# Enhancing the Resilience of Food Systems to Climate Variability in Southern Zambia: A Comprehensive Review of Vulnerability, Knowledge Systems, and Drivers of Change

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## ABSTRACT

Climate variability poses a significant threat to food systems in Agro-Ecological Zone I of Southern Zambia, a region characterized by semi-arid conditions and a high dependence on rain-fed agriculture. This review examines the vulnerabilities of food systems to climate change, assesses the roles of indigenous and scientific knowledge systems in adaptation, and identifies key socio-economic and environmental drivers of change. This article synthesizes existing literature to evaluate the vulnerability of food systems to climate variability, highlights the roles of indigenous and scientific knowledge systems in adaptation, and pinpoints key drivers of change. By integrating theoretical frameworks from climate resilience and food systems literature, this review emphasizes the complex interplay between environmental, socio-economic, and institutional factors that shape food system resilience. The article identifies critical research gaps, including the need for more empirical studies on integrating indigenous and scientific knowledge, the socio-economic barriers to adopting climate-resilient practices, and the role of governance in fostering adaptive capacity. The findings underscore the importance of a multi-dimensional approach to building resilience, combining policy interventions, community-based strategies, and technological innovations. Recommendations include the necessity for inclusive governance frameworks, community-based capacity-building programmes, and targeted financial incentives to support climate adaptation in smallholder farming communities. This review contributes to the broader discourse on climate resilience by offering a context-specific analysis that informs academic research and practical interventions in Southern Zambia and similar agro-ecological zones.

**Keywords**: Climate variability, food systems, resilience, Indigenous knowledge, agroecological zone I, artificial intelligence, knowledge systems, climate drivers

## INTRODUCTION

### Background: Climate Variability and Global Food Security

Climate variability, characterised by unpredictable changes in temperature and precipitation, poses a significant challenge to global food security. The Intergovernmental Panel on Climate Change (IPCC) has consistently highlighted the adverse effects of climate variability on agricultural productivity, particularly in regions dependent on rain-fed farming (IPCC, 2019; Thornton *et al*., 2020). These effects include diminished crop yields, an increased frequency of extreme weather events, and greater vulnerability to pests and diseases, all of which threaten food system stability (Rosenzweig *et al*., 2014; Vermeulen *et al*., 2020). Extreme weather events, such as prolonged droughts, heatwaves, and flooding, have become more common, disproportionately impacting low-income, agriculture-reliant economies (FAO, 2021; Wheeler & Braun, 2019). Moreover, climate variability affects soil moisture levels, alters growing seasons, and disrupts traditional farming practices, worsening food insecurity and malnutrition (Schlenker & Lobell, 2021). In Sub-Saharan Africa, where over 60% of the population depends on agriculture for their livelihoods, these challenges are particularly pronounced, further exacerbating poverty and economic instability (FAO, 2020; Pingali *et al*., 2019).

**Agro-Ecological Zone I of Southern Zambia**

Agro-Ecological Zone I in Southern Zambia exemplifies the global challenges faced by semi-arid regions. This area is characterized by erratic rainfall, prolonged droughts, and high temperatures, making it particularly susceptible to climate fluctuations (Makondo & Thomas, 2020; Mupuchi, 2022). On average, it receives less than 800 mm of rainfall annually, with persistent dry spells disrupting agricultural production and limiting the water supply. The primary farming practices in this region include the cultivation of maize, sorghum, and millet, all of which are highly vulnerable to changes in rainfall and temperature (Chitengi, 2021). Most of the population consists of smallholder farmers who primarily engage in subsistence agriculture, increasingly threatened by climate-related disruptions (Chibamba *et al*., 2024). Many farmers face challenges with inadequate irrigation, a lack of climate-smart agricultural techniques, and insufficient financial services to enhance their resilience (Chanza & de Wit, 2016). Additionally, land degradation and soil erosion, exacerbated by deforestation and unsustainable land management, further diminish agricultural yields (Palatnik *et al*., 2025).

