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Research Article

Computational Algorithms for Climate-Smart Agriculture in Sub-Saharan Africa

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ABSTRACT

Climate-smart agriculture (CSA) provides a vital framework for enhancing food security, resilience, and mitigation in Sub-Saharan Africa (SSA), where agriculture is highly vulnerable to climate variability and shocks. By integrating practices that sustainably increase productivity and reduce greenhouse gas emissions, CSA addresses the region's dual challenges of climate change and food insecurity. Computational algorithms offer critical tools for supporting CSA through simulation, predictive analytics, optimization, and decision-making. However, their systematic application to SSA's agricultural systems remains limited. This study investigates how algorithm development and optimization can strengthen CSA adoption in SSA. The objectives are to examine the current status of CSA practices and adoption drivers, explore algorithmic applications in modelling and resource management, identify integration barriers, and propose scalable pathways for sustainable deployment. A systematic review was conducted across six databases, focusing on literature published between 2010 and 2023. Screening yielded 32 eligible studies, which were synthesized through narrative and thematic analysis. Results highlight the use of algorithms such as particle swarm optimization, neural networks, and evolutionary computation in domains including yield prediction, drought risk assessment, irrigation scheduling, and crop disease detection. Key barriers include budgetary constraints, weak supply chains, policy gaps, and low farmer awareness, while opportunities lie in digital connectivity, climate information services, and institutional support. The findings suggest that integrating computational algorithms into CSA frameworks can enhance adaptive capacity, optimize resource use, and accelerate resilient food system transformations in SSA.

1. Highlights of the study

- Computational algorithms optimize climate-smart agriculture for food security in Sub-Saharan Africa.
- Systematic review identifies 32 studies on algorithm applications in CSA from 2010–2023.
- Algorithms enhance yield prediction, drought risk assessment, irrigation scheduling, and disease detection.
- Barriers include budget constraints, weak supply chains, policy gaps, and low awareness.
- Opportunities arise from mobile connectivity, climate information services, and institutional support.
- Integrating algorithms strengthens CSA adoption, resilience, and sustainable food systems in SSA.

2. INTRODUCTION

Climate-smart agriculture (CSA) has emerged as a critical framework for addressing the dual challenges of food security and climate change. It seeks to sustainably increase productivity, enhance resilience, and reduce greenhouse gas (GHG)

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emissions across farming systems [9][35], By integrating practices that conserve soil, water, and nutrients while reducing vulnerability to climate variability, CSA not only promotes adaptive capacity but also contributes to climate mitigation efforts. Well-designed CSA systems can transform farming landscapes into more productive and sustainable agroecosystems, with the potential to achieve net-zero or even negative carbon emissions profiles [7].

The urgency for CSA adoption is particularly evident in Sub-Saharan Africa (SSA), where agriculture remains the backbone of livelihoods yet is acutely threatened by climate shocks [1]. The region's high dependence on rain-fed agriculture, limited adaptive capacity of smallholders, and low uptake of modern technologies render its food systems highly vulnerable. Climate-induced stresses such as erratic rainfall, droughts, floods, and heat stress exacerbate chronic challenges of soil degradation, water scarcity, and food insecurity. These dynamics mirror global findings that climate variability and change disproportionately worsen the vulnerabilities of smallholder farmers, prompting stakeholders to promote CSA interventions such as agroforestry, rotational grazing, and biotechnology, which involve both synergies and trade-offs [10]. As a result, pursuing CSA pathways in SSA is no longer optional but imperative for ensuring sustainable agricultural growth, poverty reduction, and resilience building.

While CSA provides the conceptual and practical framework for resilience and sustainability, computational algorithms offer the technological backbone for its effective implementation. Algorithms step-by-step procedures for processing data and solving problems underpin virtually every digital innovation, from healthcare diagnostics and smart grids to autonomous vehicles and climate forecasting. In agriculture, algorithmic models enable simulation, optimization, and decision-making processes that improve productivity, efficiency, and adaptive management [2][31].

The design and optimization of computational algorithms tailored for CSA can facilitate data processing, predictive modelling, and artificial intelligence (AI) applications in farm systems [15]. By analyzing input–output relationships across spatial and temporal scales, algorithms can generate site-specific recommendations on crop management, irrigation scheduling, nutrient application, and risk mitigation strategies. Evidence from Malawi shows that simple irrigation adoption, supported by AI-driven predictive tools, increased maize yields and household incomes among smallholder farmers, highlighting the potential of algorithmic innovations to strengthen resilience in resource-constrained contexts [11]. Furthermore, algorithmic optimization ensures the selection of the most efficient and timely computational pathway, thereby enhancing the reliability and sustainability of CSA practices.

