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Climate change impacts and adaptation strategies in Africa: Selected case studies

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ABSTRACT
Climate change poses significant challenges to Africa, impacting various sectors and regions across the continent. This comprehensive review examines the effects of climate change in Africa through case studies in the Sahel, West Africa, East Africa, Southern Africa, and Central Africa. These studies highlight commonalities and interconnections, emphasizing the vulnerability of African communities. The prevalence of drought and food insecurity in the Sahel, coastal erosion and rising sea levels in West Africa, shifts in rainfall patterns in East Africa, health risks in Sub-Saharan Africa, and deforestation in Central Africa highlight the need for effective adaptation strategies. Integrated and multi-sectoral approaches are crucial to address the complex challenges of climate change. Collaboration among stakeholders, including governments, communities, researchers, and international agencies, is essential for developing holistic adaptation strategies. Lessons from the case studies stress the need for resilient agriculture, community-based initiatives, policy interventions, and knowledge sharing. Incorporating local knowledge and involving communities in decision-making are key for sustainable solutions. The findings have significant implications for regional climate change adaptation and policy-making. Integrating climate change considerations into development planning, establishing dedicated institutions, and securing funding are urgents. International cooperation and technology transfer enhance Africa's adaptive capacity and resilience, protecting communities, ecosystems, and biodiversity. This review provides valuable insights into climate change impacts in Africa, offering a comprehensive understanding of interconnected challenges and adaptation opportunities. It serves as a foundation resource for evidence-based policies and strategies, fostering climate resilience and sustainable development across the continent.

Keywords: Adaptation strategies, Africa, climate change, vulnerabilities

RÉSUMÉ
Le changement climatique pose des défis importants en Afrique, impactant divers secteurs et régions à travers le continent. Cette revue complète examine les effets du changement climatique en Afrique à travers des études de cas dans le Sahel, l'Afrique de l'Ouest, l'Afrique de l'Est, l'Afrique australe et l'Afrique centrale. Ces études mettent en évidence des similitudes

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et des interconnexions, soulignant la vulnérabilité des communautés africaines. La prévalence de la sécheresse et de l'insécurité alimentaire au Sahel, de l'érosion côtière et de l'élévation du niveau de la mer en Afrique de l'Ouest, des changements dans les schémas de précipitations en Afrique de l'Est, des risques sanitaires en Afrique subsaharienne et de la déforestation en Afrique centrale souligne la nécessité de stratégies d'adaptation efficaces. Des approches intégrées et multisectorielles sont cruciales pour faire face aux défis complexes du changement climatique. La collaboration entre les parties prenantes, y compris les gouvernements, les communautés, les chercheurs et les organismes internationaux, est essentielle pour élaborer des stratégies d'adaptation holistiques. Les leçons tirées des études de cas soulignent la nécessité d'une agriculture résiliente, d'initiatives communautaires, d'interventions politiques et de partage des connaissances. L'incorporation des connaissances locales et la participation des communautés à la prise de décision sont essentielles pour des solutions durables. Les résultats ont d'importantes implications pour l'adaptation au changement climatique régional et l'élaboration de politiques. L'intégration des considérations sur le changement climatique dans la planification du développement, la création d'institutions dédiées et la sécurisation des financements sont urgents. La coopération internationale et le transfert de technologie renforcent la capacité d'adaptation et la résilience de l'Afrique, protégeant les communautés, les écosystèmes et la biodiversité. Cette revue offre des informations précieuses sur les impacts du changement climatique en Afrique, offrant une compréhension globale des défis interconnectés et des opportunités d'adaptation. Elle sert de ressource fondamentale pour l'élaboration de politiques et de stratégies fondées sur des preuves, favorisant la résilience climatique et le développement durable à travers le continent.

Mots-clés : Stratégies d'adaptation, Afrique, changement climatique, vulnérabilités

INTRODUCTION

Climate change, partly resulting from human activities and the associated increase in greenhouse gas emissions, has led to significant changes in global temperature patterns, precipitation regimes, and increasing the frequency and intensity of extreme weather events (Tiba and Belaid, 2020; Abouaiana, 2022). The scientific consensus, as recognized by the Intergovernmental Panel on Climate Change (IPCC), indicates that the Earth's climate is warming at an alarming rate, largely driven by human actions (Prasad, 2019). This global phenomenon has rendered Africa particularly vulnerable due to socio-economic factors, limited adaptive capacity, and the reliance on climate-sensitive sectors like agriculture, water resources, and natural ecosystems (Myeni and Moeletsi, 2020). The IPCC has identified Africa as one of the most vulnerable continents to climate change, with projections indicating a mean annual temperature increase of 2 C by the middle of the 21st century compared to the late 20th century (Ugurlu, 2021).

The consequences of climate change in Africa are already visible through the increased occurrence and severity of extreme weather events such as heatwaves, droughts, floods, and storms (Quartey, 2020). Rising temperatures, coupled with changing precipitation patterns, are projected to have adverse effects on biodiversity, intensify water stress, increase agricultural vulnerability, and exacerbate climate-related health outcomes (Ugurlu, 2021). Consequently, climate change poses significant challenges to water availability, domestic water supply, agricultural productivity, and

hydropower generation across the continent (Oyewo *et al*., 2022).

Addressing climate change in Africa requires effective adaptation and mitigation strategies supported by international cooperation (Kaudia *et al*., 2022). This entails investing in renewable energy sources, adopting sustainable agricultural practices, restoring ecosystems, developing climate-resilient infrastructure, and addressing deforestation and biodiversity loss (Kaudia *et al*., 2022). It is crucial to integrate indigenous knowledge, involve local communities, and adopt a holistic and interdisciplinary approach to create practical and effective adaptation and mitigation strategies for Africa (Amegatcher *et al*., 2022; Kaudia *et al*., 2022). Renewable energy plays a pivotal role in mitigating climate change and reducing greenhouse gas emissions (Kaudia *et al*., 2022). African countries can transition to low-carbon economies by investing in renewable energy sources such as solar, wind, and hydropower, thus reducing reliance on fossil fuels (Kaudia *et al*., 2022). Furthermore, implementing sustainable agricultural practices like agroforestry and conservation agriculture can enhance food security, improve soil health, and reduce greenhouse gas emissions (Kaudia *et al*., 2022). Besides, addressing deforestation and loss of biodiversity is critical to mitigating climate change and preserving vital ecosystem services (Kaudia *et al*., 2022). Also, effective measures, such as improved water management, resilient agricultural practices, and early warning systems, are essential in addressing climate change-induced challenges such as through droughts, heatwaves, and climate variability, which have far-reaching consequences for agriculture, water resources, food security, economic stability, and human health (Quartey, 2020; Ugurlu, 2021). Additionally, efforts to combat deforestation, promote reforestation, and preserve biodiversity are crucial for enhancing the resilience of ecosystems and reducing the impacts of climate change in Central Africa and elsewhere (Kaudia *et al*., 2022).

This paper reviews impacts of climate change on the African continent through selected case studies, providing a comprehensive understanding of the specific challenges faced by different regions in Africa and highlighting the implemented adaptation strategies. The case studies cover a range of climate change impacts, including drought and food insecurity in the Sahel region, coastal erosion and sea-level rise in West Africa, shifts in rainfall patterns and agricultural productivity in East Africa, deforestation and loss of biodiversity in Central Africa, and droughts, heatwaves, and climate variability in Southern Africa. Through this analysis, we aim to contribute to the development of evidence-based policies and effective strategies for climate change adaptation in Africa, fostering resilience and sustainable development options across the continent.

Overview of the Sahel region and its vulnerability to climate change. The Sahel region, spanning across several countries south of the Sahara Desert, including Burkina Faso, Chad, Mali, Niger, and Senegal, faces high vulnerability to the impacts of climate change (Costa, 2020). This region is characterized by a semi-arid climate, limited and variable rainfall, and a heavy reliance on rain-fed agriculture for livelihoods and food security (Costa-Neto *et al*., 2020).

The Sahel region encounters significant challenges, including increasing temperatures, erratic rainfall patterns, and recurring droughts. In recent decades, the region has experienced a notable rise in temperature, with average temperatures increasing by about 1.5 degrees Celsius since the pre-industrial era (Costa, 2020). This rise exacerbates the region's aridity, leading to higher evaporation rates and water scarcity. Erratic rainfall patterns further compound the vulnerability of the Sahel region. Climate change influences the timing, intensity, and distribution of rainfall, resulting in irregular and unpredictable precipitation (Susilowati *et*

al., 2019). This variability poses significant challenges for agricultural practices, making it difficult for farmers to plan and manage their crops effectively. Recurring droughts are a major concern for the Sahel region, with severe consequences for agriculture, livestock, and human populations (Egbebiyi *et al*., 2019). Drought events have become more frequent and prolonged in recent decades, leading to reduced crop yields, increased livestock mortality, and food insecurity (Egbebiyi *et al*., 2019). Severe droughts in the 1970s, 1980s, and early 2000s resulted in significant humanitarian crises and loss of lives (Egbebiyi *et al*., 2019). Statistics highlight the severity of these situations in the Sahel. The Food and Agriculture Organization (FAO) reports that the Sahel region has the highest prevalence of undernourishment in Africa, with over 22% of its population suffering from chronic hunger (Mank *et al*., 2021). Additionally, the World Bank estimates that about 65% of the Sahel's cropland is already degraded, and climate change is projected to exacerbate land degradation challenges (Akinsanola *et al*., 2021; Prall and Scelza, 2022).

To address the impacts of climate change in the Sahel region, a combination of adaptation and mitigation strategies is necessary (Zampaligré and Fuchs, 2019; Austin *et al*., 2020). Promoting climate-resilient agricultural practices, such as agroforestry and conservation agriculture, improving water management systems, and supporting early warning systems for droughts are key elements of these strategies (Austin *et al*., 2020). Additionally, investments in renewable energy and sustainable development can contribute to reducing greenhouse gas emissions and fostering long-term resilience (Zampaligré and Fuchs, 2019; Austin *et al*., 2020).

Niger: Niger has been heavily affected by recurrent droughts and desertification, resulting in food insecurity and economic challenges (Zhang *et al*., 2021). Factors such as drought, high food prices, poverty, soil infertility, disease, and insect attacks have been identified as the main causes of food insecurity in Niger (Zhang *et al*., 2021). Female-headed households are particularly vulnerable to food insecurity compared to male-headed households (Zhang *et al*., 2021).

To address these challenges, Niger has implemented various adaptation strategies. Sustainable land management practices, reforestation efforts, and the promotion of agroforestry systems have been employed to restore degraded lands and improve agricultural productivity (Alvar-Beltrán *et al*., 2020). The "Keita Project," launched in 1982, aimed to increase food security and combat desertification through soil and water conservation, natural resource management, and reforestation (Alvar-Beltrán *et al*., 2020).

Cash or food transfers have also been implemented during lean agricultural seasons to mitigate shocks and seasonal food insecurity in Niger (Ayodotun *et al*., 2019; Premand and Stoeffler, 2020). Additionally, the introduction of understory forests in the Zinder and Maradi regions of Niger has helped restore rainfall patterns and soil fertility, resulting in improved crop and pasture performance (Barnieh *et al*., 2020).

It is essential to consider the potential impacts of climate change on water resources in West Africa, including in Niger. While uncertainties surround the changes in runoff, they are closely linked to variations in rainfall patterns (Costa, 2020). The region's vulnerability to climate change necessitates integrated studies to quantify the potential effects of climate change and other processes on water resources (Costa, 2020). Moreover, the neighboring Niger Delta region in Nigeria has experienced significant mangrove loss due to anthropogenic pressures such as oil and gas exploitation, urbanization, pollution, and unsustainable resource management (Epule *et al*., 2022).

Mali: Mali has faced challenges related to increasing aridity and reduced rainfall, significantly affecting agricultural activities (Guigma *et al*., 2020). To address these challenges, the country has focused on implementing climate-smart agricultural practices, including the use of improved seed varieties, agroecology techniques, and water-efficient irrigation systems (Guigma *et al*., 2020). These practices aim to enhance agricultural productivity and resilience in the face of climate change. Mali has also invested in strengthening early warning systems to enhance preparedness for droughts and other climate-related hazards (Guigma *et al*., 2020).

The impacts of climate change and other factors on food security in Mali, like in many African countries, have been further exacerbated by the COVID-19 pandemic (Erokhin and Tianming, 2020). The pandemic has disrupted agricultural activities, leading to lower harvests and higher food prices, particularly in developing economies like Mali (Erokhin and Tianming, 2020). The combination of climate change and the economic effects of the pandemic has increased the vulnerability of countries like Mali to food insecurity (Erokhin and Tianming, 2020).

Urbanization and land loss pose additional challenges to rural livelihoods in Mali (Shahzad *et al*., 2021). The expansion of urban areas, such as the city of Ségou, has resulted in the loss of agricultural land for rural communities in neighboring areas like Sebougou (Coulibaly and Li, 2020). This loss of land has significant implications for the livelihoods of farmers and underscores the need for effective land management policies.

Regarding waste management associated with urban expansion, Mali has implemented innovative practices such as terreautage, where municipal solid waste is directly used for agriculture (Pausata *et al*., 2020). While this practice benefits waste management and the environment, it has also hindered the development of institutionalized composting and landfill systems (Pausata *et al*., 2020). Decentralized options for managing faecal sludge, a challenge in densely populated urban slums of Mali, have been explored (Semiyaga *et al*., 2015). These options include decentralized treatment and end-use of faecal sludge, minimizing costs, risks, and pollution in urban slum areas (Semiyaga *et al*., 2015).

Climate change projections indicate that Southern Mali will experience continued warming, leading to increased maximum and minimum temperatures (Casas and Sanogo, 2022). These temperature changes will have implications for cereal crop production and food self-sufficiency in the region (Casas and Sanogo, 2022).

In conclusion, the Sahel region, including Niger and Mali, faces significant challenges related to climate change, such as increasing temperatures, erratic rainfall patterns, and recurring droughts. Both countries have implemented various strategies to address these challenges, including sustainable land management practices, climate-smart agriculture, early warning systems, and innovative waste management practices. However, the region continues to grapple with issues related to water resources, urbanization, land loss, and the intersection of climate change and food security. Effective policies and interventions are crucial to building resilience and enhancing adaptive capacity in the face of these challenges.

Drought events and their impacts on agriculture in the Sahel region. The Sahel region in Africa has been consistently affected by recurrent and severe drought events, posing significant challenges to agricultural productivity and rural livelihoods (Tram *et al*., 2021). The frequency and intensity of these droughts have had detrimental effects on the region's socio-economic development.

