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REVIEW ARTICLE

Socio-economic impacts of climate change and adaptation actions among smallholder fish farmers in Sub-Saharan Africa

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Abstract

Aquaculture is the world's fastest-growing food-producing sector, making it a significant contributor to food and nutrition security for the globally growing human population. Nevertheless, its long-term growth is limited by the effects of climate change. Aquaculture in Sub-Saharan Africa (SSA), which is dominated by small-scale fish farming, is increasingly threatened by climate change, which has a substantial influence on its productivity and scalability. In this context, the present research looks at the socio-economic consequences of climate change on small-scale fish producers in SSA, as well as potential adaptation techniques to the effects of climate change. A clear understanding of these socio-economic repercussions of climate change is critical for developing effective strategies to reduce future impacts and safeguard aquaculture-based livelihoods. Furthermore, understanding the socio-economic consequences of climate change on communities dependent on aquaculture is important for advising policymakers and decision-makers on formulating and implementing policies that sustain aquaculture production amidst the climate change crisis. This article suggests various adaptation strategies to increase resilience to climate change, including diversification of livelihoods and species, use and incorporation of local and indigenous knowledge, shifting to aquaculture species less vulnerable to changing climatic conditions, capacity building through aquaculture insurance schemes, continued fish supply from capture fisheries, and consolidation of equity and human rights concerns. These adaptive methods, when combined, have the potential to enhance outcomes for populations who are more susceptible owing to their unstable socio-economic conditions.

KEYWORDS
climate change, smallholder fish farmers, socio-economic, Sub-Saharan Africa, sustainability

1 | INTRODUCTION

Aquaculture has emerged as a crucial means to meet the escalating global demand for aquatic foods, particularly in light of diminishing yields from capture fisheries (Food and Agriculture Organization (FAO, 2022; Surathkal et al., 2023). Currently, aquaculture contributes 88 million tonnes, representing 49% of the approximated 178 million tonnes of the global fish production (FAO, 2022). Furthermore, fish serves as a vital source of income for approximately 520 million people worldwide (Adhikari et al., 2018). In developing countries, fish holds the status of an affordable, safe protein source, nourishing over 3 billion people and supplying more than half of the animal protein and essential minerals for more than 400 million people (Tacon & Metian, 2013). In this context, small-scale aquaculture, especially in Sub-Saharan Africa (SSA), plays a significant role in enhancing food security, alleviating poverty and driving socio-economic development (Asiedu et al., 2018).

However, a paramount concern arises in determining whether this industry can evolve sustainably to meet the present and future demands for aquaculture products. This challenge is compounded by an expanding global population and the increasing array of climate-related stressors (Myers et al., 2017). Although previous studies have examined the repercussions of climate change on terrestrial ecosystems, the aquaculture sector has been relatively overlooked, despite its growing importance in food security, nutrition and livelihoods (Dabbadie et al., 2018; Kandu, 2017). Climate change exerts a more intricate and profound influence on aquaculture compared to terrestrial agriculture due to the presence of poikilothermic species, which are especially susceptible to multiple biotic and abiotic stressors affecting reproduction, growth, physiology and behaviour (Adhikari et al., 2018).

The aquaculture sector in SSA is experiencing significant growth. In 2018, it contributed approximately 719,013 t to global aquaculture production, a notable increase from the 358,948 t recorded in 2008 (FAO, 2020). Within this region, pond-based aquaculture systems play a crucial role in production. However, these systems have encountered challenges related to their viability and sustainability, leading to the abandonment of ponds by many small-scale farmers. Issues such as floods, water scarcity and high mortality rates have been contributing factors in this trend (Asiedu et al., 2018). Adding to the complexity of the situation are the adverse impacts of climate change. Rising temperatures, ocean acidification, shifts in precipitation patterns, extreme weather events, resource access uncertainties, fish diseases, harmful algal blooms (HABs) and rising sea levels (Adhikari et al., 2018; Maulu et al., 2021; Yazdi & Shakouri, 2010) continue to exacerbate the challenges faced by the aquaculture sector. Notably, these issues coincide with a growing population, which is increasing at a rate of approximately 2.3% per annum and is projected to reach 37 million by 2030. Concurrently, poverty and hunger persist, unemployment rates remain high, and the demand for fish is on the rise.

The impacts of climate change are acutely felt by fish farmers and coastal communities, affecting their livelihoods, fish availability and quality, as well as compromising their health, safety and housing (Asiedu et al., 2018; Mozumder et al., 2023). Many small-scale fish farmers face economic hardships due to low-income levels, limited productivity, small pond sizes, insufficient technological support, and a lack of knowledge in aquaculture operations. In line with FAO (2020) data, the impacts of climate change are most acutely felt in tropical regions of Africa, characterized by high temperatures that suppress aquaculture productivity. The climate trends observed in SSA indicate a persistent temperature rise of approximately 0.7°C throughout the 20th century, pointing to a continuing temperature increase in all SSA regions (Juana et al., 2013). Projections suggest that this trend will persist into the 21st century, accompanied by rising sea levels and an increased frequency of droughts and floods (Juana et al., 2013). Arnell (2004) forecast a heightened water stress scenario for up to 370 million Africans by 2025.