In the context of SSA, algorithm development and optimization remain underexplored despite their transformative potential. Literature indicates growing attention toward CSA in the region, yet systematic investigations into how computational tools can accelerate CSA adoption are limited. Bridging this gap requires deliberate efforts to integrate algorithmic innovations with CSA frameworks, tailored to the unique agro-ecological, socio-economic, and institutional realities of SSA [13].

Sub-Saharan Africa faces persistent social–ecological challenges that hinder the widespread adoption of CSA. Barriers include limited financial resources, inadequate supply chains, weak institutional and policy support, insufficient extension services, and poor infrastructural frameworks. The lack of reliable climate services and farm-level decision-support systems further constrains adaptive responses [29]. Despite significant investments in climate modelling and Earth observation technologies, these platforms are rarely translated into site-specific advisory services for farmers. Evidence from Uganda shows that while extension services integrate CSA practices such as agroforestry, rotational grazing, and ICT-supported farmer training, these innovations remain fragmented and under-scaled [33].

Yet, opportunities exist. The region holds vast areas of underutilized arable land, while ongoing digital transformations offer prospects for harnessing data-driven innovations. The expansion of mobile technologies and improved connectivity create avenues for delivering algorithm-driven climate information services to smallholder farmers. When coupled with robust policy frameworks and multi-sectoral collaborations, algorithmic applications in CSA could unlock transformative pathways for resilience and sustainability.

The synergy between CSA and computational algorithms lies in their mutual focus on optimization and sustainability [16]. CSA emphasizes adaptive and integrated management of land, water, crops, and livestock, while algorithms provide the analytical and computational means to design, monitor, and refine these practices. For instance, algorithmic models can simulate the impacts of climate scenarios on crop yields, optimize resource allocation under uncertainty, and evaluate trade-offs between productivity, adaptation, and mitigation.

A systematic exploration of computational algorithms for CSA in SSA is therefore timely and warranted (see Table I). Such an investigation not only advances the scientific frontier but also has profound practical relevance for farmers, policymakers, and development partners. By embedding algorithmic design into CSA implementation, the region can accelerate adoption, improve efficiency, and scale transformative practices in a cost-effective and context-specific manner [8][3][6].

This study addresses the intersection of CSA and computational algorithms in SSA, focusing on the potential of algorithm development and optimization to strengthen resilience and food security [22]. The rationale is twofold. First, despite the widespread recognition of CSA as a climate adaptation and mitigation strategy, its implementation in SSA remains limited, fragmented, and poorly contextualized. Second, while algorithmic innovations have been widely applied in fields such as engineering, energy, and healthcare, their systematic application to CSA in SSA is still in its infancy. Bridging these gaps could provide actionable insights for designing site-specific CSA practices and scaling them through data-driven decision-support systems.

Building on the above context, the overarching objective of this research is to investigate the role of computational algorithm development and optimization in enhancing the adoption and effectiveness of climate-smart agriculture in Sub-Saharan Africa. Specifically, the study seeks to: Examine the current status of climate-smart agricultural practices in SSA, with particular attention to their adoption drivers, barriers, and impacts on productivity, resilience, and emissions reduction; Analyze the potential applications of computational algorithms in supporting CSA, including simulation modelling, predictive analytics, and optimization of resource use; Identify gaps and challenges in integrating algorithms into CSA frameworks, focusing on infrastructural, institutional, and socio-economic constraints in SSA; Propose pathways for developing and optimizing algorithms tailored to CSA, emphasizing scalability, site-specificity, and long-term sustainability [5][27][14]. By achieving these objectives, the study will contribute to the discourse on sustainable agriculture in SSA, offering evidence-based insights into how computational algorithms can accelerate climate-smart transformations for resilient and food-secure futures.

TABLE I. SUMMARIZES STUDY'S SYSTEMATIC EXPLORATORY KEY POINTS

Section	Key Points
Climate-Smart Agriculture (CSA)	Enhances food security, resilience, and reduces GHG emissions; critical for Sub-Saharan Africa (SSA).
Computational Algorithms	Enable data processing, modeling, AI, and optimization to support CSA implementation.
Challenges in SSA	Barriers include limited finance, weak policies, poor infrastructure, and low technology uptake.
Opportunities in SSA	Untapped arable land, digital tools, mobile connectivity, and potential for climate services.
CSA–Algorithm Synergy	CSA provides framework; algorithms offer computational means to optimize practices and decisions.
Study Rationale	CSA adoption is limited and fragmented in SSA; algorithm use in CSA remains underexplored.
Research Objectives	1.Assess CSA adoption and impacts. 2.Analyze algorithm applications. 3.Identify integration challenges. 4. Propose optimization pathways.

