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Systems Approach To Climate Change Crisis, Global Perspective, and Uganda's Outlook - A Review

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Abstract

Climate change is a complex, systemic phenomenon with far-reaching social, economic, and environmental impacts. This review adopts a systems thinking approach to explore the interconnectedness of climate systems and their cascading effects on global and regional scale climate, with a particular focus on Uganda. Systems thinking, which emphasizes interconnectedness, feedback loops, emergence, and non-linearity, provides a holistic framework for understanding and addressing climate change. A systematic literature review was conducted using structured Boolean search strategies across databases such as Google Scholar, Scopus, SpringerLink, and Nature Climate, supplemented with grey literature from organizations including the Intergovernmental Panel on Climate Change and United Nations Environment Programme. Only English-language sources explicitly addressing systems thinking in climate change mitigation or adaptation were included based on predefined relevance criteria. The review highlights the application of systems thinking to climate change mitigation and adaptation. In the context of climate change mitigation, systems thinking is applied to integrated energy systems, circular economy principles, and sustainable land-use management. Case studies from Denmark and the Netherlands illustrate the effectiveness of these approaches, such as Denmark's transition to renewable energy and the Netherlands' circular economy initiatives. These examples demonstrate how holistic strategies can reduce greenhouse gas emissions, enhance resource efficiency, and promote economic resilience. For climate change adaptation, systems thinking emphasizes resilient infrastructure, ecosystem-based adaptation, and social equity. Examples include mangrove restoration in Southeast Asia and heat action plans in Ahmedabad, India, which highlight the importance of integrating natural ecosystems and inclusive policies to build climate resilience. In Uganda, efforts to integrate renewable energy, circular economy practices, and sustainable land-use management exemplify the application of systems thinking in a developing country context. Initiatives like hydropower projects, waste-to-energy programs, and climate-smart agriculture demonstrate progress, but financial constraints, capacity gaps, and policy implementation challenges remain. The review also noted that notwithstanding the potential of a systems thinking framework to address the multifaceted challenges of climate change, its application is constrained by complexity, data requirements, institutional barriers, and equity concerns experienced most in most developing countries, Uganda included. To address these challenges, interdisciplinary collaboration, robust data infrastructure, and inclusive governance are required. The current review contributes by bridging global systems thinking frameworks with localized climate action challenges in Uganda, offering context-sensitive pathways for operationalizing holistic climate solutions.

Categories: Innovation and Technology Management, Environmental and Sustainable Engineering, Water Resources Engineering
Keywords: systems thinking, climate change mitigation and adaptation, circular economy, renewable energy, climate resilience, holistic climate governance

Introduction And Background

Climate is a complex, interconnected system comprising the atmosphere, biosphere, lithosphere, cryosphere, and hydrosphere. According to the Centre for Science Education, the interactions between these components generate the climate elements, which define the Earth's weather and climate patterns [1]. Any changes within these subsystems result in variability of climate elements, and when such variability occurs over long periods (30 years or more) with an unstable mean, it is referred to as climate change. Climate change, as a systemic phenomenon, has increasingly emerged as a global crisis with widespread social, economic, and environmental repercussions [2].

Taking a systems approach to the climate change crisis allows us to understand the intricate feedback loops and cascading effects that amplify its impacts across various domains [3]. For instance, the interconnectedness of climate and food systems is evident in the rising cases of global food insecurity [4].

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Africa, a continent highly vulnerable to climate change, exemplifies how regional systems are disproportionately affected [5]. In Eastern Africa, recent climate change-induced phenomena such as desert locust invasions highlight the far-reaching consequences on regional food security [6].

In Uganda, climate change's systemic effects are visible in multiple ways. Climate migration, driven by environmental stressors, underscores the interlinkages between climatic shifts and socio-economic displacement. Rising temperatures have also contributed to increased cases of vector-borne diseases like malaria. Additionally, extreme heat during dry periods poses significant public health risks, such as heat stress, further demonstrating how climate variability cascades through environmental, health, and social systems [2].

As the world struggles to come to terms with climate change and address its multifaceted impacts, numerous research initiatives, strategies, and protocols have been developed to combat the crisis. For instance, international agreements such as the Paris Climate Accord have set ambitious global targets for reducing greenhouse gas (GHG) emissions [7], while national governments are implementing climate action plans tailored to their specific needs [8]. In addition, advancements in renewable energy technologies, such as solar and wind power, are rapidly transforming the global energy landscape, reducing dependence on fossil fuels [9,10]. Efforts are also underway to promote sustainable agricultural practices, reforestation projects, and the development of climate-resilient infrastructure.

The gains from recent efforts in mitigation, adaptation, and building community resilience to climate change have been remarkable [5]. In many regions, communities are better prepared to withstand extreme weather events due to improved early warning systems and disaster response strategies. Innovations in clean energy have not only reduced emissions but have also created green jobs and fostered economic growth. In agriculture, climate-smart practices, such as crop diversification and water management, are helping farmers adapt to changing weather patterns and secure food supplies.

However, despite these achievements, questions remain about the sustainability of these gains. Vulnerability levels remain alarmingly high, particularly in developing countries, where limited financial and technological resources hinder adaptation efforts. Many of these nations are disproportionately affected by the consequences of climate change, including prolonged droughts and devastating floods. The lack of equitable access to climate finance further exacerbates the challenges, leaving some of the most vulnerable populations struggling to cope with the crisis.

Given that climate is a highly complex system influenced by numerous interconnected factors (Figure *1*), adopting a systems-based approach to solution development is essential.

