

Climate adaptation and decision support for resilient aquaculture in Asia and Africa

2025



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Contents

Highlights	4
Executive summary	5
1. Introduction	7
1.1. Aquatic foods for inclusive development	7
1.2. Aquatic food production in Bangladesh, Kenya, and Zambia	7
1.3. Climate vulnerability of aquaculture systems in Bangladesh, Kenya, and Zambia	9
1.4. Need for climate adaptation practices in aquaculture	10
1.5. Adaptation Decision Support System for Aquaculture (ADSS 4 Aqua): Concept and potential	10
2. Objectives	11
3. Methodology	12
3.1. Geographic focus and aquaculture prioritization	12
3.2. Overall approach	12
3.3. Literature search	12
3.4. Inclusion and exclusion criteria	13
3.5. CAP module	13
3.6. Synthesis and reporting	14
4. Results	15
4.1. Profiling aquaculture CAPs in Bangladesh, Kenya, and Zambia	15
4.1.1. Characteristics of CAPs	15
4.1.2. CAP thematic areas and impact pathways	16
4.1.3. Readiness and availability of CAPs	16
4.1.4. Gaps	17
4.2. Designing an effective Adaptation Decision Support System for Aquaculture (ADSS 4 Aqua)	21
5. Conclusion and way forward	23
References	24

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Highlights

Addressing climate risks in aquatic food systems requires integrating locally relevant adaptation practices into a structured decision-support framework.

This rapid review identified 32 climate adaptation practices (CAPs) across Bangladesh, Kenya, and Zambia, with 15 already validated and embedded in national programs or policies.

Despite the multisectoral climate-smart potential of identified CAPs, adaptation efforts remain predominantly production-centric. There is a critical gap in post-harvest, value addition, and food system-level interventions needed to translate climate-resilient production into sustained income, nutrition, and market resilience.

An Adaptation Decision Support System for Aquaculture (ADSS 4 Aqua) can accelerate the identification, selection, and scaling of climate-adaptive innovations, technologies, and enabling measures at scale.

ADSS 4 Aqua would provide a multidomain, evidence-driven platform linking climate-risk analytics, context-specific adaptation options, and institutional enablers to guide policy and investment decisions. Significant and sustained investments are required to develop, pilot, and operationalize ADSS 4 Aqua, ensuring stronger resilience of aquatic food systems to climate change.



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Executive summary

To meet rising global demand for aquatic foods will require a 22% increase in supply by 2050. Asia will need 12% more and Africa 74% more just to maintain 2022 per capita consumption levels. In Bangladesh, Kenya, and Zambia, specifically, aquaculture holds significant potential to contribute to economic growth, employment, food and nutrition security, and gender empowerment. However, increasing exposure to climate-induced hazards is undermining productivity, livelihoods, and the resilience of aquatic food systems, and investments in climate adaptation fall far short of what is needed.

The objective of this study is to synthesize existing literature on climate adaptation practices (CAPs) in the aquaculture sectors of Bangladesh, Kenya, and Zambia, and to inform the development of an Adaptation Decision Support System for Aquaculture (ADSS 4 Aqua). The qualitative review provides a consolidated understanding of emerging and context-specific adaptation options and proposes a strategic framework to support evidence-based, climate-resilient aquaculture development. The findings are intended to guide policymakers and development partners in designing pilot interventions, formulating responsive policies, and prioritizing future investments in climate adaptation within the aquaculture sector.

The review covers diverse ecological and production contexts. A five-step approach was used:

1. defining research boundaries
2. developing a CAP classification module
3. identifying and screening literature
4. consulting stakeholders through ongoing CGIAR and bilateral programs
5. extracting, synthesizing, and reporting themes.

Literature searches focused on peer-reviewed and grey sources, supported by inclusion and exclusion criteria. CAPs were analyzed across technological, managerial, institutional, and socioeconomic dimensions, as well as performance and outcome indicators, impact pathways, maturity stages, and availability under temporary research and development (R&D) or permanent policies.

Although a broad range of adaptation options has been identified globally, this review focuses exclusively on those implemented in Bangladesh, Kenya, and Zambia and are supported by empirical evidence. The review identified 32 CAPs across the three countries. Adaptations in culture systems and management practices dominate (41%), followed by fish feed, health and disease (16%), and breeding and genetics (14%). Interventions in social and economic inclusion, market and supply systems, and nutrition and public health constitute about one-fifth (20%) of CAPs, while no post-harvest or value-addition practices were identified.

Nearly half of the CAPs are classified as innovations, with enablers such as climate information services, farmer training, and supportive policies emerging as critical determinants of adoption. Nearly two-thirds (64%) of CAPs are in the validation stage, and about one-quarter (26%) remain under testing. Two-thirds (67%) are accessible through time-bound research and development initiatives, while nearly one-third (30%) are fully institutionalized within permanent programs or policies. CAPs demonstrate multisectoral benefits and generate impacts across production, food systems, and ecosystems.

Across the three countries, 15 of the 32 CAPs have reached the validation stage and are supported through permanent mechanisms. These include genetic improvement, integrated farming, diversified climate-resilient production systems, fish health and biosecurity, operational adjustments, renewable energy integration, and water-efficient resource management. Bangladesh shows the widest and most mature portfolio, particularly in selective breeding, integrated systems, brackish water diversification, clustered farming, and infrastructure adaptation. Kenya and Zambia have shown strong progress in integrated agriculture–aquaculture systems, cage culture, aquaponics, periphyton technology, and water reuse models.

Building on these insights, this report proposes using ADSS 4 Aqua—an integrated, multidomain framework designed to support evidence-based, climate-informed decision-making in aquaculture. It comprises four interconnected domains:

1. **Risk:** hazard identification and climate-risk analytics
2. **Adaptation:** context-specific practices, technologies, and approaches
3. **Knowledge/enabler:** tools, evidence, and institutional support
4. **Decision:** synthesizing inputs to generate robust adaptation pathways.

ADSS 4 Aqua is envisioned as an inclusive, participatory and dynamic system capable of guiding policy, investment, and planning toward proactive climate-resilient aquaculture.

Future directions have several requirements:

- locally contextualized starting points and tailored implementation pathways for each country
- strategic, multisectoral partnerships for co-design and scaling
- targeted investment in integrated data and modeling systems
- embedding of ADSS 4 Aqua into National Adaptation Plans (NAPs) and aquaculture policies
- prioritizing inclusivity and accessibility
- piloting, evaluation, and iterative improvement.

1. Introduction

1.1. Aquatic foods for inclusive development

Aquatic foods originate from thousands of species of aquatic animals, plants, and microorganisms living in inland, coastal, and marine ecosystems, producing a wide variety of foods throughout the year and across diverse geographic regions (Blue Food Assessment 2021; Golden et al. 2021; FAO 2024). Aquatic food systems encompass all the elements and processes related to foods derived from aquatic environments, embedded within broader economic, social, and ecological contexts. The systems cover every step from producers to consumers, as well as outcomes related to nutrition, public health, food security, socioeconomic well-being, and environmental sustainability (WorldFish et al. 2020).

Worldwide, more than 2,500 species of aquatic animals and plants are captured or cultured for food (Blue Food Assessment 2021). Global fisheries and aquaculture production increased from 19 million MT in 1950 to 185.4 million MT in 2022 (FAO 2024). Aquaculture is the fastest-growing food-producing sector and is often promoted as a solution for meeting the growing food demands, producing 130.9 MT in 2022, accounting for 59% of global fisheries and aquaculture production (FAO 2024).

