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Review

Socio-Economic, Health and Ecosystems Vulnerabilities to Climate Change in Rural Areas in Kenya: Implications for Human Capacity Resilience

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Abstract: The recent decades have brought multiple studies of natural and social systems confirming climate change and its impact on the environment and human populations. Rural Kenya, home to 70% of the population and the backbone of its agrarian economy, is particularly susceptible due to its reliance on climate-sensitive sectors. The study emerges from growing concerns about how recurring climate shocks perpetuate cycles of poverty, food insecurity and diminished adaptive capacity in rural communities, threatening Kenya's sustainable development goals. Further, existing studies often address socio-economic, health and ecosystem vulnerabilities in isolation, obscuring critical interdependencies. This scoping review aims to systematically map the interconnected vulnerabilities in rural Kenya and synthesize their implications for human capacity resilience. This scoping review, guided by the theory of climate vulnerability (exposure, sensitivity, adaptive capacity), systematically mapped these interconnected vulnerabilities in rural Kenya. Following a pre-registered protocol and PRISMA-ScR guidelines, 110 articles from 2010 onwards were analyzed using descriptive and thematic analysis. Findings reveal widespread socio-economic vulnerability, especially in ASALs, driven by droughts, erratic rainfall and rising temperatures, compounded by poverty and gender inequality. Climate change also elevates health risks, increasing infectious diseases, malnutrition, and mental health burdens. Critical ecosystems are degrading, further destabilizing livelihoods. Vulnerable populations, including women, children, pastoralists and PWDs), bear the brunt of these impacts due to structural inequities. All these challenges severely erode human capacity resilience, overwhelming traditional coping strategies. Recommendations prioritize ecosystem-based adaptation, livelihood diversification, and inclusive governance to build sustainable climate resilience in rural Kenya.

Keywords: Climate Change; Rural Kenya; Vulnerability; Socio-Economic Impacts; Health Impacts; Ecosystem Degradation; Human Capacity Resilience; Adaptation

1. Introduction

Climate change stands as a defining challenge of our era, exerting disproportionate impacts on vulnerable regions across the globe, with Sub-Saharan Africa, including Kenya, facing particularly severe consequences [1–3]. Kenya is already grappling with significant climatic shifts. A discernible warming trend has been observed since the 1960s, with projections indicating continued and potentially accelerated temperature increases throughout the 21st century [4–6]. Alongside rising temperatures, the country experiences heightened rainfall variability, characterized by unreliable seasonal rains and an increased frequency and intensity of extreme weather events, particularly debilitating droughts in arid and semi-arid lands (ASAL) regions and damaging floods often linked to phenomena like El Niño and the Indian Ocean Dipole [7–10]. These climate shifts also contribute to secondary problems like soil erosion, land degradation and pest outbreaks [9,11]. Coastal areas also face threats from accelerating sea-level rise [12,13]. Inland, many Rift Valley lakes, such as Baringo and Nakuru, have experienced unprecedented rises in water levels in recent years, submerging surrounding lands and infrastructure [14,15]. This dynamic and complex climate scenario directly threatens the stability of natural resource-dependent systems upon which rural Kenyan communities rely. Understanding vulnerability to climate change in rural Kenya requires a multidimensional approach, as climate risks affect not just the environment but also socio-economic systems, human health and ecosystems. Three major analytical frameworks are commonly employed in vulnerability assessments: the socio-economic, biophysical and integrated approaches [16,17]. Socio-economic approach assesses internal adaptive capacity using internal factors like gender and income, but often overlooks how environmental conditions, such as resource availability, affect coping with climate shocks [18]. Biophysical approach focuses on environmental hazard impacts but tends to sideline social structures and human decision-making [19]. Since both approaches alone offer only partial views, integrated methods that combine socio-economic and biophysical elements provide a more complete understanding [18]. According to Weis et al. [20] vulnerability is defined as a result of exposure, sensitivity, and adaptive capacity, noting it varies greatly even between nearby communities due to local context, household traits, and adaptation strategies. Given the strong linkage between climate, livelihoods, health and ecosystems in rural Kenya, comprehensive vulnerability assessments are vital for effective adaptation policy.

Rural Kenya, which remains home to approximately 70% of the national population as of 2023, continues to be the backbone of the country's agrarian economy, even though this proportion is gradually declining due to steady rural-urban migration [21,22]. The socio-economic stability in these areas heavily relies on climate-sensitive sectors like rain-fed agriculture and pastoralism, making communities highly vulnerable to changing rainfall patterns, temperature increases and extreme weather events [13,23]. This vulnerability frequently leads to crop failures and devastating livestock losses, threatening national food security and diminishing foreign exchange earnings [24]. Pastoralist communities residing in the ASALs, which constitute about 88% of Kenya's landmass and support nearly 70% of the national livestock herd, are particularly vulnerable [25–27]. These communities face persistent drought-induced scarcities of pasture and water, heat stress, altered livestock disease dynamics, and devastating animal mortality rates [25–29]. Such challenges have not only driven many pastoralists out of their traditional livelihoods but have also increased resource-based conflicts over water and grazing lands [30–32]. Research by Kalele et al. [33] and Segnon et al. [34] concluded that households in ASALs exhibit significant vulnerability to climate change effects, largely due to a combination of widespread poverty, food insecurity, frequent droughts, land degradation, unequal land access, and reliance on rain-fed farming, among other interconnected factors. Cumulatively, climate-related shocks have imposed substantial economic costs on the nation. Between 2010 and 2020, Kenya experienced annual economic losses equivalent to 3–5% of its gross domestic product (GDP) due to climate-related disruptions, with projections suggesting that these losses could escalate to as much as 9% by 2050 in the absence of robust adaptation strategies [35]. These escalating losses threaten to derail Kenya's progress toward key national and international development targets, including Vision 2030 and the Sustainable Development Goals (SDGs) [7]. Similar patterns are evident in other sub-Saharan nations such as Zambia, where prolonged climate stress has had

measurable macroeconomic consequences. Between 2006 and 2016, climate variability reduced Zambia's agricultural GDP by 4% and its overall GDP by 10%, while increasing the national poverty rate by 2% [36]. Gendered vulnerabilities further compound these challenges, with women in rural Kenya often bearing a disproportionate burden due to pre-existing socio-economic inequalities [37]. A study by Kenya Institute for Public Policy Research and Analysis (KIPPRA) found that women's limited access to credit, assets, and group membership in agriculture heightens household food insecurity, with climate change further deepening this economic vulnerability [38]. A 2024 UN Women analysis pointed out that Kenyan women average 4–5 hours daily on such tasks, starkly contrasting with about one hour for men. This disparity severely limits women's participation in paid labour and economic activities, perpetuating dependency and restricting their financial independence [39]. Furthermore, climate change is increasingly disrupting social infrastructure in rural areas, triggering displacement, migration, and growing tensions over scarce resources [40]. An IGAD CAEP factsheet (2024) explains how climate impacts in Kenya limit essential resources like water and pasture, especially in ASALs, leading to contested access. This resource scarcity threatens climate-sensitive livelihoods, drives food insecurity, and prompts rural migration to other areas. The resulting influx strains local infrastructure and resources in receiving communities, exacerbating social tensions between hosts and migrants [41]. In Isiolo County, for instance, prolonged droughts and erratic rainfall have displaced communities, with migrants facing food insecurity and limited access to services, while host populations grapple with increased resource competition [42]. A UNFCCC case study (2022) further illustrates how extreme events, both prolonged droughts (like the recent Horn of Africa drought) and excessive rainfall causing floods and rising lake levels (notably Lake Baringo and Lake Turkana) have forced thousands from their homes. The report highlights the direct impact on social infrastructure, with homes, clinics, and even ancestral graves being submerged by rising waters. This loss of homes and traditional livelihoods (farming, fishing, pastoralism) creates dependence on aid and can trap communities, sometimes exacerbating pre-existing conflicts over remaining resources. The destruction of or damage to infrastructure like health facilities further undermines community resilience [43]. The interconnectedness of poverty and climate vulnerability creates a detrimental cycle in rural Kenya, where poverty limits the capacity to adapt to climate change, and the impacts of climate change, in turn, exacerbate poverty.

Climate change also significantly elevates health risks in rural Kenya by altering environmental conditions key f or vector-borne disease transmission. Kenyan health risk assessments consistently recognize that multiple significant vector-borne diseases including malaria [44,45], dengue [46], Rift Valley Fever [47,48] and Chikungunya [46] are highly sensitive to changing climatic conditions. Factors like temperature, precipitation patterns, and humidity exert a strong influence on the life cycles and distribution of disease vectors like mosquitoes [49]. Simultaneously, the risk of waterborne illnesses such as cholera and typhoid surges, particularly following floods that contaminate water sources or during droughts that compromise access to safe water and sanitation [49]. Reviews of disease patterns in Kenya clearly associate major cholera and diarrheal disease outbreaks with periods following extensive flooding, such as the devastating El Niño-related floods of 1997-98 which led to tens of thousands of cholera cases [50]. As reliable water sources diminish, especially in arid and semi-arid lands (ASALs), communities are often forced to rely on distant or unsafe water points, increasing their exposure to contaminants like *Vibrio cholerae* or *Salmonella Typhi*. Furthermore, the scarcity of water severely affects essential hygiene practices, facilitating disease transmission. This link was tragically evident during the prolonged drought beginning in 2022, which triggered a widespread cholera outbreak across multiple Kenyan counties, resulting in thousands of cases and numerous deaths [51]. Health officials explicitly linked this rise in waterborne diseases to the extreme weather conditions driven by climate change [52]. Beyond disease and malnutrition, climate change imposes direct physical risks in rural Kenya through extreme weather events. Severe floods, such as those linked to El Niño rains affecting primarily rural and ASAL counties in late 2023 and early 2024, frequently result in injuries, drownings, and significant loss of life, alongside widespread displacement [53]. Research focusing specifically on East African smallholder farmers projects that future climate scenarios will intensify heat stress during key agricultural months, particularly in eastern, coastal, and northern regions of Kenya, potentially requiring farmers to significantly reduce work intensity (e.g., needing up to 75% rest per hour during peak heat) to cope, thereby threatening productivity and livelihoods [54]. Furthermore, the mental health burden associated with climate change is increasingly recognized in rural Kenya. Studies examining the intersection of climate change, displacement and conflict in ASALs point to severe impacts on psychological welfare. Communities facing resource scarcity exacerbated by climate change often experience heightened insecurity, grief from losses, and trauma related to resource-based conflicts, adding layers

to the mental health challenges [55]. Climate impacts on agriculture and livestock also severely undermine food security, contributing to rising malnutrition rates. This is especially critical in ASALs, where recurrent droughts lead to alarming levels of acute malnutrition among children under five and shorten the recovery periods between widespread food crises, as reported by [56].

