

Review

Sub-Saharan Africa Freshwater Fisheries under Climate Change: A Review of Impacts, Adaptation, and Mitigation Measures

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Abstract: Sub-Saharan Africa's freshwater fisheries contribute significantly to the livelihoods and food security of millions of people within the region. However, freshwater fisheries are experiencing multiple anthropogenic stressors such as overfishing, illegal fishing, pollution, and climate change. There is a substantial body of literature on the effects of climate change on freshwater fisheries in Sub-Saharan Africa. This study reviews the existing literature and highlights the effects of climate change on freshwater fisheries, the adaptation strategies of fishery-dependent households in response to the effects, and fisheries' management and mitigation efforts in the face of climate change. The general effects of climate change on freshwater environments include warming water temperatures, increased stratification, modified hydrological processes, and increased pollutants. These effects adversely affect the physiological processes of fish and the overall wellbeing of fishery-dependent people. To cope with the effects of fluctuating fishery resources due to climate change, fishery-dependent people have adopted several adaptation strategies including livelihood diversification, changing their fishing gear, increasing their fishing efforts, and targeting new species. Several management attempts have been made to enhance the sustainability of fishery resources, from local to regional levels. This study recommends the participation of the resource users in the formulation of policies aimed at promoting climate change adaptation and the resilience of freshwater fisheries for sustainable development.

Keywords: fish productivity; eutrophication; socio-economic effects; resilience; small-scale fishers



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1. Introduction

Freshwater fisheries provide low-cost protein, recreation, and commerce to hundreds of millions of people around the world, particularly in areas where alternative sources of nutrition and employment are scarce [1]. According to the Food and Agriculture Organization (FAO), inland capture fisheries contributed about 11.9 million metric ton of fish in 2017, equivalent to 12.7% of the global fish catch, of which Asia and Africa are the biggest producers of inland fisheries [2]. In regions where malnutrition is a critical concern, inland fisheries provide a key source of protein, essential fatty acids, and other micronutrients that are scarce in other food sources [3,4]. In sub-Saharan Africa (SSA) alone, fish is a primary source of animal protein and micronutrients for more than 200 million people, or about 30% of the African population [5]. Besides the significant contribution to food and nutrition security, the inland fishery sector accounts for about 40.4% of the 12.3 million people employed in the fishery and aquaculture sector [6]. In some SSA countries such as Chad, Mali, and Uganda, freshwater fisheries account for about 5 to 10% of the national gross domestic product (GDP) [7].

Despite the nutritional and economic significance, SSA's inland freshwater fisheries are experiencing a plethora of anthropogenic stressors such as overfishing, pollution, illegal fishing, land-use change, and climate change [8–11]. These stressors have been acknowledged to have contributed to the noticeable decline in the fish production of wild capture fisheries in several African freshwater systems. For instance, Hara [12] and Singini et al. [13] indicated that overfishing led to a decline in the abundance of the commercially important chambo, the local name for three closely related fish species of tilapiine cichlids (namely *Oreochromis squamipinnis*, *Oreochromis lidole*, and *Oreochromis karongae*) in Lake Malombe and Lake Malawi. Moreover, Gaber et al. [14] claimed that pollution of freshwater bodies resulted in several changes in the chemical and physiological processes of fish, affecting overall fish productivity. Moreover, illegal fishing was also acknowledged to be threatening freshwater fisheries. For instance, Raji et al. [15] stated that illegal fishing, which includes the use of incorrect gear and explosives, has severe repercussions on the crucial biomass of fish biodiversity and livelihood activities.

Nevertheless, Kao et al. [10] postulated that land-use change and climate change are the two most important anthropogenic stressors, which may affect freshwater ecosystems directly, as they alter the water temperature and water levels, and indirectly through changing the balance between the inputs and outputs of sediments and nutrients. There is sufficient evidence that fish production in African inland fisheries is more dependent on the external climatic drivers than on human exploitation rates and numerous management interventions [16,17]. Studies such as those of Ndebele-Murisa et al. [18], Niang et al. [19], and Woolway et al. [20] argued that climate change is significantly altering freshwater ecosystems, adversely affecting fish productivity and human societies that are dependent on fishery resources for livelihoods and food.

The impacts of climate change on freshwater fisheries remain relatively underexamined when compared with those on marine systems, even though climate change is expected to exacerbate demands on inland fisheries and fundamentally alter freshwater ecosystems [21]. The available literature indicates that some of the impacts of climate change on freshwater ecosystems include warming of the surface water, changes in the hydrological cycle, thermal stratification, eutrophication, and extreme weather events [22–25]. Faced with climate change and variability, aquatic species and human societies exhibit different responses associated with different processes. According to Macusi et al. [26], Carosi et al. [27], and Huang et al. [28], aquatic species respond to changing climatic conditions through changes in distribution, phenology, extinctions, and biological adaptations, such as changing metabolic rates, growth, and reproduction.

Aquatic ecosystems and human societies, which are dependent on natural ecosystems for livelihoods and food supply, have adapted and continue to adapt to the impacts of climate change and variability. Vasseur [29] posited that adaptation includes the idea of change in response to environmental change. Environmental change drives evolution in natural systems and promotes novel responses in human society [29]. For example, based on the temperature size rule, the average size of fish can change in response to changes in water temperature [30,31]. In response to changing aquatic species, fishers change their fishing gear, increase their fishing effort, diversify their livelihoods, and target new species [32,33]. However, some fishers' responses to coping with the impacts of climate change and variability may further aggravate the stressors already being experienced by freshwater ecosystems. Free et al. [34] argued that even though climate change affects fish productivity, climate-adaptive fishery management can mitigate many of the negative impacts of climate change on human societies.

