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Artificial intelligence in marine ecosystem management: addressing climate threats to Kenya's blue economy

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This study investigates the application of Artificial Intelligence (AI) in monitoring and managing marine ecosystems to address the impacts of climate change on Kenya's Blue Economy. It aims to assess the threats posed by climate change to these ecosystems and explore the potential of AI solutions to enhance adaptation and resilience. The research employs a comprehensive review of secondary data sources, including academic publications, reports from reputable institutions, and other relevant materials. The study analyzes existing literature on AI applications in marine ecosystem management and climate change mitigation, focusing on the specific context of Kenya's Blue Economy. The study reveals that climate change poses significant threats to Kenya's marine ecosystems, including coral bleaching, ocean acidification, sea-level rise, and disruptions to ocean currents. AI technologies offer promising solutions for monitoring and managing these impacts, with applications in predictive modeling, resource optimization, and decision support. The research highlights the need for further exploration into specific AI applications tailored to Kenya's unique coastal challenges and the importance of incorporating diverse stakeholder perspectives. Additionally, it emphasizes the necessity for long-term impact assessments of AI technologies in the context of climate change mitigation. This study contributes to the growing body of knowledge on AI applications in environmental management, particularly within the context of Kenya's Blue Economy. By identifying the potential of AI to enhance resilience and sustainability in marine ecosystems, the research offers valuable insights for policymakers, researchers, and practitioners involved in climate change mitigation and adaptation efforts.

KEYWORDS

artificial intelligence, blue economy, climate change, Kenya, ecosystem management

1 Introduction

The Blue Economy has become a focal point for fostering economic growth, societal advancement, and environmental conservation. Okafor-Yarwood et al. (2020) conceptualize it as a developmental strategy that underscores responsible and sustainable utilization of water resources, both within and beyond aquatic environments. Projections from the OECD indicate that by 2030, the ocean economy could contribute over USD 3.0 trillion to global GDP, with significant growth anticipated in marine aquaculture, offshore wind energy, fish processing, and shipbuilding and repair (OECD, 2016; Barbier, 2023; Betin and Titova, 2023; Doerr et al., 2023). Africa's economic landscape is intricately linked to its expansive coastal regions. In 2018, the Blue Economy of Africa generated approximately US$300 billion and offered employment to 49 million individuals. Forecasts for 2030 suggest a noteworthy expansion, reaching a value of US$405 billion. The pivotal driving force behind this growth is expected to be the coastal tourism sector, contributing an estimated US$100 billion to the overall economic output. The foreseeable future anticipates the various sectors comprising Africa's Blue Economy to create substantial employment opportunities, with an estimated 57 million jobs (World Bank, 2022).

Kenya asserts that the Blue Economy (BE) combines green growth and sustainable development to advance social, economic, and community development, thus it has prioritized the Blue Economy (BE) sector as a key component for achieving the country's long-term development goals outlined in the Kenya Vision 2030 (Government of Kenya (GoK), 2021). This decision is based on the potential of the Blue Economy to create employment, reduce poverty, and enhance nutrition and food security, and drive economic growth, as recognized by various international organizations and researchers. By launching several prominent BE initiatives, Kenya has assumed a leading position on the international stage. The first "Sustainable Blue Economy Conference" was held in the nation in 2018 in a joint effort with Japan and Canada. At the United Nations Ocean Conference (UNOC) in Lisbon, Portugal in 2022, Kenya once again collaborated with Portugal. The United Nations Ocean Council (UNOC) issued the "Lisbon Declaration" to restate its support for the UN Decade for Ocean Science (2020–2030), the Paris Agreement, and Sustainable Development Goal 14 (Life below water).

Additionally, the Commonwealth Blue Charter now recognizes Kenya as the leading advocate for the sustainable blue economy sector (Commonwealth Blue Charter (2018)). At the same time, Kenya is an integral element of the High-Level Panel for a Sustainable Ocean Economy, an international body that supports sustainable BE initiatives on a worldwide scale. The panel consists of fourteen member nations. Kenya and the other members of the High-Level Panel committed in December 2020 to responsibly manage all of the seas under their respective jurisdictions by 2025. Additionally, by 2030, the GoK has committed to designating 30% of its Exclusive Economic Zone (EEZ) as Marine Protected Areas (MPAs) (Overbeeke et al., 2022).

Nevertheless, the blue economy faces an imminent threat from climate change and disasters, primarily manifested through the disruption of ocean-based businesses and livelihoods and the degradation of water-related ecosystems and biodiversity (Karanja and Saito, 2018). The impact of climate change extends to alterations in ocean climate, sea level, acidity, water circulation, and ice distribution, directly affecting coastal ecosystems and the species essential for coastal economic benefits (Gaines et al., 2019). Moreover, coastal hazards such as tsunamis, floods, and earthquakes pose significant challenges to the resilience and sustainability of the blue economy. The anticipated increase in the frequency and intensity of hydrological, meteorological, and climatological disasters, including floods, tropical cyclones, and drought, further exacerbates the vulnerability of the blue economy (IPCC, 2019). Additionally, the global repercussions of the COVID-19 pandemic have severely impacted coastal tourism, fisheries, seafood production, and maritime transport (UNCTAD, 2020).