3. MATERIALS AND METHODS

A systematic search was conducted on the Web of Science digital library on computer algorithms developed to support climate-smart agriculture in sub-Saharan Africa (SSA). To ensure comprehensive coverage, various combinations of relevant terms relating to computational algorithms, adoption facilitators, and barriers were utilized. The search strategy was divided into four main concepts: Algorithms, Climate-smart Agriculture, Applications (i.e., computer-aided development, assessment, planning, scheduling, and support), and SSA. Considered methods included genetic algorithms, pattern search, swarm optimization, simulated annealing, differential evolution, differential search, artificial neural networks, evolutionary algorithms, evolutionary computation, constraint programming, and mathematical programming. Initial search verdicts were obtained by combining the first two concepts with the third, followed by adding the fourth concept. Additional relevant works known a priori or obtained from cited and citing papers were also included.

The Web of Science database was selected due to its inclusion of the most important journals classified under "Agronomy" and "Agriculture" categories. Searches were performed in the "All field" domain but covered only article titles, abstracts, and keywords to improve efficiency. The search was limited to publications from 2000 to 2022 to focus on recent developments and allow the database time to accumulate records. Searches were performed at the end of 2022 (results reported in January 2023) to minimize the omission of relevant recent works.

Following searches, retrieved records were filtered by reading titles and abstracts to remove those obviously unrelated to computational algorithms or climate-smart agriculture. All potentially relevant papers were included for full-text inspection during data extraction. Data collected from retained publications included year, institution, country, journal, type of computational method(s) used, problem(s) addressed, data collection and validation techniques, and author keywords. Patterns and trends were then identified through structured analysis of these data.

4. SEARCH STRATEGY AND ELIGIBILITY CRITERIA

A systematic review was performed on six electronic repositories using a scoping review approach to identify studies on computational algorithm development and optimization for climate-smart agriculture in Sub-Saharan Africa. The search covered publications from 2010 to April 2023. A three-stage screening process (title, abstract, and full paper) led to the selection of 32 eligible papers. Meta-data extraction included publication details, study objectives, design, dataset characteristics, algorithm purposes, types of agriculture, climate scenarios, crop species, and geographic locations. Data synthesis was conducted through narrative review methods.

Climate-smart agriculture aims to improve productivity, enhance resilience, reduce or remove greenhouse gas emissions, and enhance food security. The approach is receiving growing attention, especially in Sub-Saharan Africa, where frequent droughts and heavy rainfall events threaten cereal production. Over the past decade, computational algorithms have been developed to support key domains of climate-smart agriculture such as early warning systems for drought prediction, crop disease identification, crop yield prediction, and drought and flood risk assessments [2]-[5]. Key technologies deployed include machine learning, deep learning, artificial intelligence, and drones, with applications ranging from early warning systems to satellite image analysis. Despite the progress, challenges related to budgetary constraints, high data costs, policy design, and limited public awareness continue to impact the uptake of climate-smart agriculture in Sub-Saharan Africa. Opportunities for wider implementation arise from the growing penetration of affordable smartphones and internet access.

5. SCREENING AND DATA EXTRACTION

The screening step selects records that meet predefined eligibility criteria. Eligibility criteria can be defined according to the CHARMS checklist, which considers how study design, participant characteristics, outcomes, predictors, and other factors affect the potential for bias and applicability in a specific systematic review [2].

Screening can be conducted either manually or automatically. Two reviewers often perform manual screening and involve familiarity with the topic and careful interpretation of titles and abstracts to determine which studies to include. Automatic screening methods have been developed as an alternative to manual screening. They combine regular expressions and expert knowledge to identify relevant documents according to a given set of inclusion criteria [1]. Support Vector Machines and Natural Language Processing are examples that have been implemented in R. Some approaches have combined manual and automatic screening, first applying an automatic filter to remove clearly irrelevant documents, followed by manual screening of the remaining abstracts [6]. In one case, regular expression based on a set of keywords, followed by string distance and shared word approaches, reduced 6539 records in ISI Web of Science to 345 papers for inclusion in a systematic review. Other approaches have used search engine tools that optimize Boolean queries based on user feedback. Input includes a small set of relevant papers, a search query, and a database to be screened. The engine refines search queries to improve the ranking of search results, maximizing the number of relevant documents at the top of the candidate list.