The socioeconomic context in the region amplifies these vulnerabilities, as evidenced by high poverty rates, limited access to education, and poor infrastructure (Mupuchi, 2020; Mulenga *et al.,* 2021). Food insecurity is a pressing concern, with many households experiencing seasonal shortages and malnutrition (Nyanga *et al*., 2024). Gender disparities also hinder adaptation efforts, as women often have restricted access to agricultural resources, education, and decision-making roles (Beuchelt & Badstue, 2019). Understanding the dynamics of food systems in this zone is crucial for developing strategies to enhance resilience and ensure sustainable food security. Future research should promote drought-resistant crops, improve water harvesting methods, and enhance smallholder farmers' access to climate information (Tesfaye *et al*., 2021). Strengthening institutional support, financial systems, and local governance can empower adaptive initiatives in Agro-Ecological Zone I of Southern Zambia (Lipper *et al*., 2018).

**Objectives and Scope of the Review**

The objectives of this review were to:

1. Assess the vulnerability of food systems in Agro-Ecological Zone I to climate variability, focusing on the impacts on agricultural productivity, water availability, and food security.

2. Evaluate the role of indigenous and scientific knowledge systems in mitigating the effects of climate variability and enhancing resilience.

3. Identify the key drivers of change, including environmental, socio-economic, and institutional factors influencing food system resilience.

This review contributes to the growing knowledge of climate resilience and food systems by addressing these objectives and offering context-specific insights broadly applicable to similar agroecological zones.

## METHODOLOGY

This review adopts a qualitative, integrative approach to systematically assess the vulnerability of food systems in Agro-Ecological Zone I of Southern Zambia, with a specific focus on climate variability, resilience mechanisms, and adaptation pathways. The methodology encompasses a multi-phase process involving the systematic selection, critical evaluation, and thematic synthesis of relevant academic and institutional literature.

## LITERATURE SELECTION STRATEGY

The selection process started with a comprehensive review of peer-reviewed journal articles, policy reports, and grey literature from credible organisations like the Food and Agriculture Organization (FAO), World Food Programme (WFP), the Intergovernmental Panel on Climate Change (IPCC), World Bank, and Zambian government line Ministries such as the Ministry of Agriculture (MoA), Ministry of Green Economy and other institutional bodies. Three primary parameters informed the inclusion criteria:

i. **Topical Relevance:** Publications needed to address climate variability, vulnerabilities in food systems, adaptation strategies, the integration of indigenous and scientific knowledge, and the resilience of institutional frameworks.

ii. **Geographic Scope:** The emphasis was placed on literature addressing Agro-Ecological Zone I of Zambia and other closely related semi-arid regions in Sub-Saharan Africa.

iii. **Temporal Range:** Sources published from 2015 to 2025 were prioritized to ensure currency and relevance. However, seminal works outside this range were included when foundational to the topic.

The exclusion criteria included literature lacking empirical grounding, peer-reviewed status, or regional specificity to ensure rigour.

**Data Sources**

The review draws on data from four primary types of sources:

i. **Academic Journals:** High-impact journals in climate science, food systems, environmental studies, agroecology, and development policy were reviewed.

ii. **International Reports: Relevant** Publications from global agencies such as the FAO, IPCC, WFP, UNDP, and World Bank provided contextual data and future climate projections, which were helpful in this review.

iii. **National and Local Documents:** Policy frameworks, agricultural surveys, climate resilience and adaptation reports from the Zambian government institutions and departments and local Non-Governmental Organisations were reviewed.

iv. **Case Studies:** We reviewed region-specific empirical studies focusing on smallholder farmers' experiences with climate impacts and adaptation, especially from Zambia's agroecological Zone I and Sub-Saharan Africa.

Every source was assessed for its methodological strength, credibility, and pertinence to the Zambian context.

**Analytical Framework**

The analysis utilized a thematic content analysis approach. Key concepts such as vulnerability, adaptation, and resilience were employed to organize and interpret the data. Four primary thematic axes structured the analysis:

i. **Climate Vulnerability:** Examining how erratic rainfall, prolonged droughts, and rising temperatures affect crop yields, water availability, and food security.

ii. **Adaptation Mechanisms:** Investigating the contributions of indigenous knowledge (e.g., traditional weather forecasting, agroecological practices) and scientific innovations (e.g., climate-resilient crops, AI-driven tools).

iii. **Drivers of Change:** Identifying socio-economic, environmental, and institutional factors shaping food system transformations.

iv. **Research Gaps:** Highlighting underexplored areas, including knowledge integration and policy-enabling conditions.