For instance, Mozambique has recently grappled with a series of natural events, including droughts, floods and cyclones, which have directly and indirectly impacted aquaculture production (Malauene et al., 2021). Moreover, a study conducted in Ghana underscores that climate-related changes have the potential to significantly diminish the economic value of aquaculture products, fostering elevated levels of poverty in rural areas (Asiedu et al., 2018). Fish farming communities in Ghana are increasingly facing the brunt of climate-related challenges, including floods, droughts, unpredictable rainfall, extreme temperatures and storms. These climatic events have led to substantial losses in fish stocks, higher mortality rates, reduced fish production, damage to ponds and tanks and increased operational expenses. Over the last six decades, Ghana has experienced a noteworthy 1°C increase in temperature. This temperature rise has severe implications for both food security and the livelihoods of fish farmers, raising significant concerns. The repercussions of these climatic variations can manifest directly or indirectly and have profound socio-economic consequences for small-scale fish farming households. Smallholder fish farmers may find themselves forced to allocate additional resources to mitigate the impacts of climate change shocks (Asiedu et al., 2018).

However, it is worth noting that the socio-economic effects of climate change on aquaculture in SSA remain largely unexplored. Although a limited number of studies and reviews have touched upon the potential impacts of climate change on aquaculture, they have primarily focused on projections and forecasts, falling short in their ability to comprehensively elucidate the socio-economic consequences of climate change at the farm level. Attaining sustainable aquaculture objectives necessitates an in-depth understanding of the socio-economic implications of climate change on aquaculture, and the spectrum of available adaptation strategies at farm level in order to devise enduring climate solutions that sustain the livelihoods of aquaculture-dependent communities. This knowledge can also heighten awareness and promote the development and adoption of sustainable, climate-resilient aquaculture practices, thereby mitigating environmental threats and enhancing global food security. Hence, this article endeavours to spotlight the socio-economic consequences of climate change on smallholder fish farming communities in SSA. It further delves into viable adaptation strategies aimed at mitigating the current and future adverse effects of climate change on these communities.

The findings of this review study may serve as a guideline for governments, managers and policymakers when developing and putting into practice better ways to increase adaptive capacity in response to climate change in aquaculture and fisheries in SSA. Fisheries and aquaculture should be at the forefront of the process of climate change adaptation in formulation of policies in order to uncover the invisibility of this sector. Through mechanisms like nationally determined contributions, short-term National Adaptation Programs of Action and longer term national adaptation plans, member nations of the Paris Agreement including those within SSA are required to plan, implement and report on the progress of their adaptation efforts (Poulain et al., 2018). Consequently, it is anticipated that the results of this study will give stakeholders a foundation upon which to build adaptation plans that consider the needs, capacities and preferences of smallholder fish farmers. Therefore, it is imperative to increase public awareness of the effects of climate change and provide smallholder fish farmers with realistic fishery policies that support their efforts to build capacity for mitigation, adaptation and management.

2 | METHODOLOGY

This article synthesizes a subset of literature relevant to climate change in the aquaculture sector. Web of Science and Scopus search engines were used for the literature search, with a focused scope to prevent overly complex search terms. The literature considered encompassed various peer-reviewed document types, including reviews, scientific articles, book chapters, books, policy briefs and miscellaneous editorial materials found within the search engines, dated from 2000 to 2023. Grey literature of inferior quality, such as newsletters and bulletins with limited policy relevance, was intentionally omitted, and the primary focus was placed on peer-reviewed scientific literature. However, additional data was gathered by visiting the official websites of several relevant organizations, such as the World Fish Center and the Food and Agriculture Organization of the United Nations (FAO), in order to get an updated strategy for addressing climate change and implementing adaptation measures.

The search strategy involved the combination of the search terms 'Climate change' with 'Aquaculture' and 'Sub-Saharan Africa' to retrieve relevant literature specific to SSA. This included the following search combinations: 'Climate change' and 'Aquaculture' and 'Sub-Saharan Africa', 'Climate change adaptation' and 'Sub-Saharan Africa', and 'Climate change impacts' and 'Aquaculture'. In total, 514 documents were retrieved from the Web of Science (263 documents) and Scopus (251 documents) search engines.

Subsequently, the retrieved documents were exported to a database in ENDNOTE X8 for streamlined screening. After the removal of duplicate documents, the selection was further refined, resulting in a total of 342 unique documents. Rigorous scrutiny during the screening process, which involved a thorough examination of titles and abstracts, narrowed down the selection to a final set of 74 papers. The criteria used for the inclusion or exclusion of literature are presented in Table 1, ensuring transparency in the document selection process.

2.1 | Limitation of the study

Although these databases are highly reputable and widely used, this study may not encompass the complete spectrum of literature available within the 2000–2023 timeframe. Nevertheless, every effort has been made to ensure a comprehensive and representative review of the available literature within the scope of this research.

3 | CONCEPTUAL FRAMEWORK

We developed a conceptual framework based on the climate change concepts from the Intergovernmental Panel on Climate Change (IPCC) report (Intergovernmental Panel on Climate Change (IPCC), 2007) and the study by Maulu et al. (2021) on the effects of climate change on aquaculture production. The climate risks, made up of exposure and vulnerability to climate shocks and stresses, have various socio-economic effects on smallholder fish farmers in SSA (Figure 1). We bring in the IPCC definitions of climate risk, stresses, shocks, exposure, vulnerability and adaptation.

In this article, climate risks mean the potential for climate change to create adverse consequences for ecological systems and humans, worsening their economic social status (IPCC, 2007). Climate shocks refer to the instantaneous events caused by climate change that typically occur in a short period, whereas stresses refer to events caused by climate change that are often chronic and last for an extended duration (IPCC, 2007). Exposure is the condition of being affected by the social, economic and environmental implications of climate change (IPCC, 2007). Vulnerability means the level of susceptibility of the fish farmers, and their ability/inability to cope with the impacts of climate change, and it carries elements including sensitivity (or susceptibility to harm), and adaptive capacity (IPCC, 2007). Adaptation refers to adjustments in ecological, social or economic systems as a result of real or anticipated climate-related stresses and their impacts. It refers to changes in systems, methods and structures to minimize possible harm or to take advantage of opportunities brought on by climate change (IPCC, 2007).