Data extraction is the process of collecting relevant information from included documents and storing it systematically. Data extraction is sometimes referred to as data collection, screening, grading, or synthesis. Items extracted generally include publication-specific information and key study characteristics. As a first step in creating an aggregated database, data extraction addresses the requirements of the systematic review and facilitates data synthesis and/or meta-analysis.

6. STUDY SELECTION PROCESS

Relevant documents published up to 2024 were searched on Scopus, PubMed, CAB Abstracts, and Web of Science to identify studies with optimal machine-learning models for climate-smart agriculture. Literature was thoroughly screened.

7. DATA EXTRACTION

The systematic search identified 994 records, which were subsequently screened to remove ineligible entries. Four relevant articles from the bibliographies of the resulting set were added, bringing the total to 22. The final selection of records was subjected to in-depth appraisal and data extraction. Tabular and thematic analyses were applied in parallel to produce a synthesis that addresses the objective of developing and optimizing computational algorithms for climate-smart agriculture in Sub-Saharan Africa.

Electronic databases were systematically searched to acquire scientific literature—the search query combined terms related to computational algorithms, climate-smart agriculture, and the Sub-Saharan African context. The search spanned all fields of the searchable records, which consisted of title, abstract, author-supplied keywords, and controlled subject terms with a logical operator. The terms “Sub-Saharan Africa,” “Semi-Arid Tropics,” and “Developing World” were linked by a logical OR within a single group. Controlled subject terms were used wherever supported, and the syntax was adapted as appropriate for each resource.

8. DATA SYNTHESIS AND ANALYSIS

The literature search yielded 376 publications, with 281 titles screened for eligibility after duplicates removal. A total of 3968 records were identified from Google Scholar and other databases using search terms related to climate-smart agriculture (CSA) and computational algorithms. The review investigated 5718 different algorithms applied in the CSA context.

The data synthesis and analysis aimed to develop and enhance computational algorithms that effectively address challenges in climate-smart agriculture within Sub-Saharan Africa. The selection process focused on works that inform and support the design and optimization of algorithms to improve CSA practices. The overarching objective was to enable the development of new or refined computational methods capable of addressing the complex and region-specific issues facing agricultural systems under climate variability.

9. RESULTS

There is a general decline in agricultural productivity in sub-Saharan Africa (Figure 1).

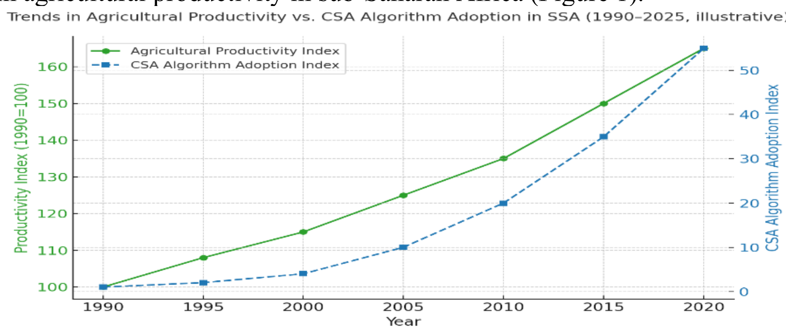

Fig. 1. Illustrates trends in agricultural productivity CSA adoption indeces in SSA over years (1990-2025)

As a result, there is an increased concentration on computational algorithms for the development and optimization of climate-smart agricultural (CSA) practices. Among various computational algorithms, Particle Swarm Optimization (PSO) has emerged as a widely adopted technique in agriculture. The centralized variants of PSO have demonstrated superior performance with respect to solution quality and convergence speed compared to decentralized approaches. The diversity of optimization algorithms applicable to the development and refinement of climate-smart agricultural practices is reviewed with the specific focus on sub-Saharan Africa aforementioned [21].

10. OVERALL CONTEXT

Climate change and its impact are among the biggest concerns related to future crop production and agricultural development in Africa. Regional climate simulations enable assessment of where and when changes in climate might have consequences for agricultural production. Models and variable outputs are used to assess the reliability and confidence of future climate projections. Agriculture has been, remains, and will likely continue to be important to the African economies and to the livelihoods of its population [12][34].

