especially pronounced in arid and semi-arid counties such as Machakos in the Lower Eastern region, where prolonged droughts and extreme temperatures have made traditional market access by foot particularly difficult for women. Participants expressed concern that climate change is not only disrupting transportation infrastructure but also exacerbating gender inequalities within aquaculture livelihoods, necessitating more inclusive adaptation planning and targeted support for women traders.

3.5. Climate Vulnerabilities in Post-Harvest Handling and Storage

The fourth element of the aquaculture value chain identified by participants as particularly susceptible to climate change impacts is the post-harvest stage, which includes processing, preservation, and storage. Across the study sites, four main post-harvest techniques were reported: sun drying, smoking, salting, and frying. Among these, sun drying emerged as the most widely used method due to its low capital requirements. However, it is also the most climate-dependent and hence highly vulnerable to changing weather patterns. Variability in temperature, humidity, and rainfall can undermine the effectiveness of sun drying, leading to quality deterioration and post-harvest losses.

A significant limitation reported by stakeholders was the general lack of cold storage and preservation infrastructure among aquaculture producers in Kenya. At the time of data collection, participants noted that modern cold storage systems were almost non-existent in smallholder operations. Victory Farms was cited as the only known commercial operation

with a functioning cooling facility. The government has constructed mini fish-processing plants in four high-production areas—Tetu and Imenti (Central Kenya), and Lurambi and Rongo (Western and Nyanza regions). However, these facilities were reported to be operating below capacity due to low production volumes in the surrounding areas and poor operational management. As a result, smallholder fish farmers continue to rely on traditional preservation methods or delay harvesting until favorable market conditions arise, in an attempt to minimize post-harvest losses.

A recurring theme in participant discussion was the lack of financial support mechanisms to improve post-harvest infrastructure. Most small-scale farmers do not have access to credit or affordable financing options that would allow them to invest in cooling, preservation, or transport facilities. The absence of affordable cold chains increases the risk of spoilage during storage and transport, especially under conditions of rising ambient temperatures. Participants emphasized the urgent need for financial institutions such as cooperative societies and microfinance banks to offer accessible loan products tailored to smallholder aquaculture. These could enable the acquisition of preservation and storage equipment. Also, resource pooling and cooperative investments among farmer groups were identified as potential strategies to fund long-term infrastructure investments and reduce post-harvest vulnerabilities.

3.6. Towards a Collaborative Framework for Climate Resilience in Aquaculture Value Chains

The identification of four critical stages within the aquaculture value chain, namely feed production, fish production, transportation and distribution, and post-harvest handling, as highly vulnerable to climate change provides an important basis for informing action. However, for this insight to effectively guide building resilience, it must be complemented by clear strategies and assigned responsibilities. This is particularly relevant in the African context, where institutional roles in climate adaptation are often fragmented or unclear, and many interventions suffer from lack of coordination and follow-through.

To address this gap, we propose an integrated framework that aligns the four value chain stages identified in this study with established adaptation pathways based on [63]. The purpose of this framework is to guide stakeholders in identifying appropriate adaptation strategies tailored to specific value chain vulnerabilities and to clarify the types of organizations and actors that should lead or support implementation efforts. An initial draft of this framework was presented and discussed during a stakeholder validation workshop. While the feedback was largely positive, further refinement through community-level consultations is recommended to ensure contextual relevance and uptake. The proximity of each adaptation pathway to a value chain node in the framework reflects its relative importance for addressing climate-related hazards at that stage. This structured approach is intended to foster cross-sectoral collaboration, enhance policy coherence, and support targeted capacity-building interventions across the aquaculture sector.

The framework presented in Figure 6 maps each value chain stage to one or more adaptation pathways (e.g., ecosystem-based, behavioral, institutional, or infrastructural) and identifies key stakeholder categories responsible for promoting climate resilience. For instance, feed production is closely aligned with ecosystem-based adaptation, behavioral change, and policy and regulatory interventions. As such, actors such as feed manufacturers and importers, aquaculture feed quality control agencies, and agricultural research institutions are highlighted as central collaborators.