The smallholder fish farmers are exposed to various climate change shocks and stresses, including changing temperature patterns, extreme weather events, shifts in precipitation levels, ocean acidification, uncertain input access, diseases and HABs, and the rise in sea level. These shocks and stresses are directly connected with their vulnerabilities, for instance, changes in temperature patterns and extreme weather events can directly affect fish health and productivity, making fish more susceptible to diseases and mortality. Shifts in precipitation levels can affect water availability and quality, which, in turn, can affect aquaculture productivity.

The exposure and vulnerability of smallholder fish farmers to these stresses and shocks have various socio-economic impacts. For example, reduced per capita income is a direct result of factors such as fish mortality and decreased productivity. Reduced access to aquafeeds is directly caused by limited access to inputs caused by shifts in precipita-

TABLE 1 Criteria for inclusion and exclusion of literature selected for review.

Criteria for excluding literature in the study	Criteria for including literature in the study
The text lacks pertinent details needed for review	The text contains sufficient relevant details to carry out the review
Text documented in a language other than English	Text documented in English
Emphasis is not on aquaculture	Focus is on aquaculture
Focus is on non-Sub-Saharan Africa countries	Focus is on Sub-Saharan Africa countries

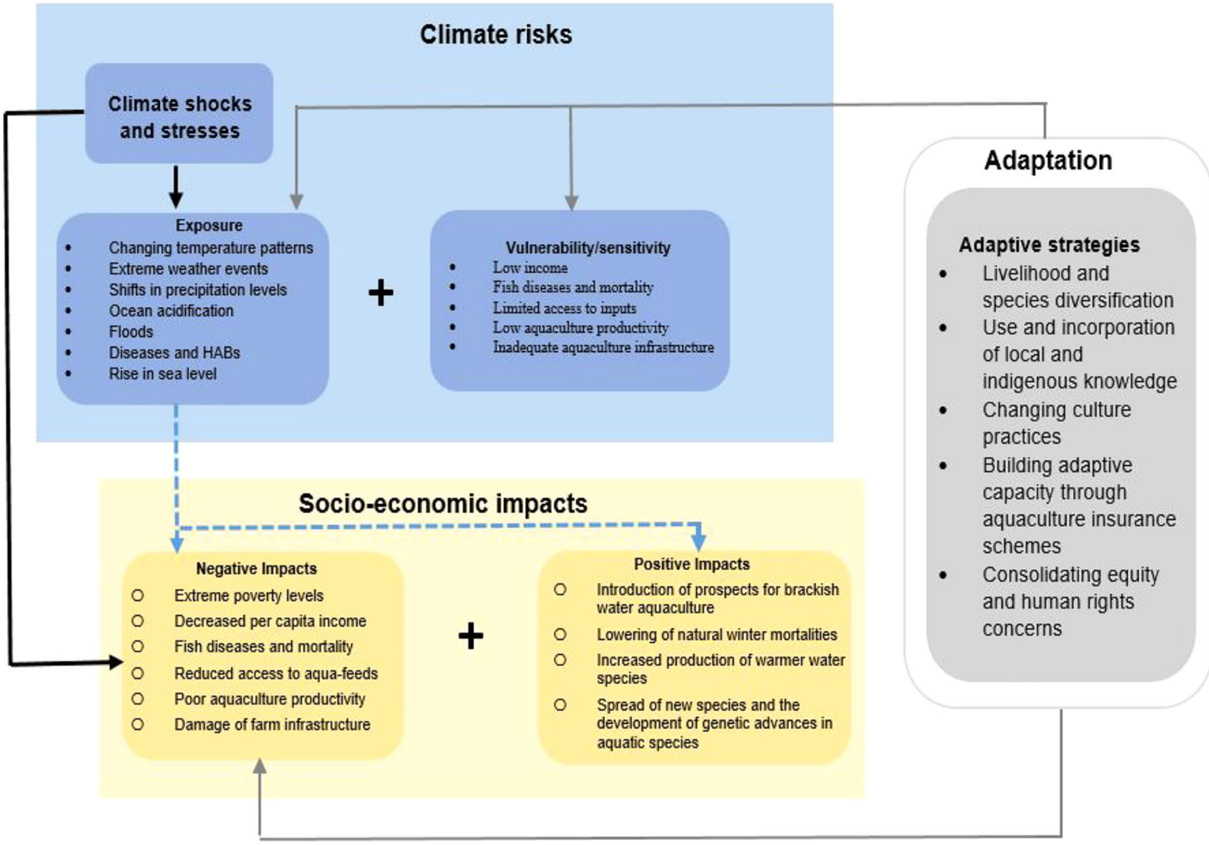

FIGURE 1 Conceptual framework of the socio-economic impacts of climate change and adaptation strategies among smallholder fish farmers in Sub-Saharan Africa. *Source*: Developed from Intergovernmental Panel on Climate Change (IPCC) (2007) and Maulu et al. (2021).

tion levels and floods, further affecting aquaculture productivity. Low aquaculture productivity, which is sensitive to factors like ocean acidification and changing temperature patterns, is a key measure of the impact on the farmers. Damaged aquaculture infrastructure, resulting from extreme weather events, sea level rise and floods, adds to the overall sensitivity of the fish farmers to the effects of climate change, making them more vulnerable.