Several studies, including those of Ndebele-Murisa et al. [35], Katikiro and Macusi [36], Mboya [37], Mohammed and Uruguchi [38], Cohen et al. [9], Utete et al. [39], and Muringai et al. [40], investigated the impacts of climate change and variability on fisheries in SSA. However, despite the significant contribution of freshwater fisheries, knowledge of climate change's actual and potential impacts and variability on SSA inland fisheries is surprisingly limited. Harrod et al. [23] stated that inland freshwater fisheries are neglected

in climate research, leaving stakeholders such as managers, fishers, and policymakers with little to no guidance regarding climate change and how it will affect inland fisheries and the future of those who rely on them for their livelihoods and food security. This will have critical implications for future food security and human wellbeing. Despite significant efforts to investigate the impacts of climate change and variability on inland fisheries at the community and national level, it is also important to understand the impacts of climate change on freshwater fisheries at a regional level. Thus, this article highlights the impacts of climate change on freshwater capture fisheries specifically in SSA based on the available literature and reports. Muringai et al. [41] conducted a similar study; nevertheless, their study looked at the entire fishery sector (both marine and freshwater). This review, however, mainly focuses on freshwater wild capture fisheries, as the impacts of climate change on marine and freshwater environments differ in magnitude and intensity. In this review, the authors went further to provide the detailed impacts of climate change on fisheries, adaptation, fishery management, and climate change mitigation measures, which were more generalized in Muringai et al. [14]. The review is divided into different sections covering changes in the climate variables in the region, the characteristics of inland freshwater fisheries, the impacts of climate change on freshwater fisheries, adaptation measures, and fishery management strategies. This review article also provides directions for future research.

2. Climate Trends and Extreme Weather Events

Distinctive seasonal climates characterize SSA, as the region lies in the tropics and includes tropical and subtropical climatic zones, except southern Africa [42]. However, numerous local environmental factors such as differences in altitude, uninterrupted expanses of plateau and plains, and other localized variables within the zones generate varying climate and weather conditions within the region [42,43]. Temperature and rainfall are the main climate variables that are acknowledged to have direct impacts on inland fisheries [23]. Research conducted by Kundzewicz et al. [44], Engelbrecht et al. [45], and Gizaw and Gan [46] showed that alterations in temperature, rainfall, and extreme weather events, and their distribution have been dramatic across SSA. According to the National Aeronautics and Space Administration (NASA), the global mean temperature has increased by more than 1 °C since 1880, and that two-thirds of this warming has occurred since 1975 at a rate of about 0.15 °C to 0.2 °C per decade [47]. Temperatures across the African continent are increasing twice as fast as the global mean estimates of 0.4 °C and 1.2 °C per century for the Northern and Southern Hemispheres, respectively [48]. Even though trends appear to be widespread over the continent, the temperature changes are not always uniform within the region [43]. This is due to differences in altitude and other localized variables such as vegetation density, the area covered by surface water, and landforms. Climate models further project an increase in temperature across the African continent in the 21st century, with SSA expected to experience the strongest warming in the region by 2050 [49]. Adhikari et al. [50] hypothesized that climate change is projected to increase mean temperatures by 1.4 °C to 5.5 °C by 2100 across Africa. Africa is susceptible to extreme rainfall variations from year to year because most of the region is semi-arid [51]. According to Kotir [43], Africa's rainfall patterns are influenced by large-scale intra-seasonal and inter-annual climate variability, including occasional El Niño–Southern Oscillation (ENSO) events in the tropical Pacific, which cause frequent extreme weather events such as floods and droughts. The problem with the region is that it suffers from a paucity of historical data for drawing robust conclusions on the observed rainfall trends over the past century [19,48]. Similar to the temperature patterns, rainfall patterns across Africa vary extremely and exhibit different scales of temporal and spatial variability [43]. In SSA, areas with sufficient historical data, such as southern Africa, the interannual variability of rainfall has increased over the past 40 years, but with recurrent droughts [43]. Some parts of SSA have experienced an increase in rainfall, but overall, it is the drop in rainfall that is often more pronounced [43]. Rapid and statistically significant decreases in rainfall have been

recorded in some parts of southern Africa [52], such as Botswana, Zimbabwe, and western South Africa [19]. Nevertheless, some parts of east Africa are becoming wetter [19,50,52]. Modeled rainfall projections through the 21st century are less certain than temperature projections and show higher spatial and seasonal dependence than temperature projections [19]. Over 80% of the climate models agree that rainfall will decrease over most parts of Africa [19]. Mean annual rainfall is projected to decline by 5%, 4%, and 5% over central, western, and southern Africa, respectively [53].

Climate change leads to changes in the intensity, frequency, duration, spatial extent, and timing of weather and climate extremes, and can result in unprecedented extremes [54]. In recent decades, Africa has suffered from a plethora of record-breaking climatic extremes, including heavy storms, heat waves, floods, and droughts due to climate change [55]. The most frequent extreme weather events experienced in SSA are floods and droughts [56]. For instance, southern Africa experienced 254 flood events, 130 large storms, and 88 droughts between the years 1980 and 2016 [48]. Extreme weather events are expected to increase in SSA due to high temperatures and the unpredictability of both the temporal and spatial distribution of rainfall events [43]. Climate models used to predict drought over southern Africa suggest that, with increased temperatures, the frequency and intensity of drought conditions will increase, but the effects vary across regions [49]. Models project that in the 2050s and 2080s, the frequency of short droughts is expected to increase by about 4–7% in the central, eastern, and southern parts of Africa [46].

