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Adapting Agriculture to a Changing Climate A Review of Strategies, Technologies, and Policy Responses

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ABSTRACT

Agriculture must simultaneously adapt to a changing climate and reduce its own greenhouse gas footprint. This review synthesizes recent peer-reviewed literature on how farming systems are adapting to climate change through agronomic practices, water management, digital and precision technologies, and climate-smart agriculture (CSA) frameworks, alongside the policy and institutional structures needed to support them. Evidence across regions shows that combined adaptation-mitigation approaches can raise yields by up to 38%, cut greenhouse gas emissions by 20–40%, and increase soil carbon by 0.3–0.8 t C ha⁻¹ yr⁻¹, though adoption remains uneven and constrained by financial, institutional, and technological barriers, particularly in low-income regions. The review closes with regional case studies and a discussion of policy gaps.

INTRODUCTION

Climate change adaptation in agriculture refers to the deliberate alteration of farming practices, technologies, and support systems to reduce vulnerability to shifting temperature and precipitation patterns [1], [2]. Unlike broader climate mitigation, which targets emissions reduction economy-wide, agricultural adaptation is necessarily local: the right response depends on crop mix, water access, farm size, and institutional capacity. Increasingly, the literature frames adaptation and mitigation not as separate tracks but as complementary pillars of climate-smart agriculture (CSA), a framework promoted by the FAO that pursues productivity, resilience, and emissions reduction together [3], [4].

This review draws on recent systematic reviews, meta-analyses, and regional case studies to summarize (1) on-farm adaptation strategies, (2) digital and precision technologies supporting adaptation, (3) the quantified performance of climate-smart agriculture interventions, (4) policy and institutional responses, and (5) re-

gional experiences that illustrate how these strategies play out on the ground.

ON-FARM ADAPTATION STRATEGIES

Reviews of the adaptation literature converge on several recurring categories of on-farm response [1], [5]:

- **Agronomic adaptation:** shifting planting dates, diversifying crop varieties and rotations, and adopting drought- and heat-tolerant cultivars to match altered growing seasons [1].
- **Water management:** improved irrigation scheduling, water-saving techniques, and, in more water-constrained systems, transitions away from water-intensive crops entirely [6].
- **Soil and land management:** conservation agriculture, cover cropping, and agroforestry to protect soil structure, moisture retention, and long-term fertility under more variable rainfall [3], [4].
- **Livestock adaptation:** adjustments to grazing management, heat-stress mitigation infrastructure, and

Table 1: Digital Technologies Supporting Climate Adaptation in Agriculture

Technology	Primary Application	Adaptation Value
Remote sensing	Crop monitoring, land-cover change detection	Early detection of drought stress and pest outbreaks
Big data / predictive modeling	Forecasting water shortages and pest risk	Enables anticipatory rather than reactive management
Artificial intelligence	Pest identification and tracking	Faster, more targeted pest and disease response
Internet of Things (IoT)	Precision fertilizer and irrigation management	Reduces input waste while maintaining yield
Nanotechnology	Soil improvement, controlled-release inputs	Improves nutrient-use efficiency under stress
Robotics	Targeted spraying, automated field operations	Reduces chemical use and labor exposure to heat
Blockchain	Supply-chain transparency	Supports traceability for resilient, diversified supply chains

Source: Parra-López et al. (2024), Computers and Electronics in Agriculture [2].

feed formulations that also reduce methane emissions [4].

A recurring theme is that adaptation and mitigation frequently reinforce each other at the practice level: conservation agriculture, agroforestry, and improved nutrient management simultaneously build resilience and lower emissions, which is the central premise of the climate-smart agriculture framework [3], [4].

DIGITAL AND PRECISION TECHNOLOGIES

A growing body of research documents how digital technologies are being integrated into climate adaptation and mitigation strategies in agriculture [2]. These tools do not replace agronomic adaptation but make it more precise and responsive to real-time conditions.

Despite this promise, adoption remains uneven. Barriers include the cost of hardware and connectivity, low digital literacy among smallholders, and a lack of governance frameworks tailored to agricultural data [2]. The literature is consistent in recommending investment in infrastructure, training, and locally adapted digital solutions rather than assuming that developed-world technology models will transfer directly [2].

QUANTIFIED PERFORMANCE OF CLIMATE-SMART AGRICULTURE INTERVENTIONS

A recent PRISMA-based review of 368 peer-reviewed studies (2012–2025) found that four CSA pathways — soil carbon sequestration, precision fertilization, methane-reducing livestock feed, and agroforestry — consistently achieved measurable co-benefits across emissions, soil health, and productivity [4]. A separate meta-analysis of CSA adoption reported yield gains of

up to 38%, alongside targeted gains from specific practices such as biochar application and precision nitrogen management [3].