"Rural Kenya is characterized by diverse ecosystems, ranging from arid and semi-arid lands (ASALs) to forests, wetlands, and agricultural landscapes [57,58]. These ecosystems provide essential services that underpin the livelihoods of the vast majority of the rural population, including food provision, water regulation, soil fertility maintenance, and cultural heritage [59,60]. However, these vital systems face increasing pressure from climate change impacts. Ecosystem vulnerability is defined as the degree to which an ecosystem is susceptible to, and unable to cope with, adverse climate effects due to its exposure, sensitivity, and adaptive capacity [61]. Climate-driven ecosystem changes, such as deforestation, drought, or flooding, trigger a cascade of interconnected problems. For example, deforestation can lead to soil erosion and reduced water availability, impacting agriculture and potentially increasing malnutrition. A study in rural Tanzania established a causal link between deforestation over five years and a significant reduction in household fruit and vegetable consumption, consequently lowering vitamin A adequacy in diets [62]. Similarly, research in Malawi found that children living in areas experiencing net forest loss had significantly less diverse diets and lower consumption of vitamin A-rich foods compared to those in areas with stable forest cover [63]. This loss of dietary diversity and micronutrient intake, combined with potentially lower overall food availability from degraded agricultural land, contributes directly to increased rates of malnutrition, including stunting, wasting, and micronutrient deficiencies [62,63]. These impacts highlight how climate change effects are not isolated, but form a complex web where ecosystem vulnerabilities exacerbate socio-economic and health challenges, potentially creating negative feedback loops that undermine community resilience in rural Kenya."

Despite increasing recognition of the multidimensional impacts of climate change, most existing studies on vulnerability in Kenya have addressed socio-economic, health and ecosystem dimensions in isolation, failing to reflect the systemic and interdependent nature of these vulnerabilities. This fragmented approach obscures the feedback loops and compounding effects between these domains, which jointly erode human capacity resilience defined as the ability of individuals, households, and communities to anticipate, absorb, adapt to, and recover from climate-related stressors [64,65]. Therefore, this scoping review is necessary to systematically map the existing literature, identify the nature and extent of evidence on the interconnected socio-economic, health, and ecosystem vulnerabilities to climate change in rural Kenya, and synthesize the implications for human capacity resilience.

2. Theoretical Review

The theory of climate vulnerability, developed through contributions from several researchers and significantly shaped and standardized by the Intergovernmental Panel on Climate Change (IPCC) particularly from its Third Assessment Report onwards [66–68], provides a framework for understanding the differential impacts of climate change. Central to this theory is the concept of vulnerability itself, defined by the IPCC as the "propensity or predisposition to be adversely affected," encompassing sensitivity to harm and the lack of capacity to cope and adapt [69,70]. This framework typically breaks vulnerability down into three interacting core components: exposure (the nature and degree to which a system encounters climatic stimuli), sensitivity (the degree to which a system is affected by those stimuli), and adaptive capacity (the system's ability to adjust, cope, or respond) [66,68]. The interplay between high exposure and sensitivity can be offset by strong adaptive capacity, while low adaptive capacity can render a system highly vulnerable even with moderate exposure or sensitivity [66,71]. Vulnerability assessments often adopt either an 'outcome' approach, focusing on residual impacts after adaptation, or a 'contextual' approach, pointing out pre-existing socio-economic and institutional conditions that shape susceptibility [72,73]. As highlighted by [69], adaptation is about how individuals, communities, and systems make thoughtful adjustments to the realities or threats of climate change whether it's shifting weather patterns or more extreme events. The goal is to reduce harm and, where possible, take advantage of new opportunities. On the other hand, coping capacity refers to the more immediate and short-term responses people and institutions use to deal with climate stress like how a household might temporarily relocate during a flood without making any long-term changes to their living situation [70]. Resilience goes a step further. It describes the ability of a system not just to bounce back but to adapt, reorganize, and still maintain its core identity and essential functions despite disruptions. It's about long-term strength and flexibility in the face of change [70]. Ultimately, understanding climate vulnerability

through this theoretical view is vital for identifying populations and systems most at risk and for designing targeted interventions to enhance resilience by addressing the specific combination of exposure, sensitivity, and adaptive capacity factors.

3. Methodology

This scoping review employed the methodological framework outlined by Arksey and O'malley [74]. This approach aligned directly with the objectives of the present study, which sought to understand the breadth and depth of documented vulnerabilities across multiple domains (socio-economic, health, ecosystems) within the specific context of rural Kenya. The established scoping review framework outlined a systematic, six-stage process designed to ensure transparency and replicability:

1. Identifying the research question;
2. Identifying relevant studies;
3. Study selection;
4. Charting the data;
5. Collating, summarizing, and reporting the results;
6. Consultation (considered an optional but valuable stage).

To further enhance the methodological rigor and clarity of the review process, this study incorporated refinements and advancements proposed by subsequent researchers, notably [75] and the Joanna Briggs Institute (JBI) methodology as detailed by Peters et al. [76,77]. These enhancements provided more explicit guidance on aspects such as clarifying the link between the review's purpose and research questions, developing and aligning inclusion criteria with the objectives a priori, utilizing iterative team approaches for study selection and data extraction, conducting comprehensive and systematic evidence searches, and employing structured methods for data analysis and presentation. Adopting these enhancements helped ensure the review was conducted with a high degree of methodological robustness, addressing potential criticisms regarding the rigor of earlier scoping study approaches.

It's important to note that while systematic, the scoping review process is often iterative rather than linear [74]. A key limitation of scoping reviews is the absence of critical appraisal or quality assessment of individual studies. This means we can map the existing research but not evaluate its methodological rigor or reliability. Therefore, our conclusions, while comprehensive in scope, cannot definitively speak to the strength of the evidence or the risk of bias in the included studies. However, as the review team gained familiarity with the body of literature, it sometimes became necessary to revisit and refine earlier stages, such as the search strategy or the specific data being charted, to ensure comprehensive coverage of the topic.

3.1. Reporting Standards

The final report of this scoping review adhered to the Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) checklist [78,79]. The PRISMA-ScR provided specific guidance for reporting scoping reviews, ensuring that the objectives, eligibility criteria, information sources, search strategy, selection process, data charting methods, results, and conclusions were presented clearly, completely and transparently [79] This facilitated reader understanding and assessment of the review's methodology and findings. A PRISMA-ScR flow diagram was generated and included in the final report to visually depict the flow of information through the different phases of the review, detailing the number of records identified, screened, assessed for eligibility, and included, along with reasons for exclusions at the full-text screening stage [80].

3.2. Review Process

The review process systematically involved several defined stages: first, identifying precise research questions to guide the investigation into climate change vulnerabilities and human capacity resilience in rural Kenya. This led to identifying relevant studies through a meticulously developed and executed search strategy, comprising various databases and grey literature. Subsequently, a rigorous study selection process, involving independent screening by multiple reviewers, ensured only highly relevant literature was included. The extracted data from these studies was then systematically charted for accuracy. Finally, the evidence was synthesized using both numerical and thematic

analyses to map key concepts and identify research gaps.

3.2.1. Identifying the Research Questions

The primary research question guiding this review was:

What is the extent and nature of the evidence on the interconnected socio-economic, health and ecosystem vulnerabilities to climate change in rural Kenya, and what are the implications for human capacity resilience? Sub-questions included:

1. What specific socio-economic, health and ecosystem vulnerabilities related to climate change in rural Kenya have been studied?
2. How were the interlinkages between these different dimensions of vulnerability described in the literature?
3. What evidence existed regarding the impact of these interconnected vulnerabilities on human capacity resilience (adaptive capacity, coping mechanisms, transformative capacity)?

3.2.2. Identifying Relevant Studies

A comprehensive search strategy was developed to identify relevant peer-reviewed and grey literature. Key electronic databases were searched, including PubMed/MEDLINE, Scopus, Web of Science, Africa-Wide Information, CAB Abstracts, African Journals Online, ScienceDirect, SpringerLink, and Taylor & Francis Online. The search strategy combined keywords and subject headings related to three core concepts: (a) climate change and variability (e.g., "climate change," "drought," "floods," "climate variability," "extreme weather"), (b) vulnerability and resilience (e.g., "vulnerability," "resilience," "adaptive capacity," "coping," "impacts"), and (c) the Kenyan context (e.g., "Kenya," "rural," "ASAL," "pastoralist," "agriculture," "health," "ecosystem," "socio-economic"). Search terms were adapted for each database. Reference lists of included studies and relevant review articles were hand-searched for additional potentially relevant publications. Grey literature sources included Ministry of Environment, Climate Change and Forestry, Ministry of Health; Ministry of Agriculture and Livestock Development, Ministry of Water, Sanitation and Irrigation, National Drought Management Authority (NDMA), World Bank, Food and Agriculture Organization (FAO), World Health Organization (WHO), United Nations Development Programme (UNDP), United Nations Environment Programme (UNEP), Intergovernmental Panel on Climate Change (IPCC), Consultative Group on International Agricultural Research (CGIAR) centers, International Centre for Evaluation and Development (ICED, Kenya Medical Research Institute (KEMRI), International Livestock Research Institute (ILRI), African Population and Health Research Center (APHRC), Adaptation Consortium, Climate Development Knowledge Network (CDKN), university repositories within Kenya. The search focused on literature published from 2010 onwards to capture contemporary understanding and impacts, primarily in English.

3.2.3. Search Strategy Development

The search strategy was developed collaboratively by the research team, potentially involving consultation with an information specialist or librarian experienced in evidence synthesis methodologies. The strategy employed a combination of keywords derived from the PCC framework and relevant subject headings (e.g., Medical Subject Headings - MeSH, Emtree) where applicable, linked using Boolean operators (AND, OR).

Search terms included terms like "climate change", "global warming", "climate variability", "extreme weather", "drought*", "flood*", "sea level rise", "temperature change", "rainfall pattern*", "ENSO", "climate hazard*", "vulnerabilities*", "susceptibilities*", "risk*", "impact*", "exposure", "sensitivity", "hazard assessment*", "socioeconomic", "livelihood*", "income", "poverty", "food security", "economic", health aspects "health", "disease*", "malaria", "nutrition*", "malnutrition", "morbidity", "mortality", "wellbeing", ecosystem aspects "ecosystem*", "environment*", "biodiversity", "water resource*", "land degradation", "desertification", "agriculture", "livestock", "fisheries", "forestry", "pastoralist*", "resilience*", "adapt*", "adaptive capacity", "coping mechanism*", "human capacity", "community based adaptation", "locally led adaptation", "climate action*", "Kenya", "Kenyan", "rural", "countryside", "non-urban", "arid", "semi-arid", "ASAL", "highland*", "coastal rural", potentially combined with specific county names or regions (e.g., Turkana, Samburu, Mombasa rural) identified as highly relevant during piloting.

An initial draft strategy was tested (piloted) in one or two key databases (e.g., Scopus, PubMed) to assess the relevance and volume of retrieved records. Based on the pilot results, the search terms and structure were refined

iteratively to achieve an appropriate balance between sensitivity (capturing as much relevant literature as possible) and specificity (excluding irrelevant studies to maintain feasibility). The final, full electronic search strategy for at least one major database was documented and included as an appendix in the final scoping review report to ensure transparency and allow for potential replication.

Search Limits and Supplementary Searching

To manage the scope of the review effectively, the following limits were applied:

1. Language: The search was restricted to studies published in the English language. This decision was based on the primary language of international scientific communication and major Kenyan policy documents, as well as the language proficiency of the review team, ensuring feasibility.
2. Publication Date: The search included studies published from January 1, 2010, up to the date the final search was executed across all databases and sources. This timeframe was chosen to capture the significant increase in research and policy attention towards climate change impacts and adaptation that occurred since the 2000s, coinciding with major international assessments like the IPCC reports and national strategy developments in Kenya.