3. Characteristics of Sub-Saharan African Inland Fisheries

Inland fisheries are fisheries exploiting wild fishery resources in waters located inland from the coastline, such as lakes, wetlands, reservoirs, floodplains, rivers, streams, and even rice fields [57]. In 2017, inland freshwater fisheries accounted for 13% or 11.9 million ton of the total global fish catch, of which five million tons were from African inland capture fisheries [2]. However, the reported figures of the inland fishery catch may be underestimated because many inland fisheries are subsistence and small-scale in nature, and most of the fish produced are consumed or traded locally without entering the formal economy [58]. Furthermore, the fish catch figures are understated because most inland fisheries operate in remote areas, and have poorly defined value chains or infrastructure for dealing with catches from inland waters, and collecting dispersed information is costly [58,59]. According to the World Forum of Fisher People (WFFP), inland fisheries are small-scale in nature and make little contribution to national GDPs [60]. Inland small-scale fisheries are characterized by the use of low-technology fishing methods, the use of non-motorized vessels or no vessels at all, and limited post-harvest transportation [57]. Researchers argue that inland small-scale fisheries employ approximately four million people more than their marine counterparts [57,61]. Small-scale fisheries are also characterized by a diverse workforce, with women representing about 50% of the workers [62,63]. Women are found along the entire small-scale fishery value chain, but they mostly dominate the post-harvest sector (processing and trading) in most fishing communities [7].

Several studies have suggested that African inland fisheries are experiencing several challenges such as pollution, overexploitation, invasive alien species, hydrological disruptions, habitat loss, and the negative impacts of a changing climate [9,35,39,64–66]. These stressors have led to a decline in primary fish production and total fish catches, particularly for small-scale fishers [67]. Most studies, for example, Ndebele-Murisa et al. [35] and Cohen et al. [9], inculpated climate change, among other factors, for declining fish productivity in some of Africa's great lakes such as Lake Tanganyika and Lake Kariba.

4. Impacts of Climate Change and Variability on SSA's Inland Fisheries

Climate change and variability are expected to affect the fishery sector in multiple ways through changes in mean temperature, rainfall amounts and patterns, and the increasing occurrence and severity of extreme weather events. However, the precise consequences cannot be defined due to the limited availability of information on the impacts of climate

change and availability on African inland fisheries [58]. Figure 1 illustrates how climate change and variability affect the socio-ecological systems (SES) of inland fisheries.

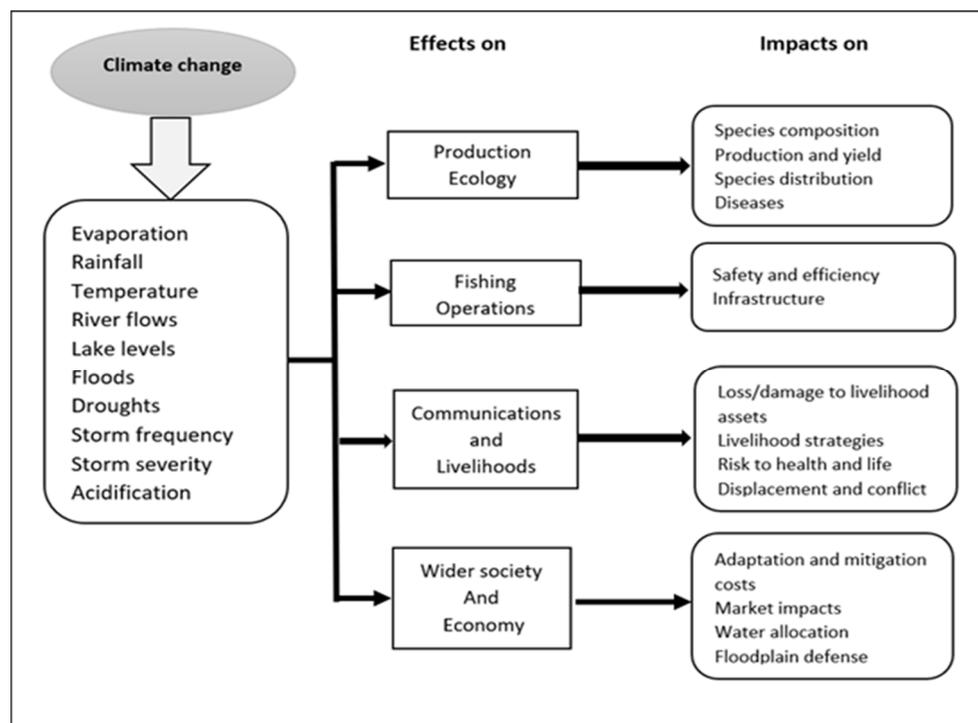


Figure 1. Impacts of climate change and variability on inland fisheries (adapted and modified from Badjeck et al. [68]).