To address the impacts of climate change, adaptation interventions are needed to enable fish farmers to build their resilience and reduce their vulnerability to climatic shocks and stresses. Livelihood and species diversification are vital strategies for smallholder farmers to adapt to changing conditions. By diversifying income sources and the species, they farm, they can reduce their dependence on a single type of fish or aquaculture method. Additionally, the use and incorporation of local and indigenous knowledge play a critical role in enhancing adaptive capacity, as they provide insights into strategies for dealing with climate-induced challenges. Changing cultural practices, such as adjusting fish farming techniques and harvesting times, can also enhance resilience to climate change impacts. Building adaptive capacity through aquaculture insurance schemes is another strategy to protect farmers from financial losses due to climate-related disruptions. These schemes can provide a safety net in the face of uncertainties related to extreme weather events and other exposure factors. Finally, consolidating equity and human rights concerns is essential for building adaptive capacity, ensuring that all members of the community have the opportunity to adapt effectively and that no one is left disproportionately vulnerable to the impacts of climate change.

4 | RESULTS AND DISCUSSION

4.1 | Socio-economic impacts of climate change

4.1.1 | Negative impacts

Extreme poverty levels

There is currently insufficient disaggregated data to assess the true household income of persons who depend on the aquaculture sector. However, small-scale fish farming communities in SSA find themselves perched at the bottom of the socio-economic ladder (Allegretti, 2019). With more than 90% of aquaculture employees engaged in small-scale operations, the sector holds the unenviable distinction of having the highest poverty prevalence among all food production sectors (Béné et al., 2007). In stark contrast, large-scale fish farmers in impoverished nations exhibit a higher degree of resilience to climate change, underpinned by factors like better farm management practices and access to resources, which their smaller counterparts often lack (Barange et al., 2018).

The significance of small-scale aquaculture in SSA cannot be overstated. It plays a pivotal role in generating employment, supporting livelihoods and contributing to economic development, particularly in developing nations (El-Sayed & Fitzsimmons, 2023). However, climate change poses a grave threat to the economic value of aquaculture products and exacerbates rural poverty, with coastal populations at the forefront of this crisis, facing risks such as hurricanes, cyclones, sea-level rise, ocean acidification, floods and coastal erosion (Kalikoski et al., 2019). For many inhabitants in low-lying coastal and floodplain areas, the spectre of flooding looms as an inevitable reality, with projections suggesting devastation for human and biological systems, including fish populations, infrastructure, natural resources, species and ecosystems (Barange et al., 2018).

Furthermore, these climate disruptions have a detrimental influence on overall aquaculture productivity and income generation (Naylor et al., 2021). In the face of climatic events, communities dependent on aquaculture for their livelihoods should either find alternative sources of income or face extreme poverty, thereby negatively impacting their well-being (Soto et al., 2019). This vulnerability is especially pronounced for communities relying on brackish and freshwater rivers, which serve as the primary source of the world's fish production. A poignant example of the impact of climate change is evident in Nigeria, where the 2012 flooding, as documented by Areola and Fakoya (2021), led to the destruction of vital aquaculture infrastructure, substantial fish mortalities and the washing away of fish stocks, resulting in a severe income reduction for affected farmers. This, in turn, triggered a cycle of impoverishment that affected not only the farmers but also the many individuals dependent on aquaculture for their livelihoods.

Moreover, climate change intensifies competition for water resources, negatively affecting aquaculture operations and giving rise to conflicts among water-dependent enterprises (Ghorai et al., 2023). This, in turn, diminishes opportunities for livelihoods, necessitates occupational shifts and exerts societal pressures. The capacity of aquaculture-dependent populations to adapt to climate change vulnerabilities is intricately linked to their sensitivity, exposure and adaptive capability, which are further influenced by their financial and social capital (Gonzalez-Pestana et al., 2023). Sensitivity to the effects of climate change is interwoven with vulnerability, existing infrastructure and the institutional framework, including government-sponsored social safety net programs. Adaptability hinges on access to insurance, technology and expertise (Fankhauser & McDermott, 2014). Poverty, gender disparities and sociocultural factors present additional hurdles, limiting their access to these vital resources and eroding their adaptability in the face of a changing climate.

Decreased per capita income

The repercussions of climate change on fish resources extend to the economic sphere, transforming nations into net importers and jeopardizing their journey towards food security, ultimately leading to a decline in per capita consumption (Abila, 2003). These economic consequences of climate change can manifest directly and indirectly. First, climate change can lead to a significant reduction in overall aquaculture production, resulting in substantial losses that directly impact fish farmers. Second, a drop in aquaculture productivity can lead to shifts in the pricing and availability of aquaculture products, influencing consumers (Li et al., 2016). However, it's crucial to note that developing nations, including those in SSA, contribute to more than half of global fish exports (FAO, 2022). A decrease in production equates to a decline in net exports, translating to reduced foreign currency revenue and diminished prospects for poverty reduction in these nations (Williams & Rota, 2011).

To exemplify, a study conducted by Asiedu et al. (2018) revealed that extreme temperatures, erratic rainfall, floods, drought, storms and erosion are prevalent challenges faced by fish farms in Ghana. Data from this study demonstrated a staggering 53.4% decrease in small-scale revenue and a 6.9% reduction in the value of small-scale aquaculture, plummeting from GH¢ 83,000 to GH¢ 120,000, resulting in a 25% reduction in fish supply. These findings underscore the severe impact of climate change on the profitability, economic value and livelihoods of the small-scale aquaculture industry. The compounding effects of floods, droughts, erratic rainfall, erosion and extreme temperatures synergistically contribute to the entrenchment of poverty within these communities, painting a stark picture of the economic turmoil induced by climate change. As such, climate change not only diminishes per capita income but also threatens the economic stability of these small-scale fish farmers in SSA, further underscoring the pressing need for adaptation strategies and global climate action.