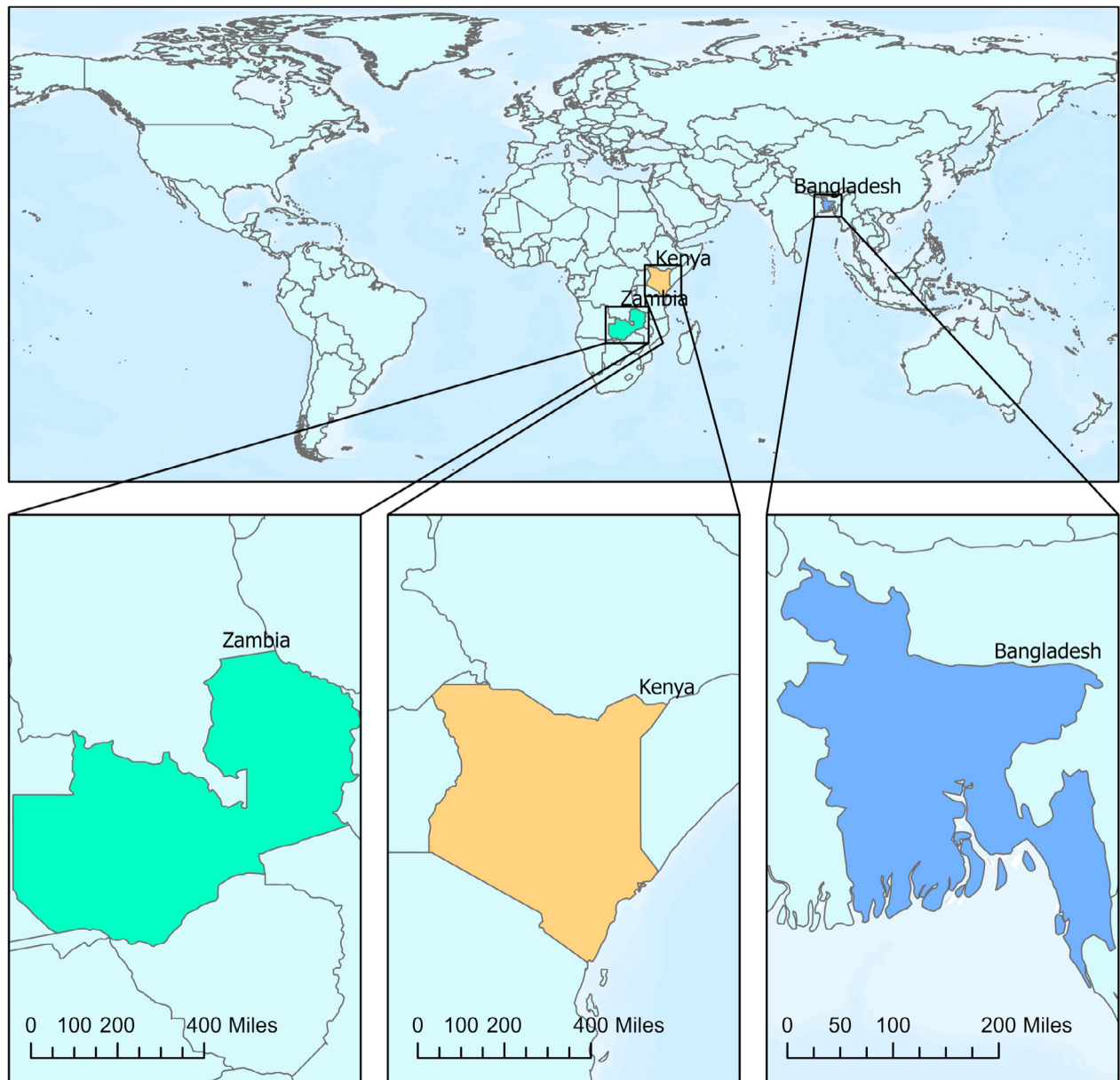
In 2022, aquatic foods supplied 15% of animal protein globally, and the value of international trade of aquatic products was USD 195 billion (FAO 2024). Aquatic food systems are key to achieving the UN Sustainable Development Goals (SDGs), driving a more sustainable and equitable global food future (Blue Food Assessment 2021; Hasselberg et al. 2024). In addition to having relatively low emissions of greenhouse gases (GHGs) compared to terrestrial foods (Gephart et al. 2021; Stanford Center for Ocean Solutions et al. 2024), aquatic food systems are important for the livelihoods, food and nutrition security, economies, and cultures of many nations, particularly developing countries (Tigchelaar et al. 2022; Crona et al. 2023; Koehn et al. 2023; Rockström et al. 2025). For instance, FAO (2024) estimated that the fisheries and aquaculture sector employed 61.8 million people worldwide in 2022.

However, aquatic ecosystems and aquatic food systems both face rising risks and disturbances from the worsening climate crisis on a global scale, which is further exacerbated by growing anthropogenic pressure on the ecosystems (Vitousek et al. 1997; Brander 2007; Allison et al. 2009; Holmyard 2014; Lam et al. 2016; Tigchelaar et al. 2021; Maulu et al. 2021). The average annual growth rate in world fisheries and aquaculture production decreased from 4.62% in 1950–1990 to 1.62% in 1990–2022 (FAO 2024). Lam et al. (2016) predicted that global fisheries revenues will decline up to 35% by 2050. Under a high carbon dioxide emission scenario, global marine catch will decline by 16%–25% (Cheung et al. 2018), and mariculture production will decline 16% (Oyinlola et al. 2021) by the end of the 21st century. The impacts of climate change increase the complexity and uncertainty of aquaculture systems, which can result in various unfavorable conditions affecting socioeconomic outcomes and management of natural resources (Galappathth et al. 2020).

1.2. Aquatic food production in Bangladesh, Kenya, and Zambia

With the world population projected to reach 9.7 billion by 2050, meeting the rising demand for aquatic animal foods will require a 22% increase in global supply, with Asia needing 12% more and Africa facing a 74% rise to maintain per capita consumption at 2022 levels (FAO 2025). Bangladesh, Kenya, and Zambia are categorized as developing nations and belong to the lower-middle-income group, according to the World Bank's classification in 2024 (Metreau et al. 2025). The aquatic food production of these countries holds significant potential to support each nation in terms of economic development, creating jobs, improving livelihoods, earning foreign currency, combating malnutrition, enhancing food security, and empowering women. These countries rank among the top 25 global producers of inland capture fisheries and also have significant inland aquaculture production (FAO 2024). Although Bangladesh ranks among the world's leading aquaculture producers, Kenya and Zambia contribute more modestly to global aquaculture output but still play important regional roles in inland aquaculture.

Figure 1. Location map of Bangladesh, Kenya, and Zambia.



Located in South Asia, Bangladesh has extensive inland and marine capture fisheries, along with a rapidly growing aquaculture industry. Globally, the country ranks second in inland capture fisheries and fifth in aquaculture production and is listed among the top 25 major producers in marine capture fisheries (FAO 2024).

In Kenya, an East African country, both inland and marine waters provide vast potential for improved aquatic food systems. Although annual fish production and consumption per capita are below the targets (Omukoto et al. 2024; KeFS 2025), the country's fishery industry has shown a gradual increase in capture fisheries production and freshwater and marine farming (Munguti et al. 2014; Opiyo et al. 2018; Emam et al. 2024; KeFS 2025).

Zambia, a landlocked country in Southern Africa, has shown significant potential for inland capture fisheries and opportunities for the development of aquaculture in both the small-scale and large-scale sectors (Tran et al. 2019; Kaminski et al. 2022; Zhang et al. 2024).

Table 1 outlines the contribution of aquatic food production to the economy, livelihoods, and food and nutrition security in Bangladesh, Kenya, and Zambia. Kenya, with both freshwater (13,600 km²) and marine (142,400 km²) resources, produces 168,424 MT of fish, slightly below Zambia's 170,000 MT, which relies solely on inland waters with a vast area of 230,000 km², highlighting potential underuse of aquatic resources in both countries. In contrast, with 47,290 km² of inland and 118,813 km² of marine waters, Bangladesh dominates total production, at 5,018,483 MT, driven by large-scale aquaculture (2,978,064 MT) alongside inland (1,411,796 MT) and marine capture (628,623 MT) fisheries. Zambia's aquaculture production (75,000 MT) is more than double Kenya's (33,423 MT), but both lag far behind Bangladesh, reflecting limited adoption of intensive aquaculture practices and constrained access to quality inputs.

Table 1. Contribution of aquatic food systems to the economy, livelihoods, food, and nutrition in Bangladesh, Kenya, and Zambia.