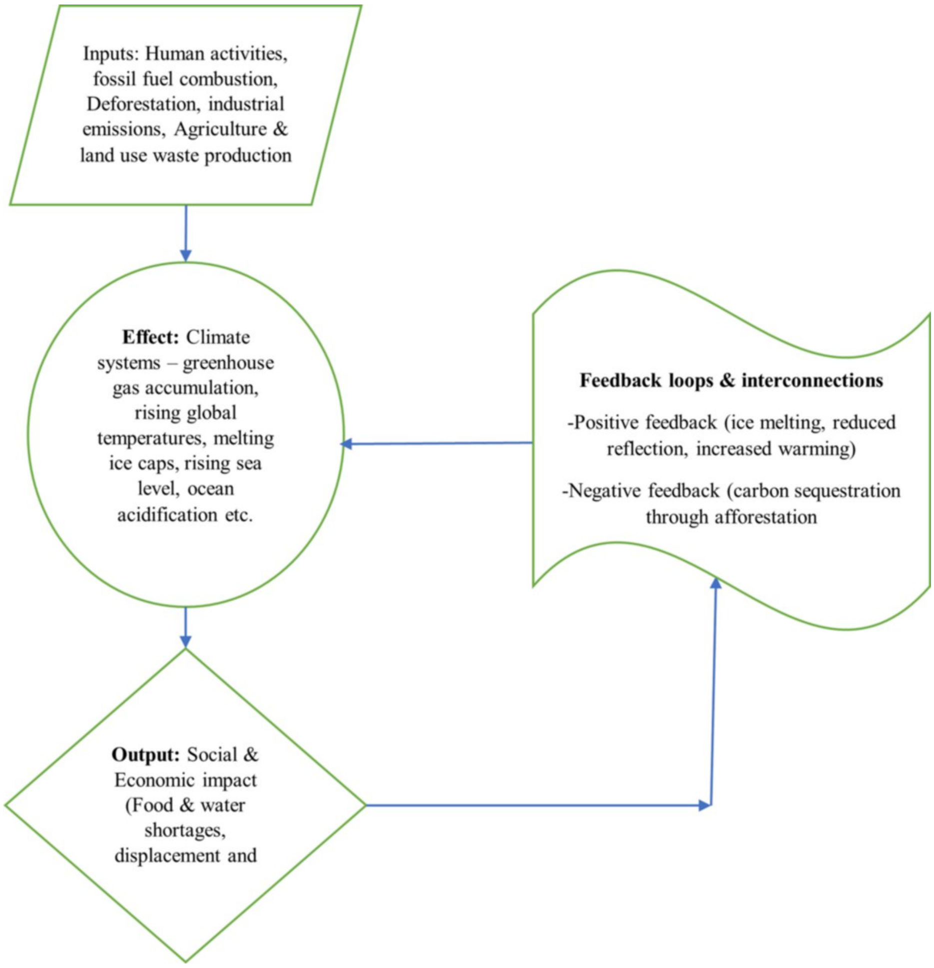

FIGURE 1: Intricate feedback loops and cascading effects of element that amplify the climate change crisis

This approach emphasizes understanding the dynamic relationships between environmental, social, and economic systems, enabling policymakers and scientists to devise more holistic and effective strategies. For example, integrating renewable energy development with sustainable urban planning, ecosystem restoration, and community-driven solutions can amplify the impact of climate action. A systems approach also encourages collaboration across disciplines and sectors, fostering innovation and ensuring that solutions are inclusive, scalable, and sustainable. By embracing this paradigm, the global community can significantly enhance its ability to address the climate change crisis and build a more resilient future for all.

This paper critically looks at the current state of knowledge regarding the systems approach to addressing the climate change crisis. It examines the foundational principles and methodologies of systems thinking, highlighting their applications to both climate change mitigation and adaptation. In addition, the paper highlights how interconnected environmental, social, and economic factors can be better understood and managed using a systems thinking approach. Real-world case studies were used to showcase the tangible benefits of implementing this approach, notwithstanding the challenges and limitations that may hinder the adoption of systems thinking methodology. In conclusion, the paper underscores the critical role of systems thinking in advancing sustainable, resilient, and equitable solutions to the climate change crisis.

Review

Methodology for the review

A systematic review approach was adopted to gather and analyze relevant academic and grey literatures on the application of systems thinking and systems approaches to climate change adaptation and mitigation. The reviewed prioritizes peer-reviewed journal articles, reports, and books that address the theoretical and practical application that relates to systems approach, systems thinking, and climate change crisis.

Scoping and exploratory searches to understand the breath of the research available in the study areas were conducted. Boolean operators like, AND, OR, and AND-OR were used to ensure a broad, yet precise capture of relevant literatures. Searches were conducted in the following preferred academic databases and platform; Google Scholar (Google scholar aggregates scholarly articles from various sources, including journals, books, and conference papers), Scopus (Scopus indexes a wide range of peer-reviewed journals across various disciplines), SpringerLink, Nature climate, and online repositories. In addition, grey literature from reputable organizations and institutions were included, for example Intergovernmental Panel on Climate Change (IPCC), United Nations Environment Programme (UNEP), and ministerial and policy documents (Government Institutional Reports).

The following inclusion criteria were used in selecting relevant studies for initial review; peer-reviewed journal articles, book chapters, institutional reports, and relevant grey literature that explicitly engaged with systems thinking or systems approaches in the context of climate change mitigation or adaptation. In addition, only English-language publications were considered. Eligible documents provided conceptual, methodological, or applied insights relevant to the topic (Table *1*).

Meanwhile, publications were excluded if the full text was not accessible, if they lacked direct relevance to either systems thinking or climate change, or if they presented purely theoretical arguments without contextual or practical application. Studies were also excluded if they were duplicates or exhibited insufficient methodological clarity (Table *1*).

Category	Inclusion Criteria	Exclusion Criteria
Publication Type	Peer-reviewed articles, books, IPCC reports, Peer-reviewed journal articles, book chapters, institutional reports, and grey literature. Publications addressing systems thinking in climate mitigation or adaptation. Conceptual, methodological, or applied insights.	Articles not available in full text. Publications lacking relevance to systems thinking or climate change. Purely theoretical pieces without context or practical application. Duplicates or studies with insufficient methodological clarity.
Time Frame	2000–2024 (captures modern systems frameworks).	Pre-2000 (unless Books and Book chapters).
Language	English.	Non-English (no translation capacity).
Focus	Explicit link to systems theory and climate.	General resilience studies without systems lens.

TABLE 1: Inclusion and exclusion criteria

IPCC, Intergovernmental Panel on Climate Change

Over 200 documents were retrieved during the initial search. The documents were screened based on titles and abstracts' relevance and full-text review. Following the screening, 100 studies were shortlisted for full-text review and 89 (Table *2*) were selected for in-depth analysis and synthesis. The 46 selected studies were critically analyzed for theoretical foundation, empirical evidence, methodological approaches, and applied contributions. Key themes, patterns, and research gaps were identified to inform the review objectives.