3.2.4. Study Selection

Studies identified through the search strategy were screened for inclusion based on pre-defined criteria.

- Inclusion Criteria: Studies were included if they: (a) focused on climate change impacts, vulnerability, adaptation, or resilience; (b) addressed at least one dimension of vulnerability (socio-economic, health, ecosystem) within the rural Kenyan context; (c) related findings implicitly or explicitly to human populations in rural Kenya; (d) were published in English from the year 2010 onwards; (e) encompassed empirical research, reviews, case studies, or substantive reports.
- Exclusion Criteria: Studies were excluded if they: (a) focused solely on urban areas of Kenya; (b) did not address climate change or variability; (c) were purely theoretical or modeling studies without specific application to rural Kenya; (d) were opinion pieces, editorials, or conference abstracts without sufficient data. The selection process involved two stages: initially, titles and abstracts were screened by two independent reviewers. Subsequently, the full texts of potentially relevant articles were retrieved and assessed against the inclusion criteria by the two reviewers. Any disagreements during the screening process were resolved through discussion or consultation with a third reviewer. A PRISMA-ScR (Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews) flow diagram (**Figure 1**) was used to document the study selection process [79].

3.2.5. Charting the Data

A data charting form (**Table 1**) was developed collaboratively by the review team to extract relevant information from the included studies.

Table 1. Outline of Data Extraction Items.

Category	Data Item	Description/Definition
Bibliographic Information	Author(s)	Last name(s) and initial(s) of author(s).
	Year of Publication	Year the source was published.
	Title	Full title of the article, report, or chapter.
	Source/Publication Type	Journal name, report series, book title, website URL, thesis; Type (e.g., journal article, gov report, NGO report).
Study Characteristics	Study Aims/Objectives	Stated purpose or research questions of the study.
	Study Design/Methodology	Overall approach (e.g., quantitative, qualitative, mixed-methods, review, modelling, policy analysis).
	Data Collection/Analysis Methods	Specific methods used (e.g., survey, interviews, focus groups, remote sensing, statistical analysis, thematic analysis).

Table 1. *Cont.*

Category	Data Item	Description/Definition
Context	Geographical Location	Specific location(s) within Kenya (e.g., County, Region, ASAL, Highland, Coastal).
	Rural Setting Description	Details provided about the specific rural environment (e.g., farming system, pastoral area).
Population	Population Description	Characteristics of the study participants/population group (e.g., smallholders, pastoralists, women, general community).
	Sample Size	Number of participants, households, or units studied (if applicable).
Climate Change Context	Climate Hazard(s) Addressed	Specific climate variability or change phenomenon focused on (e.g., drought, flood, temperature increase, rainfall variability).
Vulnerability Details	Exposure Information	How climate exposure was measured or described.
	Sensitivity Factors	System characteristics identified as contributing to sensitivity (e.g., livelihood dependence, health status, resource access).
	Socio-Economic Impacts	Key findings on impacts related to livelihoods, income, food security, poverty, economic activity, migration, conflict.
	Health Impacts	Key findings on impacts related to disease patterns (vector-borne, waterborne), nutrition, heat stress, respiratory issues, mortality/morbidity.
	Ecosystem Impacts	Key findings on impacts related to water resources, land condition, biodiversity, agriculture, livestock, fisheries, forests.
	Interlinkages	Reported connections between vulnerability domains (e.g., how ecosystem change affects livelihoods/health).
Resilience/Adaptation Details	Adaptive Capacity Factors	Factors enabling or constraining adaptation (e.g., knowledge, assets, institutions, social capital).
	Adaptation/Coping Strategies	Specific actions or strategies documented (autonomous or planned; e.g., changing crops, migration, water management, insurance).
	Resilience Outcomes/Implications	Reported effects of strategies on resilience; implications for human capacity.
	Link to Vulnerabilities	How resilience/adaptation strategies address specific (and potentially linked) vulnerabilities.
Key Findings & Gaps	Author Conclusions	Main conclusions relevant to the scoping review's questions.
	Identified Gaps	Research, policy, or practice gaps explicitly mentioned by the authors.

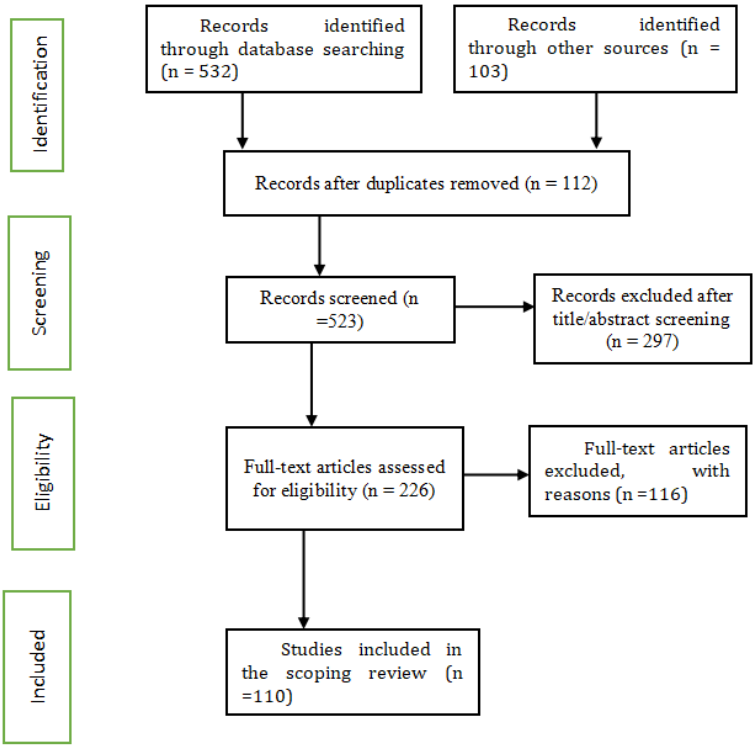

Figure 1. PRISMA flow diagram of included articles for scoping review.

The data charting form was piloted on a small subset of studies and refined as necessary. One reviewer extracted data, and a second reviewer verified the extracted information for accuracy and completeness. Data extraction was performed using the finalized charting form. One reviewer initially extracted the relevant data from each included study. To ensure accuracy and minimize errors or omissions, a second reviewer then independently checked the extracted data against the original source document. Any discrepancies identified during this verification process were resolved through discussion between the two reviewers. If consensus could not be reached, a third reviewer was consulted for arbitration. This dual-reviewer approach enhanced the reliability and validity of the charted data.

3.2.6. Synthesizing the Evidence: Collation and Summary

The synthesis stage aimed to collate and summarize the extracted data to provide an overview of the literature and map the key concepts relevant to the research questions. This involved both numerical analysis and qualitative thematic synthesis.

Numerical Analysis

A descriptive numerical summary of the characteristics of the included studies was compiled. This quantitative overview helped to characterize the extent and nature of the research field. Frequencies and distributions were calculated for variables such as:

- Specific population groups studied (e.g., focus on pastoralists, farmers, women).
- Primary climate hazards investigated (e.g., drought, floods, general variability).
- Primary domain(s) of vulnerability addressed (socio-economic, health, ecosystem, or combinations thereof).
- Extent to which studies explicitly addressed resilience or adaptation.

These numerical results were presented clearly using tables, charts, and figures within the final scoping review report to provide a snapshot of the evidence base.

Thematic Synthesis

Complementing the numerical summary, a qualitative thematic synthesis approach was employed to analyze the content of the extracted data related to the review's core concepts and questions. This process involved several steps:

1. Reviewers read and re-read the charted data to become deeply familiar with the content.
2. Key concepts, findings, themes, and patterns related to specific vulnerabilities (socio-economic, health, ecosystem), their documented interactions, resilience factors, adaptation strategies, enabling conditions, barriers, and methodological approaches were identified and coded.
3. Codes were grouped and organized into broader, more interpretive analytical themes. This process was iterative, aiming to develop themes that effectively mapped the landscape of evidence concerning the interconnectedness of vulnerabilities and resilience in rural Kenya. The synthesis actively sought to create themes reflecting the linkages identified during data extraction, providing an integrated map rather than separate domain summaries.
4. The developed themes were used to structure the narrative synthesis, describing the range of evidence related to each theme and highlighting key findings across the included studies.

This thematic analysis focused on identifying and mapping the range of concepts and evidence available, and importantly, identifying gaps in the literature, rather than conducting a critical appraisal of study quality or synthesizing quantitative effect sizes, which was beyond the scope of a scoping review.

Presentation of Results

The findings of the scoping review were presented through a combination of narrative text, tables, and figures. The narrative summary integrated the results from both the numerical analysis (describing the characteristics of the literature) and the thematic synthesis (mapping the key concepts, findings, and identified gaps). The PRISMA-ScR flow diagram (**Figure 1**) illustrating the study selection process was a key figure. The presentation clearly linked the synthesized findings back to the overarching research question and specific sub-questions guiding the review [79].

4. Results and Discussion

4.1. Socio-Economic Vulnerabilities

Based on a synthesis of 49 studies, rural areas in Kenya faces widespread and often severe socio-economic vulnerability to climate change, primarily driven by increasing drought frequency, rainfall variability and rising temperatures impacting climate-sensitive livelihoods like rain-fed agriculture and pastoralism. This vulnerability is critically shaped not just by environmental exposure but significantly by socio-economic factors including education levels, gender inequalities, poverty, and access to resources (land, water), information (climate services, extension), and institutional support, with ASAL regions emerging as particular hotspots.

4.1.1. Primary Climate Stressors

The study initially assessed key stressors; **Figure 1** illustrates the main climate-related challenges affecting rural Kenya, which underpin the vulnerabilities examined in this review.

Drought and Rainfall Variability

Drought and rainfall variability emerge as the most pervasive climate stressors across rural Kenya, explicitly identified in 43 (87.8% of the reviewed studies). Recurrent and intensifying drought conditions are a primary hazard, particularly in Arid and Semi-Arid Lands (ASALs), undermining livelihoods and food security [80]. National assessments corroborate this, highlighting drought as a leading cause of societal impacts [81]. For pastoralist communities, drought is understood beyond meteorological definitions, encompassing pasture shortages and adverse socio-economic conditions [82]. Closely linked is rainfall variability, including decreased amounts, erratic patterns, shifts in seasonality, and shortened growing seasons. This directly threatens rain-fed agriculture, which is crucial for many rural economies. For instance, smallholder farmers in Busia County experience high vulnerability due to decreased and more variable rainfall [83], while those in Machakos [84] face significant impacts from warming and drought.

The vulnerability of households in Makueni County is also significantly driven by water scarcity and climate variability [85]. Studies in Kitui County [8,82] and Mwala Sub-County, Machakos [86] further pointed out the challenges posed by erratic rainfall and prolonged droughts leading to food insecurity. In Baringo County, drought, coupled with a lack of insurance and limited government support, significantly affects household resilience [87]. Pastoralists in Turkana and Mandera counties show high vulnerability due to recurrent droughts and resource-based conflicts. The Amboseli Ecosystem in Kajiado County also sees significant livelihood vulnerability among Maasai pastoralists due to climate variability [88].