Facing the negative consequences of climate change is, however, very challenging for Africa, because of low adaptation capacity, poor infrastructure and high dependency on rainfed systems. In sub-Saharan Africa, climatic conditions have historically been favorable for rainfed agriculture, and storms more frequent. These challenges are compounded by widespread poverty and limited access to financial markets and institutions. Transformational adaptation is clearly conceptualized and understood at the climate change impacts, but application to African agriculture remains nascent. Agricultural systems are affected by more frequent and prolonged droughts, Delta various regions continue to be vulnerable to flooding, and floods reportedly caused widespread damages to critical livelihood and community assets.

11. BROADER CHALLENGES AND PROSPECTS FOR INTEGRATING

Broader challenges and prospects for integrating climate-smart agriculture with computational algorithms in sub-Saharan Africa are outlined. Adaptation strategies to increased climate variability include transformed land use, technological solutions, diversification of livelihoods, integration of local knowledge, enhanced social capital, and increased off-farm income. Low education levels and limited access to technical information hinder adoption of climate-smart techniques. Models are increasingly used to prioritize and assess effectiveness of adaptation options in a changing climate. For example, VECM-based studies have shown how dynamic interactions, such as between external debt and credit risk, can create feedback loops, illustrating the value of modeling complex interdependencies for policy interventions [25]. This paper investigates and prioritizes climate-smart agriculture options in vulnerable regions of northern Sub-Saharan Africa.

12. DISCUSSION

Climate-smart agriculture (CSA) addresses the critical challenge of achieving sustainable agricultural development in the face of increasing climate variability and food insecurity, especially in SSA [36]. SSA has experienced temperature increases at twice the global rate over the last three decades, with rainfall declining in already dry regions since the mid-1970s. Climate models predict wide temperature fluctuations, with precipitation remaining consistently below historical averages. These projections reinforce the need for investments in adapted CSA policy and practice to enhance farmers’ resilience, agricultural productivity, and food security. Population growth, world food price increases, and rising production costs are already making it difficult for farmers to support their livelihoods.

While several initiatives have addressed water and soil management to enhance adaptation, many challenges persist for SSA decision makers, planners, and extension agents. Climate and cropping system models offer potential tools to quantify and improve adaptation and mitigation options at farm and regional levels. Early developments in agricultural land-use modelling and analytical approaches during the early 1970s demonstrate the relevance of these techniques to climate adaptation and food security in SSA. Beyond yield predictions under changing climates, future projections need to account for these conditions when adjusting land-use patterns across regions and economic sectors.

Algorithms constitute sets of rules that define sequences of operations or procedures for mathematical calculations, data processing, and automated reasoning tasks. Climate-smart technologies can support food production, security, and nutrition goals. They can be used for crop and variety selection, daily agricultural and phenological advice, land-suitability analyses, risk assessments, and the provision of planting and harvest calendars.

Four types of barriers currently hinder the widespread application of CSA technologies in SSA. Budgetary constraints prevent many farmers and even some governments from investing in these technologies. International supply chains still fail to supply all the components on time or at affordable prices in some regions. Policy-related challenges, such as the lack of enabling rules or the existence of costly regulations, further complicate implementation. Finally, a lack of awareness and information among both policy makers and the public reduces adoption rates [19].

Numerous opportunities exist to expand the use of CSA technologies. Many governments have now developed investment plans aligned with the Sustainable Development Goals. Agricultural institutions and research organizations possess capacities that, if better connected across countries and sectors, could drive widespread technology implementation. Continued growth and improvements in technology infrastructure ensure that many countries will soon have the necessary tools to employ the full suite of available CSA technologies. Lastly, an increasing flow of information to associate public and private institutions fosters better cooperation and engagement.

13. IMPORTANCE OF CLIMATE-SMART AGRICULTURE IN SUB-SAHARAN AFRICA

Climate-smart agriculture (CSA) represents an approach to agricultural development that, in the context of climate change, fosters sustainable increases in productivity and incomes, promotes adaptation and resilience to climate change, and facilitates the reduction of greenhouse gas emissions where possible. Climate change poses a significant challenge to food security in sub-Saharan Africa (SSA) as almost all agricultural production derives from rain-fed systems [25][26]. Conjunctures of climate change, population growth, and environmental degradation lead to the downscaling of agricultural output per capita and create widespread food security issues. Climate considerations are therefore at the core of many agricultural and rural development policies and plans in sub-Saharan Africa. CSA simultaneously addresses the interlinked challenges of food insecurity and climate change by systematically integrating climate change adaptiveness and mitigation into the development strategy of the agricultural sector (combining the agroecological and the market- and value chain-based resilience pillars). Because rural communities in SSA are among the most vulnerable to climate change, one of the main aims of CSA should be to enhance the adaptive and absorptive capacities of agricultural production systems [28]. Contact with global and local markets, dynamics of value chain upgrading and decentralisation of policy decisions form the channels through which CSA can facilitate the transformation of agricultural systems. Climate-smart agricultural practices, while much in need of adaptation to local biophysical and socio-economic conditions, are relatively well known and documented in SSA both in terms of their mitigation potential and their likely influence on adaptation.