SI	Attributes	Bangladesh	Kenya	Zambia
1	Inland water area (km ²)	47,290	13,600	230,000
2	Marine water area (km ²)	118,813	142,400	N/A
3	Inland capture production (MT)	1,411,796	86,527	105,869
4	Marine capture production (MT)	628,623	48,474	N/A
5	Aquaculture production (MT)	2,978,064	33,423	89,342
6	Total production (MT)	5,018,483	168,424	195,211
7	Fish and fishery products exports (MT)	77,408	8,616	N/A
8	Foreign currency earnings (million USD*)	371.6	45.3	N/A
9	Contribution to national GDP (%)	2.5	0.7	3.8
10	Annual per capita fish consumption (kg)	24.75	2.93	13.2
11	Contribution to animal protein supply (%)	60	6	55
12	Number of people involved (million)	>20	1.2	>1

Source: Bangladesh (DoF 2025; FRSS 2024), Kenya (Rasowo et al. 2020; Munguti et al. 2023; Walakira et al. 2023; KeFS 2025), and Zambia (WorldFish 2024; Katongo et al. 2024; Ministry of Fisheries and Livestock 2024; FAO 2025).

*As of 12 October 2025, according to Xe Currency Converter: 1 BDT= 0.0082 USD, 1 KES=0.0077 USD, and 1 ZMW= 0.0442 USD.

1.3. Climate vulnerability of aquaculture systems in Bangladesh, Kenya, and Zambia

Climate change has been reported to negatively affect aquaculture systems in the three study countries. In Bangladesh, climate hazards impact aquatic food systems, including temperature rise, sea-level rise, salinity intrusion, intense rainfall, severe floods, droughts, cyclones, extreme weather events, water quality fluctuations, and disease outbreaks (Siddique et al. 2022; Parvin et al. 2023; Haque et al. 2025). In addition, climate drivers pose various threats to inland production (Bin Aziz et al. 2021; Islam et al. 2024; Haque et al. 2025), marine fisheries (Haque et al. 2025; Hasan et al. 2025), finfish and shellfish aquaculture (Ahmed and Diana 2015; Ahmed and Diana 2016; Islam et al. 2018; Islam et al. 2019; Sunny and Prapti 2022; Islam et al. 2024; Haque et al. 2025), hatchery productivity (Alam et al. 2021; Siddique et al. 2022; Islam et al. 2019; Islam et al. 2024) and the livelihoods of fishers and fish farmers (Dasgupta et al. 2017; Davis et al. 2018).

In Kenya, impacts of climate such as extreme changes in temperature, rainfall, floods, droughts, and sea-level rise have all affected the country's aquaculture sector (Gesami and Nunoo 2024; Mwangi et al. 2024). Climate change and variabilities have also been negatively impacting the Kenyan aquaculture industry (Adekola et al. 2022; Muthoka et al. 2024; Mwangi et al. 2024; Magesi et al. 2024; Magesi et al. 2025).

Zambia's aquaculture sector has faced similar impacts of climatic variables, such as rising temperature, change in rainfall patterns, cyclone frequency, floods, droughts, water level reduction, and disease outbreaks (Kalantary 2010; Ng'onga et al. 2019; Maulu et al. 2024). Here, too, climate change variables have been negatively impacting the country's aquaculture sector (Kakwasha et al. 2020; Lundeba et al. 2023; Manoti et al. 2024; Chileya 2024; Maulu et al. 2024), resulting in economic losses and food insecurity. With relatively limited access to financial and technical resources, adaptive capacity, and knowledge of climate change, smallholder farmers in particular are vulnerable to climate change (Kakwasha et al. 2020; Lundeba et al. 2023; Manoti et al. 2024; Maulu et al. 2024).

1.4. Need for climate adaptation practices in aquaculture

The Intergovernmental Panel on Climate Change (IPCC) defines climate adaptation as the process of adjustments in human and natural systems to actual or expected climate and its effects (IPCC 2022). CAPs are actions taken at the local, national, and global level to adjust to current and/or future climate change impacts, aiming to minimize harm and exploit opportunities. In aquaculture, CAPs refer to adaptive interventions and strategies taken to sustainably enhance aquaculture production while reducing climate risks and enhancing resilience, including measures targeting production, livelihoods, value chains and ecosystem sustainability (Cortest et al. 2025). For example, reports suggest that integrated agriculture–aquaculture systems (IAA) are an effective local-level adaptation practice to enhance production (Hasimuna et al. 2023; Lundeba et al. 2023b). Despite challenges, several adaptation practices are used in aquaculture, especially technologies and innovations such as selective breeding, feed formulation, integration of renewable energy, integrated multitrophic aquaculture (IMTA) systems, digital decision support systems (DSS), and digital water quality monitoring systems (Cortes et al. 2025; Haque et al. 2025). However, relevant and effective measures vary with local context, climate impacts, and associated risks (Chowdhury et al. 2022), so climate adaptive practices need to be locally rooted, context-specific, and tailored to address risks for a specific geography, system, or location.

Although the aquatic food sector's vulnerability to climate change is being increasingly recognized, investment in climate adaptation for fisheries and aquaculture remains substantially inadequate (FAO 2024). FAO estimates that adaptation in the aquatic food sector across developing countries will require approximately USD 4.8 billion annually by 2030. Currently, there is a pronounced financial gap, with only an average of USD 200 million per year of international public adaptation finance allocated to this sector between 2017 and 2021 (FAO 2024). Although a wide range of climate adaptation and mitigation options and their associated trade-offs have been identified for aquatic food systems, their translation into practice remains limited. Climate adaptation in aquaculture is inherently complex, with a key risk being maladaptation—interventions intended to reduce climate impacts that instead exacerbate vulnerability or generate unintended adverse consequences (Falconer et al. 2025).

1.5. Adaptation Decision Support System for Aquaculture (ADSS 4 Aqua): Concept and potential

Adapting fisheries and aquaculture to climate change requires a better understanding of which adaptations are necessary, already occurring, effective, and viable (Galappaththi et al. 2020, 2021), as well as those that require additional support and development to manage ongoing and future industry challenges. The continuing impacts of climate change will increase the complexity and uncertainty of aquaculture systems, potentially leading to diverse unfavorable conditions, such as social, ecological, and economic impacts (Johnson et al. 2019). Therefore, aquaculture operations must respond innovatively to adapt quickly and thoroughly, both mitigating challenges and harnessing new opportunities. However, despite growing attention to the human dimensions of climate change adaptation, there is a scarcity of targeted research on how adaptation decisions are assessed, guided, and implemented within the aquaculture sector. This gap underscores the need for adaptation decision support systems (ADSS) capable of systematically evaluating options, informing decision-making, and strengthening climate-resilient aquaculture development.

ADSS are tools and/or platforms that guide the decision-making process in identifying and managing climate risks and responses to promote adaptation and sustainability in complex, uncertain, or changing environments (Palutikof et al. 2019; Holsapple et al. 1993). These systems are adaptive to the local context, user-centric, and capable of self-learning and complex problem-solving by integrating various analytical tools, data sources, and models into a single interface (Palutikof et al. 2019; Chuang and Yadav 1998; Fazlollahi et al. 1997; Holsapple et al. 1993). In aquaculture, ADSS are methods, knowledge resources such as real-time data, software tools, guidance, best practices, scientific information, and data-driven insights that facilitate decision-making processes for adaptation to climate change. ADSS, such as climate-information systems (CIS), can play a crucial role in promoting climate-smart aquaculture systems in response to climatic variability (Hossain et al. 2021). Unfortunately, aquaculture lags behind other domains in developing as well as adopting such systems for climate adaptation (Stavrakidis-Zachou et al. 2021).

ADSS are essential for climate adaptation, risk reduction, and inclusive policy development in aquatic food systems. They provide evidence, forecasts, and alerts that inform strategic adaptation planning and enable data-driven decision-making across the aquaculture sector.

ADSS comprise decision support tools, adaptation platforms, and frameworks that guide best management practices under changing climatic conditions. These tools include analytical methods, knowledge resources, and cost-benefit analyses that help farmers, researchers, and policymakers evaluate adaptation options, monitor outcomes, and visualize data, such as GIS-based tools (Palutikof et al. 2019).

Emerging digital technologies are enhancing ADSS capabilities. Smart sensors, Internet of Things (IoT), and Artificial Intelligence of Things (AIoT) are increasingly applied in aquaculture for real-time monitoring, automated feeding and aeration, predictive modeling, climate pattern recognition, scenario analysis, and forecasting disease outbreaks under changing climate conditions (Rodríguez et al. 2025; Tina et al. 2025; Abdullah et al. 2024; Liu et al. 2022).

