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Review of Climate-Smart Agricultural Innovations: Enhancing Resilience and Food Security Among Pastoral and Agro-Pastoral Communities in the Somali Region, Ethiopia

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ABSTRACT

This study presents a systematic literature review of Climate-Smart Agriculture (CSA) innovations and their contributions to resilience building and food security at global and regional levels, with particular emphasis on the Somali Region. A structured review methodology was employed to extract and synthesize data from peer-reviewed journal articles, institutional reports, and policy documents focusing on dryland systems. The analysis critically examined risk characterization and adaptation responses to key climate-related stressors, including increased drought frequency, rainfall variability, and land degradation. The CSA practices assessed in this review include the adoption of improved climate-resilient crop varieties, enhanced rangeland and water management strategies, improved livestock breeds, and the provision of climate information services. The findings reveal strong empirical evidence that CSA practices can sustainably enhance agricultural productivity, increase household income, improve dietary diversity, strengthen livelihoods, and build adaptive capacity, while simultaneously generating mitigation co-benefits. However, the implementation and scaling of CSA interventions remain constrained by multiple barriers, including high upfront investment costs, limited technical knowledge, sociocultural constraints, institutional weaknesses, and inadequate extension support systems. The review underscores that effective scaling of CSA in dryland and conflict-prone settings, such as the Somali Region, requires more than technological solutions. A transformative shift in mindset and governance approaches are necessary. Integrating local knowledge systems, promoting social equity, strengthening policy coherence, and enhancing institutional and extension service capacity are critical to ensuring sustainable and context-appropriate adoption of CSA practices.

Key Words: Climate-Smart Agriculture, Pastoral and agro-pastoral systems, Climate resilience, Dryland agriculture

1. Introduction

Making the weather more erratic everywhere you go, there is blistering heat, insufficient rain, and excessive floods. The rising frequency of intense rains, storms, and floods is harming the soil. In India, where over two-thirds of people rely on agriculture, climate change poses a grave threat. The situation of Climate Change has caused the rainfall to shift towards other areas. Other parts of the world are suffering from a serious drought condition at present time. Pastoral and agro pastoral systems, which integrate livestock with rainfed crop production, are among the most climate vulnerable livelihood systems worldwide (Kiplagat et al., 2025). Their heavy dependence on rangeland condition and highly variable rainfall, combined with limited infrastructure, weak extension services and constrained access to climate resilient technologies, make them acutely sensitive to droughts, heat stress, rangeland degradation and water scarcity (Autio et al., 2021; Kiplagat et al., 2025). In many arid and semi arid lands , climate shocks translate directly into livestock mortality, crop failure, reduced income, and recurrent food shortages. For example, studies in semi arid pastoral and agro pastoral areas report very high frequencies of livestock loss, feed and water scarcity, and associated food insecurity, despite households own adaptive strategies such as mobility, water harvesting, and di-