4.1. Water Temperature

Water temperature is recognized as the most influential factor of all environmental stressors that affect inland freshwater fisheries [35,69]. Freshwater species are likely to be strongly affected by warming water temperatures due to discrete ecosystem boundaries, limiting the potential of species range shifts for tracking thermal optima compared with marine species [70,71]. Considering that inland freshwater fish are poikilotherms (thermal conformers), changes in water temperature have subsequent effects on the fishes' biological and physio-chemical processes. These effects include, but are not limited to, growth and body size, metabolism, maturation, sex determination, mortality, migration, immune response, habitat suitability, reproductive success, and distributional shifts [23,70]. There is limited literature on the effects of climate change and variability on primary and secondary productivity on SSA's inland waters. However, several studies have indicated that warming water temperatures have caused a decline in plankton productivity in SSA's lakes [18,72,73]. Plankton (phytoplankton and zooplankton), which form the aquatic food web, is sensitive to environmental change. A study by Abo-Taleb et al. [74] revealed that increasing water temperatures have resulted in a decline in plankton. Simultaneously, fish metabolism increases with increasing temperatures [70,75]; for instance, Nyboer and Chapman [75] revealed that the Nile perch's (*Lates niloticus*) metabolism rate increased in response to increasing water temperatures. Therefore, if increases in metabolic demand are not matched by increasing plankton availability, fish populations are likely to decline or become extinct due to less food availability [9,70]. For example, Magadza et al. [76] detected that the Tanganyika sardine (*Limnothrissa miodon*) of Lake Kariba declined owing to shortages of food resources (zooplankton).

Water temperatures also act as a reproduction cue and influence physiological pathways associated with gamete development [77,78]. Water temperatures influence fishes' reproduction behavior, spawning pattern and timing, gamete maturation, and the early

life histories of fish [78]. Fish species that have limited ability to adapt to changing temperatures face a greater risk of extinction or extirpation [79]. In fishery studies, the impacts of climate change are mostly associated with warming temperatures, and the effects of extreme cold temperature on fish have received little attention [80]. Nevertheless, increases in water temperature variability due to climate change increases the potential of increased cold shock events [80]. Cold shock refers to “the stress response that occurs when fish has been acclimated to a specific water temperature range and subsequently exposed to a rapid decrease in temperature, resulting in a cascade of physiological and behavioral responses” [80]. Research on marine fish has indicated that weather-induced cold shock events in 1940 resulted in large-scale fish mortalities. However, the impacts cannot be generalized for freshwater fish [80]. Harrod et al. [23] stated that this significant influence of temperature on fish physiological process led Brett, in 1970, to describe temperature as the master abiotic factor that affects freshwater fishes’ capacity to support inland fisheries. Hence, the projected increase in temperatures over SSA will have potential adverse impacts on the inland freshwater fishery sector.

4.2. Thermal Stratification

Surface water temperature is closely related to air temperature [81]. Hence, surface water temperature increases in response to warming air temperatures owing to climate change. Increasing surface water temperature leads to changes in the density structure of lakes, with a layer of warmer, less dense water at the surface and cooler water at the bottom, known as thermal stratification [82]. During the stratification period, the warmer surface water layer (epilimnion) is separated from the colder water layer (hypolimnion) beneath, and a thermocline (sharp temperature gradient) is formed at the contact zone of both layers [18]. Stratification limits the mixing of the epilimnion and hypolimnion layers, resulting in vertical profiles of different water temperatures, pH, and dissolved oxygen [18]. Furthermore, stratification limits nutrient flux into the upper surfaces [83]. Stratification is common in many deep tropical lakes in SSA, such as Chilwa, Malawi, Niger, Cabora Bassa, Chad, and Kariba [18]. For aquatic organisms, particularly fish, stratification limits habitable areas, forcing fish to balance between favorable temperatures and minimum dissolved oxygen requirements [84]. Most freshwater organisms are ectothermic (thermal conformers) and optimize their physiological performance by inhabiting habitats within specific thermal niches [25]. Therefore, in the face of warming surface water temperatures in SSA, which is already regarded as the warmest are and is projected to warm faster than the mean global increase [19], surface water temperatures might exceed the physiological tolerances of some fish species. On the other hand, waters below the thermocline might have tolerable temperatures but lack sufficient dissolved oxygen compared with the warm surface water, resulting in some fish species squeezing between these two extremes and experiencing niche compression during the stratified season [84]. In general, freshwater fish species respond to differences in thermal gradients in freshwater water bodies by shifting habitats; for example, the vertical distribution of Nile perch in Lake Victoria varied according to thermal stratification, in which fish were restricted to a depth of less than 40 m, but when the lake was isothermal (constant temperature), they tended to occur in water deeper than 40 m [84].

Contrary to Vincent [82] and Ndebele-Murisa et al. [18], who state that warming temperatures promote stratification, Mahere et al. [85] and Marshall [86] claimed that warming temperature weakens the thermocline (less pronounced stratification). A weak thermocline has been detected in studies by Mahere et al. [85] and Marshall [86] in Lake Kariba, which has been acknowledged to be experiencing warming temperatures. On the other hand, Mahere et al. [85] and Marshall [86] claimed that the perceived warming temperatures of Lake Kariba led to an increase in algal biomass and primary productivity. Therefore, the thermal stratification of inland freshwater bodies has and will continue to affect fish production, either by increasing or decreasing fish productivity.

4.3. Hydrological Cycle

The hydrological cycle describes the continuous water movement above, on, and below the surface of the Earth [87]. It is affected by only two factors, which are human activities and climate [88]. Climate change alters the present situation of the hydrological cycle and redistributes the water in terms of time and scale [89]. Studies have shown that the global hydrological cycle has already responded to the observed increase in temperature over recent decades through changes in rainfall patterns, changes in runoff, and increased atmospheric water vapor content [90–92]. Several studies have agreed that climate change will affect both the quality and quantity of available water resources in the SSA region [93,94]. According to the IPCC's climate projection models, the African dry tropics are projected to experience a decline in rainfall in the 21st century, ultimately affecting water availability and river runoff [95].