The severity of the drought problem in the Sahel is evident from statistics. According to the United Nations Development Programme (UNDP), the Sahel experiences drought periods of varying lengths every 10 to 20 years, with some lasting up to a decade (Tram *et al*., 2021). The prolonged nature of these droughts exacerbates their impacts on agricultural systems, leading to decreased crop yields, livestock losses, and increased food insecurity. Crop production in the Sahel heavily relies on rainfall as a source of irrigation, making it vulnerable to changing rainfall patterns (Ajayi *et al*., 2020). Droughts disrupt the timing and distribution of rainfall, resulting in prolonged dry spells and water scarcity for agricultural activities. This directly affects crop growth, reduces yields, and limits the availability of food for local communities.

Livestock farming, another critical component of rural livelihoods in the Sahel, is heavily impacted by droughts (Kanwal *et al*., 2020). Insufficient water resources and limited forage availability lead to malnutrition and even death of livestock, further threatening the livelihoods of pastoralist communities. Livestock losses have both immediate and long-term consequences, including reduced income, food insecurity, and a decline in the resilience of communities to future climate shocks.

The socio-economic consequences of droughts in the Sahel are far-reaching. Affected communities face increased poverty, food insecurity, and displacement (Oladejo, 2022). In response to food shortages, many households are forced to reduce their food consumption, leading to malnutrition and negative health outcomes, particularly among vulnerable populations such as children and women.

Furthermore, the economic implications of droughts extend beyond agriculture. In rural areas heavily dependent on agriculture, reduced crop yields and livestock losses contribute to decreased income and livelihood opportunities (Pearson and Newman, 2019). This exacerbates poverty and hampers efforts toward sustainable development in the region.

Addressing the impacts of droughts in the Sahel requires a comprehensive approach that combines adaptation and resilience-building measures. Investing in climate-resilient agricultural practices such as conservation agriculture, agroforestry, and water management techniques can help mitigate the impacts of droughts and improve agricultural productivity (Zida *et al*., 2019). Additionally, diversification of livelihoods through income-generating activities, education, and access to social safety nets can enhance the resilience of communities in the face of recurrent drought events (Salas-Martínez *et al*., 2021).

In conclusion, drought events in the Sahel region have severe impacts on agriculture, leading to decreased crop yields, livestock losses, and increased food insecurity. These events exacerbate poverty and hinder sustainable development efforts. As such, Implementing adaptation and resilience-building measures is crucial for mitigating the impacts of droughts and enhancing the well-being of communities in the Sahel.

Consequences for food security, livelihoods, and social dynamics in the Sahel region. The Sahel region, a semi-arid zone in Africa, is highly vulnerable to the impacts of climate change, particularly droughts (Jiang *et al*., 2022). These drought events have severe implications for regional food security, human well-being, and social dynamics, exacerbating existing challenges faced by vulnerable populations (McOmber, 2020). The sections below highlights some of the challenges.

Regional Food Security: Droughts in the Sahel region significantly affect agricultural productivity, leading to food shortages and increasing the risk of famine (Tsutsui *et al*., 2021; Epule *et al*., 2022). Insufficient rainfall and prolonged dry spells contribute to crop failures, livestock losses, and limited access to

water for irrigation (Yue *et al*., 2021). Statistics show that between 2005 and 2016, the number of undernourished people in the Sahel region increased from 11.3 million to 19.9 million (Tsutsui *et al*., 2021; Epule et al., 2022).

H**uman Well-being:** Drought-induced food insecurity in the Sahel region has profound implications for human well-being (Ndehedehe *et al*., 2021). Malnutrition rates, particularly among children, escalate during periods of food shortages (Ndehedehe *et al*., 2021). According to UNICEF, approximately 6.3 million children under the age of five in the Sahel suffer from acute malnutrition (Ndehedehe *et al*., 2021). Inadequate access to nutritious food undermines physical and cognitive development, contributing to long-term health challenges (Ndehedehe *et al*., 2021).

Social Dynamics: Droughts and food insecurity can intensify social tensions and conflicts over scarce resources, such as land and water (Ngcamu and Chari, 2020). Competition for limited resources may lead to displacement, increased poverty, and social unrest (Ngcamu and Chari, 2020). The United Nations reports that conflicts between pastoralists and farmers over access to water and grazing land have become more frequent and intense in the Sahel region (Martin *et al*., 2020). Such conflicts disrupt social cohesion, exacerbate poverty, and hinder development efforts (Martin *et al*., 2020; Ngcamu and Chari, 2020).

It is essential to implement adaptive measures and build resilience in the Sahel region to address the challenges posed by droughts and food insecurity (Mirzabaev *et al*., 2021). Integrated approaches that combine sustainable agricultural practices, water management strategies, early warning systems, and social safety nets are crucial for enhancing food security and reducing vulnerability to climate-related shocks (Zhai *et al*., 2020).

In conclusion, drought events in the Sahel region have severe impacts on food security, livelihoods, and social dynamics. These events exacerbate poverty, malnutrition, and conflicts over resources. Implementing comprehensive strategies that promote resilience and sustainable development is vital for addressing these challenges and improving the well-being of communities in the Sahel.

Adaptation strategies and their effectiveness. This section assesses the adaptation strategies implemented in the Sahel region to mitigate the impacts of drought and enhance food security. The Sahel region, characterized by its semi-arid climate and vulnerability to climate change, has faced recurrent droughts that pose significant challenges to agriculture and livelihoods. To address these challenges, various adaptation strategies have been set up, aimed at improving water management, promoting drought-resistant crop varieties, and establishing early warning systems. This analysis evaluates the effectiveness of these strategies while highlighting the associated challenges and limitations.

Improved Water Management: Effective water management is crucial for agriculture in the Sahel region, where water scarcity is a pressing issue. One adaptation strategy involves the construction and rehabilitation of water infrastructure, such as dams, reservoirs, and small-scale irrigation systems. These interventions aim to enhance water availability for agricultural activities, particularly during dry periods (Muthelo *et al*., 2019). For example, the Great Green Wall initiative, led by the African Union, aimed at combating desertification and improving land and water management across the Sahel. The initiative involved the construction of water-harvesting structures, including small dams and ponds, to support irrigation and increase agricultural productivity (Muthelo *et al*., 2019).

Drought-resistant crop varieties: Another adaptation strategy involves the introduction

and promotion of drought-tolerant crop varieties. Traditional crops often struggle to survive under drought conditions, leading to crop failures and food insecurity. Through research and development, drought-tolerant crop varieties, such as millet, sorghum, and cowpea, have been developed and disseminated to farmers in the Sahel (Epule *et al*., 2022). For instance, the "Sahel 1000" project, implemented by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), focuses on developing improved varieties of pearl millet, a staple crop in the Sahel. These varieties exhibit enhanced drought tolerance, enabling farmers to maintain crop yields even in challenging climatic conditions (Epule *et al*., 2022).

Early warning systems: Early warning systems play a critical role in disaster preparedness and response (Trogrli *et al*., 2022). They provide timely information about potential drought events, allowing communities and relevant authorities to take proactive measures (Esposito *et al*., 2022). In the Sahel, efforts have been made to establish and strengthen early warning systems to anticipate and respond to drought-related challenges (Chouwanto *et al*., 2021). For instance, the "Agrometeorological and Hydrological Monitoring and Early Warning Systems in the Sahel" project, implemented by the World Meteorological Organization (WMO), aims to enhance the capacity of national meteorological services in the region (Chouwanto *et al*., 2021). This includes the installation of weather monitoring stations, the development of forecasting models, and the dissemination of early warning information to farmers and decision-makers (Chouwanto *et al*., 2021).

Overall, these adaptation strategies have shown promise in mitigating the impacts of drought and enhancing food security in the Sahel region. Improved water management infrastructure has increased water availability for agricultural activities, while the promotion of drought-resistant crop varieties has improved crop resilience. Early warning systems have enabled communities to take proactive measures in response to drought events. However, there are challenges and limitations that need to be addressed.

The availability of organic resources for soil conservation and fertility improvement is limited in the Sahel, which can hinder the effectiveness of water and soil conservation strategies (Kathuri *et al*., 2020). Additionally, the spread of pests and diseases can still pose a threat to crop production, requiring strengthening pest management strategies (Oerke, 2005).

In conclusion, the implementation of adaptation strategies such as improved water management, use of drought-resistant crop varieties, and early warning systems has shown promise in enhancing resilience to drought and improving food security in the Sahel region. However, addressing the challenges and limitations associated with these strategies is crucial for their long-term effectiveness. Continued research, investment, and collaboration are needed to further refine and scale up these adaptation efforts in the Sahel and extend them to other regions.

Coastal erosion and sea-level rise in West Africa. Coastal erosion and sea-level rise pose significant challenges to West African countries, leading to frequent flooding and impacting infrastructure, human settlements, and ecosystems (Adesanya *et al*., 2020). Low-lying coastal areas, including Lagos and Abidjan, are particularly vulnerable to sea-level rise and increased storm intensities and frequencies (Tano *et al*., 2018). As a result, adaptation strategies are crucial for reducing risks and minimizing the impacts on coastal communities (Hallegatte *et al*., 2013). These coastal challenges also affect UNESCO World Heritage sites located in West African coastal areas, making them vulnerable to coastal flooding and erosion (Reimann *et al*., 2018).

Urgent adaptation measures are needed to protect these valuable cultural sites from the impacts of coastal erosion and sea-level rise (Reimann *et al*., 2018).

Sea-level rise not only contributes to coastal erosion but also leads to increased flooding and permanent inundation of low-lying areas (Davar *et al*., 2021; Tan *et al*., 2022). Coastal communities need to adapt to avoid or reduce these risks (Stoltz *et al*., 2021). In some areas, like Tauranga in New Zealand, coastal flooding is projected to be the primary trigger for adaptation, surpassing erosion as the main coastal hazard (Davar *et al*., 2021; Tan *et al*., 2022).

Understanding the relative contributions of sediment supplied by coastal erosion versus rivers is crucial for predicting future rates of coastal erosion (Albanai, 2020). Studies indicate that coastal erosion is the dominant supplier of sediment during sea-level rise, while rivers play a lesser role (Albanai, 2020; Sharman *et al*., 2021).
Coastal erosion and sea-level rise have severe impacts on coastal communities, including the destruction of settlements and fishponds, as well as increased inundation areas (Divinsky and Kosyan, 2021). Despite these challenges, local communities have implemented various adaptation strategies, such as planting mangroves, elevating ground levels, and shifting livelihoods toward the tourism sector (Ravens and Peterson, 2021).

Senegal: Senegal, particularly the Casamance region, faces coastal erosion and sea-level rise (Graham and Knelman, 2022). The country has implemented adaptation measures, including the construction of protective infrastructure like seawalls and breakwaters (Graham and Knelman, 2022). These measures aim to reduce erosion impacts and protect coastal communities and infrastructure. Senegal also engages local communities in ecosystem restoration projects and sustainable coastal zone management (Meguenni *et al*., 2019; Lombard and Andrieu, 2021).

Coastal erosion and sea-level rise have led to the destruction of human habitats and infrastructure, especially in vulnerable areas such as the Cape Verde peninsula, the Great Coast, and the Small Coast (Diouf *et al*., 2020). The encroachment of the coastline has been a significant issue, with an average erosion rate of 1 to 1.30 meters per year over the last 50 years (Danovaro *et al*., 2021).

Changes in mangrove zonation have also been observed in Senegal's Casamance region (Meguenni *et al*., 2019; Lombard and Andrieu, 2021). Monitoring and studying these changes are crucial for informing forestry policies and optimizing conservation efforts. Remote sensing techniques, such as object-based image analysis and linear spectral unmixing, have been used to detect and analyze changes in mangrove zonation in Senegal (Lombard and Andrieu, 2021).

Senegal has established Marine Protected Areas (MPAs) along its coastal zone to support biodiversity conservation and sustainable fisheries management (Ba *et al*., 2019). Evaluations of the impact of MPAs on the Senegalese sardinella fishery, important for national food security and employment, have been conducted (Richards *et al*., 2022). The results suggest that MPAs can slightly increase biomass and rent, but additional measures may be necessary for optimal exploitation levels and fishery sustainability (Ba *et al*., 2019).

Ghana: Ghana's coastal areas experience erosion and rising sea levels, leading to community displacement and infrastructure damage (Ayerteye and Atteh, 2020). To mitigate these impacts, Ghana promotes beach nourishment, mangrove restoration, and land-use planning measures (Ayerteye and Atteh,

2020).

Climate change has caused significant physical impacts in Ghana, including changes in temperature, rainfall patterns, and sea-level rise (Ampadu and Aziz, 2021). Shifts in the rainfall regime have resulted in longer dry seasons, disappearing wet seasons, health problems, disruptions in agriculture, flooding, and reduced precipitation affecting hydro-generating dams (Ampadu and Aziz, 2021).

Coastal erosion is a prevalent problem in Ghana, with erosion rates reaching approximately 2 meters per year in some areas (Ayerteye and Atteh, 2020). Vulnerability assessments identify the central coast and eastern coasts of Ghana as particularly vulnerable to erosion (Boateng *et al*., 2016). Aslo, coastal erosion and mining activities, such as sand and stone mining, contribute to erosion and pose threats to the tourism industry (Fu *et al*., 2022). Loss of sand from the littoral zone exacerbates erosion rates along the coastline (Fu *et al*., 2022).

In conclusion, Ghana's coastal areas are affected by erosion and rising sea levels. The country implements strategies like beach nourishment, mangrove restoration, and land-use planning to mitigate the impacts. Climate change has caused physical impacts, including changes in temperature, rainfall patterns, and sea-level rise. Coastal erosion and mining activities pose threats to the environment, socioeconomic aspects, and the tourism industry. Addressing these challenges is crucial for the long-term sustainability and resilience of Ghana's coastal areas.

Nigeria: Nigeria experiences a range of climate change impacts, such as increased temperature, changing rainfall patterns, and coastal erosion. In response, the country has implemented adaptation strategies to safeguard vulnerable communities. These strategies include promoting climate-smart agriculture, developing renewable energy sources, and implementing coastal protection measures.

Recent studies have examined various aspects of climate change and its impacts in Nigeria. For instance, a study conducted in Southern Nigeria explored the traditional perceptions of the climate change phenomenon among women crop farmers and how these perceptions influence their adaptation decisions (Monday, 2020). Another study focused on the impact of climate change on economic and social rights realization in Nigeria, highlighting the need for international cooperation and assistance in addressing these challenges (Adeagbo *et al*., 2021; Oamen and Erhagbe, 2021).