Initiating a transformative trajectory toward mitigating climate change necessitates the utilization of cutting-edge technological advancements. Among these innovations, Artificial Intelligence (AI) emerges as a pivotal force poised to redefine the paradigm of environmental stewardship. AI, within the field of computer science, encompasses the development of systems endowed with the capacity to execute tasks conventionally requiring human intelligence. This technology enables the analysis of extensive datasets, facilitating the identification of patterns, formulation of predictions, and informed decision-making (Wirtz and Weyerer, 2019). The application of AI exhibits considerable promise in augmenting the efficiency and efficacy of activities associated with the monitoring and management of climate change with potential in the marine environment.

The existing literature on AI applications for monitoring and managing marine ecosystems in Kenya's Blue Economy reveals notable gaps that warrant future research. First, there is a limited focus on specific AI applications tailored to the unique challenges faced by Kenya's coastal regions. While the potential of AI is acknowledged, further exploration into the development and implementation of AI tools customized for diverse marine environments and socio-economic contexts in Kenya is necessary. Second, the literature predominantly emphasizes the technical aspects of AI applications, overlooking diverse stakeholder perspectives.

The study therefore examines AI applications for monitoring and managing marine ecosystems to mitigate climate change impacts on Kenya's Blue Economy. To address this objective, the research answers the question: how does AI aid in mitigating climate change in Kenya's Blue Economy align with the urgent need to explore innovative solutions for environmental sustainability? The objectives of assessing the current state of Kenya's ocean environments and investigating the potential roles of AI technologies in monitoring climate change provide a structured approach to understanding and addressing the complex issues faced by the Blue Economy. The gaps identified in the literature, such as the lack of specific AI applications tailored to Kenya's coastal regions, limited stakeholder perspectives, and inadequate long-term impact assessments, underscore the necessity for this study. By bridging these gaps, the study aims to contribute new insights into customized AI solutions for sustainable marine resource management in Kenya, emphasizing

interdisciplinary collaboration, stakeholder engagement, and knowledge transfer initiatives. The study's focus on practical applications of AI technologies in mitigating climate change impacts on Kenya's Blue Economy brings a fresh perspective to existing research, offering valuable contributions to enhancing resilience and sustainability in coastal ecosystems and communities.

2 Materials and methods

This study employed a comprehensive and systematic approach to investigate the application of Artificial Intelligence (AI) in monitoring and managing marine ecosystems to mitigate the impacts of climate change on Kenya's Blue Economy. The methodology encompassed a rigorous literature review, data collection, and analysis, ensuring a robust and replicable research process. A systematic literature review was conducted to identify relevant studies, reports, and publications related to AI applications in marine ecosystem management and climate change mitigation. The review encompassed Google Scholar and Scopus database sources, including peer-reviewed academic journals, government reports, international organization publications, and reputable online databases. The search terms used in the literature review included "Artificial Intelligence," "Machine Learning," "Blue Economy," "Climate Change," "Marine Ecosystems," and "Kenya". The search was conducted in English, and the timeframe for inclusion was limited to the past decade (2014-2024) to ensure the relevance and currency of the information. The selection criteria for inclusion in the review were based on the relevance of the study to the research question, the quality of the methodology, and the clarity of the findings. Studies that specifically addressed the application of AI in monitoring and managing marine ecosystems in the context of climate change were prioritized.

Data collection involved extracting relevant information from the selected literature, including details on AI technologies, their applications in marine ecosystem management, and their potential for mitigating climate change impacts. The data were organized and categorized based on the type of AI technology, the specific application, and the environmental parameters being monitored or managed. The analysis of the collected data involved a qualitative assessment of the potential benefits and challenges of AI applications in marine ecosystem management. The analysis also considered the scalability and adaptability of these technologies to the specific context of Kenya's Blue Economy.

To assess the potential of AI in addressing Kenya's Blue Economy challenges, an analytical framework was developed based on the findings of the literature review. This framework considered the following key factors: Technological Feasibility: The technical capabilities and limitations of AI technologies in monitoring and managing marine ecosystems. Economic Viability: The cost-effectiveness and potential return on investment of AI applications in the Blue Economy. Environmental Impact: The potential positive and negative environmental impacts of AI technologies on marine ecosystems. Social Acceptability: The social and ethical considerations associated with the use of AI in environmental management. Policy and Regulatory Framework: The existing policy and regulatory landscape for AI adoption in Kenya's Blue Economy.

By considering these factors, the analytical framework provided a structured approach to evaluating the potential of AI in addressing the specific challenges faced by Kenya's Blue Economy. To provide practical insights into the application of AI in marine ecosystem management, case studies from different regions and sectors were analyzed. These case studies were selected based on their relevance to the research question, the quality of the documentation, and the availability of data. The case studies were critically assessed to identify key lessons learned, best practices, and potential challenges in implementing AI solutions. Figure 1 depicts the flowchart followed.