Sources	References Number	Counts	Year Covered
Nature & High-Impact Journals (Nature, Science, and PNAS)	2, 3, 20, 21, 23, 25, 26, 27, 29, 31, 32, 34, 40, 59, 73, 77, 78, 87, 89	19	2009–2025
Government/Intergovernmental Reports (IPCC, UNEP, World Bank, etc.)	4, 5, 6, 8, 28, 33, 38, 43, 47, 50, 52, 64, 67, 68, 82	15	2009–2025
Academic Publishers (SpringerLink, Elsevier, and Cambridge UP)	1, 7, 10, 12, 14, 17, 19, 35, 37, 41, 44, 45, 46, 48, 49, 51, 53, 54, 55, 56, 58, 62, 63, 65, 66, 69, 71, 72, 74, 75, 76, 79, 80, 81, 83, 84, 85, 86, 89	39	1989–2025
Open Repositories (JSTOR, Google Scholar, and ResearchGate)	9, 11, 13, 15, 16, 18, 22, 24, 30, 36, 39, 42, 57, 60, 61, 70	16	1992–2025

TABLE 2: References and sources

IPCC, Intergovernmental Panel on Climate Change; UNEP, United Nations Environment Programme; PNAS, Proceedings of the National Academy of Sciences of the United States of America

Foundational principles of systems thinking

The foundational principles of systems thinking (Table *3*) emphasize interconnectedness, feedback loops, emergence, and non-linearity.

Principles	Definition	Examples and Applications	Key Authors and Contributions
Interconnectedness	Relationships between elements of a system, where one element influences others.	Climate change, economic instability, ecological systems, social systems.	Wächter (2011): Critical for addressing complex problems like climate change or economic instability. Capra and Luisi (2012): Essential for understanding ecological and social systems. Sterman (2000): Importance of mapping causal relationships.
Feedback Loops	Mechanisms through which systems self-regulate (positive amplifies, negative stabilizes).	Ecological systems, economic systems, organizational behavior, unintended consequences in social systems.	Wächter (2011): Feedback loops are the "lifeblood" of systems. Sterman (2000): Role in understanding delays and oscillations. Bailey and Richardson (1992): Application in organizational and social systems.
Emergence	System behavior arising from interactions of components, not predictable from individual parts.	Biological systems, economic systems, organizational behavior, climate change.	Holland (1998): Complex systems exhibit properties beyond individual components. Goldstein (1999): Key feature of complex adaptive systems. Wheeler and Checkland (2000): Essential for addressing "messy" real-world problems.
Non-linearity	Cause-and-effect relationships are disproportionate and unpredictable.	Climate systems, system dynamics, weather patterns, chaos theory.	Wächter (2011): Small changes can lead to large effects (e.g., tipping points). Sterman (2000): Complicates modeling and decision-making. Devaney and Gleick (1989): Explored in chaos theory (e.g., weather patterns).

TABLE 3: Foundational principles of systems thinking

These principles provide a framework for understanding and addressing complex problems. These principles emphasize the importance of viewing systems holistically, recognizing the dynamic and often unpredictable nature of their behaviors. The literature reviewed highlights the relevance of these principles across disciplines, from ecology and economics to organizational management and climate science.

Anderson et al. [11] defines interconnectedness as the relationships between elements of a system, where the behavior of one element influences others, and argues that understanding these relationships is critical for addressing complex problems like climate change or economic instability. Interconnectedness is a core principle of systems thinking, emphasizing that all components of a system are interrelated and that changes in one part can have cascading effects on others. This principle highlights the importance of understanding relationships and dependencies within a system. In addition, [12] discuss interconnectedness in the context of living systems, emphasizing that no component of a system exists in isolation. They argue that this principle is essential for understanding ecological and social systems. Sterman [13], on the other hand, highlights the importance of mapping causal relationships in systems to understand how changes in one variable can propagate through the system.

Feedback loops are mechanisms through which systems self-regulate. Positive feedback loops amplify changes, while negative feedback loops stabilize systems by counteracting changes. According to Anderson et al. [11], feedback loops are the "lifeblood" of systems, driving their behavior over time. For example, it is to reinforce (positive) and balance (negative) feedback loops in ecological and economic systems. Sterman [13], on the other hand, discusses the role of feedback loops in dynamic systems, emphasizing their importance in understanding delays and oscillations in system behavior. Bailey and Richardson [14] explores the application of feedback loops in organizational and social systems, demonstrating how they can lead to unintended consequences if not properly understood.

The phenomenon where system behavior arises from the interactions of its components, rather than being predictable from the individual parts alone is referred to as emergence [15]. According to him, emergence is defined as the process by which complex systems exhibit properties that cannot be explained by the behavior of their individual components. For example, biological and economic systems behavior cannot be explained by the behavior of their individual elements. Goldstein [16], on the other hand, defines emergence is a key feature of complex adaptive systems, emphasizing its relevance to organizational and social systems. Wheeler and Checkland [17] also highlighted the importance of emergence in soft systems methodology, arguing that understanding emergent properties is essential for addressing "messy" real-world problems like climate change.

The cause-and-effect relationships in complex systems are often disproportionate and unpredictable, making it difficult to predict system behavior using linear models. Anderson et al. [11] emphasize that non-linearity is a defining feature of complex systems, where small changes can lead to disproportionately large effects; for example, a small change in global temperature can lead to disproportionate change in climate systems. According to [13], non-linearity of system dynamics can complicate modeling and decision-making in complex systems. Devaney and Gleick [18] explores non-linearity in chaos theory and demonstrated that small changes in initial conditions can lead to vastly different outcomes in systems like weather patterns.

The systems approach to climate change

Meadows, 2008, uses the term “wicked problem” to describe climate change, due to its complex and interdependent nature that defy linear solutions and are often compounded by contradictory stakeholder interests, delayed feedback, and deep uncertainties. According to Meadows [19], traditional reductionist approaches, which attempt to address climate change through isolated technical or policy interventions, often fail to account for the systemic interdependencies and feedback loops that define the problem. The systems perspective rejects reductionist, siloed strategies in favor of integrated frameworks that account for the dynamic interactions among multiple subsystems (biophysical, socioeconomic, and governance related).