14. SPECIFIC CHALLENGES OR OPPORTUNITIES FOR CLIMATE-SMART AGRICULTURE IN SUB-SAHARAN AFRICA

Climate change and weather variability threaten achievements in sustainable development in Sub-Saharan Africa, where agriculture remains the main livelihood source. Crop and livestock production systems will be particularly vulnerable to climatic changes, especially warmer temperatures and raised rainfall variability. Crop productivity is expected to decline, raising food insecurity and increasing food prices. Poverty is expected to rise if agricultural systems do not adapt to climate change and weather variability. Supporting an adaptation strategy based on Climate-Smart Agriculture (CSA), therefore, constitutes a cornerstone of development in Sub-Saharan Africa.

On the one hand, the effects of climate variability are already felt across the region. Precipitation has apparently declined while temperatures have risen, although robust trends and reliable quantification of the extent of changes remain fuzzy due to spatial heterogeneity and wide confidence intervals [4]. The overall impact on the agricultural sector has nonetheless been widely felt, with reports of crop failure, fishery collapse and livestock deaths frequently documented across the region. This situation undermines food security and erodes other pillars of development. High–frequency climate hazards such as droughts have also favoured the spread of transboundary animal and pest diseases.

Unlike other regions, Sub-Saharan Africa exhibits multiple agro-ecological zones and a wide variety of farming systems, with diverse rural livelihood sources often dominated by rain-fed subsistence farming with limited access to improved inputs and infrastructure. Consequently, farmers display a high sensitivity to climate shocks, with very low adaptive capacity and the prospect of both reduced crop and livestock productivity [21]. Promoting the uptake of climate-smart options and ensuring the sustainability of agricultural systems is currently contingent upon achieving a set of conditions, among which boosting adaptive capacity and the availability of science-led technological packages rank prominently. Although critically important, these two issues remain insufficiently developed to allow an wide-scale transition to CSA. The availability of dedicated computational technologies that deliver data-driven analytical capacity is a pre-condition for success. The need is therefore to capitalize upon emerging progresses in artificial intelligence, numerical modelling and machine learning that are aimed at developing specific and detailed technologies supporting the agricultural transition. These technologies constitute a compelling imperative to accompany the development and optimised diffusion of climate-smart options in the region, with a view to catalyse change through appropriate algorithm constructs.

15. EXAMPLES OF COMPUTATIONAL ALGORITHMS OR TECHNOLOGIES THAT COULD SUPPORT CLIMATE SMART AGRICULTURE IN THIS REGION

Climate-smart agriculture faces several challenges in the Sub-Saharan region, including tight capital constraints for smallholders, lack of assured and comprehensive supply systems, lack of coherent local and regional policies that promote the adoption of climate-smart technologies, and limited public awareness of the benefits of certain agricultural practices. Region-wide up-scaling strategies should therefore consider not only technological advances, but also the broader socioeconomic, political, and cultural conditions that determine adoption [36] [1]

At the same time, four important opportunities should guide further implementation efforts. First, a wide array of climate-smart technologies already exists for sub-Saharan Africa and should be widely made available. Second, many of these technologies provide significant economic benefits and are therefore likely to attract interest among rural populations once disincentives are eliminated. Third, much progress has been made in land use management and consumer behavioural change through grassroots and community-led initiatives, thus opening new opportunities for expansion. Finally, the development and rapid expansion of cell phone penetration provide innovative channels for information delivery and knowledge sharing; coupled with the widespread use of local radio, this provides an effective communication platform for such programs [17][18].