Fish diseases and mortality

Disease incidence is a critical factor worldwide, significantly influencing the success of aquaculture businesses (Stentiford et al., 2012). The economic toll of infectious diseases on aquaculture is staggering, with approximately $6 billion in losses each year (Jennings et al., 2016). A substantial portion of these losses can be attributed to the impacts of climate change, which has led to a shifting landscape of suitable biophysical conditions for aquaculture species over the years (Weatherdon et al., 2016). This change has raised concerns about the increased potential for species invasions and disease transmissions, a particularly salient issue for aquatic organisms migrating across borders (Pathak et al., 2013).

In SSA, the majority of farmed species are warm-water species with optimal temperature ranges of 24–30°C. Although warmer temperatures can theoretically lead to enhanced growth rates and extended production periods (Ficke et al., 2007), chronic high-temperature fluctuations push most aquaculture species beyond their thermal limits. This renders them more susceptible to disease, and the altered thermal conditions can facilitate the spread of exotic infections (Collins et al., 2020). Temperature variations can also increase infection incidence by affecting the physiology of both fish and viruses, resulting in significant economic consequences (Cascarano et al., 2021).

Additionally, extreme heat is associated with hypoxia, which induces stress, reduced feeding and increased disease incidence. This cascade effect results in decreased growth performance, lower yields and, in intensive aquaculture systems, sometimes massive fish kills (Araújo-Luna et al., 2018; Soto et al., 2019). Furthermore, elevated temperatures can lead to the emergence of new diseases or increase the pathogenicity of previously nonpathogenic species (Elsheikh, 2021). One crucial disease factor affected by both direct and indirect temperature stresses is the vulnerability of finfish and shellfish to infections (Chiaramonte et al., 2016). Rising temperatures are expected to accelerate pathogen replication, pathogenicity, life cycles, lifespan and transmission in various finfish and shellfish species (Maulu et al., 2021). As temperatures continue to rise, the establishment of epizootic diseases in aquaculture becomes a significant economic concern (Leung & Bates, 2013). Warm water disease outbreaks are expected to become more frequent, with the potential for the discovery of new pathogens (Sae-Lim et al., 2017).

For example, in Ghana, infectious spleen and kidney necrosis virus caused substantial production losses in 2019. The Tilapia lake virus, which can result in mortality rates of 10%–90% in infected fish, was recently detected in both farmed and wild Nile tilapia in Tanzania and Uganda (Mugimba et al., 2018) and was partially responsible for fish mortality in Lake Victoria in 2018. Several SSA countries halted the importation of fingerlings from affected countries, further curbing production and supply. Specialized expertise and reference laboratories for fish diseases and fish health management are limited. Although vaccination programs under public–private partnerships and breeding for disease resistance have shown promise, sustainable solutions necessitate continuous disease monitoring and surveillance within and across borders, rapid diagnosis and reinforced biosecurity measures in hatcheries and breeding centres (Ragasa et al., 2022).

Moreover, studies have shown that high temperatures can trigger toxic algal blooms, leading to catastrophic events and creating conditions conducive to infections and pathogens (Lafferty, 2009; Soto et al., 2019; Trainer et al., 2019). These algal blooms pose a threat to the environmental sustainability of aquaculture operations (Mardones et al., 2023). Substantial temperature fluctuations have a long-term impact on osmoregulation and neuroendocrine systems in cultured species, impairing cardiovascular function, immunological response and aerobic capacity (Maulu et al., 2021). Furthermore, high temperatures affect the feeding behaviour, growth performance, metabolism and physiology of numerous economically significant fish species (Maulu et al., 2021).

Reduced access to aquafeeds

One of the most significant barriers to the expansion of the aquaculture business is the high cost of feeds (Iliya et al., 2023; Obiero, Brian Mboya, et al., 2022). Small-scale farmers in SSA employ low-input, low-output aquaculture to maintain production, relying mostly on naturally occurring ecosystem services and feed (Williams & Rota, 2011). Agriculture and capture fisheries are the primary external input sources for aquaculture production, indicating the systems' strong interdependence. As more than 85% of the world's fish populations have been depleted, wild fish supplies can no longer be relied on as fish feed components (Landry, 2023). Reduced wild fish populations have negatively affected fish farmers who rely on wild fish to feed their farmed fish (Williams & Rota, 2011). Climate change is also expected to have a substantial impact on the cost of input sources such as fish oils and fish meals, as well as the viability of fish breeding programmes owing to a scarcity of wild seeds (Brander, 2007). As a result, aquaculture production costs are expected to rise, making it more difficult for small-scale producers to thrive (Bueno & Soto, 2017). Rising fishmeal and fish oil costs, on the other hand, are projected to drive scientific research into innovative protein and oil sources to replace conventional constituents in aqua feeds (Hardy, 2010; Ouko et al., 2023).

There has recently been a lot of interest in the utilization of plant protein sources in aquaculture, notably oilseeds (Sarker, 2023). For instance, 70% of the fish feed components have been replaced by plant-derived ingredients (Ytrestoyl et al., 2015). However, climate change has reduced agricultural production of plant-based ingredients like maize and other ingredients on which the aquaculture feed industry currently relies, and therefore, the sector will require to seek alternative resources in the near future to promote sustainable aquaculture growth (Khatri-Chhetri et al., 2019; Mitra, 2021). This demands the development of novel solutions to the pressing issue of climate change.