3 Kenya context

3.1 Kenya's climate landscape

Kenya is highly vulnerable to climate change due to its geographic location and socioeconomic factors (World Bank Group, 2021). The country faces escalating challenges from prolonged droughts, intense flooding, and rising temperatures, all of which have adverse effects on the Blue Economy (Government of Kenya, 2021; OCHA, 2023). While Kenya's contribution to global greenhouse gas emissions is minimal, the nation is experiencing the consequences of climate change, with over 70% of natural disasters attributed to climate-related events (GAIN, 2021). These disasters, including droughts and floods, have resulted in significant economic losses, impacting livelihoods and hindering development (Kenya Post Disaster Needs Assessment 2008–11 Drought, 2012).

Kenya's coastal marine environments, characterized by coral reefs, seagrass beds, and mangroves, are crucial for biodiversity and livelihoods (Obura, 2001). However, these ecosystems face threats from climate change, including coral bleaching due to rising sea temperatures, ocean acidification, sea-level rise, and changes in upwelling patterns (Obura et al., 2017; Doney et al., 2020; Jacobs et al., 2021). These impacts not only harm marine life but also disrupt fishing activities and coastal communities' well-being. The degradation of mangroves further exacerbates coastal vulnerability to erosion and storm surges (Hamza et al., 2022). Additionally, rising sea levels threaten coastal cities like Mombasa, with potential economic losses and damage to infrastructure (Awuor et al., 2008; Obura, 2020).

4 Impact of climate change on Kenya's ocean environments

Kenya's marine ecosystems, vital for the nation's Blue Economy, are significantly threatened by climate change (Obura, 2001). Rising sea surface temperatures (SSTs) are causing widespread coral bleaching, a phenomenon where corals expel symbiotic algae and potentially die, leading to the loss of coral cover and biodiversity (Hughes et al., 2017; Obura et al., 2017;

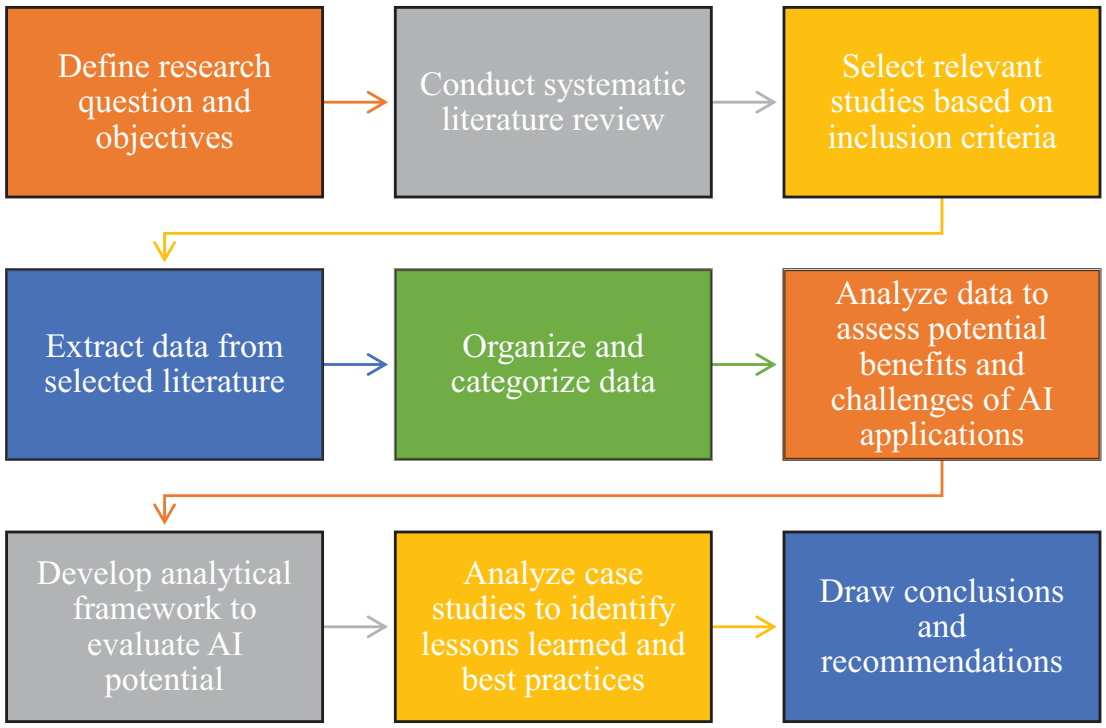

FIGURE 1
Flowchart of the Methodology.

USAID, 2018). Ocean acidification, driven by increased absorption of CO2, is reducing pH levels and harming marine organisms like corals and shellfish, with detrimental effects on fisheries and tourism (Lam et al., 2019; Doney et al., 2020). Additionally, rising sea levels are causing coastal erosion, flooding, and saltwater intrusion, threatening coastal communities and infrastructure, particularly in Mombasa (Awuor et al., 2008; Obura, 2020; Chemeli et al., 2021; Musingi et al., 2021). Climate change is also disrupting ocean currents and upwelling patterns, impacting nutrient availability, marine productivity, and the livelihoods of fishing communities (Jacobs et al., 2021). These multifaceted impacts underscore the urgent need for AI-driven solutions to monitor, manage, and mitigate the effects of climate change on Kenya's Blue Economy.