Increasing Temperatures and Heat Stress

Rising temperatures, warming trends, and heat stress are also identified as key climate vulnerabilities, mentioned in 13 (26.5% (13) of the studies. Observed temperature increases, such as the +1.25–1.29 °C rise in West Pokot [89], exacerbate water stress and negatively impact crop physiology, yields, and livestock health [84]. Studies suggest further warming, indicating that heat stress will likely become increasingly important in shaping agricultural outcomes and overall vulnerability [33]. Farmers in Machakos County perceive these temperature increases and their detrimental effects on agricultural productivity [84].

Extreme Events: Floods and Storms

While drought is a dominant stressor, floods and storms 15 studies (30.6%) also cause significant socio-economic disruption in specific vulnerable areas. Flood-prone regions like the Lower Kano Plains near Kisumu experience substantial losses, including the destruction of homes and property [90] and loss of farmland. Coastal areas are also susceptible to flooding, often compounded by storm surges [91,92]. Increased intensity of storms, particularly impacting fishing communities around Lake Victoria [93], is another noted extreme event linked to climate variability. Kirinyaga County also experiences floods and pest outbreaks alongside unpredictable rainfall [94].

Coastal Specific Hazards

Kenya's coastal communities face distinct climate threats that remain critically understudied compared to inland regions, with only 4.1% of reviewed research focusing on these challenges [91,92,95]. The coastal zone's unique vulnerability stems from compounding marine and terrestrial climate impacts, including sea-level rise threatening low-lying areas like Lamu and the Tana Delta, salinity intrusion degrading freshwater sources and agricultural land, and mangrove ecosystem collapse that undermines both coastal protection and fisheries-based livelihoods.

These interconnected hazards disproportionately affect coastal populations, where over 60% depend on climate-sensitive activities like fishing and mangrove harvesting [93], yet receive minimal attention in national adaptation planning.

The coastal climate crisis manifests through multiple pathways: projected 0.3–0.5meter sea-level rise by 2050 [95], 30–50% crop yield declines from salinity in Kilifi [96] and accelerated mangrove loss increasing community exposure to storms. These impacts compound existing vulnerabilities, as 71.7% of coastal residents live in poverty [92] and women face systemic barriers to adaptation due to limited resource access [97]. The research gap on coastal vulnerabilities reflects a dangerous oversight, as these communities sit at the frontline of climate change impacts without adequate scientific attention or policy support to build resilience.

4.1.2. Vulnerable Livelihood Systems

The dependence on climate-sensitive sectors renders rural Kenya particularly vulnerable to climate change. The reviewed studies point out specific impacts and challenges across various livelihood systems, including rain-fed agriculture, pastoralism, fisheries/aquaculture, and increasingly diversified livelihood portfolios.

Rain-fed Agriculture

Rural communities in Kenya face severe climate risks due to their heavy reliance on rain-fed agriculture, with 20(40.8%) documenting the sector's vulnerability to drought, erratic rainfall, and temperature extremes [81,84,87, 98–104]. This dependence is linked to high levels of vulnerability, especially for households relying solely on food crop production [83]. Even in higher potential areas like Kisii, climate change impacts food security [103]. The consequences include recurrent crop failures and significantly reduced crop yields, leading to income loss [84]. Water shortages are a critical constraint [86]. This translates to pervasive food insecurity, reported as near-universal in some areas [87]. Vulnerability varies by location and agro-ecological zone [18].

Pastoralism and Agro-Pastoralism

Pastoralist and agro-pastoralist communities in Kenya's arid and semi-arid lands (ASALs) are among the most climate-vulnerable populations due to their heavy dependence on climate-sensitive natural resources. At least 17 (34.7%) document the severe challenges faced by these communities across multiple counties [88, 98, 105, 106]. The impact of drought manifests in several interconnected ways. As highlighted by [107] and [108], pasture and water scarcity are primary consequences, directly threatening livestock survival and productivity. Timu et al. [108] focusing on Garbatulla Sub-County, observed declining rainfall leading to reduced milk production, a key nutritional and economic resource for these communities. The deterioration of livestock condition, with Galwab et al. [109] noting that 71.4% of livestock were in poor condition in West Pokot, further exacerbates income loss and food insecurity. In some regions, such as Turkana and Mandera, resource scarcity has also intensified conflicts over grazing lands and water [18].

Fisheries, Aquaculture and Coastal Livelihoods

Communities across Kenya that rely on aquatic resources for their livelihoods face a distinct set of climate change challenges that exacerbate existing vulnerabilities. The five studies (10.2% of 49) focusing on these systems reveal diverse impacts depending on the specific type of aquatic resource dependence and geographical location. For those involved in aquaculture, such as fish farming communities in Kitui County, a key vulnerability stems from the impact of extreme weather events. Nzilu [8] reported how changes in precipitation patterns and temperatures can directly affect water availability and quality within fish ponds, leading to potential losses in fish stock and consequently impacting the livelihoods of these farmers. This dependence on stable environmental conditions makes aquaculture particularly susceptible to the erratic nature of climate change.

Coastal communities face a different but equally significant set of threats. Mulonga and Olago [91] and Ngare et al. [92] pointed out the dangers posed by sea-level rise and saltwater intrusion. Communities residing around Lake Victoria, as studied by Pelser and Chimukuche [93], are particularly vulnerable to the increasing intensity of storms. These extreme weather events pose significant risks to fishing activities, damaging boats and fishing gear, and endangering the lives of fishers. The disruptions to fishing, a primary source of income and food for many in these communities, can lead to increased poverty and food insecurity. Moreover, Odero and Mahiri [90], focusing on the flood-prone Lower Kano Plains near Kisumu (connected to Lake Victoria), demonstrate how socio-economic factors exacerbate vulnerability to flooding, which can destroy homes and farmland, further impacting fishing-dependent livelihoods.

Mixed and Diversifying Systems

Across various primary livelihood systems (agriculture, pastoralism), livelihood diversification into off-farm and non-farm activities is frequently observed and widely recommended as a key strategy to build household resilience to climate shocks. At least 10(20.4%) document this trend, highlighting how communities supplement their primary production with various off-farm and non-farm activities [100,110]. These diversified livelihoods encompass petty trade, casual labor, remittances, beekeeping, gum and resin collection, small-scale poultry farming, mango cultivation, beadwork, eco-tourism, and urban employment [95,111]. While diversification can provide alternative income streams during climate-induced production declines, its effectiveness varies significantly across contexts [88]. Some strategies, such as irrigated horticulture or value-added crafts, demonstrate sustainable resilience benefits, while others particularly distress-driven activities like charcoal production and logging may undermine long-term ecological and economic stability [110]. The success of livelihood diversification depends on multiple factors, including access to markets, financial resources, skills training, and supportive policies [112].

4.2. Health Vulnerabilities

The predominant climate stressors identified in rural Kenya, namely increased temperatures and altered precipitation patterns (droughts and floods), act as significant drivers of a range of health vulnerabilities within these communities. An analysis of the reviewed studies reveals several key areas where climate change directly and indirectly impacts human health.

4.2.1. Infectious Diseases

Altered temperature and precipitation patterns create conditions conducive to the spread of various infectious diseases in rural Kenya. Fourteen studies (28.6%) highlight this critical health vulnerability. Changes in temperature and rainfall have been linked to shifts in malaria incidence [45,113–115], increased potential for dengue fever transmission [116,117], and a higher risk of visceral leishmaniasis (kala-azar) during periods of low rainfall and high temperatures [118]. Prolonged drought has been implicated in cholera outbreaks [119,120], while heavy rainfall and flooding are associated with Rift Valley Fever [121] and increases in various waterborne, rodent-borne, and vector-borne diseases [50,122]. Additionally, seasonal temperature and rainfall patterns affect the peak of rotavirus diarrhea [123] and drought has been shown to reduce schistosomiasis transmission by drying snail habitats [124].

4.2.2. Malnutrition and Food Insecurity

The impact of climate stressors on agriculture and livestock directly translates to increased malnutrition and food insecurity in rural areas. Five studies (10.2%) address this vulnerability. Signorelli et al. [125] found worsening trends in child wasting and maternal underweight in ASAL counties due to temperature shocks and droughts. Kenya Institute for Public Policy Research and Analysis [126] reported high food insecurity in ASAL households due to droughts and floods, characterized by poor dietary diversity. Bauer and Mburu [127] identified a high prevalence of malnutrition during drought periods in Marsabit and Northern Kenya. Straight et al. [128] revealed that prenatal exposure to drought negatively affected child growth. Mark et al. [129] demonstrated that higher local temperatures were associated with a higher prevalence of child malnutrition in North Rift ASAL counties. Additionally, Odongo et al. [130] found that the prolonged drought of 2020–2023 led to severe food insecurity and malnutrition.

4.2.3. Mental Health Impacts

The psychological toll of environmental changes on rural populations in Kenya is evident in five studies (10.2%). These studies reveal that climate change significantly impacts mental well-being, leading to various disorders and distress. Mwenda [117] in Isiolo County found a positive correlation between rainfall patterns and mental health disorders, with anxiety being a common response to droughts and floods. Ndetei et al. [131] reported increased psychological distress and suicidality among adolescents worried about perceived climate change, including droughts and floods. Mwenda [117] highlighted drought as a driver of mental health distress among pastoralists in Isiolo County. Njeru et al. [132] indicated a significant psychosocial burden on smallholder farmers due to the impact of altered temperatures and rainfall on their livelihoods. Finally, Straight et al. [133] found post-traumatic stress symptoms in young Samburu pastoralist herders due to drought and climate extremes.

4.2.4. Other Physical Health Impacts

Beyond specific diseases and malnutrition, climate stressors contribute to other physical health vulnerabilities. Five studies (10.2% of 49) touch upon these. Matzke et al. [134] found a link between higher heat exposure and increased physical activity among rural residents in Siaya County. Bakhtsiyarava et al. [135] reported that more hot months during pregnancy significantly reduced birth weight, while higher rainfall increased it. Lam et al. [136] mentioned dehydration and skin irritation due to the use of saline water during drought. Okaka and Odhiambo [50] listed drowning and injury as direct consequences of flooding. Sorensen and Balbus [137] found an association between severe weather events and increased intimate partner violence.

4.3. Ecosystem Vulnerabilities Across Rural Kenya

Rural Kenya includes a diverse variety of ecosystems, each facing unique and often overlapping vulnerabilities that are increasingly exacerbated by the impacts of climate change and direct anthropogenic pressures. This review synthesizes findings from twenty studies to discuss the documented susceptibilities and historical impacts across several key Kenyan ecosystems, pointing out the challenges faced by communities reliant on these natural environments.