16. KEY BARRIERS TO INTEGRATION; DEVELOPMENT AND OPTIMIZATION OF COMPUTATIONAL ALGORITHMS FOR CLIMATE SMART AGRICULTURE IN SUB-SAHARAN AFRICA (TABLE II)

17. BUDGET PRESSURES AND PRICE CONCERNS

Budgetary constraints and supply chain disruptions present significant impediments to scaling climate-smart agriculture (CSA) in Sub-Saharan Africa. Despite a recognized need for climate change services among farmers, knowledge and information gaps remain barriers to adoption. The region faces pressures to increase productivity while achieving zero net deforestation. The fragmented topography changes the climate as one move northward, and the rainfall decreases from 3000mm per year to less than 600mm. Most farmers rely on rainfall, making their yield extremely dependent on rainfall variations and their ability to manage water efficiently. Poor climate information and the lack of access to climate-responsive technologies further reduce the ability of farmers to respond adequately to climate change and variability. Rising industrialization and urbanization reduce resource availability and accelerate environmental degradation, exacerbating water scarcity and reducing predictability. However, investment opportunities are expanding as many institutions prioritize climate responses. Climate change threatens livelihood security, with rising temperatures, unpredictable rainfall, and increasing extreme weather events posing immediate risks to food security. Climate data and tools are getting more accessible, supporting the profiling of CSA opportunities and guiding investment prioritization, projects design, and impact assessment. Simultaneously, increasing food demand, dwindling resources, and widening income disparities present both challenges and opportunities for improving farmer livelihoods in drylands.

18. Weak Supply Chains and Limited Product Availability

In numerous cases, a product had been suggested to farmers yet remained unavailable locally. Guidance from the Global Food Security CGIAR research program cautions that when a technology or practice cannot be obtained, it can result in a loss of trust in the provider or the underlying scientific research. Accordingly, the CGIAR team that conducted this study advised against disseminating information about a product that is not physically accessible. This caution underscores the critical role of robust supply chains in ensuring that recommended climate-smart agriculture innovations can be adopted effectively by farmers [30].

The recent market development in Eastern and Southern Africa, highlighting the stagnation caused by weak or absent supply chains for agro-input products such as improved seeds, fertilisers, pesticides, and other essential materials. The figure demonstrates that, despite the spikes in maize, millet, and sorghum production in 2017 correlating with a La Niña event, long-term productivity declined after 2011, even with increasing rainfall. The stagnation in these key cereal crops results partly from the inability to increase fertiliser use and the consequent failure to develop solar-powered irrigation during a prolonged period of elevated fuel prices and supply constraints. These patterns emphasize the pressing need for enhanced supply chains and product availability to realise the full potential of climate-smart agriculture practices in the region.

19. LACK OF POLICY AND PUBLIC SUPPORT

Efforts to promote Climate-Smart Agriculture (CSA) in sub-Saharan Africa (SSA) face significant barriers from lack of policy and public support. Many regions suffer from inadequate awareness, funding, and institutional frameworks for sustainable farming methods. Policy incentives and effective dissemination of climate information remain limited, constraining farmers' adaptive capacity. Current policies span sectors and nations with common features for CSA implementation. Building governments and farmers' capacities to develop and execute adaptation and mitigation plans at diverse scales is essential. Comprehensive assessment, promotion, and integration of CSA practices into planning strategies are critical. Enhancing the institutional environment to pursue food security targets, as well as establishing relevant infrastructure and appropriate land-use practices, can improve SSA's climate resilience. Expanding the physical, institutional, and technological infrastructure that underpins productive agricultural systems further supports these goals. Opportunities exist to make development finance and official development assistance more effective and relevant to capacity needs. Public awareness, political will, and support for CSA increase when institutional structures and processes incorporate climate risk management, focusing activities and investment accordingly.

20. LACK OF TRAINING AND AWARENESS

The uptake of climate-smart agriculture (CSA) practices is constrained by a widespread lack of training and awareness among producers. Many smallholders across Sub-Saharan Africa have insufficient knowledge of climate change impacts, as well as limited understanding of viable adaptation strategies and relevant government interventions, thereby undermining adoption rates of CSA activities. Awareness of sustainable agricultural technologies, such as drought-tolerant crops and conservation agriculture, remains restricted, since these have yet to be disseminated at scale to end-users [20]. The absence of targeted information delivery mechanisms further hinders the provision of weather and market data that could otherwise assist farmers in implementing timely and effective decisions. Enhancing training programmes and mounting awareness campaigns must therefore constitute a priority for agency efforts seeking to expedite the implementation of essential climate-response measures.