The role of non-farm employment in climate change adaptation strategies by smallholder farmers in Nigeria has also been investigated, emphasizing the importance of diversifying income sources to enhance resilience (Danso-Abbeam *et al*., 2021). Additionally, the roles of religious leaders in addressing climate change challenges and achieving the United Nations Sustainable Development Goal 13 in Nigeria have been examined (Abdussalam and Abukur, 2021; Oderinde *et al*., 2022).

Studies have also explored the communication of climate change and its implications for environmental sustainability in Nigeria, emphasizing the role of media and effective communication policies (Chete, 2019; Nwaerema and Ikoro, 2021). The knowledge and perception of climate change among farming households in Nigeria have been assessed, highlighting the need for awareness and education to support adaptation efforts (Ibilewa *et al*., 2021; Madaki *et al*., 2022).

The legal perspective of converting organic waste to electricity in Nigeria and the challenges and prospects associated with it have been examined, emphasizing the potential of renewable energy sources in addressing climate change (Olujobi *et al*., 2021; Afinotan, 2022). The impacts of climate change on the agribusiness value chain in Nigeria have also been reviewed, emphasizing the need for adaptive strategies to ensure food security and

reduce climate change impacts (Nnamani *et al*., 2021; Sam *et al*., 2021).

Furthermore, studies have focused on the impacts of climate change on Nigerian ecosystems, including coastal areas, and the need for effective adaptation measures (Ikumbur and Iornumbe, 2019; Merem *et al*., 2019). The integration of climate-smart agriculture technologies and practices into policy and practice in Nigeria has been explored, highlighting the importance of promoting uptake and integration for sustainable agriculture (Ifeanyi-Obi *et al*., 2022; Tajudeen *et al*., 2022).

The constraints to farmers' choice of climate change adaptation strategies, the effects of demographic characteristics on farmers' adaptation to climate change, and the gender implications of adaptation strategies have also been investigated (Salihu *et al*., 2020; Ige *et al*., 2021). Additionally, studies have examined the impacts of climate change on food and human security, waste management, and nutrition security in Nigeria (Ifeanacho and Okudu, 2020; Kehinde and Abifarin, 2022).

The evaluation of rural households' practices for climate-smart agriculture technology, the economic evaluation of hybrid renewable energy systems, and the evaluation of climate risk and technology adoption in Nigeria have provided insights into the potential and challenges of implementing adaptation strategies (Aba *et al*., 2019; Moruf, 2020).

In conclusion, recent research in Nigeria has shed light on various aspects of climate change and its impacts, as well as the adaptation strategies being implemented in the country. These studies have contributed to the understanding of climate change challenges and the need for sustainable and resilient approaches to address them.

Impacts of sea-level rise on coastal communities, infrastructure, and ecosystems. Sea-level rise is a pressing concern for coastal communities in West Africa, as it poses significant risks to their livelihoods, infrastructure, and natural ecosystems (Storie *et al*., 2021). The region is particularly vulnerable due to its extensive coastline, low-lying areas, and socio-economic reliance on coastal resources (Mack *et al*., 2020). The following section discusses the impacts of sea-level rise in West Africa, including the loss of land, increased flooding, saltwater intrusion, damage to infrastructure, and the destruction of coastal ecosystems (Langston *et al*., 2017).

Loss of Land: Sea-level rise leads to the gradual inundation and erosion of coastal land, resulting in the loss of habitable areas and agricultural land (Trégarot *et al*., 2021). In West Africa, several studies project significant land loss due to rising sea levels. For example, the Mauritanian coastline is one of the most vulnerable worldwide to sea-level rise, putting the coastal communities at great risk of loss of essential livelihood and welfare (Trégarot *et al*., 2021).

Increased Flooding: Higher Sea levels intensify the risk of coastal flooding during storm events, causing damage to homes, infrastructure, and agricultural fields (Pollard *et al*., 2018). Coastal cities and densely populated areas are particularly at risk. In 2017, the city of Lagos, Nigeria experienced severe flooding, which resulted in the displacement of thousands of residents and substantial economic losses (Olsson, 2019). As sea levels continue to rise, the frequency and magnitude of such flooding events are expected to increase (Adelekan, 2010).

Saltwater Intrusion: Sea-level rise exacerbates the intrusion of saltwater into freshwater systems, including rivers and aquifers (Moore

and Joye, 2021). This intrusion contaminates freshwater supplies, making them unsuitable for drinking, agriculture, and industrial use (Kurt and Li, 2020; Moore and Joye, 2021). The loss of freshwater resources due to saltwater intrusion poses a significant threat to agriculture, as many crops and farming practices rely on freshwater irrigation (Moore and Joye, 2021). The Niger Delta region in Nigeria has already experienced saltwater intrusion, impacting agricultural productivity and local communities (Kurt and Li, 2020; Moore and Joye, 2021).

Damage to Infrastructure: Higher Sea levels intensify the risk of coastal flooding during storm events, causing damage to homes, infrastructure, and agricultural fields (Tano *et al*., 2018; Sutar, 2022). Increased flooding and storm surges can lead to erosion and damage to coastal infrastructure, disrupting transportation, commerce, and economic activities (Jevrejeva *et al*., 2020; Sutar, 2022). The vulnerability of coastal infrastructure to sea-level rise has been highlighted in studies focusing on specific regions, such as the Ivorian Coast in West Africa (Tano *et al*., 2018). The impacts of sea-level rise on coastal infrastructure include increased flooding, erosion, storm surge risk, and salinization of freshwater sources (Almeida and Mostafavi, 2016). The vulnerability of coastal infrastructure to sea-level rise is a significant concern, as it can result in the destruction of critical infrastructure, disruption of economic activities, and saltwater intrusion (Almeida and Mostafavi, 2016).

Destruction of Coastal Ecosystems: Destruction of Coastal Ecosystems by sea-level rise in West Africa is a significant concern due to its impacts on biodiversity, ecosystem services, and coastal communities (Nyadzi and Bessah, 2020; Nyadjro *et al*., 2021; Osemwegie *et al*., 2021). Coastal ecosystems, such as mangroves, seagrasses, and coral reefs, provide critical habitats, protect coastlines from erosion, and support fisheries (Tano *et al*., 2018; Trégarot *et al*., 2021). Sea-level rise and associated coastal erosion can lead to the loss of these ecosystems, resulting in the loss of biodiversity, reduced coastal protection, and decreased resilience to climate change impacts (Koomson *et al*., 2022). The destruction of coastal ecosystems also affects the livelihoods and well-being of local communities who depend on these ecosystems for food, income, and cultural values (Fischman *et al*., 2019). The vulnerability of coastal ecosystems to sea-level rise highlights the need for adaptive measures and sustainable management practices to protect and restore these valuable ecosystems (Grenfell *et al*., 2019). Integrated coastal zone management approaches that consider the ecological, social, and economic aspects are crucial for the conservation and sustainable use of coastal ecosystems in the face of sea-level rise (Tiando *et al*., 2021).

Addressing the impacts of sea-level rise in West Africa requires a combination of coastal management strategies, including the preservation and restoration of coastal ecosystems, sustainable land-use planning, and infrastructure resilience measures. International cooperation and financial support are crucial to assist West African countries in implementing effective adaptation strategies and building climate resilience.

Socioeconomic implications, including displacement and economic losses. This section focuses on the socioeconomic implications of coastal erosion and sea-level rise, highlighting the profound impacts on communities, livelihoods, and economies. Coastal regions in Africa are particularly vulnerable to these climate change-related phenomena, posing significant challenges to sustainable development and regional stability, resulting in:

Displacement of Communities: Coastal erosion and sea-level rise contribute to the displacement of communities living in

vulnerable coastal areas (Torikul *et al*., 2015). As shorelines retreat and land is lost to the sea, communities are forced to relocate, leading to social upheaval, disruption of traditional livelihoods, and loss of cultural heritage (Torikul *et al*., 2015; Priestley *et al*., 2021).

Loss of Livelihoods: Coastal erosion and sea-level rise have significant implications for livelihoods that depend on coastal resources and activities (Roberts and Andrei, 2015). Fishermen, farmers, and tourism-related industries are particularly affected (Roberts and Andrei, 2015). Declining fish stocks due to habitat loss and disruption of coastal ecosystems impact the livelihoods of coastal communities that rely on fishing (Anthony *et al*., 2015). Additionally, agricultural activities in coastal areas face challenges from saline intrusion into freshwater sources and soil degradation (Barnett *et al*., 2020; Corwin, 2020).

Economic Damages: The economic damages resulting from coastal erosion and sea-level rise are substantial (Melvin *et al*., 2016). Infrastructure, including buildings, roads, and ports, is at risk of damage or destruction (Melvin *et al*., 2016). Tourism, a significant source of revenue in coastal regions, is also impacted, leading to reduced visitor numbers and decreased income for local communities (Islam *et al*., 2020; Lee and Lee, 2020; Somphong *et al*., 2020).

Challenges for Vulnerable Populations: Vulnerable populations, including the poor, marginalized communities, and women, are disproportionately affected by coastal erosion and sea-level rise (Hens *et al*., 2018). These populations often lack the resources and capacity to adapt and recover from the impacts (Hens *et al*., 2018). Limited access to financial resources, information, and decision-making processes further exacerbate their vulnerability (Hens *et al*., 2018; Richards *et al*., 2022).

Implications for Regional Development and Sustainability: The socioeconomic implications of coastal erosion and sea-level rise extend beyond individual communities and have broader regional implications (Uehara *et al*., 2019). Loss of coastal land, infrastructure, and productive resources hampers economic development and hinders efforts to achieve sustainable development goals (Uehara *et al*., 2019). Coastal areas often contribute significantly to national economies, making their resilience and sustainability crucial for overall regional progress (Kanwal *et al*., 2019; Uehara *et al*., 2019; Pandy and Rogerson, 2021).

Addressing the socioeconomic implications of coastal erosion and sea-level rise requires a comprehensive approach that combines adaptive measures, sustainable land-use planning, and community engagement. Investing in coastal protection measures, such as the restoration of mangroves and the implementation of coastal defence systems, can help mitigate erosion and reduce vulnerability. Additionally, promoting sustainable livelihood diversification, empowering communities, and integrating climate change considerations into development planning are essential for long-term resilience (Thiéblemont *et al*., 2019).

Mitigation and adaptation measures to address coastal erosion. This section focuses on the mitigation and adaptation measures that have been implemented to address the pressing challenges of coastal erosion and sea-level rise in West Africa. Recognizing the vulnerability of coastal communities, infrastructure, and ecosystems to the impacts of climate change, various strategies have been employed to mitigate risks and enhance resilience in West Africa. This analysis encompasses a range of approaches, including nature-based solutions, coastal protection infrastructure, community engagement, and policy interventions.

Nature-based Solutions: Nature-based solutions involve utilizing natural systems and processes to provide effective and sustainable responses to climate change impacts (Maes

and Jacobs, 2015). In the context of coastal erosion and sea-level rise, these solutions encompass strategies such as coastal wetland restoration, mangrove afforestation, and sand dune stabilization (Maes and Jacobs, 2015). These approaches offer multiple benefits, including wave attenuation, sediment trapping, and habitat restoration. For example, in the Senegal River Delta, mangrove restoration projects have been implemented to counteract coastal erosion and enhance shoreline stability (Maes and Jacobs, 2015; Silliman *et al*., 2019; Jenewein and Hummel, 2022).

Coastal Protection Infrastructure: Coastal protection infrastructure plays a crucial role in safeguarding vulnerable coastal areas from erosion and sea-level rise (Bulleri and Chapman, 2010). Examples of such infrastructure include seawalls, breakwaters, groynes, and artificial dunes (Bulleri and Chapman, 2010). These structures help absorb wave energy, reduce erosion, and protect vital assets and communities located along the coastline. In Nigeria, the Lagos State Government has constructed seawalls and groynes to mitigate coastal erosion along the Victoria Island and Lekki Peninsula areas. These measures aim to stabilize the shoreline, protect critical infrastructure, and maintain the economic vitality of the region (Tran *et al*., 2020; Ravens and Peterson, 2021).

Community Engagement: Engaging local communities is essential for the success of coastal adaptation and resilience-building efforts (Chaudhury *et al*., 2020). Community participation promotes the incorporation of local knowledge, enhances ownership of initiatives, and fosters sustainable practices (Chaudhury *et al*., 2020). For instance, in Ghana, the Coastal Sustainable Landscapes Project involves collaborating with local fishing communities to implement sustainable land management practices and raise awareness about the impacts of climate change. This community-led approach empowers individuals to become agents of change and promotes long-term resilience (Moon *et al*., 2019; Chaudhury *et al*., 2020; Molina *et al*., 2020).

Policy Interventions: Effective policy interventions are crucial for creating an enabling environment for coastal adaptation and mitigating the impacts of climate change (Meehl *et al*., 2005). These interventions can include the formulation of coastal zone management plans, integration of climate change considerations into development policies, and the establishment of regulatory frameworks for coastal development (Meehl *et al*., 2005). In Senegal, the National Integrated Coastal Zone Management Strategy was developed to guide sustainable development and adaptation along the coastline (Meehl *et al*., 2005). The strategy emphasizes the importance of stakeholder involvement, coordination among different sectors, and ecosystem-based approaches to address coastal erosion and sea-level rise (Meehl *et al*., 2005; Trégarot *et al*., 2021; Coca-Domínguez and Rodríguez-Santana, 2022).

While these measures offer promising avenues for addressing coastal erosion and sea-level rise, challenges and trade-offs exist. Balancing the need for infrastructure development with the preservation of natural ecosystems, ensuring equitable access to resources, and securing funding for large-scale projects are ongoing challenges. Additionally, a comprehensive understanding of local ecosystems and socio-economic contexts is crucial to maximize the effectiveness and sustainability of these measures. Integrating scientific knowledge, traditional knowledge, and community perspectives is vital for developing context-specific solutions (Priestley *et al*., 2021; Sugianto *et al*., 2022).

Shifts in rainfall patterns and agricultural productivity in East Africa. This case study focuses on the observed shifts in rainfall patterns in East Africa, with a particular emphasis on the impacts on agricultural productivity in the region. East Africa has experienced prolonged

dry spells and intense rainfall events, leading to reduced crop yields and increased vulnerability. To adapt to these changes, farmers have adopted climate-smart agricultural practices such as agroforestry, conservation agriculture, and the use of drought-tolerant crop varieties. Additionally, water harvesting and storage techniques have been employed to ensure a more reliable water supply for agricultural activities. These adaptive measures aim to enhance food security and build resilience against climate-related risks (Agyekum *et al*., 2022; Mubenga-Tshitaka *et al*., 2022).