4.3.1. Semi-arid and Dryland Agro-ecosystems and Pastoral Systems

Seven studies (35%), focused on the vulnerabilities inherent in Kenya's semi-arid and dryland agro-ecosystems and pastoral systems. These regions, characterized by low and erratic rainfall, are fundamentally sensitive to climatic shifts and support millions dependent on agriculture and pastoralism. In semi-arid agro-ecologies such as Tharaka South and Kitui Central, smallholder farmers experienced water scarcity, soil degradation and diminished crop yields [138]. These farmers reported heightened climate variability, including droughts, unpredictable rainfall patterns, and rising temperatures, observations which were corroborated by meteorological data spanning from 1998 to 2018 [138]. Similarly, dryland communities in the Karamoja border region encountered acute water scarcity, significant land degradation, desertification, and the loss of communal grazing lands, with residents perceiving a shift towards a drier, hotter, and more erratic climate that directly impacted water access and traditional livelihoods [139].

Across various Arid and Semi-Arid Lands (ASALs) including Narok, Elgeyo Marakwet, West Pokot, and Turkana, agro-pastoral value chains suffered from reduced pasture yield and quality, soil infertility, the encroachment of invasive species, and shifts in traditional production zones [140]. These impacts were linked to observed increases in temperature, decreases in annual precipitation, high interannual rainfall variability, and heightened evapotranspiration, which also led to the re-emergence of pests and weeds, thereby threatening livestock production and pastoral livelihoods [140]. Maasai pastoralists in Kajiado County faced rangeland degradation manifested by dry conditions, deforestation, severe pasture depletion, and water scarcity, resulting in substantial livestock losses; these conditions were driven by frequent and severe droughts and erratic rainfall, and further exacerbated by land sub-division and human activities such as mining [141].

In Turkana County, recurrent droughts and water scarcity contributed to declining pastoralism and rangeland degradation from overgrazing and the spread of invasive *Prosopis juliflora*, compelling shifts towards fishing and more sedentary lifestyles [142]. A broader analysis of grassland ecosystems within Kenyan ASALs confirmed widespread grassland degradation, characterized by loss of vegetative cover and invasion by unpalatable species, alongside soil degradation and water scarcity, all of which severely impacted pastoral livelihoods, fostering poverty and landlessness; these were attributed to anthropogenic activities compounded by climate change effects like drought and rising temperatures [143]. However, a long-term study (1973–2007) in a semi-arid environment in southeastern Kenya suggested that while climatic factors like low rainfall were present, the primary drivers for grassland degradation, including reduced cover and woody encroachment, were predominantly increasing human and livestock population pressures that led to overgrazing and agricultural expansion [144].

4.3.2. Forested Ecosystems

Forested ecosystems in rural Kenya, including vital Water Towers such as the Mau Forest Complex and unique habitats like the Kakamega tropical rainforest, provide indispensable ecosystem services including biodiversity

conservation, climate regulation and water catchment functions. Four studies (20%) specifically addressed the vulnerabilities of these critical forest environments. In the Mukogodo forested ecosystem in Laikipia County, significant forest degradation was observed, marked by an expansion of shrubland, a reduction in grassland, an increase in bare land, the desiccation of rivers and springs, diminished wildlife populations, and overall biodiversity loss [145]. These ecological shifts were attributed to a net decrease in rainfall by 200 mm and an average temperature increase of 1.5 °C between 1986 and 2015, alongside frequent and intense droughts that profoundly impacted local pastoral livelihoods [145]. The East Mau forest ecosystem experienced extensive deforestation, which led to substantial economic losses stemming from reduced ecosystem services, including critical soil functions and hydrological regulation; observed impacts comprised severe soil erosion and biodiversity loss, with climate change further stressing the forest's capacity for carbon sequestration and influencing rainfall patterns [146].

Communities proximal to the Kakamega tropical rainforest, such as the Buyangu community, faced forest degradation including the depletion of the rainforest itself, leading to the loss of indigenous plant species, including those used for fuelwood and medicine, and a reduced overall supply of essential forest products [147]. These detrimental changes were linked to observed climatic shifts, including a consistent warming trend (maximum temperature increasing by 0.04 °C/yr and minimum by 0.02 °C/yr), decreasing mean monthly rainfall, increasingly uncertain rainfall patterns, and prolonged drought periods [147]. An assessment of Kenya's major Water Tower ecosystems the Mau Forest Complex, Mt. Elgon, and Cherangany Hills revealed extensive vulnerabilities including ongoing forest degradation, diminished water availability for dependent communities and agricultural sectors, significant biodiversity loss, adverse impacts on key agricultural crops like maize and tea, and soil degradation [148]. These vulnerabilities were projected to intensify under future climate scenarios characterized by further temperature increases, highly variable rainfall patterns (with anticipated increases in the October-December season but decreases in March-May and June-August), and an increased frequency of both droughts and floods, leading to declining stream flows [148].

4.3.3. Lake Ecosystems and their Riparian Zones

Kenya's Rift Valley lakes and other lacustrine environments are of profound ecological importance and sustain a variety of local livelihoods. Four studies (20%) investigated the acute vulnerabilities these lake ecosystems have faced, with a particular focus on recent and dramatic changes in water levels. Research on Lake Baringo's riparian areas highlighted grave concerns for the lake's ecosystem health and biodiversity due to drastic rises in water levels observed between 2010 and 2020 [149]. These increases, which corresponded with heightened rainfall in the region, led to significant flooding of riparian land, posing severe risks to properties such as buildings, roads, crops, and livestock, and threatened the displacement of thousands of households. A major ecological catastrophe feared was the potential merging of freshwater Lake Baringo with the nearby alkaline Lake Bogoria [149].

This phenomenon was not isolated to Lake Baringo; an analysis across several Great Rift Valley Lakes including Baringo, Bogoria, Nakuru, Elementaita, and Naivasha confirmed that the rising water levels experienced extensively between 2010 and 2020 strongly correlated with a substantial increase in regional rainfall, notably a 30% rise in the Baringo/Bogoria catchments [150]. These hydrological shifts directly impacted lake volumes, inundated riparian zones, and disrupted the socio-economic livelihoods of communities dependent on these critical lake resources [150]. Further investigation reinforced the significant risk of cross-mixing between Lake Bogoria and Lake Baringo due to these ongoing regional hydrological changes, with paleohydrological evidence suggesting that such an event, carrying severe ecological consequences, might represent a recurrence of past environmental patterns [150]. In a different context, research in Turkana also noted the adverse impact of a receding Lake Turkana on local fisheries, demonstrating that lake ecosystems were vulnerable not only to rising water levels but also to falling levels, depending on specific hydrological dynamics and climatic drivers [142].

4.3.4. Wetland Ecosystems

Wetlands are indispensable for maintaining biodiversity, regulating water cycles, and supporting local livelihoods; however, they are exceptionally sensitive to both climatic variations and anthropogenic disturbances. A study conducted in the Yala Wetland in Western Kenya, revealed that local communities heavily dependent on this ecosystem faced significant wetland degradation [151]. This degradation directly impacted their agricultural practices and fisheries and led to pronounced challenges in securing adequate water availability. These adverse issues were

strongly linked to both perceived and scientifically observed increases in the frequency of droughts and floods, irregularities in the onset and termination of rainfall seasons, and a statistically significant increasing trend in the short rains period and average maximum temperatures, based on an analysis of climate data from 1981 to 2018 [151].

4.3.5. River Basin Ecosystems

River basins are fundamental to the provision of water for domestic use, agriculture, and energy production throughout rural Kenya, making the stability of their hydrological regimes and the health of their riparian zones critically important. A study conducted in the Sondu Miriu River basin, found that existing hydropower projects and the livelihoods of local communities were notably vulnerable to the effects of rainfall variability and broader climate change [152]. Observed impacts included periods of decreased river flows, particularly documented between 2007 and 2018, which consequently affected hydropower generation capacity. Additionally, the basin experienced riparian ecosystem degradation stemming from deforestation for fuel and land-use changes associated with the development of hydropower infrastructure. Although future climate projections suggested a potential for increased overall rainfall albeit with more extreme events, the historical variability had already posed considerable challenges to both energy production and local ecological stability [152].

4.3.6. Mangrove Ecosystems

Coastal mangrove ecosystems in Kenya offer crucial services, including vital coastal protection, critical habitat for fisheries, and significant carbon sequestration; yet, they are situated at the interface of terrestrial and marine influences and face considerable pressure from both. A study on coastal forests which included Gazi Bay within the wider Western Indian Ocean region, identified that mangrove degradation was significantly driven by human pressures [153]. These pressures included land-use changes in adjacent areas and soil erosion from upstream catchments, which in turn led to reduced freshwater inflow and increased pollution loads into the mangrove systems. Beyond these anthropogenic factors, climatic vulnerabilities were also prominent, with changes in precipitation patterns and flooding regimes, the pervasive threat of sea-level rise and associated anomalies, and alterations in terrestrial runoff all posing substantial threats to the health, extent, and resilience of these vital coastal ecosystems [153].

4.3.7. Large, Mixed Ecosystems

Certain regions within Kenya are characterized as complex mosaics of interconnected ecosystems, including rangelands, forests, and riverine areas, which necessitate integrated approaches for their vulnerability assessment and management. Climate Change Vulnerability and Adaptation Assessment for the Greater Mara Ecosystem [154] study examined vulnerability assessment for the Greater Mara Ecosystem (GME), an area that encompasses the Maasai Mara National Reserve as well as surrounding community conservancies and agricultural landscapes. The study found that the GME had experienced significant habitat degradation and loss affecting both its extensive rangelands and forested areas. Water scarcity, particularly concerning the Mara River (with contributing factors including deforestation in its upper Mau Forest catchment), was a major issue. Furthermore, the ecosystem faced increased instances of human-wildlife conflict and the spread of invasive species. While historical climate data indicated an increase in average annual rainfall for the region, the assessment concluded that the GME was highly vulnerable to projected future climate changes, including sustained temperature increases, greater rainfall variability, and a potential rise in the frequency and intensity of both droughts and floods. These climatic threats were found to be compounded by ongoing anthropogenic pressures, most notably land-use change driven by agricultural expansion and settlement [14].

4.3.8. Ecological Niche and Biodiversity Vulnerability

Beyond the vulnerabilities observed within specific ecosystem boundaries, the fundamental ecological niches of plant species, which form the structural and functional basis of these ecosystems, were also found to be susceptible to change. A study conducted by Nzau [143] addressed this critical aspect from a species-distribution modeling perspective, looking at how climate change could impact essential plant resources across Kenya. This research specifically assessed the potential vulnerability of the ecological niches occupied by various useful Fabaceae (legume family) species throughout the country. The study's projections indicated that anticipated changes in temperature and precipitation patterns, considered under a range of future climate and socio-economic development

scenarios, would likely lead to significant alterations in the suitable habitat areas and the potential geographic range of these economically and ecologically important plant species. This finding pointed to a clear vulnerability of these vital plant resources, which are crucial for numerous ecosystem services such as maintaining soil fertility through nitrogen fixation and providing fodder for livestock. Consequently, impacts on Fabaceae species distribution were expected to have broader repercussions for the overall ecosystem functions they support [143].

4.4. Vulnerable Populations in Focus: Unequal Burdens

The research consistently identifies specific demographic and livelihood groups as bearing a disproportionate burden of climate change impacts in rural Kenya. These populations are often characterized by their direct reliance on natural resources, limited access to alternative income sources and marginalization within broader socioeconomic and political structures. The evidence consistently points out the following groups as disproportionately vulnerable in rural Kenya.