ADSS facilitates knowledge sharing and adaptive capacity building through face-to-face and online forums, peer-to-peer learning, workshops, and case studies. Adaptation platforms connect stakeholders and provide access to climate-information resources, while decision support frameworks offer structured guidance for climate risk management and adaptation planning (Palutikof et al. 2019). Case studies demonstrate how climate services and early warning systems help aquaculture actors make timely, informed decisions.

2. Objectives

The review had the following three objectives:

1. Identify location-specific climate risks and comprehensively profile existing CAPs across aquaculture production systems and geographies.
2. Assess gaps in R&D in the implementation of and evidence supporting aquaculture CAPs to guide future investments, pilots, and research agendas.
3. Identify principles and pathways for developing an ADSS that is specific to aquaculture (ADSS 4 Aqua).

3. Methodology

3.1. Geographic focus and aquaculture prioritization

Bangladesh, Kenya, and Zambia have similar levels of climate vulnerability. Over the period 1993–2022, Bangladesh ranked 31st, Zambia 35th, and Kenya 36th (Germanwatch 2025). The countries represent diverse aquatic environments, offering a comparative lens on how climate-induced stresses affect aquaculture development across ecological and socioeconomic settings. Moreover, there is a growing reliance on aquatic food systems, particularly aquaculture, to ensure food security and livelihood resilience. Although Bangladesh ranks among the top five aquaculture producers, reflecting its success in production intensification, Kenya and Zambia are still in the early stages of aquaculture development. In fact, both African countries hold substantial untapped potential for aquaculture because of their abundant aquatic resources. In all three contexts, however, climate-induced stressors are increasingly threatening aquaculture systems. Thus, the three countries provide an opportunity to address climate change impacts and generate transferable lessons for strengthening aquaculture across varied production levels, ecological contexts, and governance settings.

Aquaculture plays a critical role in national and household nutrition, food security, and rural livelihoods in Bangladesh, Kenya, and Zambia, so understanding how the sector is currently adapting—and where gaps persist—is essential for guiding climate-resilient interventions. To that end, this study focuses on identifying existing, emerging, and viable CAPs in aquaculture across the three countries and assessing how these can inform development of ADSS. The findings aim to strengthen evidence-based planning, guide future investments, and support enabling policies for climate-resilient aquaculture.

3.2. Overall approach

The methodology employed in this study uses a rapid literature review to identify, collate, and synthesize existing and viable CAPs in the aquaculture sectors in these three countries. The review followed a structured, four-step process:

1. **Research questions and study boundaries:** The analytical scope was established at the intersection of climate change, adaptation, and aquaculture, with a focus on smallholder-oriented systems in Bangladesh, Kenya, and Zambia.
2. **CAP module:** A CAP classification module was designed to organize, code, and assess adaptation practices across technological, managerial, institutional, and socioeconomic dimensions.
3. **Identification, screening, and selection of literature:** Relevant studies were identified, screened, and selected based on predefined inclusion and exclusion criteria.
4. **Stakeholder consultation:** Consultations with stakeholders were conducted in conjunction with events organized under the guise of different science programs and relevant bilateral projects. One was a workshop held on 16–17 September 2025, titled Co-Designing Sustainable Futures: Multi-Stakeholder Workshops for Transforming Animal and Aquatic Food Systems in Bangladesh, which fell under the scope of the CGIAR Science Program on Sustainable Animal and Aquatic Food (SAAF). Another was a dialogue held on 22 May 2025, titled Digital Climate Information Systems in Zambia, which fell under the scope of the PROFISHBLUE project funded by the African Development Bank and the SADC secretariat. A third was the inception workshop held in Kenya on 5–9 May 2025 that was part of the Climate-Resilient Aquaculture Systems for Africa (CASA) project funded by the Qatar Fund for Development (QFFD) and the Gates Foundation.

3.3. Literature search

A comprehensive search of published and grey literature from 2010 to 2020 was conducted using Google Scholar as the primary search engine. Search terms included combinations of “climate change”, “fish farming”, “aquaculture”, and “adaptation”. Only English-language sources were considered. Eligible documents included peer-reviewed journal articles, book chapters, technical and project reports, training manuals, and institutional publications. The search strategy intentionally captured interdisciplinary research spanning climate science, aquaculture management, socioeconomics, policy, and aquatic food systems.

3.4. Inclusion and exclusion criteria

The review applied clearly defined inclusion and exclusion criteria to ensure that only relevant evidence informed the analysis. Studies were included if they explicitly examined climate change as an external driver influencing aquaculture systems and documented adaptation strategies, responses, or deliberate actions that farmers, institutions, or other stakeholders undertook to enhance the resilience of freshwater aquaculture. Literature was considered eligible if it focused on Bangladesh, Kenya, or Zambia, or if it presented adaptation approaches broadly applicable to comparable production contexts in these countries.

Studies were excluded if they addressed marine or inland capture fisheries, as these fell outside the scope of the focus on freshwater aquaculture. Research dealing exclusively with agriculture and lacking direct relevance to aquaculture was similarly omitted. Additionally, any studies that did not align with the conceptual framework or geographical boundaries of the review were excluded.

3.5. CAP module

The CAP module served as the conceptual and analytical framework for extracting, collating, and synthesizing data. This module organizes adaptation information into a structured, multidimensional matrix to give a clear understanding of the nature, application, and impact of each CAP.

Following Obiero et al. (2024), CAPs were classified into three broad but interconnected categories: technologies, innovations, and enablers (Table 2). These categories are conceptually distinct yet complementary. Technologies refer to tangible or systemized technical solutions (e.g., tools, systems, or infrastructure) designed to address climate-related production constraints. Innovations, in contrast, encompass novel or improved practices, processes, or organized arrangements that enhance adaptive capacity; these may involve new ways of applying existing technologies or non-technological changes such as management, governance, or social innovations. Enablers represent the institutional, policy, financial, digital, and capacity-strengthening mechanisms that facilitate the development, uptake, and scaling of technologies and innovations. Importantly, while technologies may be innovative at the point of introduction, not all innovations rely on new technologies, and enablers function as cross-cutting systems that support adaptation.

Adaptation practices were mapped across multiple domains of aquaculture management, and each CAP was evaluated using a set of performance and outcome indicators (Table 3). Practices were further analyzed along three impact pathways: production, food system, and ecosystem. To assess scalability and maturity, each CAP was also categorized into different phases, such as idea, design, testing, and validation (Sartas 2020). The framework considered availability, whether it was unavailable, available temporarily through R&D, or available through permanent programs or public policies. It also considered users of the identified CAPs, such as lead organizations, or lead organizations working with partners, government bodies, or farmer groups.

Table 2. Various categories of CAPs.

Category	Description
Technologies	Tools, systems, methods, and technical solutions designed to address climate-related production challenges.
Innovations	New concepts, improved practices, or reconfigurations of existing management approaches that enhance adaptive capacity.
Enabler	Policy interventions, institutional support, digital systems, and capacity-strengthening mechanisms that facilitate adaptation.

Source: Adopted from Obiero et al. 2024.

Table 3. CAP thematic areas and indicators.

Thematic areas	Indicators
<ul style="list-style-type: none"> • Culture systems and management practices • Species selection, breeding, and genetics • Fish nutrition and feed management • Fish health, disease prevention, and biosecurity • Post-harvest loss reduction and value addition • Market access, trade, and supply chains • Social and economic inclusion, including gender and youth participation • Public health and nutrition 	<ul style="list-style-type: none"> • Risk management and resilience • Production and productivity changes • Income and economic viability • Fish health and disease outcomes • Gender and social inclusion • Energy efficiency and low-carbon potential • Post-harvest loss reduction • Market performance and financial access • Business model suitability • Capacity development needs • Environmental sustainability / nature-based solutions • Safety-net or shock-buffering impacts

3.6. Synthesis and reporting

The collated data were analyzed to identify trends, common adaptation practices, key research gaps, and policy-relevant findings across the three focus countries. The synthesis was structured to directly inform and design the ADSS for aquaculture.