The impact of extreme weather events on agricultural output in East Africa has been assessed using rainfall and temperature data (Levy and Ngeno, 2021; Okullo *et al*., 2022). Studies have also analyzed the impact of joint multiple agricultural technologies on nutrition outcomes in East Africa (Akuku *et al*., 2020; Yiridomoh, 2021). The influence of the Madden-Julian Oscillation (MJO) circulation on air-sea interactions and seasonal rainfall predictions in East Africa has been assessed (Liverpool-Tasie *et al*., 2019; Kimani et al., 2020). Regional climate projections have been developed for impact assessment studies in East Africa (Gebrechorkos *et al*., 2019; Abdalla and El-Ramady, 2022).

Investment in agricultural research and development (RandD) has been found to contribute to sectoral economic growth in East Africa (Ouru and Mose, 2021). The adoption of complementary climate-smart agricultural technologies has been studied in Tanzania (Ngute *et al*., 2021; Ogada *et al*., 2021). Indigenous knowledge has been reviewed for its potential in climate-smart agriculture in East Africa (Oyawole *et al*., 2020; Amare and Gacheno, 2021). Changes in climatic suitability and availability of agropastoral farming systems across Kenya have been analyzed (Uwimbabazi *et al*., 2022). The spatial structure of rainfall variability over East Africa has been evaluated using climate model simulations (Assan, 2022; Mbigi *et al*., 2022). A regional climate model has been customized and validated using satellite data over East Africa (Gudoshava and Semazzi, 2019; Coughlan *et al*., 2019).

The relationship between climate change, food security, and nutrition outcomes in East Africa has been examined (Oduniyi and Sylvia, 2019; Mumuni and Joseph, 2022). The impact of climate change on rural livelihoods and agricultural productivity in sub-Saharan Africa has been assessed (Dasgupta and Robinson, 2022; Sjöblom *et al*., 2022). Long-term trends in rainfall and temperature have been analyzed in East Africa (Gebrechorkos *et al*., 2019; Abdela, 2022). The link between human capital formation and economic growth in East Africa has been explored (Chavula and Turyasingura, 2022). The effectiveness of biological control of stem borers under different climate change scenarios in Eastern Africa has also been investigated (Jendritzki *et al*., 2021).

The adoption of climate-smart agricultural practices and the role of weather forecast information in East and West Africa have been studied (Uzayisenga *et al*., 2021; Agyekum *et al*., 2022). The socio-economic predictors and knowledge domains for sustainable maize intensification in Kenya have been characterized (Mucheru-Muna *et al*., 2021; Nie *et al*., 2021). The suitability of agrivoltaics for sustainable energy and food production in East Africa has been modeled (Tshililo *et al*., 2021). Future changes in climate and hydroclimate extremes in East Africa have been projected (Olaka *et al*., 2019).

These recent studies provide valuable insights into the impacts of climate change on agriculture and food security in East Africa and highlight the importance of implementing climate-smart agricultural practices and adaptation strategies to build resilience in the region.

Ethiopia: The case study explores the shifts in rainfall patterns and increased frequency

of droughts, which have affected agricultural productivity and food security in Ethiopia. Farmers in Ethiopia have reported that crop yields have been negatively affected by changes in rainfall patterns, high temperatures, floods, and crop diseases, while livestock health and production have also been impacted by climate change, specifically by rising temperatures (Messmer *et al*., 2021; Likinaw *et al*., 2022). Ethiopia has implemented various adaptation strategies, including the construction of small-scale irrigation systems, the promotion of climate-resilient crop varieties, and the introduction of sustainable land management practices such as terracing and agroforestry (Aboye *et al*., 2022; Disasa and Yan, 2022).

Other studies have examined the effects of climate variability on the Ethiopian macroeconomy, highlighting the adverse impacts on economic development (Berihun and Steven, 2021). The adoption of sustainable land management practices has been found to improve household crop production and mitigate soil erosion (Schmidt and Tadesse, 2019; Zerssa *et al*., 2021). Agroforestry has been recognized as a potential solution for climate change adaptation and mitigation in Ethiopia (Agemas, 2019; Tessema and Simane, 2020).

The frequency and spatial coverage of droughts have increased in Ethiopia over the past decades, posing challenges to rainfed agriculture and food security (Mekonen *et al*., 2020; Guye *et al*., 2021). Changes in rainfall patterns and temperature have been analyzed, and the relationship between climate change and crop yield reductions has been assessed (Xia *et al*., 2019; Eshete *et al*., 2020; Bayable *et al*., 2021). The adoption of climate-smart agricultural practices, such as the use of drought-tolerant crop varieties, has been studied (Nedumaran *et al*., 2021; Birhan *et al*., 2022).

Farmers' perceptions of climate change and their adaptation strategies have been explored, highlighting the importance of location-specific information and the role of cash crops in improving food security (Abera and Tesema, 2019; Addis and Abirdew, 2021; Dinegde *et al*., 2022; Muktar *et al*., 2022). The impact of climate change on postharvest losses and the need for reduction strategies have been examined (Godebo, 2020). The potential of irrigation as a tool for sustainable development and poverty alleviation has also been reviewed (Morsy *et al*., 2022).

Studies have also been conducted on the detection and analysis of meteorological droughts, including their seasonal and spatial trends (Nasir *et al*., 2020; Ahmed *et al*., 2021; Morsy *et al*., 2022; Shalishe *et al*., 2022). The impact of rainfall variability on soil properties and crop production has been investigated (Taye *et al*., 2021; Bedane *et al*., 2022). The role of agroforestry in counteracting the extinction of indigenous tree species has been highlighted (Danso-Abbeam *et al*., 2021; Lelamo and Kemal, 2021). The determinants of farmers' adoption of climate change adaptation and mitigation strategies have also been explored (Gari *et al*., 2019; Regasa and Akirso, 2019).

Overall, the above studies provide valuable insights into the impacts of climate change on agriculture and food security in Ethiopia and highlight the importance of implementing adaptation strategies to build resilience in the country.

Kenya: Kenya faces similar challenges to Ethiopia with respect to droughts and erratic rainfall patterns impacting agricultural activities. The country has focused on improving water management through the construction of water storage infrastructures, promoting climate-smart agricultural practices like conservation agriculture, and investing in early warning systems to enhance preparedness for climate-related disasters (Nübler *et al*.,

2020). Additionally, there are aspects of disease transmission related to weather that can influence individual health outcomes (Igobwa *et al*., 2022). The effectiveness of governmental disaster risk reduction policies in East Africa is influenced by how smallholder farmers react to droughts and adopt drought adaptation measures (Wens *et al*., 2022).

The studies conducted so far re-affirm that the economy of IGAD region as very vulnerable to climate change. The vulnerability of the population to climate change is exacerbated by the structural issues that reinforce poverty, inequality, and deprivation in society, making the poor most impacted (Kiarie *et al*., 2020). Climate variability, ranging from unpredictable, intense, and at times extreme weather events such as droughts, soil erosion, floods, and biodiversity losses, exacerbate land degradation and significantly lower agricultural potential (Kaudia *et al*., 2022).

Other studies have documented impact of climate change on pest outbreaks and use and health in Kenya (Kaudia *et al*., 2022). These and other studies provide valuable insights into the impacts of climate change on agriculture and food security in Kenya and highlight the importance of implementing adaptation strategies to build resilience in the country.

Examination of water scarcity and its effects on food security. The case study focuses on the issue of water scarcity in East Africa, stemming from changing rainfall patterns, and explores its profound effects on food security, agricultural production, and livelihoods in the region. The availability of water for irrigation, drinking water supply, and sanitation is crucial for sustainable development and the well-being of communities. This section delves into the challenges posed by water scarcity in East Africa and its implications.

Changing Rainfall Patterns: East Africa has experienced significant shifts in rainfall patterns in recent years, leading to increased variability and unpredictability. According to recent studies, the region has witnessed a decline in overall rainfall, with more frequent and intense drought events interspersed with sporadic heavy rainfall and flooding incidents (Onalenna and Rahube, 2019; Mbigi *et al*., 2022). These changes pose significant challenges for water availability and management.

Water access for irrigation: Water scarcity directly affects agricultural production in East Africa, where rainfed agriculture is predominant. Limited and unreliable rainfall hinders crop growth and reduces agricultural yields, exacerbating food insecurity in the region. The lack of access to sufficient water for irrigation further compounds the problem, making farming practices more vulnerable to climatic fluctuations. Recent statistics reveal that only 6% of agricultural land in sub-Saharan Africa is equipped with irrigation systems, significantly impeding the potential for increased agricultural productivity and food production (Vogels *et al*., 2019; Barro *et al*., 2021). Inadequate irrigation infrastructure limits the ability of farmers to cultivate crops throughout the year and adapt to changing weather conditions.

Consequences for food security and livelihoods are evident: Water scarcity directly affects food security and livelihoods in East Africa, where a significant portion of the population depends on subsistence agriculture for sustenance and income. Reduced agricultural yields and crop failures resulting from water scarcity jeopardize the availability and affordability of food, leading to increased food prices and malnutrition. Recent statistics indicate that East Africa has the highest prevalence of undernourishment in sub-Saharan Africa, with an estimated 30%

of the population experiencing food insecurity (Brewis *et al*., 2019; Rother *et al*., 2020). The impacts of water scarcity exacerbate these challenges, particularly for vulnerable groups such as smallholder farmers, pastoral communities and rural communities.

Addressing water scarcity and its effects on food security in East Africa requires a multifaceted approach. It involves implementing sustainable water management strategies, promoting water-efficient agricultural practices, investing in irrigation infrastructure, and improving access to safe drinking water and sanitation facilities. Collaborative efforts between governments, international organizations, and local communities are essential to building resilience and mitigating the impacts of water scarcity on livelihoods in the region (Grafton *et al*., 2019; Zeleke and Afrassa, 2021).

Community-based adaptation initiatives and their outcomes. This section delves into the evaluation of community-based adaptation strategies in East Africa, specifically focusing on their effectiveness in enhancing resilience to changing rainfall patterns. Several adaptation practices have been implemented in the region, including agroforestry, water harvesting, and farmer-managed irrigation systems, to mitigate the adverse impacts of climate change. These initiatives aim to improve agricultural productivity, water availability, and overall community resilience.

Agroforestry, which involves the integration of trees into agricultural systems, has shown promise in adapting to changing rainfall patterns in East Africa. By diversifying crops, providing shade, conserving moisture, and improving soil fertility, agroforestry practices help farmers cope with unpredictable rainfall and maintain stable yields. For example, recent studies have demonstrated that agroforestry systems in Kenya have increased crop yields by up to 128% compared to traditional farming methods (Tzuk *et al*., 2020; Liu, 2022).
Water harvesting techniques, such as building small-scale dams, ponds, and terraces, have also proven effective in managing water resources and supporting agriculture in regions with irregular rainfall patterns. These practices capture and store rainwater during periods of excess rainfall, allowing farmers to irrigate their crops during dry spells. In Tanzania, recent implementation of water harvesting systems has resulted in increased crop production and improved food security (Naz *et al*., 2022).

Furthermore, farmer-managed irrigation systems play a crucial role in enhancing agricultural productivity and resilience in East Africa. These systems empower farmers to take control of their water resources by constructing and managing small-scale irrigation infrastructure. By reducing dependence on rainfall and enabling year-round cultivation, farmer-managed irrigation systems contribute to increased crop yields and income stability. In Ethiopia, recent use of small-scale irrigation schemes has led to significant improvements in household food security and income (D'Onofrio *et al*., 2019; Situma *et al*., 2019).

While community-based adaptation initiatives in East Africa have demonstrated positive outcomes, they also face certain limitations and challenges. Access to resources, such as land, finance, and technical expertise, remains a significant constraint for scaling up these practices across the region. Additionally, the long-term sustainability and maintenance of adaptation initiatives require continued support and capacity building within the local communities.

In conclusion, community-based adaptation initiatives in East Africa, such as agroforestry, water harvesting, and farmer-managed irrigation systems, offer promising solutions to enhance resilience to changing rainfall patterns. These practices have shown positive impacts in

terms of improving agricultural productivity, water availability, and livelihoods. However, addressing the challenges of scaling up and ensuring long-term sustainability of these initiatives is crucial for their effectiveness in adapting to climate change in the region.

Deforestation and Biodiversity Loss in Central Africa. Central Africa is renowned for its vast stretches of tropical rainforests, which encompass the Congo Basin, the second-largest rainforest in the world (Réjou-Méchain *et al*., 2021). These forests cover approximately 200 million hectares and play a crucial role in the global ecosystem. Central Africa's forests are characterized by their rich biodiversity, carbon storage capacity, and their significance in providing livelihoods for local communities (Réjou-Méchain *et al*., 2021). The ecological significance of Central Africa's forests stems from their remarkable biodiversity. These forests are home to numerous endemic and endangered species, including iconic megafauna such as forest elephants, gorillas, and bonobos (Réjou-Méchain *et al*., 2021). The region also supports an incredible variety of plant species, many of which are yet to be fully documented and understood. The forests' complex ecosystems foster intricate relationships between species, contributing to the overall ecological balance of the region (Roth *et al*., 2020). In addition to their biodiversity, Central Africa's forests serve as important carbon sinks, sequestering and storing vast amounts of carbon dioxide (Réjou-Méchain *et al*., 2021). The dense vegetation and abundant biomass of these forests absorb carbon dioxide from the atmosphere, mitigating the impacts of climate change and playing a crucial role in global climate regulation (Yakovlev, 2020).

Preserving these forests is essential in the fight against climate change and reducing greenhouse gas emissions. Central Africa's forests also provide essential ecosystem services that benefit both local communities and the global population. These services include water regulation, soil conservation, and the maintenance of local and regional rainfall patterns (Réjou-Méchain *et al*., 2021). The forests help sustain water cycles by capturing and releasing moisture, ensuring a steady supply of freshwater to rivers, lakes, and aquifers. This is vital for supporting agriculture, ensuring clean drinking water, and maintaining the ecological balance of the region (Réjou-Méchain *et al*., 2021) Furthermore, Central Africa's forests support the livelihoods of millions of people, particularly local communities who rely on forest resources for their sustenance. Forests provide timber, non-timber forest products, medicinal plants, and food sources such as fruits, nuts, and bushmeat (Réjou-Méchain *et al*., 2021). They also offer opportunities for sustainable ecotourism, attracting visitors from around the world who appreciate the region's unique biodiversity and cultural heritage (Harilal *et al*., 2021). However, Central Africa's forests are facing significant threats and challenges, resulting in deforestation and biodiversity loss. Factors driving deforestation include illegal logging, unsustainable agricultural practices, expansion of infrastructure, and population growth (Nackoney *et al*., 2022). These activities lead to the clearing of land for commercial purposes, encroachment into protected areas, and fragmentation of habitats, thereby threatening the ecological integrity and resilience of Central Africa's forests (Shapiro *et al*., 2021).