The increasing levels of carbon dioxide (CO2) in the atmosphere are being absorbed by the ocean, leading to a decrease in pH and an increase in acidity (Doney et al., 2020; Haigh et al., 2015; Lischka et al., 2018). This process, known as ocean acidification, has been particularly pronounced in the western Indian Ocean, where Kenya's coastline is located (Roxy et al., 2020). The reduced pH levels are detrimental to marine organisms that rely on calcium carbonate for shell and skeleton formation, such as corals and shellfish. In Kenya, this has led to a decline in coral reef health, impacting fisheries and tourism, and consequently, the livelihoods of local communities (Lam et al., 2019).

The rising sea levels, a direct consequence of climate change, pose a significant threat to Kenya's low-lying coastal areas (Chemeli et al., 2021). This phenomenon has resulted in increased coastal erosion, flooding, and saltwater intrusion into freshwater sources. The degradation of vital coastal ecosystems like seagrass beds and mangroves further threatens marine biodiversity and the livelihoods of coastal communities (Hamza et al., 2022). In Mombasa, a major coastal city, the risks are particularly high, with potential inundation of a significant portion of the city and substantial economic losses projected (Awuor et al., 2008; Obura, 2020). The intrusion of saltwater into freshwater aquifers also poses a threat to water security in the region (Musingi et al., 2021).

Climate change is disrupting ocean currents and upwelling patterns, which are essential for nutrient supply and productivity in marine ecosystems (Jacobs et al., 2021). Changes in these patterns can affect the distribution and abundance of fish and other marine species, with significant implications for the livelihoods of coastal communities that depend on fishing (Ryther, 1969; Pauly and Christensen, 1995). In Kenya, these disruptions pose a threat to the sustainability of fisheries and the overall health of the marine environment.

5 Kenya's climate change response: policy, finance, and international cooperation

Kenya has demonstrated a proactive stance in addressing climate change through a multifaceted approach encompassing policy formulation, international collaboration, and financial mechanisms. Recognizing the escalating vulnerability of the nation to climate change impacts, Kenya has enacted a

comprehensive suite of climate-specific policies. These policies, including the National Climate Change Strategy (2010), the Climate Change Act (2016), the Climate Finance Policy (2018), the National Climate Change Action Plan (2018-2022), and the National Adaptation Plan (2015-2030), collectively underscore Kenya's commitment to mitigating and adapting to the adverse effects of climate change (Republic of Kenya: The National Treasury and Planning, 2021). Furthermore, Kenya's active participation in international agreements, such as the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol, and the Paris Agreement, exemplifies its dedication to global cooperation in combating climate change. These international collaborations provide a platform for knowledge exchange, technology transfer, and financial support, bolstering Kenya's capacity to implement effective climate action strategies (UNFCCC, 2006).

Kenya has allocated substantial financial resources to climate-related development, with a significant portion dedicated to mitigating climate change. In the fiscal year 2017/18, the government disbursed KES 76 billion (USD 752.4 million) towards climate action, highlighting its commitment to addressing this critical issue. However, the distribution of climate finance reveals a reliance on international partners, who contributed over half of the allocated funds. This dependence on external funding underscores the need for increased domestic resource mobilization and innovative financing models to ensure the sustainability of climate action initiatives (International Climate Initiative, 2021). Private sector investment also plays a crucial role in Kenya's climate change response, with a notable KES 98.9 billion (USD 979 million) invested in climate-related projects in the same fiscal year. While a significant portion of this investment is directed towards renewable energy generation, there is a growing recognition of the need for private sector engagement in other key sectors, such as agriculture, water management, and coastal protection, to achieve a comprehensive and resilient approach to climate change mitigation and adaptation (Republic of Kenya: The National Treasury and Planning, 2021).

While Kenya has made strides in policy development and financial allocation for climate action, the integration of Artificial Intelligence (AI) into these frameworks remains an emerging area. The potential of AI to revolutionize climate change mitigation and adaptation is increasingly recognized, particularly in the context of the Blue Economy. AI-powered tools can enhance monitoring and prediction capabilities, optimize resource management, and inform decision-making processes, ultimately contributing to a more sustainable and resilient Blue Economy.

To fully harness the potential of AI, Kenya needs to develop comprehensive policies and regulatory frameworks that address the ethical, social, and economic implications of AI deployment in the context of climate change. These frameworks should ensure transparency, accountability, and equitable access to AI technologies, while also addressing potential risks and biases associated with AI algorithms. Additionally, targeted investments in AI research and development, capacity building, and infrastructure are essential to create an enabling environment for AI innovation and entrepreneurship in the climate change domain.

By integrating AI into climate policy and finance, Kenya can unlock new opportunities for data-driven decision-making, resource optimization, and innovative solutions to address the complex challenges posed by climate change. This integration can pave the way for a more sustainable and resilient Blue Economy, ensuring the long-term prosperity of coastal communities and the preservation of vital marine ecosystems.

6 Artificial intelligence mitigating climate change

Recent years have seen the rise of artificial intelligence (AI) as an important instrument for adapting to climate change. Effective mitigation and adaptation to climate change need novel and flexible approaches due to the complexity and variety of the problems it presents. In response to these challenges, AI has developed into an effective tool that may facilitate the creation of new approaches to adapting to climate change. AI has the potential to greatly benefit several fields, including the detection of high-risk locations for climate-related calamities, and the creation of adaption plans for communities and sectors (Rutenberg et al., 2021).