Findings from diverse sources were triangulated to ensure robustness, and representative quotes, figures, and conceptual models were included where available.

**Methodological Limitations**

This review has several limitations. Firstly, although efforts were made to ensure comprehensive coverage, empirical studies are scarce in Zambia. Second, the analysis mainly depends on secondary data, which may limit the contextual depth usually found in primary field research. Lastly, publication bias could influence the diversity of perspectives, as studies yielding positive or innovative results tend to be published more frequently. Despite these limitations, this methodological approach offers a multi-dimensional understanding of climate-related vulnerabilities and adaptive capacities in the food systems of Southern Zambia, laying a strong groundwork for future empirical research.

**Theoretical Framework**

This review employs resilience theory, highlighting the significance of enhancing food systems' ability to adapt to climate stressors. Resilience theory provides a framework for understanding how food systems can respond to, recover from, and transform amid climate variability (Rachmad, 2022). Furthermore, the theory highlights the interconnectedness of environmental, socioeconomic, and governance factors that contribute to the resilience of agricultural systems (Zhai & Lee, 2024). In the context of Southern Zambia, resilience theory aids in analysing the challenges faced by smallholder farmers and identifying pathways to increase their adaptive capacity (Mallick *et al*., 2024).

**Vulnerability of Food Systems to Climate Variability**

**Agricultural Productivity: Erratic Rainfall and Rising Temperatures**

Climate variability severely affects agricultural productivity in Agro-Ecological Zone I, deeply impacting crop yields, food security, and the livelihoods of rural communities (Mulungu *et al*., 2021). Unpredictable rainfall patterns disrupt usual planting and harvesting timelines, leading to increased crop failures and lower yields (Thornton *et al*., 2014; Jha *et al.,* 2021). This inconsistency has caused extended dry periods alternated with heavy rainfall, resulting in drought, and flooding that damage crops and deplete soil nutrients (Harrison *et al*., 2020). Additionally, rising temperatures further complicate these challenges by speeding up crop maturation, reducing biomass production, and lowering the nutritional quality of essential crops like maize and sorghum (Rosenzweig *et al*., 2014; Tesfaye *et al*., 2017). Increased heat stress hampers photosynthetic efficiency and raises evapotranspiration rates, lowering soil moisture levels and diminishing crop yields (Lobell *et al*., 2019). Furthermore, elevated temperatures create environments conducive to the spread of pests and diseases, presenting further challenges to agricultural sustainability (Deutsch *et al*., 2018). Smallholder farmers in Agro-Ecological Zone I, who mainly depend on rain-fed agriculture, are especially at risk due to their limited access to irrigation infrastructure and climate-resilient technologies that could help them withstand climate-related shocks. To alleviate these risks, we can embrace drought-resistant crop varieties, adopt better soil conservation methods, and establish early warning systems for extreme weather events (Schlenker & Roberts, 2019; Challinor *et al*., 2021).

**Water Scarcity: Competing Demands and Ecological Impacts**

Water scarcity, exacerbated by erratic rainfall, over-extraction of groundwater, and increasing competition for limited resources, poses a significant challenge to agricultural sustainability in Agro-Ecological Zone I. Farmers struggle to secure sufficient water for irrigation, particularly during prolonged dry spells (Makondo & Thomas, 2020; Muller *et al*., 2019). Many rural communities depend on surface water sources such as rivers and lakes, which are increasingly depleted due to ongoing droughts and rising evaporation rates (Wada *et al*., 2020). The ecological impacts of water scarcity further threaten food production. Reduced soil moisture adversely impacts soil quality, leads to the loss of organic matter, and diminishes soil fertility, thereby impairing crop yields (Lal *et al*., 2018; van Ittersum *et al*., 2016). Furthermore, excessive groundwater extraction results in declining water tables, increased salinity, and land subsidence, complicating water accessibility issues (Scanlon *et al*., 2018). The heightened competition for water among agricultural, industrial, and domestic users intensifies the crisis. Urbanisation and economic development raise water demand, often diverting agricultural water supplies for industrial and municipal purposes, which reduces the irrigation water available to smallholder farmers (Rockström *et al.*, 2017). Implementing integrated water resource management strategies, including rainwater harvesting, conservation agriculture, and efficient irrigation systems, is vital (Connor *et al.*, 2018).