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versification (Tofu et al., 2023). Food insecurity is therefore both widespread and chronic in dryland regions, where climate variability, drought and resource degradation intersect with poverty, conflict and weak institutions (Wakweya, 2023). In light of increases in production and productivity, climate change and variability, environmental degradation and widespread rural poverty, agricultural systems must change. An integrated framework to transform agriculture through the application of climate-smart agriculture (CSA). According to (Ma & Rahut, 2024), CSA seeks "a triple win": (i) sustainably increasing agricultural productivity and incomes, (ii) enhancing the resilience of livelihoods and agro ecosystems and (iii) in the process, reducing or avoiding greenhouse gas emissions GHG (QA1). An array of climate-smart agricultural practices, like agro-forestry, better cropping varieties, no till mulching, improved inter cropping and rotation, water harvesting, integrated multi-nutrient strategy (IMNS), soil and moisture conservation, regenerative practices, etc., leads to increase in yields, farm income, input use efficiency, soil health and resilience to climate change, not to forget drop in emissions (Bhatnagar et al., 2024; Kabato et al., 2025). According to ongoing research on CSA in smallholder systems across Africa and Asia, it has been shown that food security can be enhanced, livelihood diversification can be achieved, and vulnerability to climate-related shocks can be reduced (Bishibura Erick et al., 2025; Ma & Rahut, 2024). The Somali Region of Ethiopia presents a key but under researched context for understanding climate smart agricultural innovations in pastoral and agro-pastoral systems. The area is largely dry and semi-dry, repeatedly vulnerable to drought and rangeland degradation, almost totally reliant on livestock production and small-scale crop production for livelihoods and food, similar to other any other arid and semi arid lands where the climatic risk to pastoral livelihoods is extremely high (Tofu et al., 2025). Moreover, long-standing conflict and displacement, coupled with poor infrastructure and service delivery, undermine adaptive capacity and food security. Yet emerging experiences from comparable Somali and East African dryland settings show that combining CSA practices with renewable energy, cooperative models, and gender responsive programming can substantially increase yields, diversify incomes and strengthen social cohesion under conflict and climate stress (Datta, 2025; Kiplagat et al., 2025). Against this backdrop, there is a need to systematically review climate smart agricultural innovations relevant to pastoral and agro pastoral systems in drylands, assess their contributions to resilience and food security, and identify pathways for context appropriate scaling in the Somali Region. This review synthesizes global and regional evidence on CSA and related innovations, with a particular focus on dryland agro pastoral systems, to inform research, policy and practice. The scope of the article is threefold. First, it characterizes the main climate related risks and livelihood vulnerabilities facing pastoral and agro pastoral communities in dryland contexts analogous to the Somali Region. Second, it reviews the range of CSA and related innovative practices, technologies and institutional arrangements that have been implemented in such systems, and the evidence on their productivity, resilience and food security outcomes. Third, it critically examines the constraints, trade offs and opportunities for scaling up CSA in socially inclusive, conflict sensitive and climate resilient ways in the Somali Region.

2. Materials and Methods

2.1. Type of study

This study employed a systematic narrative review approach to synthesize existing knowledge on climate-smart agriculture (CSA) practices, climate risk assessment, and resilience strategies in pastoral and agro-pastoral systems, with a particular focus on arid and semi-arid regions such as the Somali Region of Ethiopia. This approach was selected to allow both systematic identification of relevant literature and qualitative thematic synthesis across interdisciplinary sources.

2.2. Sources of literature

The review drew on a wide range of sources, including peer-reviewed journal articles, institutional and technical reports from international organizations (e.g., FAO, IFAD, World Bank, IPCC), government policy documents, and regional strategies related to climate change, agriculture, and pastoral development, and relevant theses and working papers where peer-reviewed evidence was limited.

2.3. Inclusion and exclusion criteria

2.3.1. Inclusion criteria

- Studies addressing climate-smart agriculture, climate resilience, or climate risk assessment.
- Research focused on pastoral or agro-pastoral systems
- Studies examining soil degradation, rainfall variability, drought, vegetation dynamics, or land productivity.
- Literature relevant to arid and semi-arid environments, particularly in East Africa and the Horn of Africa.

2.3.2. Exclusion criteria

- Studies not related to agriculture, pastoralism, or climate change.
- Articles lacking empirical, conceptual, or policy relevance to CSA.
- Duplicated studies or publications with insufficient methodological detail.

2.4. Key search areas

Researchers in making a keyword search used climatesmart agricultural, pastoralism, agro-pastoral, climate resilience, soil degradation, rainfall variability, vegetation dynamic, drought risk, climate risk assessment, Somali Region, and arid and semi-arid lands in combination.

2.5. Time-frame of Reviewed Literature

The review covered published literature, capturing recent advances in CSA concepts, climate risk assessment tools, and resilience-building interventions while allowing inclusion of foundational studies.

2.6. Approach for data synthesis and thematic analysis

Using thematic analysis, the selected studies were systematically screened, organized, and analyzed. Key findings from each study were coded and categorized into major thematic areas. These themes included: (1) soil-related climate risks affecting pastoral and agro-pastoral systems, such as soil erosion, fertility loss, and salinity; (2) the impacts of rainfall variability and recurrent drought on pastoralist livelihoods; (3) rangeland conditions, vegetation dynamics, and land degradation; (4) methodological approaches and practices related to Climate-Smart Agriculture (CSA); and (5) policy and institutional frameworks that enable climate resilient CSA practices, including the integration of climate risk assessment into CSA planning systems.