TABLE II: SUMMARIZES BARRIERS, DESCRIPTIONS AND POTENTIAL ALGORITHMIC SOLUTIONS

Barrier	Description	Potential Algorithmic Solutions
Budget	Limited funding for projects, resources, or equipment	- Optimization algorithms for cost minimization- Predictive analytics for ROI prioritization- Resource allocation models
Supply Chain	Delays, inefficiencies, or disruptions in procurement and logistics	- Inventory optimization algorithms- Demand forecasting (time series, ML models)- Route and logistics optimization
Policy	Regulatory restrictions, compliance requirements, or bureaucratic hurdles	- Compliance-checking algorithms- Automated policy monitoring and reporting- Decision support systems with constraints
Training	Lack of skilled personnel or insufficient transfer learning	- Personalized learning algorithms- Skill gap analysis using ML- Recommendation systems for training content

21. POTENTIAL OPPORTUNITIES AND STRATEGIC APPROACHES

Sub-Saharan Africa features some of the world's most vulnerable communities to climate variability and invasive transboundary pests. Climate-smart agriculture offers opportunities to enhance climate resilience [23][24]. Climate information and experiential learning via systems such as participatory integrated climate services for agriculture can facilitate adoption. Crop and farm-level assessments indicate that mobile phone dissemination of weather and market information increases agricultural incomes. Climate-smart agriculture and agroforestry practices play critical roles in within-season forecasting, adaptation and mitigation options. Understanding climate-related opportunities to manage risks depends on climate impact assessments. In the Sudano-Sahelian region, drought adaptation strategies and responses to heat stress dominate the literature. Pastoralists valuate the use of climate forecast information for management. Conservation agriculture systems for sustainable food security hinge on soil and cropping system research in semi-arid agro-ecosystems.

Projected rainfall declines of up to 40% by 2030 and maize productivity reductions nearing 30% threaten Southern Africa, where diverse agro-climatic conditions complicate the development of locally adapted climate-smart cropping systems. An interdisciplinary approach integrates crop growth models calibrated with long-term trial data to simulate potential maize-based systems under present and future climates and management scenarios. Farm-level sub-models, coupled with efficient frontier analysis, identify systems that minimize input use and negative externalities whilst maximizing productivity. Combining field-scale process models with optimization methods benchmarks farm-scale performance, analysing strategies that balance market sales and household food self-sufficiency. This underpins the identification of climate-smart practices and pathways within Southern Africa.
The CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) increases capacity and facilitates scaling of climate-smart agriculture (CSA) technologies in Africa through strategic partnerships and decision-support tools. UNEP assists decision-makers in smallholder production systems by devising guidance and tools to assess and manage trade-offs and synergies associated with agricultural transformation, including tools for developing scenarios that explore the implications of current trends and future policy options. IWMI developed an analytical framework to determine storage requirements and the effectiveness of water storage interventions under current and future climate conditions. Applied in the Volta Basin and the Ethiopian Blue Nile Basin, the tool evaluates water systems against hydro-climatic and infrastructure variables across multiple criteria: reliability, resilience and vulnerability (RRV), as well as interpretive indicators linked to socio-economic conditions. Climate-smart agriculture investments fall into two broad categories: resilience initiatives that enhance physical, economic and social resilience, and mitigation actions that reduce greenhouse gas emissions, improve input-use efficiency, and sequester carbon [30][32].

22. CONCLUSION

Computational algorithms support climate-smart agriculture by analysing weather patterns, soil conditions, and crop needs, fostering resilient and productive practices. In the region, targeted efforts to develop these algorithms tackle challenges posed by climate variability while optimising agricultural delivery and resilience. Climate-smart agriculture promotes sustainable food security, aids adaptation, and encourages mitigation including the preservation of land carbon stocks. Addressing drought, heat stress, soil fertility, and vulnerabilities in cropping systems guides a development path that is more sustainable, productive, and equitable. To maximise the impact of climate-smart practices, computational algorithms embedded in large data sets employ knowledge-rich techniques such as rule induction and ensemble methods, which then inform expertise, enhance technical knowledge, and lead to new conceptual tools. Challenges include access to training, farm supply chains, policies, and awareness. Positively, the region offers an attractive investment opportunity and a clear strategic framework for agricultural modernisation and agribusiness. Significant implementation remains, particularly in extension, trade, and contracting. Current efforts focus on food security; the region's climatically diverse and vulnerable countries will need support in decision-making on mitigation options for livestock, trade-offs between adaptation and mitigation, drought and irrigation management, and capacity building for greenhouse gases inventories. Where algorithms can support mathematical processes and model system behaviour, many applications are relatively theoretical or at a very early stage of exploration. Nonetheless, the combination of well-documented prior knowledge and the information-sharing requirements of climate-smart agriculture strongly motivates research focused on the implementation of specific techniques conducive to strong user focus and quality constraints. Early initiatives have identified nine fundamental considerations related to generic knowledge, specific knowledge, data sources, prioritization, user interaction, quality measures, robustness, and reduction of oversearching.

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