**Food Security: Impacts on Availability, Access, and Nutrition**

In Agro-Ecological Zone I, food security is threatened by water scarcity and declining agricultural productivity. Reduced crop yields and lower livestock output limit food availability, particularly for subsistence farming communities (FAO, 2020; Pingali *et al.*, 2019). Furthermore, extreme weather events disrupt the food supply chain, exacerbating shortages and increasing reliance on food imports, which drive up prices (Vermeulen *et al.*, 2020). Rising food costs hinder access to nutrition, disproportionately affecting low-income families. Climate-related fluctuations in food production contribute to market instability, making staple foods less affordable for vulnerable populations (Barrett, 2020; Wheeler & von Braun, 2019). Poor infrastructure and weak market connections also impede food distribution, widening the access gap between urban and rural communities (Godfray *et al.*, 2018). Climate variability adversely impacts nutrition, as decreased crop diversity limits dietary options and increases dependency on calorie-dense but nutrient-poor foods, exacerbating malnutrition and micronutrient deficiencies (Mbow *et al.*, 2019; Fanzo *et al.,* 2021). Children, pregnant women, and the elderly are particularly vulnerable to food insecurity, facing health issues such as stunting, anaemia, and weakened immune systems (Haddad *et al.*, 2016). To bolster resilience against food security challenges, policies should promote climate-smart agricultural practices, invest in irrigation, and establish social safety nets for at-risk populations. Enhancing local food production through improved storage methods, value chain enhancements, and better access to credit can also help mitigate the negative impacts of climate variability on food security (Lipper *et al.*, 2018).

**Knowledge Systems in Climate Adaptation**

**Indigenous Knowledge: Traditional Practices and Weather Forecasting**

Indigenous knowledge systems, developed over generations, provide crucial insights for climate adaptation and agricultural resilience. Essential traditional practices such as intercropping, crop rotation, and agroforestry play a significant role in maintaining soil fertility, reducing vulnerability to pests and diseases, and enhancing the efficiency of resource use (Pretty *et al.*, 2023; Altieri *et al.*, 2015). For instance, intercropping—planting various crops together in a single field—optimises land productivity and bolsters resilience against crop failure (Mason *et al.*, 2017). Additionally, Indigenous communities rely on weather forecasting methods that utilise environmental indicators, including wind patterns, cloud formations, animal behaviour, and plant phenology (Walter *et al.*, 2022; Nyadzi *et al.*, 2019). These traditional techniques offer localised insights that complement scientific climate models, enabling farmers to make well-informed decisions regarding planting and harvesting cycles (Orlove *et al.*, 2020). However, the reliability of these methods faces challenges due to the increasing unpredictability of climate change, emphasising the necessity for their integration with modern forecasting tools (Huntingford *et al.*, 2019).

**Scientific Knowledge: Modern Technologies and Climate-Resilient Practices**

By developing and applying advanced agricultural technologies, scientific progress is crucial in enhancing climate resilience. Innovations such as drought-resistant crops, precision irrigation methods, and integrated pest management are essential for improving adaptation in regions vulnerable to climate change (Lal *et al.*, 2018; Rojas-Downing *et al.*, 2017). New crop varieties that withstand heat and drought are critical for maintaining stable yields in shifting climatic conditions (Tesfaye *et al.*, 2017). Moreover, precision irrigation systems like drip and sprinkler setups enhance water efficiency by minimising waste and ensuring that crops receive the appropriate amount of moisture (Rockström *et al.*, 2017). Additionally, climate-smart pest management techniques, including biological control and targeted pesticide use, reduce the negative impacts of climate-driven pest outbreaks (Gomez-Macpherson *et al.*, 2018). However, the widespread adoption of these scientific technologies is hindered by financial limitations, inadequate extension services, and a lack of awareness among smallholder farmers (Mupuchi, 2020; Haile *et al*., 2018).