Biophysical Subsystems

The earth's climate functions as an intricate web of interconnected biogeochemical processes that maintain equilibrium through delicate feedback mechanisms [20]. These natural systems, evolved over millennia, demonstrate remarkable resilience yet remain vulnerable to anthropogenic disruption [21]. At the heart of this complexity lies the carbon cycle, where terrestrial and marine ecosystems serve as critical carbon sinks through photosynthesis and oceanic dissolution [22]. However, human activities are systematically dismantling these natural balancing mechanisms, pushing planetary systems toward dangerous tipping points [23].

Deforestation represents one of the most immediate threats to these regulatory systems. When forests are cleared, they not only release stored carbon but eliminate future sequestration capacity, creating a perilous feedback loop [24]. The Amazon rainforest exemplifies this vulnerability, with studies suggesting portions may be transitioning from carbon sink to source due to deforestation and climate stress [25].

The thawing of permafrost in Arctic regions releases ancient stores of methane and CO_2, triggering another dangerous feedback loop. Similarly, ocean acidification is impairing marine carbon sinks while threatening biodiversity [26]. The concept of planetary tipping points underscores that these changes may become self-perpetuating beyond certain thresholds [27].

The biodiversity crisis compounds these challenges [28]. Ecosystems with reduced species diversity show lower climate resilience and carbon storage capacity [29]. Current extinction rates are eroding nature's ability to buffer climate change [30].

This systems perspective reveals the inadequacy of piecemeal climate solutions [19]. Protecting natural carbon sinks must become a global priority, recognizing them as dynamic life-support systems [31]. Ripple et al. [32] noted that we are currently testing Earth's limits, and the consequence of this is urgent and comprehensive action that addresses both emissions and ecosystem restoration.

Socioeconomic Subsystems

The relationship between human systems or socioeconomic subsystems and climate change is fundamentally shaped by deep structural inequalities that create a stark divide between those driving emissions and those bearing their consequences [33,34]. While affluent populations and industrialized nations have contributed disproportionately to historical GHG emissions, marginalized communities across the global south face the most severe climate impacts despite having minimal responsibility for causing them. This climate injustice is not accidental but rather embedded within the very fabric of global economic systems, where patterns of resource extraction, energy consumption, and political power perpetuate a cycle of ecological harm and human vulnerability.

The climate inequality crisis manifests most visibly in the uneven distribution of both emissions and climate vulnerabilities. Research by Oxfam [33] reveals that the wealthiest 10% of the global population accounts for over half of cumulative carbon emissions, while the poorest 50% of those least equipped to cope with climate disruptions, contribute less than 10%. This disparity extends geographically, with low-income countries in regions like sub-Saharan Africa and South Asia experiencing intensifying droughts, floods, and food insecurity despite their negligible historical emissions [35]. At the community level, Indigenous groups, small-scale farmers, and urban poor populations face compounded risks due to preexisting socioeconomic marginalization, lacking both the financial resources and political influence to adapt effectively [36].

Essential to these inequities is the dominant economic paradigm of neoliberal capitalism, which prioritizes endless growth and profit accumulation at the expense of ecological stability. According to Moore [37], the relentless drive for resource extraction has enabled wealthy nations and corporations to externalize environmental costs onto vulnerable populations through practices like deforestation, fossil fuel expansion, and land dispossession. For instance, industrial agribusinesses in the Amazon often backed by international capital have transformed critical carbon sinks into emission sources while displacing indigenous forest guardians. Similarly, the globalization of high consumption lifestyles, particularly among urban elites in developed nations, continues to accelerate energy demand and carbon lock-in, even as renewable alternatives become technologically feasible [38].

These structural imbalances create significant barriers to effective climate action. Policy frameworks remain heavily influenced by corporate interests that resist systemic change, as seen in persistent subsidies for fossil fuels and the weak enforcement of environmental regulations [39]. Meanwhile, the nations and communities most exposed to climate risks lack meaningful representation in global decision-making forums, leaving adaptation efforts chronically underfunded. The failure of wealthy countries to meet their climate finance commitments exemplifies this institutionalized neglect, forcing vulnerable populations to shoulder adaptation costs that should rightfully be borne by major polluters [40].

Addressing these deep-seated inequities requires moving beyond technical solutions to confront the root causes of climate injustice. A transformative approach must have as a central principle of redistribution and recognizing that effective climate action cannot be separated from broader struggles for economic and political equality [41]. This includes establishing robust mechanisms for loss and damage compensation, implementing just transition policies that protect workers in sunset industries, and fundamentally rethinking economic models to prioritize well-being overgrowth. Equally crucial is the empowerment of frontline communities through land rights recognition, direct climate financing, and meaningful inclusion in policy design. Only by dismantling the structures that perpetuate ecological and social exploitation can we develop climate solutions that are both effective and equitable.

The climate crisis ultimately reflects a crisis of governance and economic organization. Technical measures to reduce emissions, while necessary, will remain insufficient if they fail to challenge the systems that concentrate wealth and power while distributing environmental harms to the most vulnerable. A just climate future demands not only cleaner technologies but also a fundamental reimagining of how societies organize production, distribute resources, and make collective decisions about our shared planetary future.

Governance Subsystems

The nation-state system, structured around territorial sovereignty and electoral cycles, systematically prioritizes short-term economic growth over long-term ecological stability, creating what political theorists term a "temporal mismatch" between political incentives and climate realities [42]. This institutional inertia manifests most visibly in the persistent gap between national emissions reduction commitments and the actual decarbonization pathways required to limit warming to 1.5°C (UNEP, 2022), with current policies projected to result in 2.8°C of warming by the century's end [43]. According to Lohmann [44], the resulting policy environment privileges market-based solutions like carbon trading over regulatory approaches, despite evidence that such mechanisms frequently fail to reduce emissions while exacerbating environmental injustices.

Fragmentation of government institution and dispersed responsibilities of climate actors across multiple governmental agencies often working at cross-purposes further exacerbates the challenges [45]. For example, energy ministries frequently promote fossil fuel expansion even as environment departments pursue emissions reductions, while trade agreements negotiated by commerce officials routinely undermine climate objectives [46]. This bureaucratic siloing reflects deeper contradictions in state imperatives, torn between maintaining economic competitiveness in a carbon-intensive global economy and addressing existential ecological threats [47].