Efforts to address deforestation and biodiversity loss in Central Africa involve various stakeholders, including governments, international organizations, local communities, and conservation groups. Regional initiatives, such as the Central African Forest Initiative (CAFI), aim to promote sustainable forest management, protect biodiversity hotspots, and enhance the livelihoods of local communities

(Nackoney *et al*., 2022). These initiatives emphasize the importance of balancing conservation goals with the socio-economic needs of the region. Community-based conservation approaches have gained recognition as effective strategies for forest protection in Central Africa. Engaging local communities in forest management, recognizing their rights, and providing alternative livelihood options are key components of successful conservation efforts (Valdez, 2022). Indigenous peoples and local communities possess valuable traditional knowledge and have a deep understanding of sustainable resource management practices. Involving them in decision-making processes and respecting their rights and cultural heritage are critical for achieving long-term conservation success (Genet, 2021).

Cameroon: Cameroon, located in Central Africa, grapples with significant deforestation and biodiversity loss (Morrison and Mendenhall, 2020). The country's rainforests, including those in the Congo Basin, face threats from illegal logging, unsustainable agricultural practices, and infrastructure development (Gwan *et al*., 2021). These activities contribute to the loss of valuable forest cover and habitat destruction for numerous plant and animal species (Ndongo *et al*., 2021). Deforestation in Cameroon has detrimental effects on biodiversity. The country is home to iconic species such as the western lowland gorilla, forest elephants, and chimpanzees, which face population declines and habitat fragmentation due to deforestation (Ndongo *et al*., 2021). Loss of forest ecosystems disrupts the ecological balance and diminishes essential ecosystem services like carbon sequestration and water regulation (Gwan *et al*., 2021).

Efforts to address deforestation and biodiversity loss in Cameroon include the establishment of protected areas and the implementation of sustainable forest management practices (Sumelong *et al*., 2022). National parks and reserves like Korup National Park and Dja Faunal Reserve aim to protect important biodiversity hotspots and provide safe havens for endangered species (Sumelong *et al*., 2022). Collaboration with international organizations and local communities promotes sustainable forest management, community-based conservation initiatives, and the development of eco-friendly livelihood alternatives (Sumelong *et al*., 2022). However, challenges remain in Cameroon's conservation efforts. Weak governance, corruption, and limited enforcement capacity hinder effective forest management and conservation (Gwan *et al*., 2021). Insufficient funding and resources pose significant obstacles to the implementation of conservation measures and the enforcement of regulations (Gwan *et al*., 2021). Strengthening governance frameworks, improving law enforcement, and enhancing the capacity of relevant institutions are crucial for addressing these challenges (Gwan *et al*., 2021).

Arising from the above, Cameroon faces significant deforestation and biodiversity loss, threatening its valuable rainforests and iconic species (Bas *et al*., 2022). Efforts to address these challenges through protected areas, sustainable forest management, and community-based conservation initiatives are underway (Nkoulou *et al*., 2021). However, addressing weak governance and securing adequate funding and resources are essential for the long-term success of conservation efforts in Cameroon (Mudoh, 2022). By prioritizing sustainable practices and engaging local communities, Cameroon can work towards preserving its rich biodiversity and ensuring the well-being of both its ecosystems and its people.

Democratic Republic of the Congo (DRC): The Democratic Republic of the Congo, located in Central Africa, faces significant challenges related to deforestation and biodiversity loss (Shapiro *et al*., 2021; Ryan *et al*., 2022). The

country's vast rainforests, a substantial part of the Congo Basin, encounter threats from illegal logging, agricultural expansion, and mining activities. These activities contribute to forest degradation and loss of critical habitats for a wide range of plant and animal species (Shapiro *et al*., 2021). Deforestation in the DRC has immense biodiversity implications. The country harbors iconic species such as the endangered mountain gorillas in Virunga National Park and baboons in Salonga National Park (Shapiro *et al*., 2021). Deforestation disrupts their habitats and puts these species at risk of extinction. Additionally, the loss of forest cover affects ecosystem services like carbon storage and regulation of water cycles (Shapiro *et al*., 2021).

Efforts to combat deforestation and preserve biodiversity in the DRC include the establishment and management of protected areas (Shapiro *et al*., 2021) National parks and reserves, including Virunga National Park and Ituri Forest Reserve, safeguard critical ecosystems and supporting wildlife conservation (Shapiro *et al*., 2021). Initiatives on sustainable forest management, community forestry, and alternative livelihoods engage local communities in conservation efforts (Majambu *et al*., 2019; Yahya *et al*., 2022).

However, challenges remain in the DRC's conservation efforts. Weak governance, corruption, and limited enforcement capacity hinder effective forest management and conservation (Melnic and Juravle, 2020). Insufficient funding and resources pose significant obstacles to the implementation of conservation measures and the enforcement of regulations. Strengthening governance frameworks, improving law enforcement, and enhancing the capacity of relevant institutions are crucial for addressing these challenges (Melnic and Juravle, 2020).

Overall, the Democratic Republic of the Congo faces significant deforestation and biodiversity loss, threatening its valuable rainforests and iconic species (Shapiro *et al*., 2021). Efforts to address these challenges through protected areas, sustainable forest management, and community-based conservation initiatives are underway (Shapiro *et al*., 2021). However, addressing weak governance and securing adequate funding and resources are essential for the long-term success of conservation efforts in the DRC (Melnic and Juravle, 2020). By prioritizing sustainable practices and engaging local communities, the DRC can work towards preserving its rich biodiversity and ensuring the well-being of both its ecosystems and its people (Majambu *et al*., 2019; Yahya *et al*., 2022).

Gabon: Gabon, located on the west coast of Central Africa, is another country grappling with deforestation and biodiversity loss. The country's rainforests, part of the Congo Basin, face similar threats from illegal logging, unsustainable agricultural practices, and infrastructure development (Osathanunkul *et al*., 2021). These activities contribute to habitat destruction and fragmentation, posing significant challenges to Gabon's unique biodiversity. Deforestation in Gabon has severe consequences for the country's diverse wildlife. Gabon is known for its population of forest elephants, gorillas, and chimpanzees, which are vulnerable to habitat loss and poaching (Osathanunkul *et al*., 2021). These species play crucial roles in maintaining the ecological balance of the rainforest ecosystems. Furthermore, Gabon's rainforests are home to numerous endemic plant species that provide important medicinal and cultural resources (Tédonzong *et al*., 2019).

To combat deforestation and biodiversity loss, Gabon has implemented initiatives focused on sustainable forest management and conservation (Osathanunkul *et al*., 2021). The country has established national parks and protected areas, such as Lopé National Park and Ivindo National

Park, to safeguard critical habitats and support wildlife conservation. Gabon also strives to promote sustainable logging practices and ecotourism as alternative sources of income for local communities (Osathanunkul *et al*., 2021). However, challenges remain in Gabon's conservation efforts. Weak governance, corruption, and limited enforcement capacity hinder effective forest management and conservation (Worah et al., 2019). Insufficient funding and resources pose significant obstacles to the implementation of conservation measures and the enforcement of regulations. Strengthening governance frameworks, improving law enforcement, and enhancing the capacity of relevant institutions are crucial for addressing these challenges (Worah *et al*., 2019).

In conclusion, Gabon faces significant deforestation and biodiversity loss, threatening its valuable rainforests and iconic species. Efforts to address these challenges through protected areas, sustainable forest management, and community-based conservation initiatives are underway. However, addressing weak governance and securing adequate funding and resources are essential for the long-term success of conservation efforts in Gabon (Osathanunkul *et al*., 2021). By prioritizing sustainable practices and engaging local communities, Gabon can work towards preserving its rich biodiversity and ensuring the well-being of both its ecosystems and its people (Worah *et al*., 2019).

Challenges remain in addressing deforestation and biodiversity loss in Gabon, including weak governance, limited resources, and the need for stronger law enforcement (Ondieki *et al*., 2021). International support and collaboration, along with increased investment in capacity building and sustainable development, are crucial for Gabon to effectively address these challenges and preserve its unique rainforest ecosystems.

Climate change impacts on deforestation rates and forest degradation. Climate change has significant implications for deforestation rates and forest degradation in Central Africa (Sy *et al*., 2019). The region is experiencing the effects of climate change, including rising temperatures, changing rainfall patterns, and increased frequency of extreme weather events (Crook *et al*., 2022). These changes contribute to the vulnerability of forests and exacerbate deforestation (Staal *et al*., 2020). One of the key factors linking climate change to deforestation in Central Africa is the increased vulnerability of forests to climate-related disturbances (Staal *et al*., 2020). Droughts, for example, are becoming more frequent and severe in the region, leading to water stress and increased forest mortality. During prolonged dry periods, forests become more susceptible to wildfires, which can rapidly destroy large areas of vegetation and accelerate deforestation (Dupire *et al*., 2019). Furthermore, climate change impacts agricultural activities in Central Africa, leading to the expansion of agricultural frontiers and infrastructure development (Correa *et al*., 2019). Changing climatic conditions, such as shifts in rainfall patterns or temperature increases, can affect the suitability of certain areas for agriculture (Correa *et al*., 2019) As a result, farmers may be forced to clear additional forested land to establish new agricultural fields or expand existing ones, contributing to deforestation (Trancoso *et al*., 2022).

Infrastructure development, driven by the need to adapt to and mitigate climate change impacts, can also lead to deforestation (Trancoso *et al*., 2022). For instance, the construction of roads, dams, and energy projects may require the clearing of large tracts of forested land (Trancoso *et al*., 2022). This development often opens up previously inaccessible areas for human exploitation, including illegal logging and unsustainable agricultural practices (Condé *et al*., 2019; Trancoso *et al*., 2022).

The combination of climate change impacts, including increased vulnerability of forests, expansion of agricultural activities, and infrastructure development, poses a significant challenge to Central Africa's forests. These factors not only contribute to deforestation but also exacerbate forest degradation, which further reduces the resilience and capacity of forests to withstand future climate-related disturbances (D'Aprile and Gentilucci, 2022).

Addressing the impact of climate change on deforestation and forest degradation in Central Africa requires a multifaceted approach (Edwards *et al*., 2019). It involves implementing measures to enhance forest resilience, promote sustainable land use practices, and mitigate climate change itself (Royer-Tardif *et al*., 2021). Efforts to enhance forest resilience include reforestation and forest restoration initiatives. These actions aim to restore degraded forest areas, increase forest cover, and improve the overall health and resilience of ecosystems. By restoring forests, the capacity of the region's ecosystems to adapt to climate change and resist deforestation is strengthened (Gamette and Talburt, 2020).

Promoting sustainable land use practices is crucial for reducing the expansion of agricultural activities driven by changing climatic conditions (Correa *et al*., 2019). This includes encouraging agroforestry systems, which integrate tree planting with agricultural production, and supporting sustainable farming techniques that minimize the need for further deforestation (Correa *et al*., 2019).

Mitigating climate change is a critical component of addressing deforestation and forest degradation in Central Africa (Stokeld *et al*., 2020). Reducing greenhouse gas emissions, particularly from the burning of fossil fuels, can help slow down the pace of climate change and alleviate the pressure on forests (Stokeld *et al*., 2020). This requires transitioning to cleaner and more sustainable energy sources and adopting policies that promote low-carbon development pathways (Stokeld *et al*., 2020).

International cooperation is essential in addressing the climate change impacts on deforestation and biodiversity loss in Central Africa (Demaze *et al*., 2020). Collaborative efforts involving governments, international organizations, and local communities can support the implementation of climate change adaptation and mitigation measures (Demaze *et al*., 2020). Financial support and capacity-building initiatives are also necessary to assist Central African countries in effectively addressing the challenges posed by climate change and deforestation (Demaze *et al*., 2020). In conclusion, climate change has significant impacts on deforestation rates and forest degradation in Central Africa (Sy *et al*., 2019). The region's forests are increasingly vulnerable to climate-related disturbances, such as droughts and wildfires, while changing climatic conditions drive the expansion of agricultural activities and infrastructure development (Correa *et al*., 2019). Addressing these challenges requires a comprehensive approach that combines efforts to enhance forest resilience, promote sustainable land use practices, and mitigate climate change itself (Demaze *et al*., 2020; Royer-Tardif *et al*., 2021). International cooperation and support are crucial in achieving long-term conservation and sustainable development goals in Central Africa (Demaze *et al*., 2020).

Consequences for biodiversity, including endangered species and habitat loss. The consequences of deforestation and forest degradation in Central Africa have severe implications for biodiversity (Bonfim *et al*., 2022). The region is home to rich biodiversity hotspots and numerous endemic species that are highly vulnerable to the loss of their natural habitats (Schüßler *et al*., 2020).

Deforestation in Central Africa results in the destruction of biodiversity hotspots, which are areas with exceptionally high levels of species diversity and endemism (Bonfim *et al*., 2022). These hotspots are characterized by a unique combination of climatic and environmental conditions that support the existence of numerous specialized species found nowhere else in the world. The clearing of forests within these hotspots disrupts the delicate ecological balance, leading to the loss of species and reduced overall biodiversity in the region (Bonfim *et al*., 2022).

One of the major impacts of deforestation is the disruption of ecological corridors and fragmentation of habitats. Forests provide critical connectivity between different habitats, allowing species to move and migrate, access resources, and maintain genetic diversity (Bonfim *et al*., 2022). When forests are cleared or fragmented, these corridors are interrupted, isolating populations and hindering their ability to disperse and find suitable habitats. This fragmentation increases the risk of local extinctions and reduces the resilience of ecosystems to environmental changes (Bonfim *et al*., 2022).

Deforestation in Central Africa poses a significant threat to iconic and endangered species, including gorillas, chimpanzees, and elephants. These species play crucial ecological roles as keystone or umbrella species, influencing the structure and dynamics of their habitats and serving as indicators of ecosystem health (Schüßler *et al*., 2020). Forest clearance and habitat loss directly impact their survival and increase their vulnerability to poaching, human-wildlife conflicts, and the spread of diseases. As their habitats shrink, these species face reduced access to food, shelter, and mating opportunities, further jeopardizing their long-term survival (Schüßler *et al*., 2020).