2.7. Conceptual framework for climate-smart agriculture in the Somali Region

2.7.1. Concept of climate-smart agriculture

Climate Smart Agriculture (CSA) is an approach to transforming and reorienting agricultural systems under climate change to achieve three interlinked pillars: (i) sustainably increase productivity and incomes, (ii) enhance adaptation and resilience, and (iii) reduce or avoid greenhouse gas emissions (Tilahun et al., 2025). Food and Agriculture Organization (FAO) of the United Nations and subsequent reviews consistently define CSA around this "triple win" of productivity, adaptation, and mitigation in support of food security and development goals (Lipper et al., 2014; Zheng et al., 2024). CSA is not a single technology but a context-specific bundle of practices, services, and institutions, ranging from precision and regenerative agriculture, agroforestry, integrated soil fertility management, conservation tillage, and small-scale irrigation to climate information services and insurance (Begna & Wakweya, 2025; Kabato et al., 2025; Ojha et al., 2025). In dryland and pastoral systems, CSA is particularly relevant because it addresses rainfall variability, soil and rangeland degradation, and high climate risk by promoting water-efficient irrigation, drought-tolerant crops, improved rangeland management, fodder production, and better livestock feeding and husbandry (Bogale & Erena, 2022; Kabato et al., 2025).

2.7.2. Climate change impacts on pastoral and agro-Pastoral systems

Climate change in the Somali Region has led to increased temperatures and highly variable, often declining rainfall, causing recurrent droughts that severely impact pastoral and agro-pastoral livelihoods. These changes have resulted in significant livestock losses, reduced crop yields, water scarcity, and food insecurity, with pastoral households perceiving worsening climate conditions over recent decades (Abrham & Mekuyie, 2022; Samatar, 2024). Adaptation strategies in the region include adopting drought-tolerant and early-maturing crop varieties, small-scale irrigation, water harvesting, improved livestock breeds, and local innovations such as destocking during droughts and better rangeland management (Abrham & Mekuyie, 2022; Michael, 2017). Despite these efforts, challenges remain due to limited access to resources, inadequate social safety nets, poor infrastructure, and policy gaps that hinder effective climate resilience (Michael, 2017; Tofu et al., 2025). Climate-smart agricultural innovations tailored to the Somali Region's dryland context focus on enhancing water use efficiency and promoting resilient crops and livestock to sustain productivity under climate stress (Abrham & Mekuyie, 2022; Samatar, 2024). Strengthening community-based institutions, improving access to climate information, and fostering supportive policies are critical for enhancing adaptive capacity and reducing vulnerability among pastoral and agro-pastoral communities in the Somali Region (Michael, 2017; Tofu et al., 2025).

2.7.3. Climate smart agricultural innovations

Climate-resilient crop varieties:

Drought-tolerant and heat-tolerant varieties are widely promoted; breeding targets heterogeneous drought-prone environments and integrates genomic tools for resilience (Ahmed et al., 2022; Cooper & Messina, 2022). Climatesmart varieties (e.g., groundnut, maize) show strong associations with higher yields and food security when combined with other CSA practices (Zheng et al., 2024).

Improved rangeland management and fodder production:

Adaptive grazing, improved pasture conservation, crop residue hay, and fodder banks reduce feed gaps during drought and are positively influenced by extension and climate information services in agro pastoral zones (Koluman et al., 2025; Madaki et al., 2025). Integrated crop–livestock systems and improved forage management are core to climate-resilient livestock systems (Ahmed et al., 2022; Koluman et al., 2025).

Water harvesting and irrigation innovations:

Micro catchments, supplemental irrigation, small-scale water harvesting, and water-efficient irrigation (drip, smart irrigation) are key in arid regions, improving water productivity and buffering dry spells (Madaki et al., 2025; Xing & Wang, 2024). Institutional support for irrigation infrastructure strongly shapes adoption (Tanti et al., 2022; Zagre et al., 2024).