The democratic deficit in global climate governance further erodes policy effectiveness. While Indigenous communities and frontline populations possess critical knowledge and stakes in climate outcomes, decision-making remains concentrated among technical elites and political actors distant from climate impacts [48]. This exclusion replicates colonial patterns of resource governance, with Global North institutions dominating climate finance flows while local communities bear adaptation burdens [49]. Even progressive policy instruments like the Green Climate Fund remain mired in bureaucratic hurdles, with only 12% of funds reaching local actors directly [50].

Emerging polycentric governance arrangements offer partial solutions but face structural limitations. Subnational climate networks like C40 Cities demonstrate how municipal actors can bypass national gridlock [51], while rights-based litigation is forcing some governments and corporations to align with climate science [52]. However, these decentralized approaches lack the coordination and resource-mobilization capacity required for economy-wide transformations [53]. The fundamental challenge remains reconstructing governance systems to overcome short-termism, corporate capture, and institutional fragmentation - a task requiring nothing less than democratic renewal alongside economic paradigm shifts [54].

The Role of Technology and Governance in Climate Action

The prevailing climate change mitigation paradigm remains narrowly focused on technical solutions such as renewable energy deployment, carbon capture technologies, and efficiency improvements, while systematically neglecting the underlying political-economic structures that drive ecological breakdown [37].

To explore the role of technology and governance in climate action, we draw on Malm and Hornborg’s [55] theory of climate reductionism, which critiques the tendency to frame the complex, multidimensional crisis of anthropogenic climate change as a narrowly technical problem of rising atmospheric CO_2 disconnected from its structural roots in capitalist systems of production and consumption. Within this framework, the neoliberal extractivist model, dominant since the 1980s, has intensified ecological degradation through a set of interlocking mechanisms [24,56]. First, the unitization of nature has transformed ecosystems into commodified "natural capital," subject to the same growth imperatives that drive fossil capitalism [57]. Second, the global division of labor continues to externalize environmental costs to the Global South, where 90% of deforestation occurs to service Northern consumption patterns [58]. Third, the growth-dependent structure of modern economies requiring 3% annual GDP growth to maintain stability directly conflicts with ecological limits [58]. These structural factors remain conspicuously absent from mainstream climate policy frameworks, including the IPCC's mitigation scenarios, which frequently rely on unproven negative emissions technologies rather than addressing production and consumption dynamics [59].

In Uganda, climate policy landscape exemplifies this disconnect. While the country has implemented progressive renewable energy policies increasing solar capacity from 20 MW in 2015 to 120 MW in 2023, its climate action plans systematically avoid confronting the land grabs driving deforestation [60]. In total, between 1990 and 2010, Uganda lost 31% of its forest cover, a decline from 5 million hectares to 3.6 million hectares, the forest land grabbing is one of the major factors currently driving this loss [61]. These concessions, often justified as "green investments" in biofuel crops, have displaced 35,000 people from the Bugoma Forest alone while accelerating carbon emissions [33]. The paradox highlights how techno-fixes become complicit in ecological destruction when decoupled from structural analysis.

Application of systems thinking to climate change mitigation

Climate change mitigation is action to reduce climate change by limiting the emission of GHGs in the atmosphere. Designing an effective climate change mitigation strategy calls for creative and comprehensive strategies that can lower GHG emissions and improve carbon sinks. The current traditional reductionist approaches such as replacing fossil fuels with clean energy sources overlooked the intricate and interconnected character of climate systems. Therefore, an effective foundation for creating successful mitigation solutions is systems thinking, which highlights the interactions and feedback loops found in complex systems [13]. To demonstrate the usefulness of systems thinking in promoting sustainable mitigation solutions, we examined its application, with a particular emphasis on integrated energy systems, circular economy concepts, and sustainable land-use management.

Integrated Energy Systems

Integrated energy system is defined as cost-effective, sustainable, and secure energy system in which renewable energy production, infrastructure, and consumption are integrated and coordinated through energy services, active users, and enabling technologies [62]. Systems thinking approach to integrated energy systems aims at reducing emissions while maintaining reliability through integrating renewable energy sources, energy storage, and demand-side [63]. Traditional energy systems often rely on centralized fossil fuel-based power generation, which is a major contributor to GHG emissions. In contrast, integrated energy systems leverage renewable energy sources such as wind, solar, and hydropower, combined with advanced energy storage technologies and smart grid solutions to optimize energy use and reduce emissions [63].

In Denmark, transition to renewable energy exemplifies the success of systems thinking in energy systems. The country has integrated wind energy into its grid, achieving over 50% of its electricity demand from wind power in 2020 [64]. This transition was facilitated by a combination of policy support, technological innovation, and public-private partnerships, demonstrating the importance of a holistic approach to energy system design.

Circular Economy

The circular economy is a systems-based approach that promotes resource efficiency and waste reduction by closing material loops and minimizing resource extraction [65]. Traditional linear economic models, which follow a "take-make-dispose" pattern, are unsustainable and contribute significantly to GHG emissions. In contrast, the circular economy emphasizes reuse, recycling, and remanufacturing to create closed-loop systems that reduce emissions and resource consumption [65].

The Netherlands has been a pioneer in implementing circular economy principles [66]. Known globally for its innovative approach, the Dutch government has set ambitious targets to transition to a fully circular economy by 2050, with interim goals of reducing primary resource use by 50% by 2030 [62]. These targets are part of a comprehensive national strategy that emphasizes reducing dependency on raw materials, minimizing waste, and fostering sustainable production and consumption patterns.

The approach to the Netherland circular economy is characterized by its focus on systemic change, involving collaboration between government, businesses, and research institutions. For instance, the country has implemented industrial symbiosis initiatives, where waste from one industry becomes a resource for another, creating closed-loop systems that minimize waste and maximize resource efficiency [67]. In addition, the Netherlands has invested in waste-to-energy projects, which convert non-recyclable waste into energy, thereby reducing landfill use and GHG emissions [68]. Above all, the supportive policies and funding mechanisms created by the Dutch government is accelerating the transition to a circular economy.