**Integrating Indigenous and Scientific Knowledge: Challenges and Opportunities**

Integrating indigenous and scientific knowledge systems presents a transformative opportunity to enhance climate resilience. By combining the local, experiential wisdom of indigenous farmers with the empirical and technological advancements of modern science, we can achieve a more holistic and adaptive approach to climate adaptation (Makondo & Thomas, 2020; Reid *et al*., 2019). For instance, merging indigenous weather forecasting techniques with meteorological data can improve the accuracy and applicability of climate predictions for local farming communities (Howden *et al*., 2018). However, this integration encounters several challenges. Communication barriers between indigenous knowledge holders and scientific researchers often obstruct knowledge-sharing efforts (Agrawal & Perrin, 2021). Furthermore, differing validation criteria—where scientific knowledge is frequently regarded as more rigorous and systematic—can marginalise indigenous practices (Ensor *et al*., 2021). Limited institutional support and inadequate policy frameworks hinder the formal recognition and integration of indigenous knowledge into climate adaptation strategies (Ford *et al*., 2016). Collaborative platforms that facilitate mutual learning and knowledge exchange should be established to confront these challenges. Participatory research involving scientists and local farmers can foster trust and co-develop culturally and scientifically relevant adaptation solutions (Nelson *et al*., 2017). Moreover, policy initiatives should prioritise documenting and institutionalising indigenous knowledge, ensuring its ongoing relevance in climate adaptation efforts (Chanza & de Wit, 2016).

**The Role of Artificial Intelligence in Climate Adaptation**

Artificial Intelligence (AI) is rapidly emerging as a powerful tool for addressing the challenges posed by climate change, especially in agriculture. In Zambia, AI applications are increasingly recognized for their potential to optimise agricultural practices, manage resources more efficiently, and improve resilience to climate variability. Below are several key AI applications with empirical evidence and potential implementation barriers.

**AI Applications in Agriculture in Zambia**

**AI-Driven Precision Agriculture**

Artificial Intelligence (AI) has found extensive application in agriculture, notably in precision farming, to boost crop yields, lower operational costs, including labour expenses, and enhance productivity (Sharma *et al*., 2020). Technologies like machine learning (ML) models are employed in precision agriculture to optimise resources such as water, fertilizers, and pesticides (Shaikh *et al*., 2022; Sharma *et al*., 2020). Additionally, machine learning helps predict soil characteristics like organic carbon content and moisture levels, forecasts crop yields, and identifies diseases, weeds, and plant species (Rashid *et al*., 2021; Adewusi *et al*., 2024; Sharma *et al*., 2020). AI algorithms process large datasets from sensors, drones, and satellite images, offering real-time insights into crop health, soil conditions, and the best times for irrigation and planting (Javaid *et al*., 2023). A study by Mbale & Phiri (2025) demonstrated that IoT in intelligent agriculture significantly improves crop monitoring and automates irrigation through real-time environmental data. Their research highlighted IoT technologies' potential to transform agriculture by enhancing water efficiency, boosting crop yields, and promoting sustainable farming practices in Zambia. A study by Kumar *et al*. (2023) confirmed the efficacy of AI-driven irrigation systems in Zambia's Choma District, where drone-based monitoring and AI algorithms enabled farmers to optimise water use, achieving a 30% reduction in water wastage alongside enhanced crop yields. The adoption of precision farming technologies in Zambia has resulted in considerable advances in crop management, particularly for maize and vegetables, which are vital for the livelihoods of smallholder farmers (Kunda & Phiri, 2023)

Despite these successes, several obstacles hinder the widespread implementation of precision farming in Zambia, including high initial technology costs, insufficient infrastructure (like reliable internet access), and limited technical expertise among farmers. Moreover, farmers' access to financial resources is often a barrier to investing in AI-driven technologies.