Livestock management and breed improvement:

Heat and disease-tolerant breeds, improved feeding, rotational grazing, and integrated crop–livestock systems enhance productivity and resilience while reducing emissions intensity (Ahmed et al., 2022; Koluman et al., 2025). Destocking, supplementary feeding, and improved pasture preservation are central adaptation strategies in agro pastoral systems (Koluman et al., 2025; Madaki et al., 2025). . Early warning systems and climate information services Weather and climate information services, seasonal forecasts, and early warning systems help farmers adjust planting dates, destocking, irrigation, and feed management, significantly supporting de-risking in African drylands (Singh & Chudasama, 2021).

2.7.4. CSA and food security pathways: availability, access, stability

CSA improves availability through higher and more stable yields, better soil moisture and fertility, and improved livestock productivity (Ahmed et al., 2022; Zheng et al., 2024). It enhances access by raising incomes (higher yields, value chains, diversified production) and lowering production risk (Gemtou et al., 2024; Zheng et al., 2024). Stability is strengthened via diversified crops and enterprises, risk management tools, climate information, and reduced sensitivity to drought and rainfall variability (Ahmed et al., 2022; Zheng et al., 2024).

Evidence from arid and semi-arid regions:

Cross-country data from West Africa show CSA adoption linked to higher land productivity and improved food consumption scores; bundles that include climate-smart varieties and organic fertilizers yield the strongest gains (Tabe-Ojong et al., 2023). Reviews across Africa find CSA adoption often increases productivity, incomes, dietary diversity, and food security while reducing production risk and emissions (Ahmed et al., 2022; Zheng et al., 2024). In semi-arid Tanzania, mulching and integrated soil–water management reduced household food insecurity by about 21–22% (Bishibura Erick et al., 2025). Integrated, nature-based adaptation pathways (water management, soil rejuvenation, productivity) are most effective for vulnerable dryland communities (Singh & Chudasama, 2021).

2.7.5. Adoption Barriers and Enabling Factors: Institutional, socio-economic, and cultural factors

CSA adoption is shaped by land tenure security, access to credit, markets, and extension, education, farm size, gender, risk perception, social networks, and perceived profitability and ease of use (Mnukwa et al., 2025; Tanti et al., 2022; Thottadi & Singh, 2024). High upfront costs, liquidity constraints, insecure tenure, and limited climate information reduce uptake, especially of capital-intensive practices (irrigation, improved breeds) (Manono et al., 2025; Tanti et al., 2022). Gendered constraints (land, information, finance) often lower women's adoption rates (Manono et al., 2025; Mnukwa et al., 2025).

Role of extension, policy, participation:

Strong, pluralistic extension systems (farmer field schools, participatory demonstrations, Information and Communication Technology enabled advisory services) consistently increase CSA adoption and effective use of innovations such as irrigation, crop diversification, and improved seeds (Madaki et al., 2025; Thottadi & Singh, 2024). Policies that provide subsidies, climate risk finance, and integrate CSA into national strategies and dryland roadmaps are critical for scaling (Tanti et al., 2022). Community-based and participatory approaches, living labs, innovation platforms, and cooperatives help align innovations with local needs, blend scientific and indigenous knowledge, and build collective capacity for climate-resilient mixed farming systems (Ofosu et al., 2025).

3. Results and Discussion

3.1. CSA innovations and resilience to climate shocks

CSA practices (improved varieties, soil and water conservation, agroforestry, mixed crop–livestock) significantly increase household and system resilience, by reducing production risk, improving resource use efficiency, and strengthening adaptive capacity (Ma & Rahut, 2024; Zheng et al., 2024). In Ethiopia, CSA adopters show 28–41 percentage higher resilience indices than non adopters across crop, livestock and soil Climate-Smart Agriculture Practices (Teklu et al., 2023). Reviews confirm CSA reduces vulnerability and stabilizes yields under climate stress (Bhatnagar et al., 2024).