Moreover, deforestation in Central Africa leads to the loss of vital ecosystem services provided by forests. Forests play a key role in carbon sequestration, acting as carbon sinks and helping mitigate climate change by absorbing and storing significant amounts of carbon dioxide (Lawson *et al*., 2022). When forests are cleared, the carbon stored in trees is released into the atmosphere, exacerbating greenhouse gas emissions and contributing to global warming. The loss of forests also disrupts water regulation, impacting the hydrological cycle and reducing the availability of freshwater resources (Lawson *et al*., 2022). Forests play a crucial role in regulating rainfall patterns, preventing soil erosion, and maintaining water quality. When forests are removed, the capacity to retain water is reduced, leading to increased surface runoff, soil degradation, and increased vulnerability to floods and droughts (Lawson *et al*., 2022).

Efforts to address the consequences of deforestation and biodiversity loss in Central Africa involve a combination of conservation strategies and sustainable land management practices (Govender *et al*., 2021). Conservation initiatives focus on protecting and restoring critical habitats, establishing and managing protected areas, and implementing anti-poaching measures to safeguard endangered species (Hoffmann, 2022). These efforts are often carried out in collaboration with local communities, recognizing their role as custodians of the land and involving them in conservation decision-making processes (Govender *et al*., 2021; Hoffmann, 2022).

Sustainable land management practices aim to promote the sustainable use of natural resources while minimizing the impact on ecosystems (Kelebe *et al*., 2019). This includes implementing agroforestry systems that integrate trees with agricultural activities, adopting sustainable logging practices, and

promoting responsible land-use planning to balance conservation objectives with socio-economic development (Sall and Ouedraogo, 2019).

International support and cooperation are crucial for addressing the consequences of deforestation and biodiversity loss in Central Africa (H sková *et al*., 2020). Financial assistance, capacity-building programs, and knowledge-sharing initiatives can help Central African countries strengthen their conservation efforts, enhance governance frameworks, and develop sustainable economic alternatives that prioritize biodiversity protection and ecosystem integrity (H sková *et al*., 2020).

In conclusion, deforestation and forest degradation in Central Africa have profound consequences for biodiversity (Bonfim *et al*., 2022). The loss of biodiversity hotspots, disruption of ecological corridors, and threats to iconic and endangered species highlight the urgency of addressing deforestation in the region (Schüßler *et al*., 2020). Additionally, the loss of vital ecosystem services, such as carbon sequestration, water regulation, and soil conservation, has far-reaching implications for the well-being of both local communities and the global population (Lawson *et al*., 2022). By implementing effective conservation strategies and sustainable land management practices, in collaboration with international support, Central Africa can mitigate the consequences of deforestation and preserve its rich biodiversity for future generations.

Conservation efforts and sustainable forest management practices. Central Africa is witnessing concerted efforts to address deforestation and biodiversity loss through various conservation initiatives and sustainable forest management practices. These endeavors involve the collaboration of international organizations, governments, and local communities, recognizing the importance of a multi-stakeholder approach (Nana and Kinzonzi, 2022).

Conservation initiatives in Central Africa aim to protect critical ecosystems and biodiversity hotspots. The establishment of protected areas plays a crucial role in safeguarding valuable habitats and providing safe havens for endangered species (Lowore, 2020). National parks, reserves, and wildlife corridors are created to ensure the long-term conservation of key areas, such as Virunga National Park in the Democratic Republic of the Congo, Korup National Park in Cameroon, and Ivindo National Park in Gabon. These protected areas not only serve as biodiversity strongholds but also support scientific research, ecotourism, and environmental education (Lowore, 2020).

International organizations, such as the Central African Forest Initiative (CAFI), play a vital role in coordinating regional conservation efforts. For example, CAFI supports Central African countries in developing national forest monitoring systems, implementing land-use planning, and promoting sustainable livelihoods (Mukherjee, 2021). The initiative also emphasizes the importance of securing financial resources and fostering partnerships with donor countries, private sectors, and civil society to achieve sustainable forest management goals (Mukherjee, 2021).

Governments in Central Africa are actively engaged in conservation efforts, recognizing the need to balance economic development with environmental sustainability (Fitzgerald *et al*., 2021). They collaborate with international organizations to develop and implement policies and regulations that promote sustainable forest management, discourage illegal logging, and combat deforestation. Governments also work towards strengthening governance frameworks, improving law enforcement, and enhancing the capacity of relevant institutions to ensure effective implementation of conservation

measures (Fitzgerald *et al*., 2021).

Local communities play a crucial role in forest conservation and are key partners in achieving sustainable outcomes. Community-based conservation approaches empower local communities to actively participate in decision-making processes and management of natural resources (Zost *et al*., 2019). Recognizing the rights of indigenous peoples and local communities, including land tenure and traditional knowledge, is essential for effective and sustainable conservation. Indigenous knowledge systems, passed down through generations, offer valuable insights into sustainable resource management practices, ecological resilience, and the coexistence of humans and nature (Zost *et al*., 2019).

Promoting sustainable forest management practices is vital for maintaining the integrity of Central Africa's forests. This includes implementing certification schemes such as Forest Stewardship Council (FSC) and Program for the Endorsement of Forest Certification (PEFC) (Soloviy *et al*., 2019). These schemes ensure that timber and forest products come from responsibly managed forests, adhere to strict environmental and social criteria, and support the conservation of biodiversity and ecosystem services. Certification not only provides market access for sustainably sourced products but also encourages sustainable practices among forest-dependent communities and industries (Soloviy *et al*., 2019).

However, several challenges persist in conservation efforts in Central Africa. Weak governance, corruption, and limited enforcement capacity hinder effective forest management and conservation (Perera *et al*., 2022). Insufficient funding and resources pose significant obstacles to the implementation of conservation measures and the enforcement of regulations. Strengthening governance frameworks, improving law enforcement, and enhancing the capacity of relevant institutions are crucial for addressing these challenges (Perera *et al*., 2022).

Furthermore, capacity building is essential to empower local communities, government agencies, and civil society organizations to actively participate in conservation efforts (Charnley *et al*., 2022). This includes providing training, technical support, and access to resources to enhance skills in sustainable forest management, conservation planning, and monitoring. Collaboration and knowledge-sharing between countries, institutions, and stakeholders can foster innovation, learning, and the exchange of best practices (Charnley *et al*., 2022).

In conclusion, Central Africa is actively pursuing conservation efforts and sustainable forest management practices to combat deforestation and biodiversity loss. The collaboration of international organizations, governments, and local communities is crucial in protecting critical habitats, promoting sustainable practices, and ensuring the long-term conservation of the region's forests. By strengthening governance, securing funding, and investing in capacity building, Central Africa can overcome challenges and seize opportunities to preserve its rich biodiversity and foster sustainable development for the benefit of present and future generations (Turner and Wels, 2020).

Droughts, Heatwaves, and Climate Variability in Southern Africa. Southern Africa is a region characterized by diverse climate patterns and ecosystems, with countries such as Zimbabwe, Malawi and Mozambique facing unique climate challenges. These countries exhibit varying degrees of vulnerability to climate change due to their geographical location, topography, and socioeconomic factors.

Southern Africa experiences seasonal rainfall

variability, influenced by large-scale climate forcing. The relationship between large-scale circulations and rainfall anomalies plays a crucial role in predicting seasonal rainfall patterns (Philippon *et al*., 2011). For example, the El Niño/Southern Oscillation (ENSO) phenomenon, particularly the warm ENSO phase, is associated with extreme interannual variability of seasonal precipitation in Eastern Africa (Mutemi, 2019). Understanding these circulation patterns and their connection to rainfall variability enhances the predictability of climate conditions in specific regions of southern Africa (Philippon *et al*., 2011).

Climate variability in southern Africa has wide-ranging implications for the region's ecosystems (Nhemachena *et al*., 2020). The positive phase of the subtropical Indian Ocean dipole (SIOD) influences inter-annual rainfall variability in parts of southern Africa during the austral summer (Nhemachena *et al*., 2020). This climatic mode impacts rainfall distribution and can have significant consequences for agricultural activities in the region (Nhemachena *et al*., 2020). However, the lack of comprehensive records on concurrent climate changes limits our understanding of the ecological evolution and the development and dispersal of early human populations in southern Africa (Chase, 2021).

Climate change in southern Africa poses risks to wildlife and ecosystems. Recent research suggests that climate change, combined with other factors, may have contributed to a mass mortality event of African elephants in Botswana. The impact of climate change on megafauna is a growing concern in the region (Wang *et al*., 2022). Additionally, climate change influences the distribution and diversification of species in southern Africa. Geological and climatic changes since the Miocene have shaped the genetic structure and biogeography of various organisms, including tortoises and bird species, in the region (Zhao *et al*., 2020; Mapani *et al*., 2021).

The impacts of climate change in southern Africa extend beyond the natural environment and significantly affect human populations. The region is highly vulnerable to climate change, with rural land users among the most vulnerable groups (Berger *et al*., 2019). Climate change exacerbates food insecurity in southern Africa, particularly for marginalized rural communities (Mthembu, 2021). Smallholder farmers, who depend heavily on rain-fed agriculture, are particularly susceptible to climate variability and extreme weather events. Droughts and heatwaves have resulted in reduced crop yields, livestock losses, and water scarcity, leading to food insecurity and economic instability (Verschuur *et al*., 2021).

Zambia: Located in central-southern Africa, Zambia experiences a variable climate influenced by the Inter-Tropical Convergence Zone (ITCZ) and El Niño-Southern Oscillation (ENSO) patterns (Diouf *et al*., 2020). The country is prone to droughts and floods, impacting agriculture, water resources, and food security (Musonda *et al*., 2020). Droughts result in reduced crop yields, increased food prices, and malnutrition, while intense rainfall and flooding pose risks to infrastructure, displacement of communities, and the spread of waterborne diseases (Musonda *et al*., 2020; Milupi *et al*., 2022).

Agricultural expansion driven by factors like the post-2007 crisis and Chinese investment offers an opportunity to improve food security in Zambia (Munyenyembe, 2021; Ndhlovu and Manda, 2021). However, the experiences of small-scale farmers in rural areas remain understudied (Ndhlovu and Manda, 2021). To address the impacts of changing climatic conditions, climate-smart agriculture solutions, including insurance, have been implemented to support rural smallholder families (Kajwang, 2022).

Improving agricultural productivity is crucial for household food security and income generation in Zambia. Climate variability, with unpredictable rainfall patterns, poses challenges to crop and animal production (Tembo *et al*., 2020). Crop diversification and income diversification are emphasized as strategies to mitigate the impacts of climate change on agriculture and food security in Zambia. Land size also plays a role in increasing the probability of diversification and improving per capita income in the presence of climate change (Holleman *et al*., 2020).

Water quality and availability are significant considerations in Zambia, particularly for hydropower and land-use change (Winton *et al*., 2021). Climate change and environmental threats, such as droughts and occasional flooding, have implications for agricultural sustainability and well-being. Variations in climate and environmental parameters have been observed across different regions of the country (Lemenkova, 2021) Optimized crop management practices are needed to mitigate the impacts of climate change on rainfed maize yields in Zambia (Siatwiinda *et al*., 2021).

In addition to agriculture, climate change affects various sectors in Zambia. Low rainfall, droughts, and environmental degradation impact water supply, sanitation, and health (Hubbard *et al*., 2020; Sichali *et al*., 2020). Limited access to water and sanitation in peri-urban areas presents a significant developmental challenge (Hubbard *et al*., 2020). The impacts of climate change on energy resources, such as hydro, wind, and solar, have also been studied (Nyoni *et al*., 2022). Climate change risks to urban food systems have implications for sustainable food production and access (Blekking *et al*., 2022).

Efforts to enhance the effectiveness, scalability, and sustainability of agricultural climate services in Zambia are essential for building resilience to climate change. However, challenges including limited institutional capacity and high poverty levels need to be addressed (Hansen *et al*., 2022). The adoption of environmentally sustainable practices by agricultural cooperative members is crucial for promoting sustainable agriculture (Pretty and Bharucha, 2014).

Generally, Zambia's variable climate and extreme weather events, including droughts and floods, significantly impact agriculture, water resources, and food security. The expansion of agricultural land and adoption of climate-smart agriculture solutions offer opportunities to improve food security. However, addressing challenges related to water and sanitation, vulnerability to climate change impacts, and the need for sustainable practices in various sectors are crucial for the resilience and sustainability of Zambia's economy and society.

Namibia: Situated on the southwestern coast of Africa, Namibia experiences a predominantly arid to semi-arid climate. The country is highly vulnerable to the impacts of climate change due to its aridity, limited water resources, and dependence on rain-fed agriculture (Nikodemus and Hájek, 2022).

Namibia has historically experienced recurrent droughts, which are exacerbated by climate change (Rensburg and Tortajada, 2021). These prolonged periods of drought have severe consequences on agriculture, livestock, and water availability, leading to crop failures, livestock losses, and increased food insecurity (Rensburg and Tortajada, 2021). Furthermore, heatwaves are also a significant challenge in Namibia, with temperatures soaring to extreme levels (Nikodemus and Hájek, 2022). Heatwaves pose risks to human health, livestock, and ecosystems, including dehydration, heatstroke, and increased vulnerability to diseases (Nikodemus and Hájek, 2022).

Namibia has implemented various adaptation

strategies to address climate vulnerabilities, such as the construction of water infrastructure and the promotion of climate-smart agriculture practices (Nikodemus and Hájek, 2022). Community-based initiatives, including water management committees and early warning systems, have also been established to enhance resilience in the face of droughts and heatwaves (Nikodemus and Hájek, 2022). Furthermore, recognizing the importance of gender-responsive approaches in climate change adaptation, Namibia has undertaken efforts to address the specific needs and vulnerabilities of women and men, promoting their equal participation and access to resources (Angula *et al*., 2021).

The impacts of climate change in Namibia extend beyond the environment and agriculture sectors. The health sector is also affected, with climate change contributing to the spread of vector-borne diseases and increasing the risk of heat-related illnesses (Opoku *et al*., 2021). Building the knowledge of health professionals on climate change impacts is crucial for effective preparedness and response (Opoku *et al*., 2021). In conclusion, Namibia's arid and semi-arid climate makes it highly vulnerable to the impacts of climate change, including droughts and heatwaves. These extreme events have severe consequences on agriculture, livestock, water availability, and human health. The country has implemented various adaptation measures, including water infrastructure development and climate-smart agriculture practices. Strengthening gender-responsive approaches and enhancing the knowledge of health professionals on climate change impacts are important steps towards building resilience in Namibia.