AI-enabled solutions provide several advantages for climate change adaptation, such as pinpointing susceptible regions and creating measures to safeguard infrastructure and populations from the impacts of climate change (Bag et al., 2023). One application case is the real-time monitoring and analysis of the impacts of severe weather events using sensors and drones driven by AI. This enables more effective reaction and management of the impacts. In a similar vein, decision-makers may proactively safeguard communities and enterprises by using predictive models developed using machine learning algorithms to account for the effects of climate change. Furthermore, AI has the potential to maximize resource use and decrease emissions, which may help lessen the effects of climate change (Zhang et al., 2020; Mihiretu et al., 2023).

Climate change is a multifaceted problem that presents significant dangers to society, the environment, and the economy. One of the main obstacles in dealing with climate change is creating efficient adaptation techniques to reduce the risks and effects of climate change. To create effective adaptation programs, governments and communities need access to precise and pertinent information. AI's primary advantage lies in its capacity to swiftly and precisely evaluate vast quantities of data. This makes it a crucial tool for pinpointing places most susceptible to the effects of climate change, including those prone to flooding, landslides, or drought (Nost and Colven, 2022). Utilizing AI to assess data like climate models, satellite images, and weather patterns enables governments and communities to create precise adaption strategies customized to the specific hazards in certain locations (Chen et al., 2021).

Artificial intelligence programs can forecast the potential impacts of rising sea levels in various regions by seeing patterns and correlations that humans would overlook. One such effort is FloodNet, which analyzes satellite photos and makes real-time flooding predictions using artificial intelligence (Gangisetty and Rai, 2022). By analyzing river and water body photos using deep learning algorithms, the system

can forecast the occurrence and severity of flooding depending on variables including water level, water velocity, and topography. Another example is the CoastalDEM project (Kulp and Strauss, 2018) which uses AI to generate coastal elevation maps with a high level of detail. To improve the accuracy and detail of coastal area maps, the technology integrates satellite imagery with machine learning algorithms to detect and fix faults in elevation data. This data may be used to pinpoint regions that are most in danger of flooding or erosion as a result of rising sea levels, and then to create adaptation plans that specifically target those places to save those communities and their infrastructure.

Artificial intelligence (AI) may also examine weather models to pinpoint locations prone to upcoming temperature and precipitation shifts. Artificial intelligence models can forecast the potential impacts of climate change in various places by analyzing massive databases of climate model output using machine learning algorithms (Jain et al., 2023). The DeepSD (Deep Learning for Spatiotemporal Data) framework is an AI-powered initiative that analyzes data from climate models to forecast regional-scale changes in precipitation and temperature. To forecast future changes to various climatic variables and to discover complicated correlations between them, the system employs deep learning algorithms. Applying AI to adapt to climate change presents both opportunities and threats. These include both technological challenges associated with data quality and interpretation and societal and ethical considerations, such as privacy concerns and technology inequality (Sirmacek and Vinuesa, 2022).

7 Sub-Saharan Africa's AI landscape: challenges, emerging initiatives, and global collaboration

One may easily perceive a lack of activity in AI research and development in Africa. African nations are consistently portrayed as underperforming or are entirely excluded. African governments are seen to have poor preparedness to use the advantages of AI in their operations and public service delivery, according to Oxford Insights International Development Research Centre (2019) which publishes the AI readiness index. Additionally, no African government was listed among the top 50 governments in the Global Government Artificial Intelligence. Among 54 nations, six African countries included in the research were positioned in the lowest 25% across seven factors: Talent, Infrastructure, Operating Environment, Research, Development, Government Strategy, and Commercial Ventures (Tortoise Intelligence, 2019). The African region rated poorly in almost every metric and rating when several datasets were used to extensively evaluate AI R&D activity worldwide (Perrault et al., 2019). This included the number of AI articles published and referenced, AI-focused patents, conferences, and technical performance. These worldwide indicators suggest very little activity and a pessimistic forecast for future activity.

Kenya has demonstrated a proactive stance in embracing the adoption of AI (AI) technology, positioning itself as a prominent nation within the African continent with regards to its preparedness for AI integration index (See Figure 2). According to the 2023 Government AI Readiness Index report, Kenya attained the notable position of 6th place (Oxford Insights Government Readiness AI Index, 2023).

Global indexes may not accurately reflect the level of activity in Africa. African governments and several other institutions often do not have their activities documented or discussed on the World Wide Web. Private sector activities may be limited in contrast to those in industrialized nations, yet the comparison lacks significance. AI conferences organized in Africa highlight African-led and Africa-focused AI research and display the wide range of such projects. The Deep Learning Indaba, initiated in 2017, focuses only on African AI research and development and has seen a twofold increase in participation in each of the subsequent two years. In 2018, the annual event generated significant interest,