3.2. Effects on food security and livelihood diversification

CSA adoption is consistently associated with higher yields, incomes, dietary diversity and food security (Mujeyi et al., 2021). Evidence from Africa and Asia shows improved varieties, intercropping and conservation practices raise yields and incomes, improving food consumption and diet quality (Kabato et al., 2025). CSA also supports economic diversification via value addition, diversified crops and mixed systems (Ma & Rahut, 2024).

3.3. Benefits of context-specific innovations for pastoral/agro pastoral systems

Studies stress that CSA effectiveness is highly context dependent; interventions aligned with local agro ecology and livelihoods (e.g., integrated crop–livestock, rangeland and water management, safety nets) yield the strongest resilience gains (Zuma-Netshiukhwe et al., 2025). Participatory, landscape-specific portfolios of CSA options are recommended for smallholder and mixed systems (Teklu et al., 2023).

3.4. Limited adoption: infrastructure, finance, knowledge gaps

Across regions, CSA adoption remains uneven and often low due to limited credit, high upfront costs, poor infrastructure, weak extension, land tenure insecurity and policy gaps (Kabato et al., 2025). Knowledge and advisory deficits, especially for women and remote farmers, further constrain uptake (Autio et al., 2021; Zuma-Netshiukhwe et al., 2025). Recent systematic reviews highlight that there is a strong potential role for local knowledge in CSA. When farmers' indigenous practices are co-designed with scientific knowledge to develop or adapt CSA, the CSA becomes more relevant, acceptable, adoptable, and scalable. On the contrary, if local knowledge is ignored, mal-adaptation, rejection, and exclusion of vulnerable groups may occur. To sum up, local knowledge is essential for a more equitable and effective CSA (Hellin et al., 2023; Ogunyiola et al., 2022).

4. Conclusion and Recommendations

4.1. Conclusion

Climate-smart agricultural innovations in pastoral and agropastoral systems of the Somali Region provide a practical course of action towards building resilience and enhancing food security. The evidence suggests that adopting CSA technologies and approaches such as climate-informed livestock production systems, sustainable landscape, efficient water resources management, targeted early warning and advisory services on pests and diseases, and others is likely to harness agricultural productivity and food security, diversify livelihoods, strengthen adaptive capacity, and reduce emissions. It is local adaptation, strong institutional support, and policy coherence that make these benefits possible.

For climate-smart agriculture (CSA) to effectively contribute to climate adaptation and mitigation, as well as to improving food security and resilience among pastoral and agro-pastoral communities, it must incorporate a broad range of approaches and practices rather than relying on only one or two CSA technologies or components. Climate-smart agriculture (CSA) knowledge should be grounded in the effective integration of scientific knowledge and indigenous knowledge systems. The implementation of CSA should also follow participatory and inclusive approaches that incorporate local validation, consensus building, and transparency. Moreover, CSA approaches and technologies must be conflict-sensitive, particularly in the context of the Somali Region, which is characterized by fragility and recurrent conflict. This is essential to prevent maladaptation and to ensure inclusive and sustainable climate adaptation strategies.

4.2. Recommendations

Climate-smart agriculture (CSA) initiatives should incorporate comprehensive assessments of agricultural landscapes that consider ecological diversity and environmental sustainability. To address the key challenges identified in this review, regional development strategies and the enabling policy environment for CSA implementation need to be strengthened. Extension services and the provision of climate information should also be improved to enhance awareness, adoption, and effective utilization of CSA innovations among pastoral and agro-pastoral communities. Furthermore, greater emphasis should be placed on promoting participatory, community-driven CSA practices that integrate both scientific knowledge and indigenous knowledge systems to ensure local relevance and sustainability. There is also a strong need to scale up water harvesting practices and rangeland rehabilitation initiatives to reduce vulnerability to drought, feed shortages, and land degradation. Future research should focus on documenting indigenous knowledge and exploring ways to integrate it with modern agricultural innovations. Finally, improved cooperation and coordination among government institutions, non-governmental organizations, and research institutions are essential to strengthen CSA implementation and ensure effective knowledge sharing.

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Conflict of interest

The authors declare that there is no conflict of interest associated with the publication of this review article.

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