South Africa: South Africa is grappling with multiple climate change impacts, including increased temperatures, water scarcity, and the spread of vector-borne diseases. To tackle these challenges, the country has implemented various adaptation measures. These include water conservation initiatives, the promotion of renewable energy, and the integration of climate change considerations into healthcare systems to address emerging health risks.

Recent studies have highlighted the importance of addressing the impacts of climate change in South Africa. For example, research conducted in Cape Town examined the effects of persistent droughts on water security in the city, emphasizing the need for effective water conservation measures (Chitimira, 2021; Mulaudzi and Kioko, 2022). Another study focused on the vulnerability of maize producers to climate change in the Makhuduthamaga Local Municipality, highlighting the adverse effects of high temperatures and inadequate rainfall on crop production (Matimolane et al., 2022).

Efforts to address climate change in South Africa require a multidimensional approach. Studies have emphasized the importance of integrating climate change considerations into policy and planning processes, as well as promoting cross-sectoral collaboration and community-based adaptation strategies (Chersich and Wright, 2019; Johnson *et al*., 2021; Matamanda *et al*., 2022). The impacts of climate change on health in South Africa have also been a subject of recent research. A study explored the nexus between climate change adaptation strategies and smallholder farmers' food security status, emphasizing the need for adaptive measures to ensure food security in the face of changing climate conditions (Oduniyi and Sylvia, 2019). Another study examined the implications of water scarcity for construction projects in South Africa, highlighting the importance of considering water availability in project planning and management (Rother *et al*., 2020; Ramantswana *et al*., 2021).

The role of renewable energy in mitigating climate change impacts has also been a focus

of recent research in South Africa. Studies have examined the potential of renewable energy sources, such as wind and solar power, to contribute to the country's energy transition and reduce greenhouse gas emissions (Rae and Erfort, 2020). Additionally, research has explored the impact of renewable energy consumption on environmental sustainability and economic development in South Africa (Chersich and Wright, 2019; Liu, 2022). Furthermore, research has highlighted the need to address the social and economic inequalities that exacerbate vulnerability to climate change impacts in the country (Mhlanga and Garidzirai, 2020; Wang *et al*., 2020; Simon and Khambule, 2021).

In conclusion, recent research in South Africa has shed light on the diverse impacts of climate change and the importance of adaptation measures in addressing these challenges. Studies have examined the effects of climate change on water resources, agriculture, health, energy, and socio-economic systems in the country. The findings underscore the need for comprehensive and integrated approaches to climate change adaptation and mitigation in South Africa.

Drought events, heatwaves, and their impacts on agriculture and water resources. Drought events and heatwaves in Southern Africa have significant implications for agriculture and water resources, which are vital for the region's food security, livelihoods, and ecosystems (Fraga *et al*., 2020; Araújo *et al*., 2022;). For example, droughts and heatwaves have profound effects on agricultural productivity and livelihoods in Southern Africa by causing crop failure and reduced yields. Insufficient rainfall and high temperatures during droughts and heatwaves lead to water stress and soil moisture deficits, resulting in crop failures and reduced yields. The lack of water availability affects plant growth, development, and productivity, leading to significant economic losses for farmers (Thami and Chimusa, 2019). In Zimbabwe, for example, droughts have resulted in reduced crop yields and increased food insecurity, particularly for smallholder farmers (Manyanga *et al*., 2022). The impact of climate change on water resources and food security in South Africa has been assessed (Krell *et al*., 2021; Kwame *et al*., 2022). Relatively, limited water availability and degraded pastureland during droughts have a direct impact on livestock farming (Thami and Chimusa, 2019). Insufficient water for drinking and irrigation, coupled with the scarcity of fodder, lead to livestock losses, reduced body condition, and increased susceptibility to diseases, further jeopardizing rural communities' livelihoods (Thami and Chimusa, 2019). In Zambia, droughts have been linked to livestock losses and a decrease in animal productivity (Musonda *et al*., 2020).

Importantly, Droughts and heatwaves also have significant implications for water resources in Southern Africa: Droughts deplete water sources such as rivers, reservoirs, and groundwater, leading to reduced water availability for domestic, agricultural, and industrial use. This creates water scarcity, particularly in regions dependent on rain-fed agriculture, and exacerbates challenges in accessing clean and reliable water supplies (Romaguera *et al*., 2014). In Namibia, for instance, water scarcity during droughts has resulted in reduced water availability for both domestic use and irrigation (Nikodemus and Hájek, 2022).

Droughts also disrupt aquatic ecosystems, impacting wetlands, rivers, and biodiversity. Reduced water levels affect aquatic habitats, fish populations, and the overall ecological balance, threatening the region's biodiversity and ecosystem services (Mlambo, 2018). In Zimbabwe, droughts have been found to impact the availability of water for ecosystems, affecting biodiversity and the ecological health of rivers and wetlands.

Scarce water supplies can trigger conflicts among communities, agricultural users, and industries, exacerbating tensions and compromising equitable water distribution (Emadodin *et al*., 2021). Competition for limited water resources can lead to social and economic tensions, further exacerbating the challenges faced by communities and hindering sustainable water management. In Zambia, conflicts over water resources have been observed between farmers and mining companies, highlighting the complex dynamics and competing water demands (Ndhlovu and Manda, 2021).

Socioeconomic impacts: Droughts and heatwaves have far-reaching socioeconomic impacts in Southern Africa. Notably, Drought-induced crop failures and reduced agricultural productivity contribute to food insecurity, affecting vulnerable populations. Reduced access to affordable and nutritious food leads to malnutrition, stunting, and other health challenges, particularly among children and women, undermining the region's development progress (Banze *et al*., 2018). In Zimbabwe, droughts have been linked to increased food prices and limited access to food, particularly for marginalized rural communities (Sithole *et al*., 2021).

Droughts and heatwaves also result in significant economic losses in the agricultural sector, affecting employment, income, and rural livelihoods. The heavy reliance on rain-fed agriculture makes Southern African economies susceptible to climate-related shocks and disruptions, leading to reduced economic growth and stability. In Mozambique, droughts have impacted agricultural productivity, resulting in economic losses and hindering rural development (Nuvunga *et al*., 2020).

Relatively, prolonged droughts and their associated impacts can force rural communities to migrate to urban areas in search of alternative livelihoods and better access to resources, leading to increased pressure on urban infrastructure and social services. This influx of people can strain urban resources, exacerbate social inequality, and potentially lead to social unrest and conflicts (Mujeyi *et al*., 2021). In Zimbabwe, the impacts of droughts on rural communities have been identified as a driver of internal migration to urban centers (Mujeyi *et al*., 2021).

Addressing the impacts of droughts, heatwaves, and climate variability on agriculture and water resources in Southern Africa requires a multi-faceted approach (Dougill *et al*., 2021). This includes the development and implementation of climate-smart agricultural practices, such as cultivation of drought-resistant crop varieties, efficient irrigation systems, and soil management techniques, to enhance agricultural resilience and productivity (Thami and Chimusa, 2019; Dougill *et al*., 2021). Additionally, water management strategies, early warning systems, and improved water storage infrastructure are crucial for ensuring water availability and resilience in the face of changing climate patterns (Romaguera *et al*., 2014). Strengthening regional cooperation for water resource management, promoting sustainable practices across sectors, and integrating climate change considerations into policy frameworks are essential steps towards building resilience and ensuring long-term water security in Southern Africa (Emadodin *et al*., 2021).

Furthermore, supporting small-scale farmers and rural communities through social safety nets, access to financial services, and capacity-building initiatives can enhance their adaptive capacities and improve their resilience to climate-related challenges (Dithebe *et al*., 2019). Collaboration between governments, civil society organizations, and international partners is crucial for implementing and scaling up these adaptation measures, ensuring that the

most vulnerable populations are effectively supported (Banze *et al*., 2018; Dougill *et al*., 2021). By addressing the impacts of droughts, heatwaves, and climate variability, Southern Africa can strive towards a more sustainable and resilient future for its agriculture and water resources, while safeguarding the well-being and livelihoods of its communities.

Consequences for food security, economic stability, and human health. Droughts, heatwaves, and climate variability in Southern Africa have far-reaching consequences for food security, economic stability, and human health, exacerbating existing vulnerabilities and socio-economic challenges in the region (Banze *et al*., 2018; Tschumi *et al*., 2021).

Malnutrition and health risks: Limited food availability and poor nutritional intake during periods of drought and heatwaves increase the risk of malnutrition, especially among vulnerable groups such as children, pregnant women, and the elderly (Schmeltz and Gamble, 2017; Banze *et al*., 2018). Malnutrition can lead to stunted growth, weakened immune systems, and various health complications, further exacerbating the region's health challenges (Schmeltz and Gamble, 2017).

Dependence on food imports: Declining agricultural productivity due to climate-related events necessitates increased reliance on food imports, which can strain national economies and exacerbate issues of food affordability and accessibility (Banze *et al*., 2018). Importing food to compensate for domestic shortfalls poses challenges in terms of cost, availability, and food sovereignty, further compromising food security.

Economic stability: The impacts of droughts, heatwaves, and climate variability extend to economic stability in Southern Africa, affecting livelihoods, employment, and overall economic development:

- **Agricultural losses:** Droughts and heatwaves result in significant economic losses in the agricultural sector, affecting farmers, agribusinesses, and rural livelihoods (Banze *et al*., 2018). Drought-induced crop failures and livestock losses result in reduced agricultural income, exacerbating poverty and food insecurity. Small-scale farmers and rural communities, who heavily rely on rain-fed agriculture, are particularly vulnerable to these impacts, as their livelihoods are closely tied to agricultural activities (Banks *et al*., 2015). In Mozambique, droughts have led to decreased agricultural production, affecting farmers' income and food availability (Nuvunga *et al*., 2020). On the other hand, floods have had widespread destruction in Madagascar, Malawi and Mozambique.

- **Impacts on employment:** Agriculture is a significant source of employment in Southern Africa, particularly in rural areas. Droughts and heatwaves can lead to job losses, both directly in the agricultural sector and indirectly in related industries such as food processing and distribution (Banze *et al*., 2018). The loss of jobs further exacerbates poverty, unemployment, and rural-urban migration.

- **Disruption of economic sectors:** Climate variability and extreme weather events disrupt various economic sectors beyond agriculture. Industries such as tourism, energy, and manufacturing can experience reduced productivity, increased operational costs, and disruptions in supply chains, impacting overall economic stability (Banze *et al*., 2018). For instance, reduced water availability can limit hydropower generation, leading to energy shortages and increased reliance on costly alternatives.

- **Human Health:** Droughts, heatwaves, and climate variability also have significant

implications for human health in Southern Africa, affecting physical and mental well-being. For example, water scarcity and compromised sanitation during droughts can lead to increased waterborne diseases, including diarrhea, cholera, and dysentery (Schmeltz and Gamble, 2017). Limited access to safe drinking water and proper sanitation facilities heighten health risks and can contribute to disease outbreaks, further straining health systems and resources (Schmeltz and Gamble, 2017).

There are also heat-related illnesses. For example, heatwaves pose significant health risks, particularly for vulnerable populations (Chen *et al*., 2022). High temperatures and heatwaves can lead to heat stress, heatstroke, and other heat-related illnesses, especially in urban areas with inadequate cooling infrastructure and limited access to healthcare services. The elderly, young children, and individuals with pre-existing health conditions are particularly susceptible to these risks (Kovats and Hajat, 2008).

Prolonged droughts, food insecurity, and economic instability can have adverse mental health effects on individuals and communities. Anxiety, stress, and depression may increase as people face ongoing climate-related challenges and uncertainties, affecting their overall well-being and social cohesion (Kovats and Hajat, 2008).

Strategies for climate-resilient health systems and disease management. Addressing the consequences of droughts, heatwaves, and climate variability requires a multi-dimensional approach that integrates climate adaptation and mitigation strategies with sustainable development goals, ensuring the well-being and prosperity of Southern African communities. Additionally, promoting community resilience, social safety nets, and risk-sharing mechanisms can support vulnerable individuals and communities in coping with climate-related challenges (Berry *et al*., 2009). Strengthening regional cooperation, knowledge exchange, and advocacy for climate action can also contribute to long-term resilience-building efforts in Southern Africa (Berry *et al*., 2009).

To effectively address the changing climate and associated health risks in Sub-Saharan Africa, it is crucial to develop and implement strategies that build climate-resilient health systems and effectively manage diseases (Ligsay *et al*., 2021; Iyer and Toé, 2022). These strategies should integrate climate adaptation, public health measures, and community engagement to ensure a holistic and effective response.

Strengthening Health Infrastructure and Services: To build climate-resilient health systems, the following strategies can be implemented:

- Climate-informed infrastructure planning: Incorporating climate projections and vulnerability assessments into the design and construction of healthcare facilities can ensure their resilience to extreme weather events and changing disease patterns (Fine, 2022). This includes considering factors such as flood-resistant construction, energy-efficient designs, and adaptable infrastructure that can withstand climate-related stresses.
- Enhancing surveillance and early warning systems: Developing robust disease surveillance systems that integrate climate and environmental data can enable early detection and response to climate-sensitive diseases (Willetts *et al*., 2022). Monitoring climate indicators, vector populations, and disease incidence can help identify emerging health risks and inform targeted interventions.
- Capacity-building and training: Building the capacity of healthcare workers to understand and respond to climate-related health risks is crucial. Training programs

on climate change and health, including disease management, emergency response, and health promotion, can enhance preparedness and improve health outcomes (Bowen and Friel, 2012). This includes providing healthcare professionals with the knowledge and skills to adapt to changing disease patterns, understand the connections between climate and health, and communicate climate-related risks to communities (Bowen and Friel, 2012).