Poor aquaculture productivity

Climate change stands as a looming threat to global food production, posing a significant risk to the quality and quantity of aquaculture food production and, by extension, the overall food supply, particularly concerning access to dietary protein (Maulu et al., 2021). Fish, in particular, are highly vulnerable to the temperature fluctuations brought about by climate change (Adhikari et al., 2018). The escalation of global temperatures leads to substantial mortality, especially among cold-water species like salmon, due to prolonged heat stress (Gubbins et al., 2013), thereby diminishing aquaculture productivity. Temperature variability affects the metabolism, physiology, feeding behaviour and growth performance of aquaculture species such as shellfish and finfish (Lubembe et al., 2022). Extended stress alters cardiorespiratory function, aerobic capacity and immunological response in many commercially important fish species (Zhang et al., 2019). For instance, West African countries are grappling with rising sea temperatures, which not only impact capture fisheries but also undermine the productivity of various aquaculture species, affecting the livelihoods of millions of people dependent on aquaculture (Katikiro et al., 2010).

Furthermore, escalating ocean temperatures and the associated ocean acidification gradually diminish the ocean's capacity to absorb carbon, leading to alterations in water system hydrology and hydrography, as well as the occurrence of red tides (Cochrane et al., 2009). These effects result in increased management costs and decreased output, placing the economic and social sustainability of aquaculture production in jeopardy. The seas are estimated to contain roughly 50 times more CO_2 than the atmosphere (Seggel et al., 2016). If global temperatures rise by 1.5°C or more, the projected increase in CO_2 absorption by the oceans will significantly impact the growth, development, calcification, survival and abundance of various aquatic species (IPCC, 2018). High CO_2 deposition in the ocean may lead to increased water acidity, undermining the environmental sustainability of aquaculture production systems in SSA that operate in marine environments by deteriorating water quality and causing poor productivity (Clements & Chopin, 2016). Thermal stratification can also alter the availability and distribution of nutrients in the water, and in the event of upwelling, aquaculture enterprises operating in open seas and lakes, such as fish cage farming, would face substantial financial losses (Seggel et al., 2016).

Damage of farm infrastructure

Climate change exerts a detrimental impact on the safety and resilience of aquaculture infrastructure, leading to asset loss or damage, particularly in coastal zones. These effects have far-reaching consequences, including threats to human health and life, displacement, conflicts, market and trade disruptions, water, and resource allocation challenges, and more (Barange et al., 2018; Soto et al., 2019). Rising sea levels resulting from climate change, along with storm surges, pose a significant threat to coastal cultural systems and the associated infrastructure (Sainsbury et al., 2021). This, in turn, impacts the efficiency, scale and quality of aquaculture output, resulting in substantial losses. Low-lying terrains are particularly vulnerable to flooding, which can destroy aquacultural assets, wash away or enable farmed animals to escape and, in some cases, introduce disease and predators (Handisyde et al., 2014).

Furthermore, extreme weather events significantly impact critical infrastructure, including aquaculture sites, post-harvest facilities and transportation routes (Cochrane et al., 2009). Certain climate models predict an increase in tropical storm peak wind speeds and precipitation intensities. Storm surges, driven by low air pressure and high winds, can inundate low-lying coastal areas, causing damage to aquaculture facilities (Hsiao et al., 2021). Strong winds have the potential to devastate aquaculture infrastructure, with potentially severe and financially ruinous consequences (Handisyde et al., 2014).

An illustrative example of this impact can be seen in Central Mozambique, where in 2019, the region was struck by Cyclones Idai and Kenneth. In Zambezia province, aquaculture producers suffered the loss of 169 fishponds, 2 cages and 606,000 fry, whereas in Sofala Province, 58 fish tanks, 204 cages and 257,500 fish fries were lost (Muhala et al., 2021). Aquaculture production in Mozambique is primarily practiced by small-scale farmers with limited investment capacity, relying heavily on support from the government and private sectors. The destruction of their aquaculture infrastructure resulted in significant losses for fish farmers who depend on the sector for their livelihoods. This not only impacts individual livelihoods but also has broader socio-economic implications, underscoring the urgent need for resilience-building measures and the safeguarding of aquaculture infrastructure against the impacts of climate change.

4.1.2 | Positive impacts of climate change

The implications of climate change on aquaculture are not always unfavourable. Among the benefits are the introductions of prospects for brackish water aquaculture, the lowering of natural winter mortalities and the extending of growing seasons at higher latitudes (Pathak et al., 2013). Temperature increases within the species' tolerance limits may lengthen culture period, particularly in temperate locations, and increase the production of warmer water species such as tilapia (Collins et al., 2020). Large-scale producers operating hatcheries in protected regions may benefit from market possibilities created by the loss of valuable species in the wild as a result of coral reef deterioration (Bell et al., 2010). Moreover, greater temperatures may aid in the spread of new species and the development of genetic advances in aquatic species (Bueno & Soto, 2017). These options can increase social sustainability in SSA by boosting production and job opportunities, as well as economic sustainability by raising revenues and lowering management expenses in these sectors. To attain these goals, improvements in molecular biology and the use of practical genetic improvement methods in fish farming will be required (Maulu et al., 2021).