**AI for Pest and Disease Management**

AI-based pest and disease management tools are becoming increasingly vital in Zambia's Agroecological Zone I, where climate variability exacerbates pest and disease outbreaks. Integrating technologies such as the Internet of Things (IoT), machine learning (ML), and artificial intelligence (AI) enhances disease forecasting models, enabling proactive disease control and sustainable agricultural practices (Delfani *et al*., 2024). In their study of the efficacy of AI-based pest prediction systems in Zambia, Kunda and Phiri (2023) demonstrated that mobile apps predicted pest outbreaks with 85% accuracy, resulting in a 20% reduction in crop losses. Additionally, using Convolutional Neural Networks (CNN) to detect tomato leaf disease achieved a 95.8% accuracy rate, further showcasing AI's potential in pest management. These innovations are crucial in Agroecological Zone I, where climate-induced pest dynamics require timely, data-driven interventions. Ali *et al*. (2024) highlight AI's ability to analyze large-scale weather and pest datasets, providing real-time insights into spatial-temporal pest dynamics, essential for developing integrated pest management strategies. AI's role in early detection and forecasting thus offers significant promise in mitigating the evolving challenges smallholder farmers face in Zambia (Kunda & Phiri, 2023).

However, implementing AI for pest management in Zambia presents challenges, including the lack of reliable data sources and the potential digital divide between rural and urban farmers. Additionally, many smallholder farmers in Zambia still rely on traditional knowledge and practices, which can be challenging to integrate with AI-based systems (Boamah *et al*., 2025). Moreover, the cost of smart mobile phones and low internet penetration in rural areas can hinder the widespread adoption of such technologies (Kala, 2023; Mambwe, 2015).

**AI-Enabled Climate Forecasting and Decision Support Systems**

Artificial Intelligence has been applied to enhance climate forecasting models by integrating vast amounts of environmental data, including historical weather patterns, soil moisture, temperature, and precipitation forecasts (Dewitte *et al*., 2021). This enables farmers to make better decisions regarding planting times, irrigation schedules, and crop variety selection, thereby improving their resilience to climate change (Chinchorkar, 2025). AI can better serve agricultural planning, resource allocation, and climate adaptation planning. A notable example is the collaboration between the Zambian Ministry of Agriculture and AI researchers to develop a climate decision support system for smallholder farmers. The system uses machine learning analyses to analyze seasonal climate data and customized recommendations for crops to plant based on the weather conditions. A pilot project in the Southern Province showed that farmers who utilized the AI-driven advice experienced a 15-20% increase in yield compared to those who did not use the system.

The complexity of integrating AI-based systems into existing agricultural practices, limited internet connectivity (Bhangar & Shahriyar, 2023), and the challenge of ensuring that AI-driven advice is understandable and actionable for smallholder farmers all contribute to the issue of trust, as farmers may hesitate to rely on AI predictions instead of traditional knowledge or local weather patterns.

**AI for Water Management**

The growing demand for agricultural productivity and sustainability, amid finite water resources and climate change, drives the need for more efficient water management practices (Ashoka, et al., 2024). Through automated and precision irrigation systems, AI-based predictive models, and AI-driven water quality monitoring, AI technologies significantly improve water efficiency and agricultural output. These systems optimize irrigation scheduling using real-time data, enhance the precision of water application, and ensure water quality, thereby supporting sustainable agricultural practices (Sinwar, *et al*., 2020). AI technologies are increasingly employed to optimize water management in agriculture (Elshaikh, *et al*., 2024). In their study on the Applications of Artificial Intelligence in Precision Irrigation, Elshaikh, *et al*., (2024) demonstrated that natural plant species can be effectively cultivated with AI-supported irrigation systems and that these systems have great potential for water conservation and ecological balance. Despite their success, several challenges remain in scaling up AI-driven water management systems. These challenges include the high initial capital required for installation, the complexity of integrating these systems into smallholder farming operations, and the lack of technical expertise necessary for operating and maintaining the equipment (Ramdinthara, *et al*., 2022). Furthermore, some farmers encounter difficulties accessing essential hardware, such as sensors and irrigation infrastructure, which are often costly.