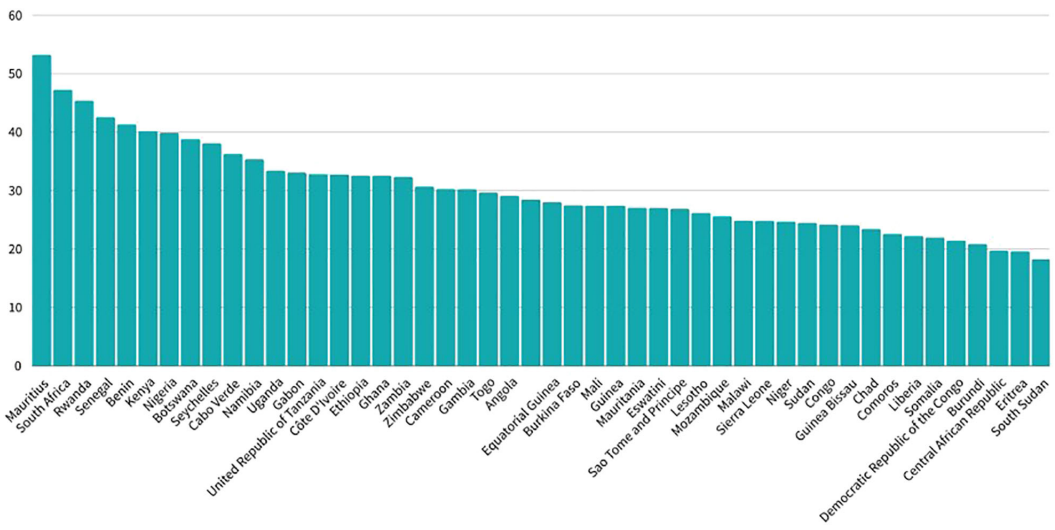

FIGURE 2
Oxford Insights Government Readiness AI Index 2023.

leading to the organization of 13 mini-conferences known as "IndabaX" conferences throughout several African nations. Conferences are crucial for several reasons; especially as African researchers have challenges in attending AI conferences held in other regions (Knight, 2019). African citizens confront substantial obstacles, prompting the International Conference on Learning Representations, a major AI conference, to choose Africa as the location for its 2020 conference, a decision that aimed to increase African involvement (Johnson et al., 2018).

Global technology corporations are now directing part of their AI research and development efforts towards Africa. Google established an artificial intelligence (AI) research facility in Ghana in 2019. Microsoft released a whitepaper emphasizing the significance of AI research in Africa (Microsoft Access Partnership University of Pretoria, 2018). IBM researchers at the IBM laboratory in Nairobi have generated a substantial number of technical advancements (Weldemariam et al., 2020). Global technology businesses are motivated to operate in Africa to reduce prejudice by enhancing diversity among researchers and their working environment (Adeoye, 2019).

8 Case studies on AI use in climate change mitigation in Kenya

In Kenya, innovative applications of artificial intelligence (AI) are being employed to combat climate change and advance sustainability goals. The Kenyan government has embraced geospatial AI as a key component of the National Tree Growing and Restoration Campaign. This initiative utilizes AI to identify and preserve natural water towers, and essential forested landscapes that play a crucial role in maintaining the nation's water resources (CIO Africa, 2023). Additionally, the AZ Forest Kenya project by AstraZeneca employs AI to analyze and monitor tree growth, effectively reducing deforestation (AstraZeneca, 2023). By leveraging AI for monitoring and management, the project collaborates with local communities to establish a circular economy, generating local economic benefits that contribute to climate change mitigation.

In the field of agriculture, Kuzi, an AI solution, utilizes satellite data, soil sensor information, ground meteorological observations, and machine learning to predict desert locust swarms. Providing farmers with a heat map of high-risk areas in Kenya months in advance, the system sends SMS alerts to farmers when locusts are highly likely to attack, aiding in timely preventive measures (ISSUU, 2021). Amini AI, another initiative, acts as a central repository for verifiable and immutable environmental data, utilizing satellite data and machine learning. This platform offers valuable insights to farmers and supply chain operators, facilitating climate resilience planning and agricultural insurance risk assessments, and contributing to Africa's transition to climate-smart agriculture (Kene-Okafor, 2023).

In the area of climate adaptation research, the AI4D Africa study focuses on analyzing climatic trends and developing predictive AI models for climate change effects in Kenya. This project, particularly concentrating on terrestrial plant diversity and conservation, aims to assess the impacts of climate change on the environment and the livelihoods of pastoral communities (AI4D, 2024). Additionally, the Flood Forecasting Initiative such as Flood Hub, empowers Kenyan communities to predict flooding using AI, enabling the development of early warning systems and better preparedness. By employing AI models to forecast riverine floods up to seven days in advance and providing detailed inundation maps, the initiative aids in informed decision-making and effective responses to potential flooding events (Matias, 2023).

AI technologies offer indispensable contributions to monitoring climate change in Kenya's Blue Economy, providing vital support for enhancing resilience and managing key environmental aspects. Utilizing forecasting and prediction models, AI enables the development of analytical frameworks focused on monitoring and controlling water quality, fish stock dynamics, and biodiversity. Notably, AquaMnara stands out as an example, utilizing data-driven AI solutions like water quality monitoring devices to assist fish farmers in optimizing production and efficiency in aquaculture (Africa Europe Foundation, 2024).