The aforementioned changes in the hydrological processes will affect water discharge patterns, consequently affecting water availability for fisheries, and physio-chemical processes and conditions [23]. Research has indicated that surface runoff plays two crucial roles in freshwater fisheries, which include transporting nutrient-supplying sediments (a source of fish feed) [96,97], and providing a suitable habitat for freshwater organisms [98]. During years of abundant rainfall and flooding, extensive nutrients are released in the flood plains, leading to explosive population growth at all levels in the fishery food chain [7]. For example, a study by Mboya [37] identified the number of fishers in the Mbita Division of Homa Bay Country in Kenya increased when there was high rainfall, as compared with low-rainfall periods, due to high fish productivity, influenced by the availability of fish feed and habitat suitability. In addition, several climate models have agreed that precipitation decreases with an increase in temperature [23]. Increasing temperature results in increased evaporation [99], and the issue of evaporation and decreasing rainfall can lead to habitat loss and fishery degradation [23]. Drying up of lakes and a reduction in river flow have already been observed in arid and semi-arid regions of SSA [100], which has negatively impacted the southern African fishery sector due to fishery habitat loss. For instance, the Global Climate Model Data (under the A1B emission scenario) projects that the river runoff in the Zambezi River basin will decline by between 13% and 34%, depending on the subregion, within the Zambezi region by 2030 [101]. This might negatively affect the fishery sector in the Zambezi River basin.

Furthermore, climate change and population growth in SSA have led to increased demand for freshwater resources by several sectors such as energy, manufacturing, and agriculture [102]. As a result, a fishery within a multi-user dynamic will probably lose out to other sectors [103]. This situation is highly noticeable in SSA, where crops are mainly rain-fed or irrigated. Therefore, climate change is expected to alter the hydrological cycle, affecting the freshwater ecosystems' physio-chemical process, fish productivity, and human communities that are dependent on the ecosystem for food and livelihoods.

4.4. Eutrophication

Eutrophication is an enrichment of a relatively closed and slow-flowing water body (such as a river, lake, reservoir, or freshwater wetland) by dissolved nutrients that causes structural changes in the ecosystem, such as stimulation of the proliferation of algae and other plankton in the water, depletion of fish species, the general deterioration of water quality, and other effects that reduce and preclude use [104,105]. All water bodies are subject to natural and slow eutrophication processes, but in recent decades, anthropogenic activities have accelerated the progression and extent of eutrophication in several water bodies [106,107]. The use of fertilizer for agricultural purposes, industrial effluent disposal, and sewage disposal into freshwater ecosystems are some of the human activities contributing significantly to eutrophication [106].

Several studies have concurred that climate change and variability can directly or indirectly influence eutrophication within water bodies due to interactions between meteorological factors and nutrient availability [107–109]. Moss et al. [108] stated that rising

temperatures due to climate change lead to amplified rates of bacterial activity, which depletes oxygen from the water and stimulates the release of nutrients already present in the bottom sediments, increasing nutrient inputs in lakes and estuaries by increasing the rate of nutrient release from soils and the conversion of nutrients into forms that algae can easily use. In addition, increasing water temperatures accelerate the growth of cyanobacteria (a group of bacteria that grow in the water and are blue-green in color) [107,110,111]. Warming temperature increases the dominance, growth rate, geographical distribution, activity, and persistence of hazardous cyanobacteria species [112,113]. Cyanobacteria produce highly toxic secondary metabolites known as cyanotoxins, which are hazardous to some aquatic species, animals, and humans [111]. Cyanobacteria can affect fish species in several ways, including degeneration of fish tissue, reduced fertilization, and fish mortality [114–116]. However, the effects vary among fish species, the toxins produced, and the concentrations ingested. In humans, some known toxins such as nodularins, microcystins, and cylindrospermopsins can cause gastrointestinal disturbances, skin toxicity, liver, and kidney damage [111].

Besides the temperature changes, which enhance algal blooms on water bodies, changes in the hydrological cycle also contribute to water eutrophication [107]. According to Nazari-Sharabian et al. [107], rainfall and runoff play a significant role in transporting sediments and nutrients into the receiving water bodies. Rainfall is projected to increase in some parts of east Africa in the 21st century [19]. Therefore, the water quality of freshwater bodies (for example, water bodies in East Africa) might be prone to high nutrient concentrations and increased contamination owing to increased rainfall and runoff, which are responsible for transporting and depositing sediments and nutrients into water bodies [97]. On the other hand, in areas where rainfall is projected to decline, freshwater bodies are also prone to the risk of eutrophication due to low water flows and reduced water volume available for dilution of nutrients [107]. Eventually, the increased concentration of nutrients can cause deoxygenation by lowering the dissolved oxygen concentration [117], which is vital for fish survival. There is limited knowledge on the impacts of climate change on the eutrophication of freshwater systems specifically in SSA. However, the projected changes in climate factors are expected to interact and intensify eutrophication in SSA's water bodies, causing harm to both fish species and fishery-dependent communities.