4. Results

4.1. Profiling aquaculture CAPs in Bangladesh, Kenya, and Zambia

The rapid review identified 32 CAPs for aquaculture across Bangladesh, Kenya, and Zambia, spanning both on-farm and off-farm domains (Table 4). These countries are adopting diverse solutions to address a broad range of climate concerns, including extreme temperatures, erratic rainfall, salinity intrusion, water scarcity, flooding, and rising carbon footprints. Bangladesh exhibited the highest number of CAPs across both domains, followed by Zambia for off-farm and Kenya for on-farm interventions.

CAPs fall into three main categories: technologies, innovations, and enablers. However, an individual CAP can fall under more than one category. Nearly half of the CAPs (~47%) are innovations—new ideas, improved practices, or reconfigured management approaches. Technologies constitute about 17%, including tools, farm systems, and methods designed to tackle specific climate challenges, and they are often supported by enabling measures such as policy reforms, capacity building, and digital solutions. Digital tools, improved production systems, genetic improvement, and diversified farming models represent prominent technology and innovation pathways. Capacity- and policy-oriented enablers, such as training, climate-informed decision support, business model development, and responsive policy propositions, facilitate sustained adoption of these practices across the three countries.

Bangladesh's higher number of CAPs likely reflects its vulnerability and exposure to a wide range of climate stresses, like temperature extremes, erratic and intense rainfall, tidal inundation, salinization, waterlogging, freshwater scarcity, multiple flood types, and cyclones, as well as ongoing coping mechanisms as a dynamic deltaic country. Additionally, the country's large aquaculture sector plays a crucial role in determining its CAPs. In contrast, Kenya, a country in East Africa with a coastline on the Indian Ocean, faces similar climate threats, but the size of its aquaculture sector somewhat moderates the impacts. Meanwhile, Zambia, as a landlocked country in Southern Africa, faces comparatively fewer but intense climate pressures, primarily from rising temperatures, prolonged drought, changing rainfall patterns, and severe floods. Its relatively growing aquaculture sector also affects the country's approach to climate adaptation.

4.1.1. Characteristics of CAPs

Although a broad range of adaptation options has been identified globally, this review focuses exclusively on practices implemented in the three study countries and supported by empirical evidence. According to the literature, several CAPs are present across all three countries, albeit under different forms or terminologies, including digital decision support systems such as Agvisely in Bangladesh and Blue Resilience in Zambia. Similarly, digital media such as Prokriti O Jibon, Mati O Manush, and Banglar Krishi in Bangladesh, and Shamba Shape Up in Kenya and Zambia provide access to knowledge of climate adaptation in local languages. Species-specific CAPs are in progress and adopted in all three countries. Carps in Bangladesh, Nile tilapia in Kenya, and three-spotted tilapia (kafue bream) in Zambia are all considered resilient species for culture.

Some CAPs exist in diversified forms, such as IAA, insect-based feeds, and protein-enriched feeds. IAA subsystems, which are available in all three countries, include rice–fish/shrimp/prawn culture, rice–shrimp/prawn–finfish polyculture (such as *gher* farming in Bangladesh), fish–other crops farming, fish/shrimp/prawn–vegetable farming, fish–livestock farming, fish–poultry farming, and a combination of these subsystems for multi-outputs. Protein-enriched feeds (sinking and value-added floating), made from plant-based, animal-based, and pellet formulations, are adopted in all three countries. These feeds help improve the efficiency and productivity of aquaculture systems, which is crucial for climate adaptation. By enhancing fish growth and survival rates, they can help mitigate the impacts of changing climate conditions, such as temperature fluctuations, water quality degradation, and reduced availability of natural feed sources. In countries like Bangladesh, Kenya, and Zambia, where aquaculture is a key part of the economy, such feed strategies are vital for sustaining food security and livelihoods in the face of climate-related stresses. For instance, artemia, as live feed culture in Bangladesh, plays an essential role in supporting the early stages of aquatic species like crab, shrimp, and prawn culture and farming, contributing to the overall resilience of coastal aquaculture systems in the face of climate-related stresses, particularly salinization.

Some CAPs are available in two countries. For example, novel insect-based feed from black soldier fly (BSF), recirculatory aquaculture systems (RAS), IMTA, integration of solar energy, and integration of IoT in aquaculture are all found in Bangladesh and Kenya, while artificial propagation is found in both Kenya and Zambia. Some CAPs are available only in one country. For example, clustered shrimp farming using specific pathogen-free (SPF) shrimp / prawn post-larvae (PL), small indigenous species (SIS) with carps (carp-SIS polyculture) and mud crab fattening are only found in Bangladesh, while fingerling pond culture systems and periphyton technology are only found in Kenya.

Since shrimp farming is highly sensitive to water quality and temperature, using SPF PL ensures healthier shrimp with a lower risk of disease. This is significant because warming waters and changing salinity levels can exacerbate disease, while clustering farms in specific areas makes it easier to manage water quality more efficiently and share resources, like monitoring systems, which reduces the impact of erratic rainfall, flooding, and temperature extremes.

Conversely, polyculture systems, such as carps-SIS, provide biodiversity and ecological balance, which enhances the resilience of the system to climate stressors like seasonal floods during monsoons caused by heavy rain. Mud crabs are more resilient to fluctuating salinity and temperature, both of which are increasing because of climate change. This makes them excellent candidates for aquaculture in coastal areas, which are often affected by rising sea levels and extreme weather events like cyclones and floods. It also offers an alternative livelihood for coastal communities, providing a buffer against income loss from more traditional fisheries or agriculture.

4.1.2. CAP thematic areas and impact pathways

The identified CAPs for aquaculture are dominated by culture systems and management practices (41%), followed by fish feed, health and disease (16%), and breeding and genetics (14%) (Table 5). Interventions targeting social and economic inclusion, markets and supply chains, and nutrition and public health collectively account for about one-fifth (20%) of CAPs, while post-harvest and value addition practices for aquaculture have not been reported on. Across all thematic areas, the CAPs exhibit multisectoral climate-smartness, primarily targeting risk reduction, productivity gains, income resilience, gender inclusion, improved nutrition, and lower environmental impacts. Their impact pathways consistently intersect with the domains of production, food system, and ecosystem, indicating a comprehensive adaptation potential across the aquaculture value chain.

For instance, CIS are mostly risk management measures—both on-farm for operational decision-making relevant to culture systems and also off-farm for strategic decision-making that applies to management practices. However, CIS also intersect with production, income, public health and nutrition, capacity, safety nets, finance, and business. For example, a 1% increase in aquaculture production by managing climate risks using CIS could provide 24,000 t of fish for 1 million people, with protein at a recommended daily allowance of 60 g for Bangladesh, and the potential economic value of aquaculture CIS could be up to USD 14 million a year, if appropriate CIS can offset 10% of the damage.

In some cases, CAPs support climate resilience simultaneously through impact pathways at the farm (production), society (food system), and environment (ecosystem) levels. One example is integrated artemia farming, particularly in high saline coastal zones during the dry season. Another example is diversifying aquaculture in the same zone during the pre-monsoon, monsoon, and post-monsoon seasons with shrimp, crab, and tilapia for a year-round culture system. Both examples show how a CAP can have multiple impacts at multiple levels—from production through the socioeconomic system to the ecosystem level.

4.1.3. Readiness and availability of CAPs

Figure 2 illustrates the overall readiness and availability of the identified CAPs. Of all documented practices, 64% are at the validation stage and have undergone field testing or pilot implementation, while 26% are in the testing phase. Only 6% of CAPs are at the idea or concept stage, indicating that most practices have progressed beyond initial development. In terms of availability, 67% are accessible through timebound institutional research, development initiatives, or advocacy programs, whereas 30% have advanced to full validation and are integrated into permanent programs and public policies.

Across Bangladesh, Kenya, and Zambia, 15 CAPs in aquaculture have reached the validation stage and are supported through permanent programs or public policies (Table 6). These CAPs are genetic improvement, integrated farming, climate-resilient production diversification, fish health and biosecurity, operational adjustments, renewable-energy solutions, and water-smart resource management. Bangladesh has the broadest portfolio, particularly in selective breeding, integrated systems, diversified brackish water practices, clustered farming approach, and infrastructure adaptation. Kenya and Zambia contribute

through validated IAA systems, cage culture, aquaponics, periphyton technology, and water reuse models. A common strength across all three countries is the institutionalization of enabling measures such as climate literacy, skilled farmer training, and standardized farm management protocols.