4.4.1. Women

Women face heightened vulnerability due to a combination of factors. They often bear disproportionate responsibility for household tasks like collecting water, firewood and food, and caring for children and the sick, tasks that become significantly more arduous and time consuming under conditions of drought or after floods. For instance, [18] found that in pastoral rangelands, female-headed households were perceived to be more vulnerable to climate-induced stresses, with the gender of the household head being a significant factor in perceived vulnerability. Similarly, [155] identified that female-headed households in the Turkana region specifically lacked the necessary labor for herding and had limited access to better pastures, which were often located in conflict-prone areas, thereby compounding their climate vulnerability.

The Adaptation Learning Programme [156] in Garissa County also highlighted differential vulnerability by gender within pastoral and agro-pastoral communities, noting that the transition to new livelihood strategies like agropastoralism, while offering opportunities, also presented new risks that could disproportionately affect women. Furthermore, a study by Kamau [157] on agro-weather advisories suggested that there are barriers for women and other vulnerable groups in accessing and potentially paying for climate information services, which are crucial for adaptive capacity. These findings indicate that women's vulnerability is rooted in their roles in resource management, limited access to and control over resources, and constraints in accessing information and decision-making power, all of which are exacerbated by climate change impacts such as drought, water scarcity, and reduced agricultural productivity.

4.4.2. Children

The specific vulnerability of children, particularly young adolescents, to climate change in rural Kenya was a central focus of the study by Logie et al. [158]. This multi-method qualitative inquiry across six climate-affected regions found that young adolescents (10–14 years), especially girls, faced heightened risks due to their developmental stage, limited socioeconomic resources, and reliance on caregivers. Climate change-induced resource insecurities (food, water, sanitation) directly linked to increased sexual and reproductive health (SRH) vulnerabilities, including sexual and gender-based violence (SGBV), transactional sex, and school dropout. The study emphasized how exposure to droughts, extreme heat, heavy rainfall, and flooding disrupted their education and increased risks of violence and exploitation.

Gender inequities were found to further magnify these risks for girls. Further, children, especially those under five, are highly susceptible to the health consequences of climate change. They face increased risks of malnutrition (including stunting) due to food insecurity [56,129]. They are more vulnerable to waterborne diseases like diarrhea, a major cause of child mortality, due to contaminated water and inadequate sanitation. Exposure to HAP increases their risk of acute respiratory infections. Children are also vulnerable to the mental health impacts of climate-related disasters and stress, including PTSD. Climate-induced migration or illness can disrupt their education, affecting their future opportunities. Pastoralist youth face unique stresses related to their demanding labor under harsh conditions.

4.4.3. Persons with Disabilities (PWDs)

Persons living with Disabilities (PWDs) represent a critically vulnerable group however, they are not well studied. International Disability Alliance [159] study with persons with disabilities (including women and youth) in Baringo County revealed profound and intersecting vulnerabilities. This group faces exposure to repeated flooding, unpredictable rain, heatwaves, drought and desertification. Their sensitivity is heightened by marginalization, discrimination, attitudinal, communicational and physical barriers, dependence on land and natural resources, and pre-existing health conditions. Critically, their adaptive capacity is severely limited by restricted access to inclusive evacuation procedures, social protection, employment opportunities, and accessible housing, alongside the loss of ancestral wisdom and community bonds due to displacement. The study highlighted that climate change led to unpredictable weather patterns causing displacement, exacerbated health conditions, food insecurity, loss of social protection, violent conflicts, and the erosion of culture and land rights. Furthermore, indigenous women and youth with disabilities experienced compounded discrimination.

4.4.4. Pastoralists and Agro-pastoralists

Studies focusing on pastoral and agro-pastoral communities, particularly in arid and semi-arid lands (ASALs) like Isiolo, Garissa, Turkana, and West Pokot Counties, consistently demonstrate high vulnerability. Exposure is primarily to increasing frequency and intensity of droughts, alongside risks from floods and changes in rainfall patterns [107,155,159]. Sensitivity in these populations stems from their deep reliance on climate-sensitive natural resources, specifically water and pasture for livestock, which form the basis of their livelihoods and food security [107,159]. Warmer, drier conditions negatively impact livestock health, productivity, and survival. Female-headed households in Turkana face particular sensitivity due to lack of labor for herding and limited access to better pastures, often located in conflict-prone areas [155]. Adaptive capacity among pastoralists, while historically reliant on mobility and traditional risk management, is increasingly low according to Sonwa [155]. Lolemtum [107] reported low adaptive capacity (87%) in West Pokot pastoralists due to low education levels, poverty, and limited understanding of climate variability. Traditional mobility is hindered by conflict over resources and changing land use, contributing to overgrazing in accessible areas. Youth in the Maasai community face challenges as traditional climate prediction methods become less reliable [160].

4.4.5. Smallholder Farmers

Smallholder farmers, prevalent in various regions including coastal areas [92] and Kisii County [161], are highly vulnerable due to their significant dependence on rain-fed agriculture [100]. Their exposure includes decreased and erratic rainfall, poor distribution, late onset of seasons, increased temperatures, dry spells, flooding, and frequent droughts [92,100]. Projected climate changes suggest maize production losses, with other crops and livestock also expected to suffer [157]. Sensitivity for smallholder farmers is intrinsically linked to their reliance on climate-dependent agricultural production for food security and income. High poverty levels and food insecurity exacerbate this sensitivity [92]. Declining yields of major food crops have been reported [100]. Also, adaptive capacity is often constrained by factors such as lack of capital, limited land, insufficient information, inadequate communication channels, limited access to funds and support, and insufficient technical capacities [100,161]. While farmers perceive climate changes and adopt climate-smart agriculture (CSA) practices like crop diversification, changing planting times, and crop rotation, adoption is influenced by socio-economic factors such as household size, income, credit access, and perception [100]. Access to timely and accurate agro-weather advisories is crucial for empowering decision-making, but barriers exist, particularly for women and vulnerable groups [157].

4.4.6. Elderly

The elderly in rural areas, although not the primary focus of all studies, are identified as a vulnerable group within broader community analyses. The Logie et al. [158] study included elders in focus groups in climate-affected regions. While the summary does not detail specific climate vulnerability for the elderly in the same structured way as other groups, the general context of climate-exacerbated resource insecurities (food, water, sanitation) impacts all community members, including the elderly. Older people in semi-arid environments are exposed to severe changes in rainfall, drought, floods, and increased human and livestock diseases.

4.4.7. Low-Income Communities/Impoverished Populations

Low-income and impoverished populations are inherently more vulnerable to climate change impacts across all rural settings in Kenya. They are exposed to the same climate hazards as other rural groups, including droughts, floods, heatwaves, and storms [92]. Sensitivity in these communities is high due to limited socioeconomic resources, reliance on climate-sensitive livelihoods (agriculture, casual labor), and inadequate housing and infrastructure which offer less protection against extreme weather [92,158]. Existing inequalities in wealth, technology and information access further increase their sensitivity. Climate change and extreme weather events exacerbate resource insecurities (food, water, sanitation), directly impacting the well-being of low-income households [158]. The spread of climate-sensitive diseases like malaria and cholera also disproportionately affects impoverished populations with limited access to healthcare [44,45].

Adaptive capacity is severely constrained by poverty, lack of financial safety nets, limited access to information and support, and inadequate institutional planning that addresses their specific needs [92]. While some studies on smallholder farmers (often low-income) indicate adoption of adaptation strategies, this is influenced by access to resources and information [100] The high demand for agro-weather advisories among smallholder farmers, but unwillingness to pay, particularly among those with smaller acreage, highlights the financial barriers to adaptation. Indigenous communities, often among the impoverished, face constrained adaptive capacity due to inadequate communication and limited access to funds and technical support [158].

4.5. Implications for Human Capacity Resilience

Climate change manifests in rural Kenya through a range of impacts that directly and indirectly have significant implications for the human capacity resilience of the affected communities.

4.5.1. Conceptualizing Human Capacity Resilience in the Rural Kenyan Climate Change Context

Climate change significantly affects rural Kenya by intensifying environmental, economic and social vulnerabilities. This intensification directly influences the human capacity resilience of these communities. Human capacity resilience itself refers to the ability of individuals, households and communities to anticipate, absorb, adapt to, and transform in response to climate-induced shocks and stresses, while maintaining essential functions and striving toward sustainable development [162,163]. This resilience is shaped by three interrelated capacities [164]. Absorptive capacity reflects the ability to buffer and cope with immediate climate-related impacts. Adaptive capacity denotes the capability to adjust behaviors, practices, or resources to reduce risks or capitalize on emerging opportunities. Finally, transformative capacity entails fundamentally restructuring systems and institutions when existing frameworks become untenable. These capacities function dynamically within the local socio-ecological systems of rural Kenya. The severity of projected climate impacts suggests that merely absorbing shocks or making incremental adaptations may be insufficient; transformative changes in livelihoods, resource management, and governance structures will likely be necessary for long-term sustainability [82,165,166].

Table 2 outlines six interconnected components that shape human capacity resilience in rural Kenyan communities confronting climate change. These include knowledge systems, practical skills, health status, social capital, access to information and financial services, and agency in governance. Each component supports adaptation by enabling individuals and communities to anticipate, respond to, and recover from climate-related stresses. Together, these elements form the foundation for building adaptive capacity that is locally grounded and sustainable.

Table 2. Overview of the key components of human capacity resilience pertinent to rural Kenyan communities facing climate change, drawing from various theoretical frameworks and grounding them with local examples.

Component	Definition/Description	Relevance to Rural Kenya (with examples)
Knowledge Systems	Formal education, vocational/technical skills, indigenous and local knowledge (ILK) systems related to agriculture, resource management, health, etc.	Essential for understanding climate risks, adopting climate-smart practices (e.g., drought-resistant crops), managing natural resources sustainably, utilizing traditional medicine, and local weather forecasting.
Skills and Labor	The practical abilities, health, and availability of the workforce to engage in productive activities, adapt livelihoods, and implement new techniques.	Enables implementation of adaptive strategies (e.g., soil and water conservation), diversification into new income-generating activities, and maintaining household productivity despite climate stressors.

Table 2. *Cont.*

Component	Definition/Description	Relevance to Rural Kenya (with examples)
Health and Well-being	The physical, mental, and social well-being of individuals and communities, serving as a foundation for active participation and coping.	Good health is crucial for labor productivity, cognitive function for learning and decision-making, and overall capacity to respond to and recover from climate shocks and health impacts (e.g., increased disease burden).
Social Capital	Networks, trust, norms of reciprocity, and collective action capabilities (bonding, bridging, linking) within and between communities.	Facilitates mutual support during crises, sharing of information and resources (e.g., seeds, labor), collective problem-solving for resource management, and accessing external assistance and influencing policy.
Access to Information and Financial Resources	Availability of climate information (e.g., early warning systems), market information, and access to financial services (credit, savings, insurance).	Enables informed decision-making, proactive planning for climate events, investment in adaptive technologies or livelihood diversification, and financial recovery from climate-related losses.
Agency and Governance	The capacity of individuals and communities to participate in decision-making processes, influence policies, and access support from local and national institutions.	Ensures that adaptation strategies are locally relevant and equitable, promotes accountability, and facilitates access to public services, resources, and legal frameworks that support resilience building.