4.5. Extreme Weather Events

Droughts and floods are the most recorded extreme weather events in most parts of SSA [56]. The changes in the intensity, duration, and frequency of these extreme weather events can affect the fishery sector and fishery-dependent communities in several ways, such as changes in the amount of water flowing within the river [118], damage or loss of stock [119], damage or loss of fishing equipment and infrastructure, loss of fishing days, and posing a danger to life [23,33]. For instance, a study on the impacts of flooding on fishing families in the Pedro community in Nigeria revealed that 76% of fishers experienced a reduction in fish catches, destruction of fishing implements, loss of family income, and disruption of children's schooling due to flooding in their area [120]. In addition, Bêche et al. [121] stated that inland freshwater ecosystems are particularly susceptible to prolonged drought because suitable habitat and refugia may be severely reduced or eliminated for periods ranging from hours to years. In a multi-user scenario, droughts increase human pressure on the already scarce freshwater resources through withdrawing freshwater from water bodies for agricultural use or manufacturing purposes, which can reduce habitat connectivity during dry days, adversely affecting aquatic species [121]. According to Lake [122], water deficit due to droughts can cause streams to shrink in size and fall in level, cause standing water bodies to shrink in volume and surface area, and increase salinity in freshwater estuaries. Gao et al. [123], for example, claimed that the shrinking of Lake Chad was due to persistent droughts and increased water withdrawal for agricultural purposes. The lake is believed to have shrunk from 22,000 km² to approximately 300 km² between the 1960s and the 1980s,

resulting in a loss of fish habitat and a reduction in fish production [123,124]. During the same period, drought conditions caused a 50% drop in fishery production in the Niger Delta [91].

Therefore, the projected increase in extreme weather events over the SSA region will amplify the existing anthropogenic impacts on fisheries and fishery-dependent communities. However, extreme weather events do not only negatively affect fisheries; they can also enhance fish productivity. For instance, Talbot et al. [125] suggested that flooding can also provide many benefits such as creating wildlife habitats, increasing fish production, recharging groundwater, and recharging wetlands. In addition, Mboya [37] suggested that flooding increased fish production in the Mbita Division of Homa Bay Country in Kenya. Therefore, the expected increase in flood events over SSA might positively benefit fisheries in the region.

4.6. Socio-Economic Impacts

4.6.1. Implications for Food and Nutrition Security

At present, SSA is home to more than 1 billion people [126], and population growth projections indicate that the SSA region could account for more than half of the world's population growth between 2019 and 2050, with a projected addition of 1.05 billion people [127]. Fish and the fishery sector play an important role in supporting the food and nutrition security of the growing population. At present, fish is the main source of animal protein and micronutrients for approximately 200 million people or 30% of the continent's population [5,128]. In recent years, food insecurity has been rising in Africa. Hence, the continent is not on track to meet Sustainable Development Goal (SDG) Number 2, which aims to eliminate hunger by 2030 [129]. About 256 million people or 20% of the African population are undernourished, of which 239 million people are in SSA and 17 million in North Africa [129]. In addition, Mohammed and Uraguchi [38] stated that SSA accounts for 28% of underweight children in the world. Fish can play a crucial role in addressing the issues of undernourishment, hunger, and underweight. Studies such as Psaki et al. [130], Ijarotimi [131], Drammeh et al. [132], and Brglez et al. [133] have suggested that insufficient food or nutrient intake is one of the key factors responsible for undernutrition. Fish is acknowledged to be a cheap source of animal protein, but is consumed in small quantities by low-income households [134]. Fish, particularly small fish such as Lake Tanganyika sardine, are rich sources of multiple essential micronutrients such as iron, calcium, zinc, vitamin A, and vitamin B12, which are usually lacking in most diets [134]. These small fish, which are widespread in some lakes of SSA (Cahora Bassa, Kariba, Kivu and Tanganyika), can contribute significantly to low-income household diets and help alleviate undernourishment. Furthermore, Mohammed and Uraguchi [38] indicated that deficiencies in essential and non-essential proteins and vitamins are the main causes of being underweight in children.

Studies have detected declining fish productivity and catches across several of SSA's freshwater ecosystems owing to climate change, for example, Cohen et al. [9] and Utete et al. [39]. Declining fish catches, particularly those of small-scale fishers, adversely affect the food and nutrition security of fishery-dependent households or communities through a decline in animal protein availability and reduced income generated from fishing. In addition, small-scale fishers in Lake Kariba reported declining incomes from fishing and fishery-related activities [40]. The income generated from fisheries can be used for purchasing a variety of foods with higher calories, which enhance food and nutrition intake. Thus, the impacts of climate change on freshwater fisheries will worsen the existing problem of food and nutrition insecurity in SSA.

4.6.2. Economic Impacts

Inland fisheries support the national economies of several countries in SSA, such as Tanzania, Mali, Democratic Republic of Congo, Malawi, Mozambique, etc., mainly through employment creation, as a source of foreign currency, contributing to the GDP, and boosting government revenues through fishery taxes and agreements [6]. The sector is an economic base industry and supports several secondary economic activities such as boat

construction, fish processing, and international logistics [135]. There are limited national figures on the contribution of inland fisheries to employment and the GDP of African nations. However, the United Nations Conference on Trade and Development (UNCTAD) stated that fish is one of the highest value traded commodities, accounting for about 10% of global agriculture exports, of which 53% of global fisheries exports are from developing countries, 43% from developed countries, and 4% from the least developed countries [136]. There are inadequate fishery export data for most countries in SSA; however, in west Africa, fisheries contribute about 2% of the total exports [53,137]. West African countries such as Guinea-Bissau, Mauritania, and Senegal are net exporters of fish products. Therefore, fisheries contribute significantly to their national GDPs. In Zimbabwe, fisheries contribute significantly to job creation in the face of the high national unemployment rates [138].

Recreational fisheries contribute significantly to several national economies in SSA [139]. The recreational fishery industry is common in several countries in SSA such as Angola [139], South Africa [140], and Zimbabwe [11]. Du Preez and Hosking [140] stated that the recreational trout (*Oncorhynchus mykiss*) fishing industry is a source of income and an employment creator in some of the most rural parts of South Africa. In West Africa alone, recreational fishing generates about USD 152 million per year for the region [11]. A study by Shelton et al. [141] indicated that the trout population in freshwater ecosystems in South Africa decreased during warmer periods, thereby affecting recreational fishing. Therefore, the continuous warming of freshwater temperatures due to climate change might negatively affect the recreational fishing industry and the incomes and livelihoods of rural communities in the region.