4.1.4. Gaps

This review highlights important progress in identifying and validating CAPs for aquaculture across the three study countries; however, it also reveals substantive gaps in the breadth, balance, scale, and strength of evidence.

Gaps in the coverage of adaptation options are evident across the three countries. Several adaptation practices that are increasingly emphasized in global aquaculture–climate discourse are largely absent or weakly documented in the reviewed countries. These practices include climate-risk-informed spatial planning, climate-resilient hatchery and seed production systems, insurance-linked adaptation, and post-harvest and cold-chain resilience. In particular, adaptation options addressing downstream value-chain vulnerabilities (post-harvest losses, market disruptions, price volatility under climate shocks) are not reported despite their importance for income stability and food-system resilience. Similarly, ecosystem-based adaptation approaches beyond integrated farming, such as wetland restoration linked to aquaculture, remain limited or geographically concentrated.

The review also indicates an overemphasis on on-farm production technologies and management practices, relative to broader resilience-building interventions. Although culture systems, feeding strategies, and breeding innovations dominate the CAP landscape, comparatively fewer practices address institutional resilience, governance, finance, insurance, infrastructure planning, or social protection mechanisms that enable producers to absorb, adapt to, and recover from climate shocks. There is also limited integration of social inclusion, gender, and nutrition objectives across many CAPs.

While most CAPs have progressed beyond the conceptual stage, a validation-to-scale gap remains pronounced. Although 64% of practices are validated and 30% are embedded in permanent programs or public policies, a substantial share continues to depend on timebound projects and external institutional support. This raises concerns regarding long-term sustainability, financial viability, and scalability, particularly for technology-intensive CAPs such as RAS, IoT-enabled systems, IMTA, and digital decision support tools.

Interestingly, validated aquaculture practices are not always validated as climate adaptation practices. Several CAPs, such as IAA, IMTA, improved feeds, cage culture, and selective breeding, have a strong evidence base for enhancing productivity and efficiency under general conditions. However, there is often limited or indirect empirical evidence showing their effectiveness in explicitly reducing climate vulnerability, enhancing resilience to extreme events, or improving recovery after climate shocks.

These evidence gaps highlight that, while existing CAPs may help buffer short-term risks and incremental changes, they are unlikely to fully address intensifying climate extremes, cumulative ecosystem degradation, and systemic market and livelihood disruptions without deeper integration, scaling, and diversification of adaptation strategies.

Table 4. Overview of climate adaptation practices (CAPs) for aquaculture in Bangladesh, Kenya, and Zambia.

CAP (three letter ISO code for the countries*)		Climate concerns confronted	Adaptation category
Off-farm	On-farm		
Climate information and advisory services (BGD, ZMB)	Operational adjustments in fish farming (BGD, ZMB)	Maximum and minimum temperatures, dry spells, heavy and very heavy rain	Innovation**
Digital decision support systems (BGD, ZMB)		Maximum and minimum temperatures, dry spells, heavy and very heavy rain	Technology*** + Enabler**** (Digital)
Training on climate informed decision-making (BGD, ZMB)		High/low temperatures, erratic/intense rain	Enabler (Capacity)
De-risking aquaculture using climate services (BGD)		Extreme heat, cold spells, erratic/intense rain	Enabler (Policy)
Climate responsive policy propositions (BGD)	IMTA (BGD, KEN)	Salinization, carbon footprint reduction, eutrophication, acidification	Innovation + Enabler (Policy)
	Selective breeding and genetically improved fish (BGD, KEN, ZMB)	Temperature and water quality fluctuations, water scarcity, drought, flood	Innovation + Enabler (Policy)
	Integrated artemia farming (BGD, KEN)	Seasonal variability of freshwater, salinity	Innovation + Enabler (Policy)
	Carp-SIS polyculture in homestead ponds and seasonal waterbodies (BGD)	Intense rain, flash/monsoon flood, drought	Innovation + Enabler (Policy)
Capacity building and skill development of small-scale producers (BGD, KEN, ZMB)	IAA (BGD, KEN, ZMB)	Seasonal variability of freshwater influx, salinity intrusion, unpredictable rainfall patterns, rising temperature	Innovation + Enabler (Capacity)
	Clustered shrimp farming using SPF PL (BGD)	Salinity increases, extreme heat, dry spells, cold spells	Innovation + Enabler (Capacity)
	Hapa nursing and cage farming (BGD, KEN, ZMB)	Flash flood	Innovation + Enabler (Capacity)
	Mud crab fattening / integrated crab fattening with shrimp or finfish (BGD)	Tidal inundation, water logging, salinity increase	Innovation + Enabler (Capacity)
	Diversification of aquaculture production (BGD, ZMB)	Freshwater crisis, salinity increase, disease risk, temperature stress	Innovation + Enabler (Capacity)
	Production facility adjustment and system / infrastructure improvement (BGD, ZMB)	Rising temperature, frequency of droughts, floods, cyclones	Innovation + Enabler (Capacity)
IoT for pond water quality monitoring remotely (BGD, KEN)	IoT for precise decision-making in fish farming operations (BGD, KEN)	Water temperature, dissolved oxygen, pH fluxes	Technology + Innovation + Enabler (Digital)
Controlled aquaponics (BGD, ZMB)	Integrated aquaponics (BGD, ZMB, KEN)	Water quality and quantity	Technology
Biosecurity training modules on antimicrobial use and resistance (BGD, ZMB, KEN)	Fish health and biosecurity measures (BGD, ZMB, KEN)	Temperature drop, salinity, flooding, water quality fluctuation	Innovation + Enabler (Capacity)
Solar/renewable energy for off-farm operation (BGD, KEN, ZMB)	Solar/renewable energy in farm operation (BGD, KEN)	Carbon footprint	Innovation + Enabler (Capacity)
Sustainable business model for water reuse / wastewater treatment (ZMB)	Improved resource use (rainwater harvest, water storage, water reuse, water use efficiency) (ZMB)	Water scarcity	Innovation + Enabler (Capacity)
	Biofloc fish farming (BGD, KEN, ZMB)	Drought / water scarcity	Technology
	RAS (BGD, KEN)	Temperature fluctuations, storms, heavy rainfall, flood, water scarcity	Technology
	Integrated floating cage aquageoponics system (BGD)	Temperature rise, salinization	Innovation
Climate-adaptation knowledge / success stories—mass awareness (BGD, ZMB, KEN)		Overall climatic stress	Enabler (Digital + Capacity)
	Periphyton-based production technology (PPT) (KEN)	Water quality fluctuation, rising temperature	Technology

Note: Any of the above CAPs missing for a particular country does not indicate that the practice is absent in that country. For example, artificial propagation and PPT are available in Bangladesh; however, no available literature has identified or reported them as CAPs in Bangladesh.

*BGD ~ Bangladesh; KEN ~ Kenya; ZMB ~ Zambia

**Innovation ~ new idea, improved existing practice, existing management in a new way to deliver value

***Technology ~ tools, methods or systems developed to solve a problem

****Enabler ~ policy/capacity/digital

Table 5. Thematic area, climate-smartness category, and impact pathway of the identified CAPs for aquaculture.

CAP thematic area	CAP smartness indicator	CAP impact pathway
Culture systems and management practices (41%)	Risk-Yield-Income-Nutrition-Health-Gender-Market-Capacity-Carbon-Nature-Energy-Business-Safety Net	Production-Ecosystem
Fish feed, health, and disease (16%)	Risk-Yield-Income-Nutrition-Health-Gender-Market-Capacity-Carbon-Nature-Energy-Finance	Production
Breeding and genetics (14%)	Risk-Yield-Income-Health-Gender-Market-Capacity-Carbon-Nature-Energy-Business	Production
Social and economic inclusion (8%)	Risk-Yield-Income-Nutrition-Gender-Capacity-Carbon-Nature-Energy-Business-Safety Net	Food System
Marketing, trade, and supply channels (6%)	Risk-Yield-Income-Health-Gender-Market-Capacity-Carbon-Nature-Energy-Finance-Business	Food System
Nutrition and public health (6%)	Risk-Yield-Income-Nutrition-Gender-Capacity-Carbon-Nature	Food System
Post-harvest loss and value addition (0%)	-	-

Figure 2. Readiness and availability status of CAPs.