**Potential Barriers to AI Implementation in Zambia**

i. **High Cost of Technology:** Many smallholder farmers in Agroecological Zone I of Southern Zambia lack the financial capacity to invest in AI-driven technologies (Ramdinthara, *et al*., 2022). Purchasing and maintaining equipment such as drones, sensors, and mobile devices can be prohibitively expensive. Furthermore, implementing AI solutions for crop management and irrigation may require external funding or subsidies, which low-resourced farmers cannot manage.

ii. **Digital Divide:** In rural Zambia, limited internet access and the high cost of mobile phones and data plans restrict smallholder farmers' ability to access AI-based tools and services. Although mobile phone penetration is increasing (Dewitte *et al*., 2021), many rural farmers still face challenges due to insufficient internet access, which hinders the effective use of AI tools.

iii. **Lack of Technical Expertise:** Utilizing AI technologies in agriculture necessitates technical knowledge and skills. In Zambia, there is a shortage of trained personnel capable of operating, maintaining, and troubleshooting AI-driven systems (Ramdinthara, *et al*., 2022). Additionally, farmers require training to interpret and apply AI-generated insights effectively.

iv. **Data Availability and Quality:** AI applications heavily rely on high-quality, reliable data to function effectively. In Zambia, many farmers lack access to the data that AI systems require, such as real-time weather data and precise crop health information (Dewitte *et al*., 2021). The absence of infrastructure for data collection, particularly in remote areas, poses a significant challenge to the widespread use of AI.

v. **Cultural and Social Barriers:** Due to traditional farming practices and scepticism about the effectiveness of modern technologies, there may be resistance to adopting AI technologies. Farmers may prefer to rely on their own knowledge or that of their community, which makes them less likely to trust AI recommendations or incorporate them into their farming practices.

Artificial Intelligence has the potential to revolutionize agriculture in Zambia by enhancing climate resilience through better resource management, pest control, climate forecasting, and optimized water use (Kunda & Phiri, 2023). However, significant barriers remain, including the high cost of technology, limited data access, technical challenges, and a digital divide between urban and rural areas (Sinwar, *et al*., 2020). To address these issues, targeted policy interventions, investments in infrastructure, and capacity-building efforts are essential to make AI technologies more accessible and practical for smallholder farmers in Zambia.

**Drivers of Change in Food Systems**

**Climate Change: Impacts on Growing Seasons and Pest Populations**

Climate variability profoundly impacts agricultural productivity by altering growing seasons and exacerbating pest and disease outbreaks. Rising temperatures and unpredictable rainfall disrupt planting schedules, decrease yields, and lead to frequent crop failures (Mbow et al., 2019; Challinor et al., 2021). These climatic changes also affect soil moisture, causing prolonged droughts or excessive flooding, negatively influencing crop growth (Rosenzweig *et al*., 2020). Additionally, climate change contributes to the increasing pest populations. Warmer conditions favour pest proliferation, enabling them to spread to new areas and reducing the effectiveness of traditional pest control measures (Deutsch *et al*., 2018; Bebber *et al*., 2019). Furthermore, humidity and precipitation fluctuations affect crop disease spread, rendering previously resilient crops more vulnerable to pathogens (Jactel *et al.*, 2021). These challenges demand adaptive approaches such as integrated pest management, climate-smart agriculture, and the development of pest-resistant crop varieties (Godfray *et al.*, 2018).