National economies dependent on freshwater fisheries as a source of revenue and employment generation are highly vulnerable to climate change and variability. The observed impacts of climate change and variability on fisheries include changes in the distribution of fish species, declining fish productivity, shrinking fishing grounds, and the disappearance of valuable fish species [9,35,41]. For example, research in West Africa has suggested that fish landings in this region are expected to drop by 26% by the 2050s under the Special Report on Emissions Scenario (SRES) A1B, and a substantial decline (about 50%) in fish landings is predicted in six west Africa countries (Ghana, Ivory Coast, Liberia, Nigeria, Togo and Sierra Leone) under the same SRES A1B climate change scenario [135]. Therefore, the predicted decline in fish landings under the SRES A1B climate scenario is expected to result in a 21% drop in total landed value and a 50% loss in fishery-related jobs by the year 2050 [135]. Furthermore, the drought conditions observed in the Niger Delta of West Africa in the 1970s and 1980s resulted in losses of about USD 20 million per year [91]. In addition, small-scale fishers of Lake Kariba in Zimbabwe indicated that declining fish catches are affecting the income derived from fisheries and the related activities [40,142].

Therefore, fast-tracking climate change will intensify the existing impacts of climate change on fisheries, such as declining fish productivity, consequently affecting the ability of the fishery sector to support economic growth through its contribution to the GDP and creating employment.

5. Fisheries' Climate Change Adaptations in Sub-Saharan Africa

Historically, nature and human societies have adapted to environmental change. Adaptation to climate change is generally defined as the "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities" [143]. The literature shows that freshwater fish species adapt to environmental change through changing their biological process and phenology [123,144]. For instance, in ectotherms, which dominate freshwater ecosystems, the surrounding temperature influences metabolic rates. Since they cannot regulate their body temperature independently, any temperature change alters their metabolism, physiological processes, and growth rates [145]. Empirical studies on the effects of abiotic factors on the distribution of the Nile perch of Lake Victoria revealed a negative relationship between temperature and the Nile perch [69,146,147]. In addition, James and Washington [148]

stated that fish species migrate to suitable habitats in the face of changing environmental conditions such as increasing temperatures. Fishery-dependent communities or households also adjust to fluctuating fishery resources. The adaptation of fishing communities to climate change can be autonomous or planned [149], and can be at an individual, community, national, or regional level [41].

Diversifying livelihoods, targeting new species, migration, changing fishing gear, and relying on social networks are some of the short-term strategies adopted by fishers, particularly small-scale fishers, to deal with the consequences of climate change [33,150]. For instance, fishers in Lake Wamala in Uganda changed their fishing gear, increased the time spent on fishing grounds, targeted new species, and diversified to non-fishery-related livelihoods to deal with the impacts of climate change [33]. Furthermore, Mgana et al. [151] postulated that some fishers of Lake Tanganyika adopted new technologies such as homemade light-emitting diodes (LEDs) to enhance their fish catches. Besides the use of LEDs to catch fish, McLean et al. [152] also reported that most households in Lake Tanganyika used mosquito nets to catch fish, which has had adverse effects on fish ecology.

Despite the need to adapt to changing fish productivity and fish distribution, some of the fishers' adaptation strategies are detrimental to freshwater ecosystems. They might result in the extinction of valuable species, consequently affecting the livelihoods and food and nutrition security of fishery-dependent people in the long term. Musinguzi et al. [33] argued that fishers' strategies for increasing their productivity can be beneficial in the short term but can reduce the resilience of freshwater ecosystems due to unsustainable fishing practices. For example, the increasing number of fishing boats and illegal fishing gear used by fishers in Lake Victoria led to overexploitation and capture of immature fish, specifically the Nile perch [153]. According to Njiru et al. [153], catches of Nile perch were dominated by juvenile fish, with about 95% of the catch being below the size of maturity. In addition, in Mida Creek, Kenya, about half of the small-scale fishers use mosquito nets as fishing gear, mainly targeting prawns and juvenile fish [154]. In Lake Wamala, Uganda, fishers also changed their fishing gear by reducing the mesh size from 88.9 mm to 38.1 mm (a non-selective mesh size) [33]. The use of mosquito nets and nets with a smaller mesh size will result in the heavy exploitation of non-target species and juveniles [155].

Despite the fishers' efforts to adapt to changing natural ecosystems, Agrawal [156] claimed that the capacity to adapt depends on how institutions regulate and structure their interactions amongst themselves and external actors. Thus, the success of fishers' adaptation efforts largely hinges upon the nature of existing formal and informal rural institutions [157]. For instance, inland fisheries contribute 85% of Tanzania's fish yield, and the Tanzanian National Adaptation Plan of Action mentions fishing in the section on water, but it does not highlight the impacts of climate change on inland fishers [158]. In addition, the 2015 Fisheries Act of Tanzania mandated the creation of Beach Monitoring Units (BMUs), which are aimed at conserving fishery resources, to allow fish stocks to regrow [158]. A 6-month ban on fishing in Lakes Nyumba and lakes was imposed by these BMUs, thereby affecting the livelihoods and food security of fishery-dependent communities along the shores of Lakes Nyumba and Mungu. Fish stock conservation undermines the adaptation of fishers to declining fish catches; for example, in Botswana, capture fisheries fall under the Ministry of Environment, Wildlife, and Tourism, and under a wildlife management approach, the focus is on conservation and less on sustainable utilization of fisheries for food security [159].