Land-Use Management

Land-use management is another critical area where systems thinking can enhance climate change mitigation. Balancing competing demands for land use, such as agriculture, forestry, and urban development, is essential for optimizing carbon sequestration and biodiversity conservation. Unsustainable land-use practices, such as deforestation and intensive agriculture, contribute significantly to GHG emissions and biodiversity loss [68].

A systems approach to land-use management involves integrating multiple objectives, such as food security, carbon sequestration, and ecosystem conservation, into a cohesive strategy. For example, agroforestry systems, which combine trees with crops and livestock, have been shown to enhance carbon sequestration while improving soil health and biodiversity [69]. Similarly, urban green infrastructure, such as green roofs and urban forests, can mitigate emissions by sequestering carbon and reducing the urban heat island effect [70].

The Outlook

We observed that the application of systems thinking to climate change mitigation offers a promising pathway for addressing the complex and interconnected challenges of reducing GHG emissions and enhancing carbon sinks. Integrated energy systems, circular economy principles, and sustainable land-use management are key components of a systems-based approach to mitigation. The case studies from Denmark and the Netherlands are a clear demonstration of the practical effectiveness of systems thinking in driving sustainable mitigation strategies. Scaling up these approaches and addressing potential barriers to implementation, such as policy fragmentation and technological limitations should be a major future intervention by both actors in the climate change fight.

Application of systems thinking to climate change adaptation

Climate change adaptation is the process of adjusting to the effects of climate change, both current and anticipated [71]. Designing effective climate change adaptation strategies required a comprehensive strategy that incorporate the complex issues in the climate systems. Using relevant literatures, we reviewed the importance of systems thinking in designing effective climate change adaptation strategies, looking at the three fundamental principles of resilient infrastructure, ecosystem-based adaptation, and social equity.

Resilient Infrastructure

Sustainable development, particularly in the context of water and agriculture, requires infrastructure capable of withstanding climate impacts. Climate change poses significant threats to water resources and agricultural productivity, making adaptive infrastructure planning essential for mitigating these risks. Wilby and Keenan [72] emphasize the importance of integrating climate projections into urban and rural planning to enhance resilience, particularly in addressing flood risks, which are exacerbated by changing climatic conditions.

Water infrastructure, such as irrigation systems, reservoirs, and drainage networks, must be designed to cope with increased variability in precipitation patterns, including more intense rainfall events and prolonged droughts. For instance, in agricultural regions, resilient water infrastructure can ensure reliable water supply for crops, even during periods of water scarcity, thereby safeguarding food security. Wilby and Keenan [72] highlight the need for adaptive strategies, such as the construction of flood-resistant storage facilities and the implementation of water-efficient irrigation technologies, to reduce vulnerability to climate-induced water stress.

In addition to water management, agricultural infrastructure must also be climate resilient. This includes the development of robust storage facilities for crops, climate-smart farming equipment, and infrastructure that supports sustainable land management practices. For example, the use of green infrastructure, such as vegetative buffers and wetlands, can help manage stormwater runoff, reduce soil erosion, and improve water quality, all of which are critical for agricultural sustainability [72].

Furthermore, the integration of climate projections into infrastructure planning can help identify vulnerable areas and prioritize investments in regions most at risk from climate impacts. This proactive approach not only enhances the resilience of water and agricultural systems but also supports long-term sustainable development by ensuring that infrastructure can adapt to future climate conditions.

Ecosystem-Based Adaptation

Leveraging natural ecosystems provides cost-effective and sustainable solutions for enhancing climate resilience, particularly in the context of water and agriculture. Natural ecosystems, such as wetlands, forests, and riparian buffers, play a critical role in regulating water cycles, mitigating floods, and maintaining soil health, which are essential for agricultural productivity and water security. According to Berrang-Ford et al. [73], the importance of ecosystem-based approaches, such as wetland restoration, in building adaptive capacity in vulnerable regions is significant. Wetlands, for instance, act as natural water filters, reducing sediment and nutrient runoff into agricultural fields, while also serving as buffers against extreme weather events like floods and droughts [73]. These nature-based solutions not only protect communities from climate impacts but also preserve biodiversity, which is vital for maintaining ecosystem services that support agriculture and water availability.

In agriculture, integrating natural ecosystems into farming practices such as agroforestry, conservation tillage, and the use of cover crops can improve water retention in soils, reduce erosion, and enhance resilience to climate variability. For example, agroforestry systems, which integrate trees with crops and livestock, have been shown to improve microclimates, reduce water evaporation, and increase groundwater recharge [74]. Similarly, restoring riparian buffers along rivers and streams can reduce agricultural runoff, improve water quality, and provide habitats for pollinators and other beneficial species, thereby supporting both agricultural productivity and ecosystem health [75].

Moreover, ecosystem-based approaches are often more cost-effective than engineered solutions, such as dams or irrigation systems, and they provide co-benefits such as carbon sequestration, habitat creation, and recreational opportunities. For instance, the restoration of wetlands not only enhances water storage and filtration but also sequesters carbon, contributing to climate change mitigation [76]. These strategies are particularly valuable in developing regions where financial resources for infrastructure are limited, and communities rely heavily on natural resources for their livelihoods.

Social Equity

Ensuring that adaptation strategies address the needs of vulnerable populations is essential for equitable resilience, particularly in the context of water and agriculture. Water is a critical resource for agricultural productivity, and its availability and quality are increasingly threatened by climate change. Vulnerable populations, such as smallholder farmers, rural communities, and indigenous groups, often bear the brunt of these challenges due to their reliance on rain-fed agriculture and limited access to water management infrastructure. Inclusive adaptation practices must prioritize these marginalized communities to promote social justice and ensure that climate responses do not exacerbate existing inequalities.

Berrang-Ford et al. [73] highlights the importance of inclusive adaptation strategies that address the specific needs of vulnerable populations. For instance, in the agricultural sector, adaptation measures such as improved irrigation systems, water harvesting techniques, and drought-resistant crops can significantly enhance resilience. However, these interventions must be designed and implemented in ways that are accessible to marginalized communities. This includes ensuring that women, who often play a crucial role in water management and agricultural activities, have equal access to resources and decision-making processes.

Besides, equitable water governance is very important for sustainable agriculture and social equity. Policies that promote fair distribution of water resources, protect water quality, and involve local communities in decision-making can help build resilience and reduce vulnerability. This includes, community-based water management initiatives, which have been used to improve water security and agricultural productivity while fostering social cohesion and equity [77]. By ensuring that adaptation strategies are accessible and equitable, we can build a more resilient and just society in the face of climate change.