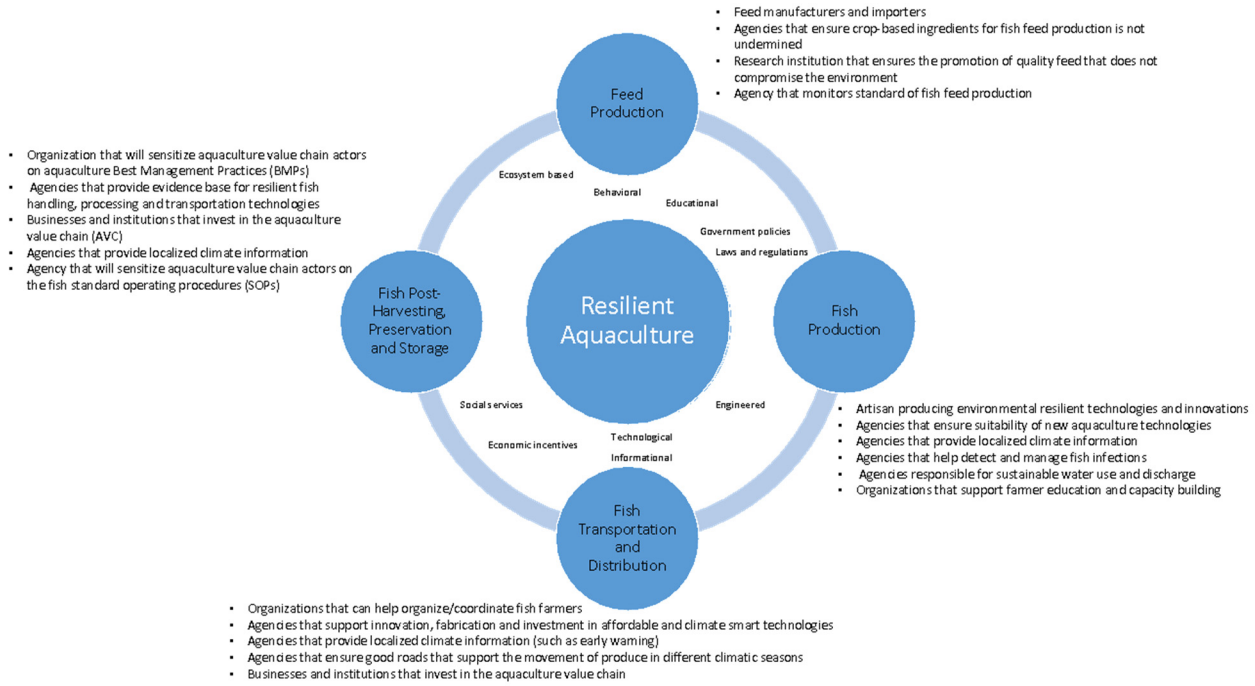

Figure 6. A framework for climate-resilient aquaculture.

4. Discussion

This study identified four critical components of the aquaculture value chain in Kenya that are most vulnerable to climate change: feed production, fish production, transportation and distribution, and post-harvest processing. Building on this, we propose a framework that integrates these value chain elements with established climate adaptation pathways [63], aimed at guiding collaborative and multi-stakeholder action for a climate-resilient aquaculture sector.

The emphasis on collaboration aligns with existing evidence across diverse sectors highlighting the necessity of multi-actor involvement in climate resilience efforts [64–66]. Our framework serves to support the identification of key stakeholders at each stage of the aquaculture value chain and outlines their potential roles in fostering resilience. Notably, the aquaculture value chain is not confined to national boundaries. This is particularly evident in Kenya's dependence on imported fish feed. As such, international actors must also be seen as integral to resilience-building strategies. However, collaborative action in the aquaculture sector, as in other domains, remains complex. As Berkes (2009) [67] observed, coordinating stakeholders with divergent interests in environments marked by distrust and institutional fragmentation can be difficult, particularly in settings where political and socio-economic inequalities shape participation. This study reinforces the need for platforms such as producer associations and cooperatives, which can serve as vehicles for coordination, trust-building, and co-production of climate-resilient infrastructure. Evidence from Kenya suggests that there is a growing willingness among actors to engage in such collective efforts. Ostrom and Ahn (2009) [68] argue that social trust and cooperation are essential for the governance of common-pool resources, such as fisheries—an insight that resonates strongly with our findings. Despite the risks posed by climate hazards, some impacts have also catalyzed cooperation among farmers. Field data revealed that smallholder farmers have implemented innovative solutions, including raised wooden and concrete ponds and recirculating aquaculture systems. These represent localized adaptive responses to climate risks and show strong potential for replication and also for working together among stakeholders. To further strengthen resilience, access to quality inputs

(seed and feed), timely climate information, credit, and insurance is essential [43]. The development of farmer field schools and aquaculture hubs could provide a structured space for knowledge-sharing, service delivery, and investor engagement. Encouragingly, Kenyan farmers appear receptive to forming such collaborative platforms, which can enhance creditworthiness and unlock access to formal financial systems.

A significant finding of this research is the gendered disparities that influence vulnerability and adaptation capacity. Consistent with earlier studies [69–71], our results highlight how structural barriers reduce the adaptive capacity of women in aquaculture. Addressing these inequalities is essential to achieving a truly resilient aquaculture sector. Potential pathways for addressing this could include expanding the role of women and marginalized groups in aquaculture governance through networks such as women-led networks that promote participatory decision-making processes, and support for equitable representation to enhance sector-wide responsiveness to climate challenges. This includes ensuring participation across different scales of production (small, medium, and large) and across socio-economic strata (from low- to high-income farmers). Secondly, there is a need for capacity building that promotes technical training and knowledge exchange for disadvantaged groups through community-led learning approaches. "Learning by doing" strategies can help reduce dependency on external actors, build local ownership of adaptive practices, and improve the uptake of appropriate technologies.