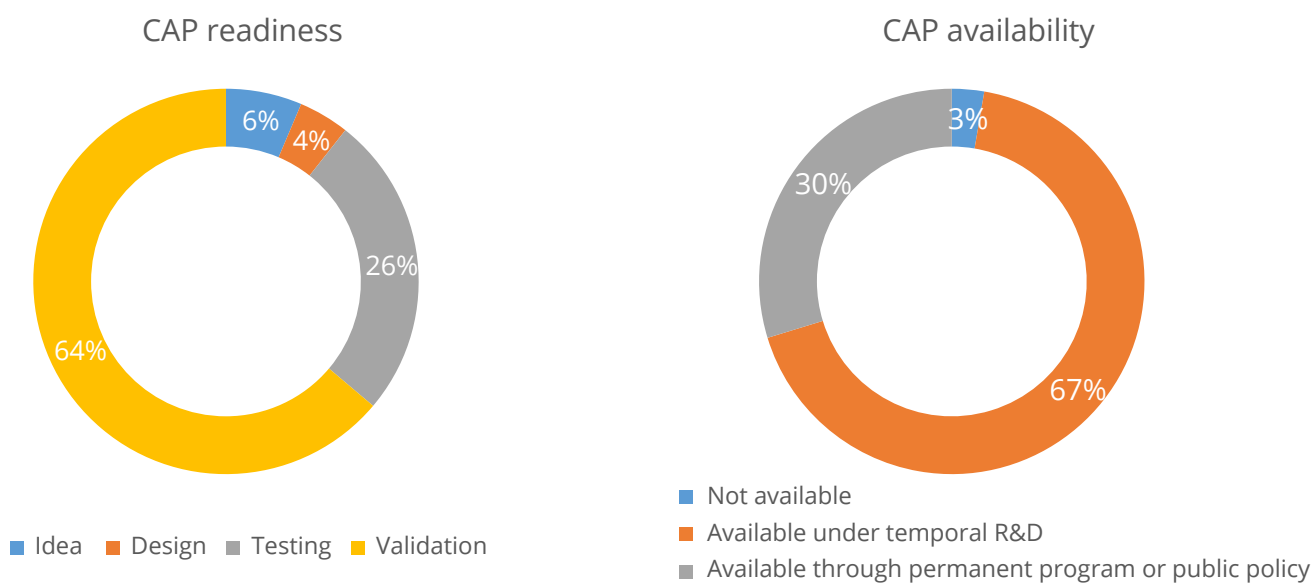


Table 6. CAPs at the validation stage and available through permanent programs or public policies.

Climate adaptation practice (CAP)	Bangladesh	Kenya	Zambia
Selective breeding and genetically improved fish strains	<ul style="list-style-type: none"> Genetically Improved Farmed Tilapia (GIFT) Rohu (G2–G5) Silver carp (G2–G4) Catla (G2–G3) 	<ul style="list-style-type: none"> African catfish strain (F3) GIFT Improved Nile tilapia (F8) Nile tilapia Sagana strain (F9) 	<ul style="list-style-type: none"> Kafue bream (G2) Three-spotted tilapia
IAA	<ul style="list-style-type: none"> Gher farming systems Rice–shrimp/prawn–finfish Dike cropping 	<ul style="list-style-type: none"> Integrated aquaculture–poultry–livestock–horticulture systems 	<ul style="list-style-type: none"> Integrated fish–crop–livestock systems
Aquaculture diversification in climate-vulnerable areas (salinity intrusion, water scarcity, freshwater variability)	<ul style="list-style-type: none"> White-leg shrimp–mud crab–seabass–mullet Artemia–carp–shrimp/prawn–tilapia Crab fattening–shrimp–finfish Carp–mola polyculture 	Not documented	Not documented
Clustered farming approach	<ul style="list-style-type: none"> Cluster-based shrimp farming using SPF PL 	Not documented	Not documented
Advanced fingerling production and cage farming	<ul style="list-style-type: none"> Hapa nursing for production of large fingerlings 	<ul style="list-style-type: none"> Hapa nursing for production of large fingerlings 	<ul style="list-style-type: none"> Hapa nursing for production of large fingerlings
Climate-resilient and nutrition-sensitive aquaculture	<ul style="list-style-type: none"> Fingerling production of fast-growing improved strains (e.g. G3 rohu, GIFT) integrated with SIS 	Not documented	Not documented
Production facility adjustment and system/infrastructure improvement	<ul style="list-style-type: none"> Construction of wider and higher dikes Improvement of coastal and inland embankments Monsoon fencing Relocation of production systems Use of pond liners Modification of pond size 	Not documented	<ul style="list-style-type: none"> Modification of earthen ponds (increased size and depth) to improve fish growth
Climate-informed operational adjustments in fish farming	<ul style="list-style-type: none"> Adjustment of growing period Early or delayed stocking Intermittent harvesting 	Not documented	<ul style="list-style-type: none"> Adjustment of growing period Early or delayed stocking Intermittent harvesting
Fish health management and biosecurity measures	<ul style="list-style-type: none"> Periodic monitoring of fish health and water quality 	<ul style="list-style-type: none"> Periodic monitoring of fish health and water quality 	<ul style="list-style-type: none"> Periodic monitoring of fish health and water quality
Aquaponics	<ul style="list-style-type: none"> Pilot initiatives 	<ul style="list-style-type: none"> Pilot initiatives 	<ul style="list-style-type: none"> Pilot initiatives
Renewable energy use in farm operations	<ul style="list-style-type: none"> Solar-powered farm operations 	Not documented	<ul style="list-style-type: none"> Solar-powered farm operations
Sustainable business models for improved resource use efficiency	Not documented	Not documented	<ul style="list-style-type: none"> Rainwater harvesting Water storage and reuse Improved water-use efficiency
Floating farming systems	<ul style="list-style-type: none"> Integrated floating aqua geaponics systems 	Not documented	Not documented
Periphyton-based production technology	Not documented	Not documented	<ul style="list-style-type: none"> Adoption of PPT to enhance productivity
Climate literacy and skills development	<ul style="list-style-type: none"> Capacity building on climate literacy and technical skills 	<ul style="list-style-type: none"> Capacity building on climate literacy and technical skills 	<ul style="list-style-type: none"> Capacity building on climate literacy and technical skills

4.2. Designing an effective adaptation Decision Support System for Aquaculture (ADSS 4 Aqua)

Strengthening climate resilience in the aquaculture sector is increasingly critical, given its high exposure to climate hazards and the growing frequency of climate-induced disruptions. Effective adaptation requires coordinated action across multiple stakeholder levels, including farm owners and workers, aquaculture communities, service providers, research and innovation institutions, and governance systems involving policymakers and implementing agencies. Scientific evidence on climate impacts and adaptive responses in aquaculture is expanding and governance frameworks for enhancing adaptive capacity are improving. However, significant gaps remain in identifying, developing, and systematically selecting technological solutions and innovations that can operationalize resilience at scale. As adaptation options proliferate, stakeholders require structured guidance to assess and prioritize decisions in a consistent and evidence-based manner (Soto and Garcia Sampaio 2025).