A case of Uganda

Uganda is in southeast Africa between 1º S and 4º N latitude, and between 30º E and 35º E longitude (Figure *2*). Its natural features are very diverse, including volcanic hills, mountains, and lakes. The average altitude is about 900 meters above sea level. It is bordered by mountains on both Eastern and Western sides.

The climate of Uganda is mostly tropical with systematic rainfall and sunshine patterns. However, the seasons are changing with the rainy season becoming more variable in length and droughts more ubiquitous pervasive, especially in eastern and northeastern Uganda [78]. These variation in seasons therefore can potentially affect the development of Uganda.

We explored Uganda's efforts in using integrating systems thinking as part of its climate change mitigation strategy. We examined the concept of renewable energy, circular economy practices, and sustainable land-use management used in managing the climate change crisis.

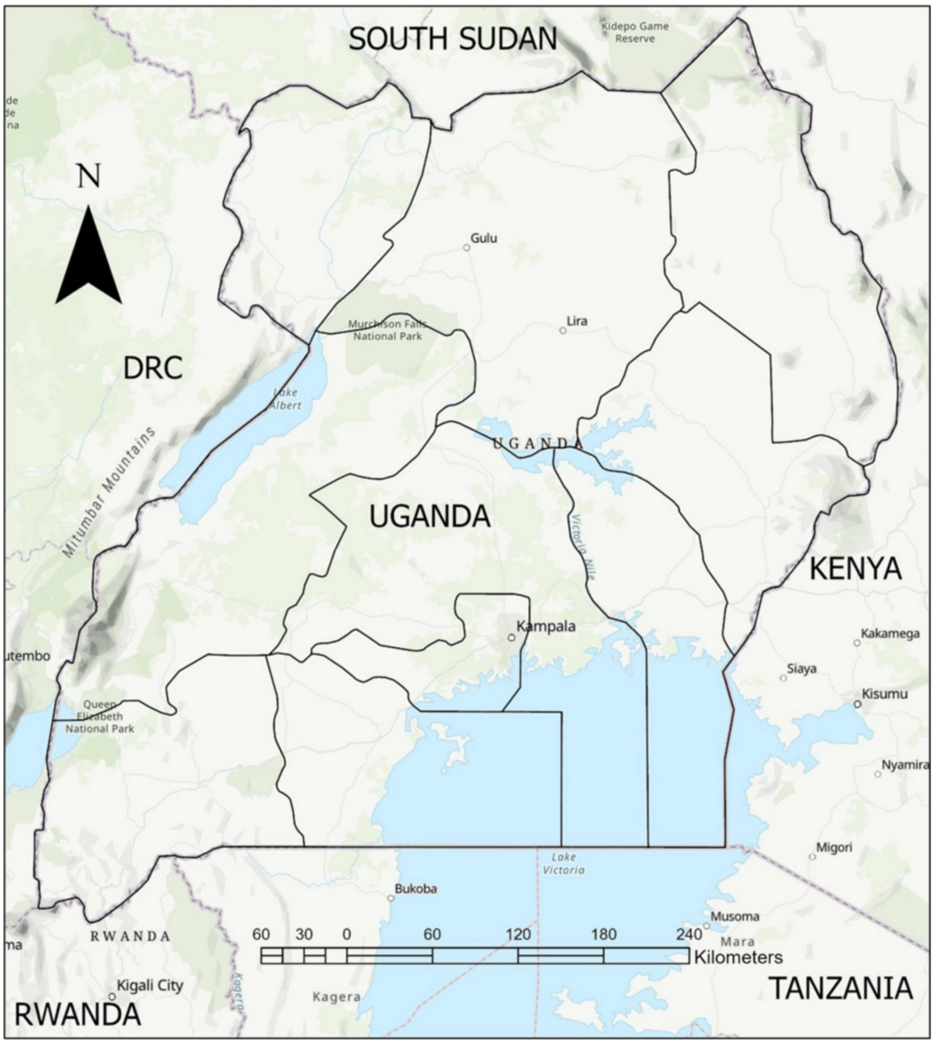

FIGURE 2: Uganda and its relief

Integrated Renewable Energy Systems

Uganda's energy sector is predominantly reliant on biomass, which accounts for over 90% of the country's energy consumption, leading to deforestation and increased GHG emissions [79]. To mitigate this, the Uganda government has embraced renewable energy systems, particularly solar, hydro, and biomass energy, as part of a systems thinking approach.

Uganda has invested in large-scale hydropower projects, such as the Bujagali and Karuma dams, to diversify its energy mix and reduce reliance on fossil fuels [80]. These projects are integrated with grid expansion programs to ensure energy accessibility and reliability. Off-grid solar systems, such as solar home systems and mini-grids, have been deployed in rural areas to provide clean energy access while reducing deforestation [81]. Programs like the Uganda Solar Energy Association promote the adoption of solar technologies. Improved cookstoves and biogas systems have been introduced to reduce biomass consumption and GHG emissions [79]. These initiatives are part of a broader strategy to integrate renewable energy into Uganda's energy system. Despite progress, challenges such as financing, infrastructure gaps, and policy implementation remain barriers to scaling renewable energy systems [80].

Adopting Circular Economy Principles

The government of Uganda is making deliberate effort to integrate circular economy principles into its waste management and industrial practices to promote resource efficiency and reduce emissions. For example, in Kampala, the capital city, waste management systems are being redesigned to convert organic waste into biogas and compost, reducing landfill emissions and creating economic opportunities [82]. Uganda has implemented policies to ban single-use plastics and promote recycling. For example, the National Environment Management Authority has partnered with private sector actors to establish plastic recycling plants. In the agricultural sector, crop residues and animal waste are being repurposed for biogas production and organic fertilizers, closing nutrient loops and reducing emissions [22]. These initiatives demonstrate Uganda's commitment to circular economy principles, though scaling these efforts requires stronger policy frameworks and public awareness.