Our findings show that aquaculture practices can also inadvertently contribute to environmental degradation, thereby compounding climate risks. A case in point is the mismanagement of effluents, which can lead to the blockage of water channels and increased flooding. Although aquaculture contributes less to greenhouse gas emissions than sectors such as livestock farming [72,73], its environmental footprint, especially from unmanaged effluents, remains significant. This underscores the need for effective effluent management strategies in aquaculture. Ultimately, the sustainability and resilience of feed production systems hinge on the ability of various stakeholders, including environmental regulators, aquaculture extension officers, systems engineers, and producers, to coordinate efforts. The National Environment Management Authority (NEMA) is the lead regulator responsible for overseeing effluent discharge. However, beyond regulation, there is a critical need to promote Best Management Practices (BMPs), including integrated aquaculture systems that enable the reuse of waste nutrients [74,75]. Implementation of such practices falls under the mandate of the State Department for Blue Economy and Fisheries and requires enhanced farmer education, technical capacity building, and multi-sectoral collaboration. Therefore, building climate-resilient aquaculture systems requires both technological innovation and institutional cooperation to ensure the integrity of the feed supply chain. These findings point to the double-edged nature of aquaculture: while it holds potential for climate adaptation and food security, it must be carefully regulated to prevent maladaptive outcomes. Effective waste management policies and environmental safeguards are necessary across the value chain.

Finally, while the study presents the value chain as a segmented framework for analysis, it is important to recognize that these stages are deeply interconnected. Disruptions or poor management in one segment—such as inadequate waste treatment—can have cascading effects on others, such as water scarcity or disease in fish production systems. This reinforces the need for a holistic, systems-oriented approach to building climate-resilient aquaculture infrastructures.

The proposed framework is generic in nature and is informed by the Kenyan case study. While it provides a useful starting point for understanding the key adaptation approaches that can be adopted to promote resilience at different stages of the aquaculture value chain and the type of organisations that should be engaged with, its applicability and

transferability to other contexts require critical consideration. The four stages identified reflect the fundamental components of a relatively developed aquaculture system and may therefore offer a useful reference point for countries with similar sectoral characteristics and developmental contexts to Kenya. However, the framework should not be assumed to capture the full complexity of aquaculture systems and value chains across different developmental, institutional and economic settings.

In particular, the four stages identified in the Kenyan case study may be differentiated into a greater number of stages in other contexts, with additional sub-stages and specialised actors emerging within each. For example, fish health, biosecurity and welfare; waste management and resource recovery; and certification and quality assurance may constitute distinct stages or areas of activity in more established or differently structured aquaculture systems. These elements did not emerge as major themes in the Kenyan case study and, consequently, are not represented as prominent components of the framework. Their relative absence should not, however, be interpreted as evidence of their limited relevance to aquaculture more broadly. Rather, it reflects the particular priorities, institutional arrangements and sectoral characteristics captured through the Kenyan research.

The framework is best understood as a contextually grounded and potentially adaptable analytical starting point, rather than a definitive or universally applicable representation of the aquaculture value chain. Its primary contribution lies in providing an initial structure for identifying adaptation strategies for key stages and associated organisations. When applied beyond Kenya, particularly in other African contexts, the framework should be reviewed to account for differences in the level of aquaculture system development and institutional arrangements.

Future research should therefore test and refine the framework across a broader range of developing and developed country contexts. This would allow for the identification of more robust stages and confirm the appropriateness of strategies proposed across each stage of the value chain. Such validation would help strengthen the framework's analytical robustness and explanatory value. Ultimately, the framework should be regarded as an initial conceptual contribution that can be iteratively refined through application and empirical validation across diverse settings.

5. Conclusions

This paper used the case of aquaculture in Kenya to examine the specific stages of the aquaculture value chain most vulnerable to climate change. It presents a framework for building climate resilience across the value chain through a collaborative, multi-stakeholder approach, identifying both relevant actors and suitable adaptation pathways for each stage. In doing so, the study addresses a notable gap in knowledge around the co-production of climate-resilient aquaculture infrastructure. While promoting collaboration, we acknowledge the inherent challenges such as power imbalances and institutional fragmentation, but our findings also reveal promising signs of stakeholder openness and existing grassroots initiatives that support collective action.

Given the growing role of aquaculture in ensuring food security and its vulnerability to climate-related risks [19,76], the integration of targeted resilience strategies is essential to safeguard its sustainability. A climate-resilient aquaculture sector may also serve as a catalyst for attracting further investment. As this paper puts forward a proposed framework, future research should focus on refining and applying this model in different geographic and institutional contexts to test its broader applicability and impact.

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O.A. and M.G.; data curation, O.A.; writing—original draft preparation, O.A., M.G. and P.O.; writing—review and editing, O.A., M.G. and P.O.; visualization, O.A.; supervision, O.A. and P.O.; project administration, O.A. and M.G.; funding acquisition, O.A. and M.G. All authors have read and agreed to the published version of the manuscript.

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