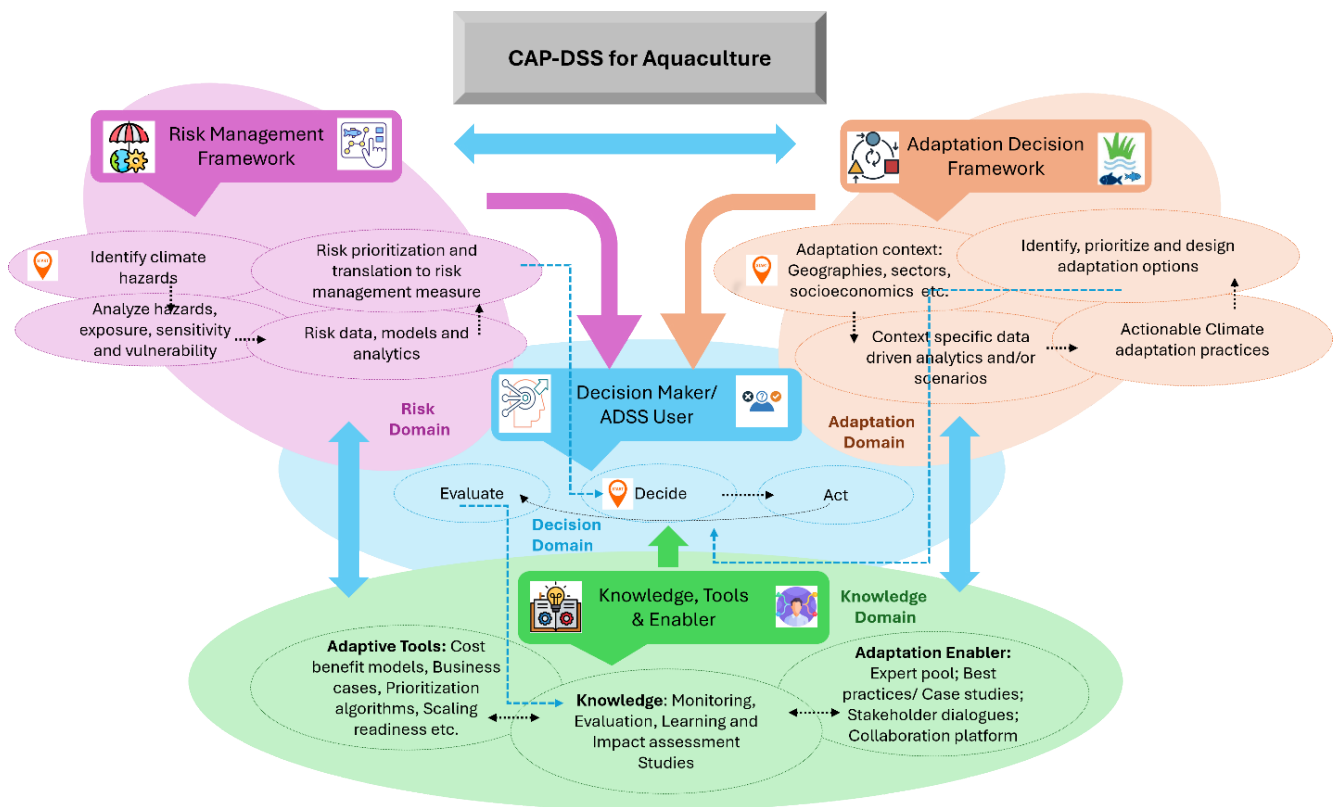
Here, we propose a comprehensive ADSS 4 Aqua (Figure 3). This framework is designed to help develop, implement, and scale climate-adaptation strategies using informed, data-driven, and analytically robust decision-making. ADSS 4 Aqua is structured around four interlinked domains: risk, adaptation, knowledge/enabler, and decision. Each performs a distinct but complementary function within an integrated system.

1. **Risk:** The risk domain's purpose is to identify, analyze, quantify, and prioritize climate risks. Therefore, this domain is diagnostic and analytical (i.e., what could go wrong, where, and how bad could it be). Accordingly, it can guide decision-makers through a risk management framework that helps identify climate hazards, assess risk, and translate risk data, models, and analytics into risk management measures.
2. **Adaptation:** The adaptation domain uses risk insights to design, evaluate, and implement responses. Therefore, this domain is prescriptive and decision-oriented (i.e., what should be done about the risk). Accordingly, it can identify context-specific and actionable adaptation practices to support all stages of planning and implementation.
3. **Knowledge/enabler:** This domain consolidates tools, evidence, and enabling resources, allowing policymakers to evaluate the CAPs for economic viability, socioecological acceptance, and impact, and access expert networks, forums, and collaboration opportunities.
4. **Decision:** Risk, adaptation, and knowledge/enabler domains all feed into and are overarched by the decision domain, where users synthesize insights, make decisions, and contribute evaluative inputs that, in turn, enrich the knowledge domain.

In a nutshell, the risk domain focuses on assessing and prioritizing climate risks by analyzing hazards, exposure, sensitivity and vulnerability, while the adaptation domain focuses on context-specific identification, evaluation, action plan development to reduce those risks. Although both domains draw on similar climate and socioeconomic data, they serve different decision purposes: risk analysis diagnoses the problem, whereas adaptation planning determines and delivers solutions. Recently, FAO developed the Aquaculture Adaptation Framework for Climate Change (Aqua-Adapt) as a tool to support the development and implementation of strategies to improve aquaculture's resilience to climate change (Soto and Garcia Sampaio 2025). The ADSS 4 Aqua sketched here is a possible model, which would perform using the best available scientific information, local knowledge, and adaptation frameworks at its back end like Aqua-Adapt. The framework must be fully inclusive and participatory (gender and small-scale actors), especially while choosing the best options for adaptation.

If developed and operationalized, ADSS 4 Aqua would serve as an interactive, living system that keeps decision-makers connected and informed, enabling data-driven and evidence-based decisions, and the scaling of climate-adaptive measures. It integrates multiple data sources such as climate projections, biophysical factors, and socioeconomic conditions to assess vulnerabilities and provide tangible outputs, like risk maps and context-specific management advisories. By supporting evidence-based analysis and scenario planning, ADSS 4 Aqua would enable a shift from reactive to proactive governance, helping policymakers design targeted policies, guide aquaculture land-use planning, and allocate resources toward options that address multiple climate risks simultaneously.

Figure 3. Decision support system for climate adaptation practices (CAPs) in aquaculture.



5. Conclusion and way forward

Aquaculture systems in Bangladesh, Kenya, and Zambia are increasingly exposed to climate uncertainties that necessitate coordinated, data-driven, and progressive adaptation approaches. This rapid review identified 32 CAPs for aquaculture across three countries, most of which are at the validation or pilot stages and primarily focused on on-farm production systems, management practices, and genetic improvement. Bangladesh exhibits the most diverse and mature portfolio, while Kenya and Zambia show more limited and selective adoption. Several CAPs demonstrate multidimensional benefits for production, livelihoods, and ecosystems, and a subset has been institutionalized through permanent programs or public policies.

However, significant gaps remain. Adaptation efforts are uneven across countries and climate risks, with strong emphasis on farm-level technologies and limited attention to value chains, post-harvest systems, finance, governance, and ecosystem-based adaptation. Most CAPs remain small-scale and project-driven, and many are validated as general aquaculture practices rather than explicitly evidenced as climate-adaptive solutions. There is a lack of robust field-based evidence on climate-resilience outcomes, large-scale mainstreaming, and system-wide integration, indicating the need for a more comprehensive and evidence-driven aquaculture adaptation agenda.

ADSS 4 Aqua, the adaptation decision tool proposed here, offers a strategic opportunity to enhance national and sectoral resilience, though action is required across several priority domains. Effective development of ADSS 4 Aqua must begin with clearly defined, country-specific entry points that reflect local ecological conditions, production systems, institutional capacities, and user needs. Strategic partnerships will be essential to drive this process. Establishing multisectoral collaborations and linking governments, research institutions, private sector actors, farmers' associations, and development partners together will enable co-design, co-development, and eventual scaling of the ADSS.

A phased implementation pathway is recommended. ADSS 4 Aqua should first be developed, tested, and piloted in a few key geographies to demonstrate feasibility, validate technical components, and generate evidence to refine it and scale it more broadly. Continuous monitoring, evaluation, and learning should guide iterative improvements, ensuring ADSS 4 Aqua remains responsive to evolving climate risks, scientific advancements, and user needs.

Embedding ADSS 4 Aqua within NAPs, aquaculture and fisheries policies, digital agriculture strategies, and climate-resilience programs will ensure institutional uptake, policy coherence, and long-term sustainability. Prioritizing inclusivity and accessibility, particularly for small-scale farmers, women, and youths, is essential to ensure broad-based benefits and equitable adoption. In a nutshell, the effectiveness of ADSS 4 Aqua will depend less on how sophisticated the climate data or digital tools are and more on its ability to connect decision-relevant climate risks with credible, context-specific adaptation options embedded within existing institutional and policy frameworks.

As this review highlights, adaptation for small-scale aquaculture farmers is urgently needed. Adaptation solutions exist, and many are already being tested and used in Bangladesh, Kenya, and Zambia. Yet implementation at scale is lagging, hampered by a lack of evidence, financing, and guiding frameworks at the local and national levels. Dedicated investment in inclusive design, development, and long-term operation of ADSS 4 Aqua can enable a resilient future for this growing sector, benefitting especially small-scale actors, women, youths, and marginalized groups.

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