Sustainable Land-Use Management

Land-use management is critical for Uganda's climate change mitigation efforts, given its reliance on agriculture and the need to balance food security with environmental conservation. Uganda has implemented reforestation programs, such as the National Forestry Authority's efforts to restore degraded forests and promote agroforestry. These initiatives enhance carbon sequestration while supporting livelihoods. Climate-smart agricultural practices, such as conservation tillage, intercropping, and agroecology, are being promoted to reduce emissions and improve soil health [83]. Programs like the Uganda Climate-Smart Agriculture Program integrate these practices into national policies. Uganda has also developed land-use planning frameworks to balance competing demands for agriculture, forestry, and urban development. For example, the National Land Use Policy (2019) emphasizes sustainable land management to optimize carbon sinks and biodiversity conservation. However, challenges such as land tenure conflicts, population pressure, and limited funding hinder the full implementation of sustainable land-use practices [83].

The effort by Uganda government to transition to renewable energy, adoption of circular economy principles, and sustainable land-use management demonstrate the adoption of systems thinking to climate change mitigation as seen in the Uganda Renewable Energy Policy (2007).

Challenges and limitations of systems approach

Despite systems approach offering significant solutions to addressing the climate change crisis, its implementation faces several challenges. These include the inherent complexity of systems thinking, data requirements, institutional barriers, and equity concerns. We expounded on these challenges and their implications for climate change mitigation and adaptation.

Complexity of Systems Thinking

Systems thinking, by its nature, involves understanding and managing complex, interconnected systems. While this holistic perspective is a strength, it also poses significant challenges in terms of communication, implementation, and decision-making. The complexity of systems thinking can make it difficult for stakeholders, including policymakers and the public, to grasp and act upon.

Sterman [13] highlights the cognitive challenges associated with systems thinking, noting that humans often struggle to understand feedback loops, delays, and nonlinear relationships inherent in complex systems. This complexity can lead to oversimplification or misinterpretation of system dynamics, undermining the effectiveness of interventions. In addition, Voinov and Bousquet [84] noted the difficulty of translating systems models into actionable policies, particularly when stakeholders have varying levels of expertise and competing priorities. Overcoming these barriers requires carefully designed curricula with special focus on systems analysis as cross-cutting discipline.

Data Requirements For Systems Analysis

Effective systems analysis relies on robust, high-quality data to model interactions and predict outcomes. However, data availability and accessibility remain significant challenges, particularly in developing countries or for underrepresented systems such as small-scale agriculture or informal settlements. Incomplete or fragmented data can limit the accuracy and applicability of systems models.

Liu et al. [85] noted the challenges of integrating data from diverse sources, including remote sensing, social surveys, and economic indicators, to create comprehensive systems models. They pointed out that data gaps and inconsistencies can hinder efforts to understand and address climate change impacts. Furthermore, data collection and analysis often require significant financial and technical resources, which may not be available in resource-constrained settings [86]. Addressing these data challenges is essential for realizing the full potential of systems approaches.

Institutional Barriers to Implementation

The adoption of systems-based strategies is often hindered by institutional barriers, including siloed governance structures and short-term political cycles. Climate change requires long-term, integrated solutions that transcend traditional administrative boundaries and sectoral mandates. However, many institutions are ill-equipped to support such approaches.

Folke et al. [87] highlights the mismatch between the long-term, adaptive nature of systems thinking and the short-term, reactive nature of many political and institutional frameworks. They argue that siloed decision-making and rigid bureaucratic structures can impede the implementation of holistic strategies. Similarly, the authors [88] identify the lack of cross-sectoral collaboration and coordination as a major barrier to climate action. Overcoming these institutional challenges requires transformative governance reforms and the development of adaptive, inclusive decision-making processes.

Equity Concerns in Systems Approaches

Without careful consideration, systems approaches may inadvertently exacerbate existing inequalities. Climate change disproportionately affects vulnerable populations, including low-income communities, women, and indigenous peoples. Systems-based strategies that fail to account for these disparities risk perpetuating or worsening social and economic inequities.

Raworth [89] critiques traditional systems models for often neglecting issues of power, justice, and equity, noted that systems thinking must incorporate a social justice lens to ensure that climate solutions are inclusive and equitable. Also, Schlosberg and Collins [41] emphasize the importance of participatory approaches that engage marginalized communities in the design and implementation of climate policies. Addressing equity concerns is not only a moral imperative but also essential for the legitimacy and effectiveness of systems-based strategies.

Conclusions

Climate change is a multifaceted global challenge that requires innovative and integrated approaches to address its complexities. A systems approach, rooted in systems thinking, has emerged as a promising framework for understanding and mitigating climate change. In this review, we explored the benefits of adopting a systems approach, focusing on holistic understanding, synergistic solutions, and long-term resilience, supported by scientific literature. A systems approach emphasizes the interconnectedness of natural, social, and economic systems, enabling a more comprehensive understanding of the drivers and impacts of climate change. Climate change is not an isolated phenomenon but a result of dynamic interactions between atmospheric processes, human activities, and ecological systems. Systems thinking allows researchers and policymakers to map these interactions and identify leverage points for intervention. By adopting a holistic perspective, stakeholders can better anticipate unintended consequences and design more effective interventions.

It was noted that one of the key advantages of a systems approach is its ability to generate synergistic solutions that address multiple challenges simultaneously. Climate change mitigation and adaptation strategies often intersect with other societal goals, such as public health, economic development, and social equity. Systems thinking enables the identification of interventions that deliver co-benefits across these domains. For example, the transition to renewable energy not only reduces GHG emissions but also improves air quality and public health. Sustainable urban planning, which integrates green infrastructure and public transportation, can enhance resilience to climate change while promoting economic growth and social inclusion. These examples underscore the potential of systems-based strategies to create win-win solutions.

In addition, climate change is characterized by deep uncertainty, with future impacts and societal responses difficult to predict. A systems approach is particularly well-suited to building long-term resilience, as it emphasizes adaptability, flexibility, and the capacity to learn from feedback. Resilience thinking is a core component of systems approaches and focuses on maintaining system functionality in the face of shocks and stresses. By adopting a systems perspective, policymakers can design interventions that are robust to a range of future scenarios. In addition, integrating insights from multiple disciplines and addressing interconnected challenges, systems thinking provides a powerful framework for tackling climate change. Future research should continue to explore the practical applications of systems-based thinking, particularly in the context of policy design and implementation.

Additional Information

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All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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