4.2 | Climate change adaptation strategies

4.2.1 | Livelihood and species diversification

Diversification provides farmers with more possibilities for making a living while also improving resistance to climate change (Zolnikov, 2019). Diversification of income requires the integration of aquaculture production systems with other sectors, such as agricultural production systems, as discrete or integrated systems (Maulu et al., 2021). Diversification of livelihoods is critical, particularly in places or countries where aquaculture production is expected to drop and agricultural production is expected to increase (Blanchard et al., 2017). Fish farmers should be encouraged to explore non-aquaculture revenue-generating enterprises in order to reduce their reliance on fish products and diversify their income. Due to the financial reliance of communities on small-scale fish farming, it would be preferable to teach these alternative skills not just to small-scale fish farmers, but also to their families (Short et al., 2021). Yet, sustainable livelihood diversification requires government policies that encourage resource efficiency, equality and environmental preservation (Stacey et al., 2021).

The diversity of species and culture systems may provide for resilience in the case of a climate-related disaster (Sinha, 2023). Diversification has the potential to bring economic, social and ecological stability to aquaculture systems at the farm and community levels, particularly for small-scale and family-run firms (Harvey et al., 2017). A strategy of farming more species using established technologies and continual domestication of new species is expected to give fish farmers more options in the face of changing environmental conditions and unforeseen socio-economic consequences (Blanchard et al., 2017). However, such diversifications need research and development expenses, particularly for species that are not yet commercially viable. These expenses include the expenditures of assessing and mitigating environmental and socio-economic hazards, as well as the development of species-specific biosecurity strategies to prevent possible diseases (Harvey et al., 2017). Diversification should focus on a limited number of 'new' species rather than spreading research funds among multiple candidate species, new agricultural or processing methods and new marketing platforms (Harvey et al., 2017).

4.2.2 | Use and incorporation of local and indigenous knowledge

Better aquaculture producer livelihood diversification necessitates the incorporation of indigenous knowledge into governmental decisions (Leal Filho, 2011; Obiero et al., 2023). Despite the fact that scientific knowledge provides a broad understanding of climate change and its potential consequences, indigenous knowledge may provide specific details about the physical environment, infrastructure systems, livelihood status, behaviour and other features required for community resource management (Kettle et al., 2014). Utilizing conventional approaches and indicators to forecast changes in weather patterns, for example, may help farmers prepare for expected changes and develop resilience (Zolnikov, 2019). It is unclear how such inclusion was used to boost aquaculture productivity. However, rural people have utilized it effectively in various sectors, such as agriculture.

In Kenya, for example, traditional knowledge assisted some agricultural communities in preparing for the effects of climate change and reducing their vulnerability to food insecurity (Leal Filho, 2011). The conduct and actions of insects, birds and animals; the influence of wind; and the alignment of the moon are utilized as indicators to provide insights into both immediate and prolonged weather forecasts. These forecasts, in turn, guide adaptations in agricultural practices and communal endeavours. Additionally, despite its underutilized status, the combination of indigenous and scientific knowledge may be one of the most effective instruments for supplementing other adaptation techniques (Makondo & Thomas, 2018; Obiero, Klemet-N'Guessan, et al., 2022).

The local and indigenous knowledge could be acquired by fostering community engagement and participation, encouraging active involvement of local communities in decision-making processes related to aquaculture and climate adaptation. Ethnographic studies and surveys within the targeted communities can be conducted to document traditional practices, beliefs and observations related to weather patterns, agriculture and aquaculture. Collaboration with local institutions, such as educational organizations and Non-governmental Organizations (NGOs), can be established to tap into existing reservoirs of indigenous knowledge. Integrating local and indigenous knowledge into formal education programs will ensure the transmission of traditional practices to younger generations (Mbah et al., 2021). These options will collectively empower local communities, enriching the climate adaptation strategy with a holistic understanding of the environment and facilitating sustainable practices in aquaculture.

4.2.3 | Changing culture practices

Changing culture practises (e.g. species and production systems) can provide effective adaptation strategies (Handisyde et al., 2017; IPCC, 2018), such as the development of storm-resistant fish farming systems (e.g. studier fish cages) and the widespread use of information technology to share weather and market information (De Young et al., 2012). An integrated multi-trophic aquaculture system is more ecologically friendly, sustainable and financially profitable than a monoculture system as it blends finfish farming with other species (Osch et al., 2019). Fish farmers in SSA may also exploit changed resources, such as land, by using novel aquaculture techniques (e.g. aquaponics).

Aquaculture zoning mechanisms at the watershed level, biosecurity frameworks, risk analysis and strategic environmental assessments that account for the additional impacts on aquaculture farms would allow the industry to face potential threats such as diseases and eutrophication-related challenges that climate change can exacerbate (De Young et al., 2012; FAO, 2009). Moreover, exploring new aquaculture alternatives, such as transitioning to mariculture, may give further adaptive choices. Moving away from freshwater systems would lessen both the impact on water availability and the competition for its use across sectors (De Young et al., 2012).

Additionally, one of the most prevalent adaptation tactics is to modify species to make them more tolerant to climate change (De Young et al., 2012). The modification can be done by prioritizing species with inherent resilience to fluctuating environmental conditions, such as temperature variations and water quality changes (De Young et al., 2012). Identifying and selecting species that exhibit adaptability to a range of feed sources contribute to sustainable aquaculture practices, especially in regions where feed availability may be influenced by climate-induced factors. Moreover, choosing breeding targets based on feed efficiency is paramount, as it not only enhances the economic viability of aquaculture but also aligns with sustainable practices by minimizing greenhouse gas emissions (Sae-Lim et al., 2017).