**Economic Factors: Market Dynamics and Financial Barriers**

Economic factors significantly influence the resilience of food systems. Smallholder farmers, who are responsible for a substantial portion of food production in Agro-Ecological Zone I, often face financial constraints that hinder their ability to adopt climate-resilient practices (FAO, 2020; Barrett *et al.*, 2021). Limited access to credit, high input costs, and fluctuating market prices increase their economic vulnerability, making them less likely to invest in sustainable farming methods (Pingali *et al.*, 2019). Price volatility and weak market connections restrict economic opportunities for these farmers (Vermeulen *et al.*, 2020). The lack of reliable infrastructure and storage facilities also leads to post-harvest losses, reducing potential profits and worsening food waste (Godfray *et al.*, 2018). Furthermore, global economic trends, such as trade barriers and supply chain disruptions, significantly impact local food markets, making farmers more vulnerable to external shocks (Swinnen & Kuijpers, 2020). To address these economic challenges, it is essential to implement targeted policies that improve market access, provide financial support, and promote investments in resilient agricultural technologies (Jayne *et al.*, 2019).

**Policy and Governance: Institutional Frameworks and Governance Challenges**

Building climate-resilient food systems depends greatly on effective policy and governance. Essential policies that promote sustainable agriculture, provide financial incentives, and enhance institutional capacities are crucial for boosting adaptive capacity (Rushton *et al.*, 2023; Lipper *et al.*, 2018). Government interventions should strengthen extension services to assist farmers and provide adequate training and support for adopting climate-smart technologies (Reid *et al.*, 2019). Despite these requirements, governance challenges such as bureaucratic inefficiencies, corruption, and weak policy enforcement pose significant barriers to practical adaptation efforts (Nyanga *et al.*, 2024; Ford *et al.*, 2016). Decentralised governance models that involve local communities in decision-making have demonstrated the potential to enhance policy implementation and ensure adaptation strategies are tailored to specific contexts (Nelson *et al.*, 2017). It is crucial to bolster institutional frameworks through increased funding, capacity-building initiatives, and collaboration among various stakeholders to improve the resilience of food systems (Chanza & de Wit, 2016).

**Research Gaps and Future Directions**

**Knowledge Integration: Bridging Indigenous and Scientific Knowledge**

This review indicates that more empirical studies are needed to integrate Indigenous and scientific knowledge systems. Research should concentrate on developing frameworks that facilitate effective knowledge sharing and collaboration, ensuring that Indigenous expertise is incorporated into formal adaptation strategies. Future studies must explore methods for validating Indigenous knowledge within scientific contexts while preserving its relevance. Additionally, interdisciplinary research is essential to assess the long-term benefits of combining traditional and modern climate adaptation techniques for agricultural sustainability and food security.

**Socio-Economic Barriers: Addressing Poverty and Inequality**

Future research must explore socio-economic barriers to adopting climate-resilient practices, particularly in marginalised communities. Special attention should focus on gender-specific vulnerabilities, as women often face limited access to resources, land ownership, and decision-making power, despite their essential contributions to food production. Furthermore, studies must investigate how education, financial inclusion, and access to extension services can enhance the adaptive capacity of smallholder farmers. Additional research is also critical to assess the impact of social safety nets, microfinance programmes, and cooperative farming initiatives on reducing economic disparities and strengthening resilience.

**Policy and Institutional Support: Strengthening Governance Frameworks**

Further investigation is necessary to assess the effectiveness of policy measures and institutional structures in fostering climate resilience in agroecological Zone I. This study examines how participatory governance and community-centric approaches can strengthen food system resilience. Additionally, research should analyze the scalability and impact of localized climate policies, such as land tenure reforms, disaster risk management strategies, and public-private partnerships that support smallholder farmers. The role of multi-level governance systems in aligning national and local adaptation efforts should also be explored. Finally, comparative analyses of policy successes across diverse agroecological regions in Zambia can provide valuable insights into best practices for enhancing governance frameworks.

## CONCLUSION

Developing resilient food systems in Agro-Ecological Zone I of Southern Zambia requires a comprehensive strategy integrating policy initiatives, community-driven approaches, and technological advancements. By blending traditional and scientific knowledge, addressing socio-economic challenges, and enhancing governance structures, stakeholders can boost the adaptive capacity of smallholder farmers and secure food sustainability amidst climate fluctuations. This review enriches the ongoing conversation on climate resilience, providing context-specific insights relevant to Southern Zambia and similar agroecological regions globally. The outcomes lay the groundwork for future research and policy measures focused on cultivating climate-resilient food systems and advancing sustainable development objectives.

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