In the area of blue carbon offset initiatives, AI technologies play a pivotal role in supporting projects such as mangrove conservation, reforestation, and seaweed farming, fostering community-led income generation systems that promote economic, socio-cultural, and environmental sustainability. Carboni Tourism exemplifies this approach by being an AI-driven and community-centered platform, enabling tourists to offset carbon emissions and contribute to local climate initiatives (Carboni Tourism, 2024). Furthermore, AI contributes to the development of a strategic framework for a climate-resilient Blue Economy, aiding in the identification of critical climate issues, prioritization of areas for development, and implementation of activities to achieve climate resilience goals. RegisTree is an illustrative example, utilizing IoT and AI to build a platform that empowers coastal communities to actively contribute to resilience and Net Zero Goals, onboarding climate-positive projects for carbon markets (TECA, 2024).

Kenya's commitment to preserving its marine biodiversity and ensuring sustainable coastal resource management is exemplified through the establishment of Marine Protected Areas (MPAs). Among these sanctuaries, Watamu National Marine Park stands as a trailblazer, founded in 1968 as East Africa's pioneer MPA, marking a significant milestone in marine conservation efforts. Similarly, the Malindi Marine Reserve, established in 1977, focuses on safeguarding coral reefs and diverse marine life across its expansive 20 square kilometers. Additionally, the Kisite-Mpunguti Marine National Park, renowned for its rich marine species diversity, offers a sanctuary for iconic wildlife like dolphins, whales, and sea turtles, while also serving as a popular destination for ecotourism (Tuda and Omar, 2012).

Digital Twins of the Ocean emerge as transformative tools, seamlessly integrating hydrography and oceanography to craft virtual replicas of the ocean. In the context of Kenya's Marine Protected Areas (MPAs), these digital replicas offer invaluable capabilities for predicting climate change impacts, monitoring marine resources, and fostering sustainable ocean development. By providing detailed insights into the ocean's dynamic state and

evolution over time, Digital Twins has become instrumental in supporting decision-making processes within ocean governance frameworks. In the specific context of MPAs, these virtual representations enable authorities to assess the health of marine ecosystems, track changes in biodiversity, and make informed decisions for the conservation and sustainable management of these critical areas. The application of Digital Twins in Kenya's MPAs enhances the efficiency and effectiveness of conservation efforts, contributing to the overall resilience and health of the marine environment (Brönner et al., 2023).

These diverse examples underscore the transformative role of AI in promoting climate change in Kenya. Through the strategic utilization of technology, Kenya is taking significant steps towards building a more sustainable and resilient future in the face of climate change. Table 1 provides a concise overview of specific AI applications, their mechanisms for mitigating climate change, and relevant examples. Figure 3 complements the table by visually depicting the broader mechanisms through which AI impacts marine management, encompassing data collection, analysis, prediction, decision support, and ultimately, improved ecosystem health.

TABLE 1 Applications of AI for Climate Change Mitigation in Kenya.

AI Application	How AI Mitigates Climate Change	Example
Predictive Modeling	Forecasts climate change impacts by analyzing data to identify vulnerable areas and assess risks.	FloodNet, CoastalDEM
Geospatial AI	Identifies and preserves natural resources like water towers, monitors tree growth, and reduces deforestation.	National Tree Growing and Restoration Campaign, AZ Forest Kenya project
Machine Learning	Predicts desert locust swarms, providing farmers with early warnings and enabling timely preventive measures.	Kuzi
Data Repository	Acts as a central hub for verifiable environmental data, offering insights for climate resilience planning and agricultural insurance risk assessments.	Amini AI
Climate Adaptation Research	Analyzes climatic trends and develops predictive models for climate change effects, aiding in understanding impacts on the environment and livelihoods.	AI4D Africa
Flood Forecasting	Empower communities to predict flooding, enabling early warning systems and better preparedness through AI models and inundation maps.	Flood Hub
Water Quality Monitoring	Optimizes production and efficiency in aquaculture by utilizing AI-driven water quality monitoring devices.	AquaMnara
Blue Carbon Offset Initiatives	Supports projects like mangrove conservation and seaweed farming, fostering community-led income generation and environmental sustainability.	Carboni Tourism
Strategic Framework Development	Aids in identifying critical climate issues, prioritizing development areas, and implementing activities to achieve climate resilience goals.	RegisTree
Digital Twins of the Ocean	Creates virtual replicas of the ocean, enabling prediction of climate change impacts, monitoring of marine resources, and sustainable ocean development.	Digital Twins in Kenya's Marine Protected Areas (MPAs)

9 Conclusion and recommendations

The Blue Economy of Kenya is currently at a critical crossroad, confronted with escalating threats from climate change that jeopardize both coastal economies and ecosystems. The diverse impacts of climate change, ranging from altered ocean climates and sea level rise to acidification and disrupted ocean currents, present formidable challenges to the sustainability and prosperity of Kenya's marine environments. Addressing these challenges requires urgent and innovative solutions to secure the future of the Blue Economy. Artificial Intelligence (AI) emerges as a transformative tool, providing advanced capabilities for monitoring and managing the impacts of climate change on Kenya's Blue Economy. AI technologies offer the potential to enhance stakeholders' understanding of evolving environmental conditions, optimize resource management strategies, and make informed decisions to counteract the adverse effects of climate change. As Kenya continues to prioritize the development of its Blue Economy sector as a key driver of economic growth and sustainable development, the integration of AI applications into monitoring and management practices becomes indispensable. Collaborative efforts among government agencies, research institutions, and international partners are crucial to harnessing AI's potential, building resilience, fostering innovation, and ensuring the enduring viability of Kenya's Blue Economy in the face of climate change challenges.