4.2.4 | Building adaptive capacity through aquaculture insurance schemes

Small-scale farmers are the most vulnerable to climate change due to a lack of adaptive capacity to create resilience against climatic disasters (Barange et al., 2018). However, an insurance scheme might help them build resilience. Despite receiving a lot of attention, insurance for aquaculture farmers is still in its early stages on a worldwide basis (Pongthanapanich et al., 2016). Insurance policies have a bigger impact than just reducing the immediate consequences of climate risk on primary farmers. One such wide benefit is that it encourages the use of better farm management practices and new technologies, which minimizes disease risks and, as a result, enhances farmer creditworthiness (Pongthanapanich et al., 2016). It also assists farmers in being more organized and participating in risk management programmes in a more cost-effective way. These advantages improve the flexibility of fish farm operations and the overall robustness of the value chain (Abu-Samah et al., 2021).

Aquaculture insurance should be seen as a public investment and collaboration among the government, insurers, farmer groups and other value chain participants (Secretan, 2007). As a result, a well-designed insurance policy will help governments reduce the cost of catastrophe recovery and rehabilitation activities. Some governments have included it in their climate change adaptation strategies and use it as a social safety net for small, resource-constrained farmers (Rahman, 2012). In addition to climate change issues, the aquaculture insurance market's existence may be dependent on how efficient and low-risk aquaculture develops (Barange et al., 2018). As aquaculture is a relatively young industry, more studies should be conducted to determine the economic benefits of the insurance scheme and implications for SSA's fish producers. More benefits which have been documented include greater access to money, enhanced security for employees and other stakeholders, and more consistent market access, in addition to directly insuring the aquaculture firm against the effects of climate change (Secretan, 2007).

4.2.5 | Consolidating equity and human rights concerns

Equity should be at the forefront of climate-related discussions. Equity prioritizes current disparities and vulnerable populations because it recognizes that trade-offs across time and space make climate change inherently unjust (Finkbeiner et al, 2018). Climate change may disproportionately affect those who have contributed the least to the issue, such as small-scale fish farming groups in developing countries (Guerrero, 2018). Human rights are at the heart of equity (FAO, 2022). Climate change may have an influence on a population's right to food, clean water, education, health and housing, with disproportionate consequences for the poor, elderly, minorities, women and children (Wright et al., 2023). Equity and human rights are emphasized in the Paris Agreement, the FAO Committee on Fisheries and Aquaculture for 2021 and the Voluntary Guidelines for Achieving Sustainable Small-Scale Fishing. The aquaculture industry's adaptation to climate change should integrate equality and human rights in both procedures and outcomes (FAO, 2022). Transparency, involvement, access to justice and nondiscrimination are all major procedural concerns. The right to life, as well as the rights to food, shelter, water and a means of sustenance, are critical outcome issues. Adaptation planning necessitates the involvement and empowerment of vulnerable people, especially small-scale fish producers (Hanich et al., 2018). SSA governments should investigate the vulnerabilities of the aquaculture industry and respond equally while adhering to human rights norms. The governments should be proactive in their catastrophe preparations, whether catastrophic or gradual, and give access to robust infrastructure and public services (FAO, 2022).

5 | CONCLUSION

This review highlights the socio-economic effects of climate change on the smallholder fish farmers in SSA. Climate change has increased the need to improve the resilience of aquaculture systems. Fish is the most accessible and affordable source of animal protein, particularly for SSA's rural poor socio-economic classes. Demand and consumption of these aquatic fish products will rise as income levels rise and people become more aware of the nutritional and health benefits of fish. In this regard, we explored the probable socio-economic implications of climate change on aquaculture production and suggested several adaptation methods. According to the empirical literature, the current geopolitics, laws and regulations, socio-economic status, specific community needs, market capacity, trade/tariff laws, unique institutional factors, exposure, sensitivity and the nature of vulnerability within each country and region will determine the priority of adaptation actions. Aquaculture farmers should adapt to the available possibilities in the near future in order to build resilience and preserve production in a changing environment. Overall, these adaptation techniques will enhance outcomes for vulnerable socio-economic groups while also contributing to SSA's resilience to climate change.

5.1 | Future research

Our current research presents a vital starting point towards directing future research into the vulnerability of smallholder fish farmers' livelihood systems to climate change and variability. Future research is required to move towards an improved characterization of livelihood vulnerabilities and to identify the most appropriate means for smallholder fish farmers to cope with and adapt to the impacts of climate change.Nevertheless, based on the findings of this research, it can be concluded that efforts to reduce smallholder fish farmer's vulnerability to climate change should be multifaceted to simultaneously tackle, exposure, sensitivity and adaptive capacity. Additionally, most of the socio-economic consequences identified in this review explore the negative impacts. Future research should investigate and discuss the beneficial effects of climate change on local livelihoods. Such an approach would be critical for directing the future of aquaculture sector.

AUTHOR CONTRIBUTIONS

Mavindu Muthoka: Conceptualization; methodology; validation; writing—original draft. **Kevin Okoth Ouko**: Conceptualization; methodology; writing—original draft. **Jimmy Brian Mboya**: Conceptualization; methodology; writing—original draft. **Nicholas Outa**: Writing—review and editing. **Erick Ogello**: Conceptualization; writing—review and editing. **Merceline Ndinda Ndambuki**: Writing—review and editing. **Kevin Obiero**: Conceptualization; methodology; writing—review and editing. **Robert John Ogola**: Methodology; writing—original draft. **Dick Chune Midamba**: Writing—review and editing. **Lucy Njogu**: Writing—review and editing.

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The current study was a review, and no animal or human subjects were used. Therefore, there was no ethical approval needed.

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