On the other hand, a study by Mubaya and Mafongoya [157] on the role of institutions in managing local-level climate change adaptations in the Nyaminyami area (where fishing is the primary livelihood) located in Kariba Rural District in Zimbabwe revealed that institutions in Nyaminyami played a significant role in facilitating climate change adaptations in the area through strengthening the education and health sector. Nevertheless, the potential adaptation strategies for fishers seem to be limited due to expensive fishing licenses not being affordable for poor communities [157]. Therefore, local institutions play a crucial role in the success of fishers' adaptations to the impacts of climate change. Local

institutions in SSA need to acknowledge the importance of fisheries to livelihoods and food security for the locals, and acknowledge that the climate is changing at an alarming rate, and thus, there is a need to promulgate policies that enable fishing communities to adapt to the changing environment.

6. Fishery Management and Climate Change Mitigation Strategies

The 2030 SDG Number 14 highlights the importance of protecting, conserving, and sustainably using marine and aquatic resources for sustainable development [160]. Throughout history, traditional authorities and government institutions were and still are responsible for managing fish resources. Purcell and Pomeroy [161] suggested that co-management should be adopted in the management of small-scale fisheries in developing countries, particularly in the tropics. Co-management is a “relationship between a resource-user group and another organization or government agency for management purposes in which some degree of responsibility and authority is conferred to both parties” [161]. Sub-Saharan African countries such as Malawi, Mozambique, Nigeria, Senegal, South Africa, Zambia, and Zimbabwe have adopted co-management for managing fisheries, with the desire to improve fishers’ compliance with fishery regulations by involving fishers in decision-making, and to reverse the depletion of fish stocks [162]. According to Donda [163], co-management of fisheries enables fishers to influence the decision-making process through information sharing, allowing them to acquire scientific information on the ecological conditions of their ecosystem. In the climate change adaptation context, access to scientific information such as weather forecasts enhances the adaptive capacity of fishing communities to the impacts of climate change [163]. Moreover, co-management between fisheries managers and fishers can develop adaptive strategies by combining scientific information with local knowledge and experience of change and responses over time [164]. This helps in the design and implementation of location-specific and holistic adaptations and mitigation measures.

There is limited literature on the climate change mitigation strategies implemented by the fishery sector to deal with the impacts of climate change, particularly in the SSA region. Most common mitigation strategies are aimed at fish conservation, particularly curbing overfishing and fish species depletion. These strategies include, but are not limited to, the type of fishing gear used, restriction of access, the number of licenses granted, and the time and period of the year when fishing is allowed [162].

7. Conclusions and Recommendations

The study reviewed the existing literature and knowledge on the impacts of climate change on SSA’s inland freshwater fisheries, and climate adaptation and mitigation strategies. The literature reveals that climate change is one of the key threats to the inland freshwater fishery sector in the region, as it interacts and amplifies the other existing anthropogenic stressors. Changing climate variables, particularly temperature and rainfall, alter the physiological and phenological processes of fish, which have contributed to the decline in fish productivity and fish catches in several freshwater bodies in SSA. Fishery-dependent communities use several different strategies to deal with the fluctuations in fishery resources. However, some of the strategies applied have detrimental effects on fish resources in the long run. Furthermore, the fishery management and climate mitigation strategies used by fishery managers and managing institutions mainly focus on the conservation of fishery resources, subsequently undermining the livelihoods and food security of the resource users. Effective fishery management and climate change adaptation and mitigation cannot be achieved without the inclusion of the resource users. Therefore, to formulate successful climate adaptation and mitigation strategies and policies, resources users’ or fishers’ participation in decision-making processes is crucial. The principal resource for adapting to the impacts of climate change is the fishers themselves, and their indigenous knowledge of the local environmental systems and their expertise. Hence, co-management between fisheries managers and fishers can help enhance fishers’ adaptation to the im-

pacts of climate change, and the involvement of fishers in policy making may result in the formulation of robust and holistic policies for sustainable fishery development.

However, the identified impacts of climate change on freshwater fisheries, fishers' adaptation strategies, and mitigation measures are location-specific and vary greatly across regions or communities. Therefore, to fully understand the location-specific impacts of climate change and how resource users adapt and safeguard the natural resources, this study encourages future researchers to conduct local climate change vulnerability assessments, as they are crucial for guiding local climate change adaptation and mitigation measures. Local studies should focus on assessing the biophysical and socio-economic impacts of climate change on freshwater fisheries. Furthermore, SSA is characterized by a paucity of statistical data on freshwater fish catches, the number of fishing vessels, and the total number of people engaged in fisheries, particularly at national levels; hence, fishery managers and researchers should record all the relevant fisheries statistics for monitoring and controlling fish stocks and fishing activities. Statistical data can also be used for future research purposes. To fully understand the socio-economic effects of climate change on fishery-dependent communities or countries, a value chain analysis of the freshwater fisheries in SSA and the impacts of climate change on each stage of the value chain should be investigated.

To mitigate the impacts of climate change on fisheries, fishery managers should protect fish reserves from further anthropogenic pressures such as overfishing and poor land-use practices. Furthermore, capacity building in fishing communities is an important factor which will improve the adaptive capacity of fishers to the impacts of climate change. Increasing general awareness of the impacts of climate change on freshwater ecosystems and the adaptive capacities of fishing communities will help implement holistic adaptation measures for the probable climate-mediated changes still to come.

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