Sources: Adapted from frameworks and information in [66, 168] and contextualized with findings from [168].

4.5.2. Erosion of Human Capacity Resilience by Climate Vulnerabilities in Rural Kenya

The identified climate vulnerabilities directly and indirectly erode these crucial components of human capacity resilience in rural Kenya. The degradation of ecosystems, such as loss of pasture, water scarcity and deforestation, severely undermines the resource base for traditional livelihoods like pastoralism and rain-fed agriculture [88,98,105,106]. This not only impacts income and food security but also leads to the devaluation and loss of associated indigenous knowledge systems (ILKS) concerning resource management, traditional medicine, and local coping strategies. For example, the disappearance of specific medicinal plants due to habitat degradation makes traditional health knowledge less applicable [169], and the reduced reliability of IK-based weather forecasting due to increasingly erratic climate patterns weakens local adaptive decision-making capabilities. This erosion often occurs gradually, through chronic stresses like persistent water scarcity or recurrent food insecurity, steadily weakening knowledge, health, and social cohesion, thereby making communities progressively more vulnerable to major climate events.

Socio-economic shocks, including climate-exacerbated poverty and displacement from floods or resource conflicts, significantly restrict access to formal education and skill development opportunities. When children are forced to contribute to household labor, such as fetching water over increasingly longer distances due to drought, their educational attainment is compromised. This limits the acquisition of new knowledge and skills vital for adapting to changing economic landscapes or diversifying livelihoods effectively, thereby diminishing the human capital crucial for resilience. Reduced income and the depletion of assets also curtail the financial capital available for investing in adaptive measures. A critical, often overlooked, impact is the intergenerational loss of resilience; when children suffer from malnutrition affecting cognitive development or miss out on education due to climate-induced poverty, their future adaptive capacity is severely compromised, perpetuating a cycle of vulnerability.

The increased burden of climate-sensitive diseases like malaria, waterborne illnesses, respiratory infections and widespread malnutrition directly impairs physical health and cognitive development, particularly in children. This reduces labor productivity among adults, increases household healthcare expenditures, and diverts resources from other essential needs, weakening overall community resilience. For instance, widespread malaria can incapacitate significant portions of the agricultural workforce during critical planting or harvesting seasons. The devaluation or loss of indigenous knowledge related to health and medicine, as traditional medicinal plants become scarce, is not merely a cultural loss but a direct impediment to practical, locally-tested adaptation strategies. This can force a greater, sometimes premature or inappropriate, reliance on external solutions that may be costly, inaccessible, or unsustainable.

While social capital is a cornerstone of community resilience, the heightened competition for dwindling resources like water and pasture can strain social relationships and even lead to conflicts, potentially eroding existing social capital networks. Displacement caused by climate impacts can also disrupt established community structures and support systems. It is also crucial to recognize that climate impacts do not affect all members of rural communities uniformly. Women, youth, the elderly, and impoverished households often bear a disproportionate burden

of these impacts. Women, for example, frequently face increased workloads (such as fetching water over greater distances), greater food insecurity, and more limited access to resources and decision-making power, all of which severely curtail their adaptive capacity and deepen existing socio-economic inequalities.

4.5.3. Traditional Coping Strategies Employed by Rural Communities in Kenya Against Climate Variability and Shocks

Rural communities across Kenya have developed and continue to utilize a diverse array of coping strategies, deeply embedded in their traditional knowledge and practices, to navigate the increasing challenges posed by climate variability and shocks. These strategies include various aspects of their livelihoods, including livestock and crop management, resource utilization, and economic and household adjustments.

Livestock Management (Pastoral/Agro-pastoral)

For pastoral and agro-pastoral communities, livestock are central to their livelihoods and cultural identity. In the face of climate variability, they employ a range of livestock management techniques. Seasonal mobility or longer-distance relocation to track pasture and water, adjusting herd composition (e.g., shifting towards goats/camels), changing herd size (destocking through sales, culling), splitting herds, using emergency fodder or local browse, loaning animals, and traditional disease control.

Crop Management (Farming/Agro-pastoral)

Agricultural communities, including those practicing agro-pastoralism, have also developed diverse strategies to cope with climate variability and shocks affecting crop production. Diversifying crops grown, planting drought-resistant or early-maturing varieties (sorghum, millet, green grams), inter-cropping, adjusting planting dates, small-scale irrigation where possible, water harvesting techniques.

Resource Management

Effective management of natural resources is paramount for the long-term resilience of rural communities facing climate challenges. Conserving pasture in areas close to homesteads provides a critical buffer during periods of scarcity. Traditional systems for managing reserve grazing areas, often governed by communal rules and seasonal restrictions, ensure the sustainable use of these vital resources. Water harvesting techniques play a crucial role in securing water for domestic use and agricultural purposes. These include the construction of rooftop water harvesting systems, sand dams that store water within riverbeds, and water pans that capture surface runoff during rainy seasons. These locally adapted resource management practices contribute significantly to the overall coping capacity of the communities.

4.5.4. Economic/Household Strategies

Diversifying income sources (engaging in small business, wage labor, selling charcoal/firewood), reducing consumption/food rationing, selling assets (livestock, land), relying on social networks for support (borrowing, sharing), utilizing savings, seeking remittances from migrated family members.

4.5.5. Pathways to Strengthening Human Capacity Resilience

Building resilience in rural Kenyan communities requires a comprehensive and forward-thinking approach that transcends mere coping mechanisms, focusing instead on proactive adaptation and transformative strategies. This necessitates investments in enhancing knowledge and skills, improving access to vital information and financial resources, strengthening social safety nets and intentionally empowering vulnerable populations, particularly women and youth.

4.5.6. Building Knowledge and Skills: The Foundation of Adaptive Capacity

A fundamental pillar of strengthening human capacity resilience lies in enhancing human capital through education, skills development, and awareness initiatives. A well-informed and skilled populace is better positioned to comprehend climate risks, embrace innovative technologies, seize emerging opportunities, and actively engage in planning and decision-making processes [170]. Key strategies include integrating climate change adaptation into formal education curricula at all levels, developing targeted vocational training programs focused on climate-smart agriculture, sustainable livestock management, and green jobs, and implementing broad-based public awareness campaigns utilizing accessible language and diverse communication channels, including indigenous knowledge sys-

tems. Furthermore, strengthening the institutional capacity of government agencies, civil society organizations, and private sector entities is crucial for effective climate action planning and implementation [171].

4.5.7. The Critical Role of Climate Information Services (CIS)

Access to timely, accurate, and usable climate information services (CIS) is a vital component in empowering adaptive decision-making, particularly within climate-sensitive sectors such as agriculture and pastoralism. Effective CIS enables farmers and herders to make informed choices regarding planting schedules, crop selection, livestock movement, and water management strategies [172]. While Kenya has made strides in CIS provision through the Kenya Meteorological Department (KMD) and collaborations with regional and international partners, significant challenges remain in ensuring accessibility for remote and vulnerable communities, enhancing the usability and local relevance of information, establishing robust feedback mechanisms, integrating indigenous forecasting knowledge, and ensuring the long-term sustainability of CIS initiatives. Addressing these challenges through user-centered approaches, investments in observation networks, improved prediction capabilities, capacity building for both providers and users, and strategic use of information and communication technologies (ICTs) is essential for maximizing the effectiveness of CIS [173].

4.5.8. Financial Inclusion: Empowering Resilience Through Access to Finance

Financial inclusion, encompassing access to and the use of appropriate financial services, can significantly bolster the capacity of rural households to manage climate-related risks, invest in adaptation measures, and build overall resilience. Savings provide a crucial buffer against shocks, access to credit facilitates investments in resilient technologies and livelihood diversification, and insurance mechanisms help mitigate the impact of catastrophic losses [174]. Innovative models, such as savings-led approaches, value-based care insurance, digitized agricultural finance, and climate-inclusive insurance schemes leveraging mobile technology, are emerging to address the specific needs of rural communities. However, persistent challenges, particularly for women, including lower incomes, lack of collateral, limited financial literacy, and restrictive gender norms, need to be addressed through gender-intentional product design, robust consumer protection frameworks, and investments in financial and digital literacy [175].

4.5.9. Social Protection Systems: Providing Safety Nets and Enhancing Shock Responsiveness

Social protection (SP) programs, particularly cash transfer initiatives, play a vital role in alleviating poverty, safeguarding households against shocks, and enabling investments in human capital, thereby contributing significantly to resilience. Kenya's National Safety Net Programme (NSNP), including programs like the Hunger Safety Net Programme (HSNP), has demonstrated positive impacts on food security, asset retention, and access to savings and credit during drought periods [176]. A key aspect of enhancing resilience is strengthening the shock-responsive capacity of social protection systems to provide timely assistance during climate-related crises. This requires reliable early warning systems, pre-agreed triggers for intervention, pre-arranged financing mechanisms, and scalable delivery systems. Efforts to expand SP coverage, improve targeting accuracy, enhance benefit levels, and integrate complementary services are crucial for building a more comprehensive and effective "productive safety net system" [177].

4.5.10. Targeted Empowerment: Focusing on the Agency of Women and Youth

Recognizing their distinct vulnerabilities and their potential as powerful agents of change, targeted efforts to empower women and youth are indispensable for building inclusive and effective climate resilience. Empowerment in this context entails enhancing access to resources, information, and services, amplifying their voices and participation in decision-making processes, and challenging restrictive social norms and power structures [178]. Initiatives focusing on women's economic empowerment through entrepreneurship support, savings groups, and access to clean energy and resilient agriculture, as well as efforts to engage youth in green jobs, leverage their networks for awareness and innovation, and ensure their inclusion in policy processes, are critical for fostering transformative change within communities [171].

5. Recommendations

5.1. For Policy (Government of Kenya - National and County Levels)

5.1.1. Integrate Climate Adaptation into National and County Development Planning

To systematically embed climate change adaptation, the Government of Kenya should mandate climate risk screening at the initial phase of all new policies, programs, and projects across all ministries and county departments. This means developing clear, standardized guidelines and practical training modules for planners to conduct Climate Vulnerability Assessments (CVAs) at both national and county levels. These assessments must be tied to specific, ring-fenced budgetary allocations within annual national budgets and County Integrated Development Plans (CIDPs) to ensure dedicated funding for implementation.

Furthermore, inter-ministerial and inter-county coordination mechanisms should be significantly strengthened through the establishment of dedicated, legally mandated working groups or task forces, potentially overseen by the Ministry of Environment, Climate Change and Forestry. These bodies should have regular, formalized reporting structures to ensure cohesive climate action, especially concerning shared resources like trans-county water basins and ecosystems.

5.1.2. Prioritize Investment in Climate-Resilient Livelihoods and Food Systems

For promoting climate-smart agriculture (CSA), the government should launch a national subsidy program for certified drought-tolerant crop varieties and provide accessible micro-financing options for smallholder farmers to invest in efficient water management technologies like drip irrigation kits and small-scale water harvesting structures (e.g., farm ponds, subsurface dams). This should be coupled with establishing practical, hands-on demonstration farms in each ward to showcase best practices and facilitate farmer-to-farmer learning.