The study therefore recommends that Kenya and by extension all coastal developing countries should invest in robust data collection systems and infrastructure to gather comprehensive and real-time data on ocean environments, climate change indicators, and the health of marine ecosystems. This will provide a solid foundation for AI applications in climate change mitigation. Countries should also utilize AI algorithms to develop predictive models that can forecast climate change impacts on the Blue Economy. These models have the potential to: assist in identifying vulnerable areas, assessing risks, and informing adaptation and resilience strategies; encourage collaboration among researchers, policymakers, and stakeholders to share knowledge, best practices, and data; establish partnerships with international organizations and leverage global initiatives to access expertise and resources in AI for marine ecosystem monitoring; promote education and training programs to build AI expertise within the marine and environmental sectors, to enable the development and deployment of AI technologies tailored to the specific needs and challenges of Kenya's Blue Economy; incorporate AI-driven insights and recommendations into policy

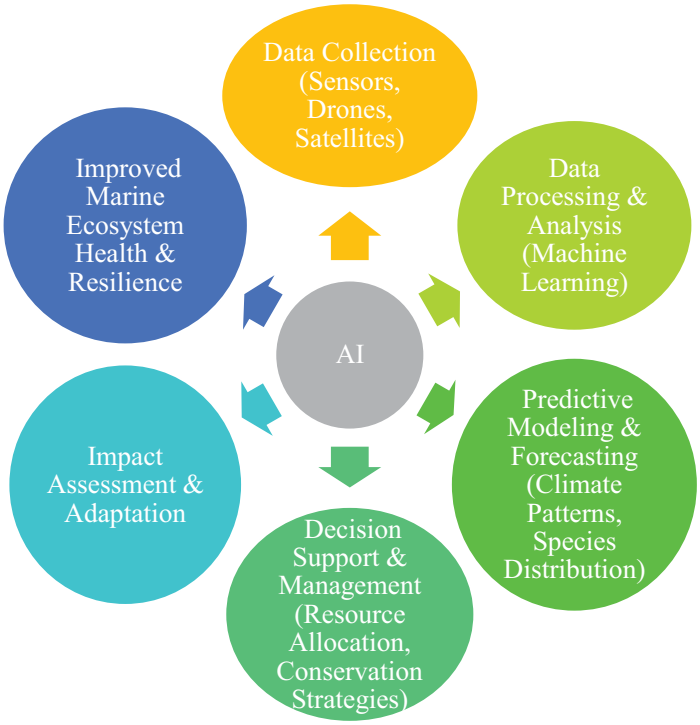

FIGURE 3
AI in Marine Management. *Data Collection:* AI-powered tools like sensors, drones, and satellites gather vast amounts of data on ocean conditions, marine life, pollution levels, and climate variables (Whang et al., 2023). *Data Processing & Analysis:* Machine learning algorithms process and analyze this data to identify patterns, trends, and anomalies that might not be apparent to human observers (Taherdoost, 2022). *Predictive Modeling & Forecasting:* AI models use the analyzed data to predict future scenarios, such as the spread of invasive species, the impact of rising sea temperatures on coral reefs, or the potential for harmful algal blooms (Sarker, 2022). *Decision Support & Management:* These predictions inform decision-makers in creating effective management strategies, such as adjusting fishing quotas, establishing marine protected areas, or implementing pollution control measures (Pielke, 2021). *Impact Assessment & Adaptation:* AI helps assess the effectiveness of management actions and adapt strategies as needed based on real-time feedback and changing conditions (Lemos et al., 2022; Pendy, 2023). *Improved Marine Ecosystem Health & Resilience:* By enabling proactive and adaptive management, AI contributes to healthier marine ecosystems that are more resilient to the impacts of climate change and other stressors (Fava et al., 2023).

frameworks and decision-making processes related to the Blue Economy; ensure that policymakers have access to timely and accurate AI-generated information to inform sustainable management strategies; foster an environment conducive to innovation and entrepreneurship in AI for climate change mitigation and provide funding, incentives, and support for startups, research institutions, and private sector initiatives focused on developing AI solutions for the Blue Economy.

10 Future research

There still exist gaps in the literature that need further insight. Future studies should adopt a more holistic approach that considers the needs, concerns, and contributions of various stakeholders, including local communities, government agencies, research institutions, and international partners. Additionally, there is a need for long-term impact assessments of AI technologies in addressing climate change impacts on Kenya's Blue Economy. In addition, future research should evaluate sustained effectiveness and scalability over extended periods, considering evolving environmental conditions, technological advancements, and policy frameworks. Furthermore, the interdisciplinary nature of addressing climate change impacts on marine ecosystems requires more exploration of the potential benefits of interdisciplinary collaboration. Future studies could investigate synergies and challenges associated with interdisciplinary approaches to enhance the efficacy of AI solutions. Lastly, addressing knowledge transfer and capacity-building initiatives related to AI applications in Kenya's Blue Economy is crucial for ensuring the effective adoption and utilization of AI tools by relevant stakeholders.

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