Promoting Climate-Sensitive Disease Management: To effectively manage diseases in the context of climate change, the following strategies can be implemented:

- Vector-borne disease control: Implementing integrated vector control measures, such as insecticide-treated bed nets, indoor residual spraying, and larval source management, can help mitigate the transmission of diseases like malaria, dengue fever, and Zika virus (Gebremeskel *et al*., 2022). This includes targeted vector control interventions based on climate and environmental risk assessments, as well as community-based approaches to engage local populations in vector control activities.
- Water and sanitation interventions: Ensuring access to safe drinking water, adequate sanitation facilities, and proper hygiene practices is essential to prevent waterborne diseases during periods of water scarcity and flooding (Ligsay *et al*., 2021). This involves implementing climate-resilient water and sanitation infrastructure, promoting water conservation practices, and educating communities on safe water handling and hygiene.
- Immunization campaigns: Strengthening immunization programs and expanding coverage can help protect communities from vaccine-preventable diseases. Climate-informed immunization strategies can address shifting disease dynamics and changing disease transmission patterns (Yang, 2022). This includes assessing the impact of climate change on vaccine efficacy, adapting immunization schedules, and integrating climate information into vaccination campaigns.
- Health education and behavior change: Community engagement, health promotion campaigns, and behavior change communication can raise awareness about climate-related health risks, disease prevention, and adaptation measures. Empowering communities with knowledge and tools to protect themselves and promote resilient health practices is vital (Fabricante *et al*., 2021). This includes promoting climate-resilient behaviors, such as proper waste management, personal protection measures, and seeking healthcare services in a timely manner.

Collaboration and Partnerships: To strengthen climate-resilient health systems and disease management, collaboration and partnerships are essential:

- Multi-sectoral collaboration: Promoting collaboration across sectors, including health, environment, agriculture, and disaster management, can facilitate a coordinated response to climate-related health challenges (Nejati *et al*., 2022). Interdisciplinary approaches that bring together experts from different sectors are needed to address the complex interactions between climate, ecosystems, and health. This includes joint planning, data sharing, and resource mobilization across sectors.
- Regional and international cooperation: Sharing knowledge, best practices, and resources among countries and international organizations can strengthen capacity-building efforts, support research and development, and foster knowledge exchange on climate-resilient health systems and disease management (Liu, 2022). This involves regional collaborations for early

warning systems, joint research initiatives, and the establishment of networks for learning and sharing experiences.

- Community participation: Engaging communities in decision-making processes, integrating traditional knowledge systems, and involving local stakeholders in planning and implementation can ensure that climate-resilient health strategies are contextually appropriate and effectively address local needs and priorities (Rajapaksha *et al*., 2022). This includes participatory approaches, community-based adaptation strategies, and empowering communities to actively contribute to their own health and well-being.

Implementing climate-resilient health systems and disease management strategies in Sub-Saharan Africa requires sustained political commitment, adequate funding, and long-term planning (Widhiyoga and Ikawati, 2022). It also calls for collaboration between governments, civil society organizations, academia, and international partners to address the complex challenges at the intersection of climate change and health (Iyer and Toé, 2022). By prioritizing adaptation and resilience-building, countries can better protect public health and enhance their capacity to respond to the evolving health risks associated with climate change (Tyas and Prakoso, 2022). Building climate-resilient health systems not only improves health outcomes but also contributes to sustainable development and the overall well-being of communities in Sub-Saharan Africa (Kotchi *et al*., 2019; Neogi *et al*., 2022). Continued efforts in this direction are crucial to safeguard the health and well-being of populations in the face of a changing climate.

Cross-cutting Issues. By examining these interconnections, we can gain a comprehensive understanding of the complex and intertwined nature of climate change impacts on the continent (Dee *et al*., 2021). One common theme across the case studies is the vulnerability of African communities to climate change (Ayodotun *et al*., 2019; Dasgupta and Robinson, 2022). Whether it is drought and food insecurity in the Sahel, coastal erosion and sea-level rise in West Africa, shifts in rainfall patterns in East Africa, or health risks in Sub-Saharan Africa, communities face unique challenges and risks (Dasgupta and Robinson, 2022). The interconnected nature of these vulnerabilities highlights the need for holistic and integrated adaptation strategies that address multiple sectors simultaneously (Baninla *et al*., 2022).
Climate change poses significant threats to food security and livelihoods across the continent (Chersich and Wright, 2019; Kutywayo *et al*., 2022). The case studies on drought and food insecurity in the Sahel and shifts in rainfall patterns in East Africa demonstrate how changing climate patterns impact agricultural productivity and, consequently, the availability and accessibility of food (Chersich and Wright, 2019; Kutywayo *et al*., 2022). The interconnections between these regions emphasize the need for cross-regional collaboration and knowledge sharing to develop climate-resilient agricultural practices and enhance food security (Palinkas *et al*., 2020; Lieber *et al*., 2021; Kutywayo *et al*., 2022). Statistics reveal that Africa has the highest prevalence of undernourishment, with approximately 250 million people suffering from chronic hunger (Palinkas *et al*., 2020; Lieber *et al*., 2021). Climate change exacerbates this issue, with estimates suggesting that by 2050, an additional 38 million people in Africa may be at risk of hunger due to its impacts (Lieber *et al*., 2021).

The case studies on coastal erosion in West Africa and shifts in rainfall patterns in East Africa also highlight the interconnectedness between water resources and ecosystems (Amegatcher *et al*., 2022). Rising sea levels

and coastal erosion not only threaten coastal communities and infrastructure but also impact valuable coastal ecosystems such as mangroves and coral reefs (Appiagyei *et al*., 2022). Furthermore, changing rainfall patterns affect water availability, leading to water scarcity and its subsequent impacts on agriculture, ecosystems, and human health (Amegatcher *et al*., 2022). The cross-cutting theme of water scarcity underscores the importance of integrated water resource management approaches and nature-based solutions to ensure sustainable water supply and ecosystem conservation (Amegatcher *et al*., 2022).

The case study on health risks and disease patterns in Sub-Saharan Africa highlights the interconnection between climate change and public health (Overland *et al*., 2021; Asubiaro and Elueze, 2022). Changing climate conditions influence the distribution of vector-borne diseases such as malaria and dengue fever, posing significant health risks to communities (Asubiaro and Elueze, 2022). These impacts are further exacerbated by socio-economic factors, weak health systems, and inadequate infrastructure (Asubiaro and Elueze, 2022). It is estimated that climate change is already responsible for over 60,000 deaths annually from malaria alone in sub-Saharan Africa (Overland *et al*., 2021). The interconnectedness between climate change and health underscores the importance of building climate-resilient health systems, promoting disease surveillance and prevention measures, and enhancing access to healthcare in vulnerable communities (Asubiaro and Elueze, 2022).

By recognizing and understanding these interconnections, policymakers, researchers, and stakeholders can develop comprehensive and integrated approaches to address climate change impacts in Africa (Ihinegbu, 2021; Baninla *et al*., 2022). This requires collaboration across sectors, regions, and disciplines to develop adaptive strategies, enhance resilience, and promote sustainable development in the face of a changing climate (Ihinegbu, 2021).

Implications for regional climate change adaptation and policy-making. The synthesis of the case studies offers valuable insights into the implications of the findings for regional climate change adaptation strategies and policy-making in Africa. It underscores the urgent need for integrated and multi-sectoral approaches that address the complex and interconnected challenges posed by climate change (Bhowmik, 2021; Epule *et al*., 2021). Effective climate change adaptation requires collaboration and partnerships among various stakeholders, including governments, local communities, civil society organizations, and international agencies (Bhowmik, 2021). Furthermore, it highlights the importance of incorporating local knowledge and engaging communities in decision-making processes to ensure context-specific and sustainable solutions (Epule *et al*., 2021).

Integrated and Multi-Sectoral Approaches: The case studies reveal the interconnected nature of climate change impacts across sectors such as agriculture, water resources, health, and ecosystems. Addressing these challenges requires integrated approaches that consider the interdependencies and trade-offs between different sectors (Thomas *et al*., 2021). For example, efforts to enhance agricultural resilience should be linked to water management strategies, ecosystem conservation, and health initiatives to achieve synergistic and sustainable outcomes (Chersich and Wright, 2019; Thomas *et al*., 2021; Sakapaji, 2022).

Collaboration between Stakeholders: Climate change adaptation in Africa necessitates collaboration and partnership between various stakeholders, including governments, local communities, academia, private sector entities, and international organizations. By fostering dialogue and collaboration,

stakeholders can pool resources, share knowledge, and collectively develop strategies that are contextually appropriate and effective (Rahmawati *et al*., 2019). Successful examples of collaboration can be seen in community-based adaptation projects where local communities, NGOs, and government agencies work together to implement climate-resilient practices (Chersich and Wright, 2019; Rahmawati *et al*., 2019; Sakapaji, 2022).

Incorporating Local Knowledge and Community Engagement: The active involvement of local communities and the incorporation of indigenous knowledge are essential for developing climate change adaptation strategies that are relevant and sustainable (Lim, 2021). Local communities possess valuable knowledge and experiences regarding climate variability and traditional adaptation practices (Lim, 2021). Integrating this knowledge with scientific expertise can lead to context-specific and culturally appropriate solutions. Furthermore, engaging local communities in decision-making processes and empowering them to participate in the design and implementation of adaptation measures ensures ownership and long-term effectiveness (Chersich and Wright, 2019; Lim, 2021; Sakapaji, 2022).

By synthesizing the findings from the case studies, policymakers in Africa can gain a comprehensive understanding of the commonalities and interconnections among different sectors and regions. This understanding can inform the development of evidence-based policies and strategies that promote climate change adaptation and resilience at the regional, national, and local levels (Bhowmik, 2021).

Lessons learned and best practices for addressing climate change impacts in Africa. Building Resilient Agricultural Systems: One key lesson learned from the case studies is the importance of implementing climate-smart agricultural practices. These practices involve using climate-resilient crop varieties, adopting sustainable irrigation techniques, practicing agroforestry, and promoting soil conservation measures (Hasanov *et al*., 2019). For example, in Ethiopia, the Climate-Smart Agriculture program has successfully increased agricultural productivity and enhanced the resilience of farmers to climate change impacts (Yiridomoh, 2021). Statistics show that for every $1 invested in climate-resilient agriculture in Africa, there is a potential return of $4.40 in increased crop production (Mahmood *et al*., 2020; Yiridomoh, 2021). These practices not only help farmers adapt to changing climate conditions but also contribute to reducing greenhouse gas emissions and improving food security.

Strengthening Community-Based Adaptation: Engaging local communities in the adaptation process is crucial for effective climate change response (McNamara *et al*., 2020). The case studies highlight the importance of community-based adaptation initiatives that empower local stakeholders and integrate traditional knowledge with scientific approaches. In Niger, the "Farmer Managed Natural Regeneration" approach, which involves protecting and regenerating indigenous trees, has led to increased agricultural productivity, restoration of degraded land, and improved livelihoods (Biswas *et al*., 2020; Seleguim, 2021). Community-based adaptation efforts provide opportunities for capacity building, knowledge sharing, and collective decision-making. They enable communities to identify and implement context-specific adaptation measures that consider their socio-economic and cultural circumstances.

Policy Interventions and Institutional Support: Strong policy frameworks and institutional support are essential for addressing climate change impacts at the national and regional levels (Virues-Contreras *et al*., 2020). The case studies emphasize the need

for integrating climate change considerations into development planning and policy-making processes. Countries like Kenya have developed comprehensive National Climate Change Action Plans, which provide a roadmap for climate change adaptation and mitigation actions (Chersich and Wright, 2019; Phillips, 2021). Additionally, establishing dedicated institutions, such as climate change departments or agencies, helps coordinate efforts, mobilize resources, and ensure effective implementation of climate change initiatives. Adequate funding mechanisms, both domestic and international, play a critical role in supporting adaptation and resilience-building efforts.

Knowledge Sharing and South-South Cooperation: The case studies demonstrate the importance of knowledge sharing and South-South cooperation in addressing climate change impacts (Halsnæs *et al*., 2020). African countries can learn from each other's experiences and exchange best practices in adaptation and mitigation strategies. Platforms like the African Adaptation Initiative and regional climate change centers facilitate knowledge exchange, capacity building, and collaboration among African nations (Xuan *et al*., 2021; Verkerk *et al*., 2022). Furthermore, international cooperation, technology transfer, and financial support from developed countries are crucial for enhancing Africa's adaptive capacity and resilience.

By incorporating these lessons learnt and best practices into future initiatives, Africa can effectively address climate change impacts, reduce vulnerability, and promote sustainable development across the continent.

CONCLUSION

This comprehensive review has provided valuable insights into the diverse impacts of climate change across the African continent, shedding light on the vulnerabilities of different regions and sectors. The case studies presented have highlighted the urgent need for action to address the challenges posed by climate change in Africa. From the case studies, several key findings have emerged, emphasizing the importance of adaptation and resilience-building measures.

The Sahel region's vulnerability to drought events has underscored the significance of improved water management, use of resilient crop varieties, and early warning systems in mitigating drought impacts and enhancing resilience. In West Africa, coastal erosion and rising sea levels called for the implementation of coastal protection measures, ecosystem-based adaptation strategies, and sustainable land use practices to safeguard coastal communities, infrastructure, and ecosystems. The changing rainfall patterns in East Africa have significant implications for agricultural systems and food security, necessitating community-based adaptation initiatives focused on water management, agroforestry, and livelihood diversification. Similarly, Central Africa's critical issue of deforestation highlights the importance of conservation efforts, sustainable land use practices, and policies to combat deforestation in preserving biodiversity and mitigating climate change impacts.

The case studies have also emphasized the impacts of climate change in Southern Africa, particularly droughts, heatwaves, and climate variability. These events have far-reaching consequences for agriculture, water resources, food security, economic stability, and human health. Climate-smart agricultural practices, water resource management, and climate-resilient health systems are crucial in addressing these impacts and building resilience in the region. Furthermore, the review has highlighted the risks posed by climate change to public health systems and healthcare infrastructure in sub-Saharan Africa. Vector-borne diseases, exacerbated by climate change, necessitate

the strengthening of climate-resilient health systems, early warning systems, and integrated disease management approaches.

To effectively address the impacts of climate change in Africa, it is imperative to prioritize evidence-based decision-making, policy formulation, and long-term planning. Continued research, monitoring, and data collection are essential for enhancing our understanding of climate change impacts and improving predictions for informed decision-making. Additionally, international cooperation, financial assistance, technological transfer, capacity building, and knowledge sharing are vital for supporting African countries in their efforts to develop and implement context-specific adaptation and mitigation measures.

Importantly, sustained efforts are urgently needed to protect vulnerable communities and ecosystems, promote sustainable development, and build resilience in the face of climate change in Africa. By working together, stakeholders, policymakers, and international partners can create a more resilient Africa that thrives amidst climate change, preserving its rich biodiversity, supporting the well-being of its people, and securing a sustainable future for generations to come.

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The authors declare that there is no conflict of interest in this paper.

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