To support sustainable pastoralism, specific strategies include establishing and maintaining a network of strategically located, community-managed boreholes and water pans, alongside establishing fodder banks at designated livestock markets. Disease surveillance should be enhanced through mobile veterinary units and real-time reporting systems, while market access can be improved by rehabilitating feeder roads to livestock markets and promoting value addition through meat processing cooperatives. Community-led rangeland management should be formalized through land tenure reforms and local by-laws that support rotational grazing and conflict resolution mechanisms over pasture and water.

For vulnerable coastal communities, the government should invest in large-scale, nature-based solutions like extensive mangrove reforestation projects, develop strict zoning regulations to prevent construction in high-risk areas, and provide financial incentives for adopting sustainable fishing practices, such as promoting responsible aquaculture and discouraging destructive fishing gear.

5.1.3. Enhance Ecosystem-Based Adaptation and Disaster Risk Reduction

Investing in the restoration and sustainable management of critical ecosystems (forests, water towers, wetlands, mangroves, rangelands) to enhance their resilience and the services they provide, including natural flood mitigation and water regulation, requires the establishment of dedicated national funds, potentially leveraging carbon credit mechanisms, to support community-based restoration initiatives. These funds should offer matching grants to local community groups engaged in conservation.

To strengthen early warning systems for multiple climate hazards, the government must increase the density of automated weather stations and river level sensors, especially in remote and vulnerable areas, integrating this data into a centralized, accessible platform. It should then develop localized, multi-hazard alerts that translate technical data into easily understandable, actionable messages, disseminated through diverse channels like community radio, SMS alerts in local languages, and public address systems. This should include establishing "last-mile" community early warning committees to facilitate effective information flow and activate local preparedness plans.

Furthermore, developing and enforcing land-use plans that discourage settlement in high-risk zones and protect critical ecological areas means expediting the legal gazettement of comprehensive county-level land-use plans that explicitly delineate high-risk zones (e.g., floodplains, steep slopes) and critical ecological areas. This requires strict enforcement of zoning and building codes, with clear penalties for illegal developments, backed by increased capacity for county physical planners and building inspectors.

5.1.4. Strengthen Health System Resilience to Climate Change

To integrate climate change considerations into public health policies, the Ministry of Health should establish a national surveillance system for climate-sensitive diseases, utilizing predictive modeling based on climate forecasts to anticipate outbreaks and enable proactive vector control. Programs addressing malnutrition linked to climate-induced food insecurity should scale up social protection programs offering nutritional support, particularly for children under five and lactating mothers in ASALs. It's also vital to recognize and integrate mental health support services within community health frameworks, training community health workers to identify climate-related psychological distress and provide referral pathways to accessible psychosocial support.

5.1.5. Target and Empower Vulnerable Populations

To develop and implement gender-responsive climate adaptation policies, the government must mandate equal representation of women in all climate decision-making bodies. Specific strategies include allocating dedicated funds for women's access to climate information, land tenure security, and ownership of climate-resilient technologies. Social protection programs (e.g., cash transfers) must be shock-responsive, with triggers based on early warning data, allowing for rapid scale-up to climate-vulnerable households. This also involves developing specific disability-inclusive disaster preparedness plans, ensuring accessible shelters and evacuation routes, and actively including Persons with Disabilities (PWDs) and their representative organizations in all adaptation and disaster management processes.

5.1.6. Promote Financial Inclusion and Risk Transfer Mechanisms

To facilitate access to appropriate financial services for rural communities, the government should expand agent banking networks into remote areas and promote digital financial literacy programs tailored for smallholder farmers and pastoralists. Government incentives, such as interest rate subsidies or matching grants, could encourage rural communities to utilize savings and credit for adaptation investments. For expanding weather-indexed insurance and other risk-sharing mechanisms, the government could explore public-private partnerships to subsidize premiums for vulnerable farmers and pastoralists, establish an accessible claims processing system, and launch extensive awareness campaigns on the benefits and mechanics of such schemes.

5.2. For Practice (Development Partners, NGOs, CSOs, Private Sector)

5.2.1. Capacity Building and Knowledge Dissemination

Develop and deliver tailored training programs for communities, local leaders, and extension workers on climate change adaptation, sustainable land and water management, and climate-resilient livelihood practices, integrating indigenous knowledge with scientific information.

Support the co-production and dissemination of accessible and actionable Climate Information Services (CIS) using diverse communication channels (radio, mobile phones, community meetings) and local languages.

5.2.2. Support Livelihood Diversification and Value Chain Development

Implement projects that promote diversification into climate-resilient agricultural and non-agricultural income-generating activities (e.g., beekeeping, eco-tourism, value addition to local products).

Facilitate access to markets and strengthen value chains for climate-resilient products to ensure better returns for producers.

5.2.3. Implement Ecosystem-Based Adaptation Projects

Partner with communities to implement on-the-ground projects for ecosystem restoration (e.g., reforestation, mangrove rehabilitation, rangeland restoration) and sustainable natural resource management.

Promote community-based natural resource management (CBNRM) models that empower local institutions.

5.2.4. Focus on Inclusion and Empowerment of Vulnerable Groups

Design and implement projects with a strong focus on women, youth, PWDs, and other marginalized groups, ensuring their active participation and benefit from adaptation initiatives.

Support women's savings groups, leadership development, and access to climate-resilient technologies and resources.

5.2.5. Promote Innovation and Private Sector Engagement

Promote and pilot innovative technologies and approaches for climate adaptation (e.g., solar-powered irrigation, climate-resilient housing, digital financial services).

Engage the private sector in developing and scaling up climate-resilient solutions and services for rural communities.

5.2.6. Strengthen Monitoring, Evaluation, and Learning (MEL)

Implement robust MEL frameworks for adaptation projects to track progress, measure impact, and facilitate adaptive management and learning. Share lessons learned widely.

5.3. For Research (Academic Institutions, Research Organizations)

5.3.1. Address Knowledge Gaps on Specific Vulnerabilities

Prioritize research on the specific climate vulnerabilities and adaptation capacities of critically understudied coastal communities and Persons with Disabilities (PWDs) in rural Kenya.

Conduct in-depth studies on the mental health impacts of climate change on different demographic groups in rural Kenya and evaluate effective community-based interventions.

5.3.2. Evaluate Effectiveness and Scalability of Adaptation Options

Undertake longitudinal studies to assess the long-term effectiveness, cost-benefit, and socio-cultural acceptability of various adaptation strategies (e.g., different CSA practices, livelihood diversification options, ecosystem-based approaches) across diverse agro-ecological zones and socio-economic contexts.

Investigate challenges and enablers to the uptake and scaling of successful adaptation interventions.

5.3.3. Enhance Understanding of Climate Information Services

Research best practices for the co-production, translation, communication, and integration of scientific and indigenous climate knowledge to enhance the usability and uptake of Climate Information Services by diverse end-users.

Assess the impact of CIS on decision-making and resilience outcomes.

5.3.4. Investigate Socio-Economic Dynamics and Transformative Adaptation

Deepen research on the nexus between climate vulnerability, poverty dynamics, gender inequalities, and access to resources to inform more equitable adaptation strategies.

Explore pathways for transformative adaptation that involve fundamental shifts in livelihood systems, governance structures, and institutional arrangements in the face of profound climate change.

5.3.5. Strengthen Climate Modeling and Impact Projections

Improve downscaled climate models for Kenya to provide more localized and accurate projections of climate change impacts on specific sectors (agriculture, water, health, ecosystems).

Research the cascading impacts and potential tipping points within socio-ecological systems in rural Kenya.

5.3.6. Economic Analysis of Climate Impacts and Adaptation

Conduct comprehensive economic assessments of climate change impacts on different sectors and livelihoods in rural Kenya.

Analyze the costs and benefits of various adaptation interventions to inform investment decisions and policy priorities.

6. Conclusions

The synthesis of research unequivocally demonstrates that rural Kenya is grappling with widespread and severe socio-economic vulnerability driven primarily by escalating climate change impacts, most notably increasing drought frequency, rainfall variability, and rising temperatures. These climatic stressors critically undermine climate-sensitive livelihoods, particularly rain-fed agriculture and pastoralism, which form the economic backbone for a majority of the rural populace. Crucially, this vulnerability is not solely a consequence of environmental exposure but is profoundly shaped and exacerbated by a confluence of socio-economic factors, including education levels, pervasive gender inequalities, poverty, and inequitable access to essential resources such as land, water, climate information services, and institutional support. Arid and Semi-Arid Lands (ASALs) emerge as particular hotspots of this intensified vulnerability, facing recurrent crises that threaten food security and overall well-being.

The repercussions of these climate stressors extend deeply into various facets of rural life. Beyond the direct impacts on agriculture and pastoralism, which lead to recurrent crop failures, livestock losses, and diminished productivity, other livelihood systems such as fisheries, aquaculture, and coastal enterprises face unique and significant threats, including storm intensification, sea-level rise, and saltwater intrusion challenges that are critically understudied in coastal regions. This environmental degradation is mirrored in the health sector, with climate change acting as a potent driver for infectious diseases, widespread malnutrition, and significant mental health challenges.

Furthermore, empirical evidence from various studies indicates pervasive degradation across critical ecosystems in rural Kenya, undermining the natural resource base upon which livelihoods and environmental stability depend. This degradation is observed in grassland ecosystems, vital forested areas including the nation's water towers such as the Mau Forest Complex, Mt. Elgon, and Cherangany Hills, the expansive Arid and Semi-Arid Lands (ASALs), and crucial wetland ecosystems like the Yala Wetland and the areas surrounding Lake Baringo The deterioration of these ecosystems, particularly water towers, has profound consequences for water availability, impacting agriculture, pastoralism, and domestic water supply across extensive regions.

The burden of climate change is not evenly distributed; specific demographic groups, including women, children, Persons with Disabilities (PWDs), pastoralists, smallholder farmers, the elderly, and low-income households, bear a disproportionate share of the impacts. These groups often face compounded disadvantages stemming from their reliance on natural resources, limited access to alternative incomes, and marginalization within socio-economic and political structures, which severely curtails their adaptive capacity. Women, for instance, often encounter increased workloads and limited access to resources, while children face heightened risks to their health, education, and safety. Persons with Disabilities experience profound and intersecting vulnerabilities that are often overlooked in adaptation planning.

Consequently, the cumulative effect of these climate-induced vulnerabilities is a significant erosion of human capacity resilience across rural Kenya. Traditional coping mechanisms, while historically important, are increasingly proving insufficient in the face of the current scale and pace of climate change. The degradation of natural resources devalues indigenous knowledge systems, socio-economic shocks limit educational and skill development opportunities, and health impacts reduce labor productivity and strain household resources. To counteract this, strengthening human capacity resilience is paramount. This necessitates a comprehensive approach focusing on proactive adaptation and transformative strategies. Key pathways include investing in knowledge systems and skills development, enhancing access to timely and usable climate information services, promoting financial inclusion to empower investment in resilient practices and bolstering social protection systems to provide robust safety nets. Critically, targeted empowerment of the most vulnerable populations, particularly women and youth, is essential to ensure equitable and effective climate action, fostering the agency required to navigate the complex challenges ahead and build a more sustainable and resilient future for rural Kenya.

Author Contributions

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