A separate concern raised across this literature is result variability: reported gains depend heavily on baseline soil condition, climate zone, and implementation quality, meaning these ranges should be read as evidence of potential rather than guaranteed outcomes [3], [4].

POLICY AND INSTITUTIONAL RESPONSES

Governments and international bodies track agricultural adaptation through structured policy categories. The OECD's 2023 Agricultural Policy Monitoring and Evaluation report offers one widely referenced taxonomy of adaptation actions and programmes [7]:

Beyond these operational categories, the literature emphasizes those policy responses succeed when they combine several elements: institutional support, financing mechanisms such as insurance and credit access, extension services that transmit climate information, and inclusive design that accounts for vulnerable and smallholder farmers who face the steepest adoption barriers [4], [8], [9]. Policy frameworks that address adaptation and mitigation jointly — rather than as separate legislative tracks — are increasingly identified as more effective at sustaining long-term resilience [8].

REGIONAL CASE STUDIES

Table 2: Quantified Benefits of Climate-Smart Agriculture Practices

Metric	Reported Range	Practice(s)
CSA yield boost	20–38%	Combined CSA adoption (climate-resilient varieties, conservation agriculture, agroforestry, precision agriculture)
Biochar productivity gain	15.1%	Biochar application
Global warming potential reduction	27–35%	Biochar and agroforestry vs. conventional systems
Nitrogen-use efficiency gain	15–20%	Precision agriculture / nutrient management
GHG emission reduction	20–40%	Soil carbon sequestration, precision fertilization, methane-reducing feed, agroforestry
Soil carbon increment	0.3–0.8 t C ha ⁻¹ yr ⁻¹	Same four CSA pathways
Productivity improvement	10–25%	Same four CSA pathways

Sources: Devarajan et al. (2026), Results in Engineering [3]; Awais, Wang & Ashraf (2026), Climate Smart Agriculture [4].

Table 3: OECD Categories of Agricultural Adaptation Policy

Category	Description	Examples
Infrastructure and technological approaches	Enabling or implementing technological innovation or infrastructure development	Irrigation and drainage investment, regional water infrastructure, crop/livestock technology
Behavioural and cultural approaches	Enabling changes in farmer behaviour	Adjusting planting dates, changes in growing location, altered livestock management
Pest, disease, and invasive species control	Managing biological risks intensified by climate change	Invasive species inspection, collaborative pest-spread monitoring
Breeding and genetic approaches	Supporting cultivar or breed development and selection	Development of drought- or heat-tolerant varieties and breeds

Source: OECD, Agricultural Policy Monitoring and Evaluation 2023 [7].

California, United States: Water-Centered Adaptation

California's agricultural sector, a major contributor to US food production, has centered its adaptation response on water security amid an increasingly volatile hydrological cycle. Research on the state's water future highlights groundwater management, crop-switching, and infrastructure investment as core adaptation levers, illustrating how adaptation priorities shift toward water governance in regions where water — not temperature alone — is the binding constraint [6].

Burkina Faso: Climate-Smart Practice Adoption Among Smallholders

In Burkina Faso, where smallholder farmers depend heavily on rain-fed agriculture, research using multivariate probit models found that climate-smart practices meaningfully affect agricultural resilience, though adoption depends on farmer access to information, credit, and extension services [9]. This underscores a pattern seen throughout the Sub-Saharan African literature: technology and practice availability alone does not guarantee adoption without institutional support.

Coastal Bangladesh: Stakeholder-Informed Adaptation

In southeastern coastal Bangladesh, a region highly exposed to sea-level rise and salinity intrusion, farmer and stakeholder interviews identified locally adapted cropping calendars, salinity-tolerant varieties, and community-level water management as priority adaptation strategies, emphasizing that adaptation planning is most effective when it incorporates farmer and stakeholder knowledge directly rather than being designed top-down [10].

South Africa: Integrated Climate-Smart Food Systems

A 2025 review of South African climate-smart food systems found that adaptation strategies such as drought-resistant crops, precision agriculture, and agroecological practices are most effective when reinforced by supportive policy environments, citing the country's Climate Change Bill and Agricultural Disaster Risk Management Framework as examples of legislative scaffolding that enables practice-level adaptation [8].

Vulnerable and Smallholder Groups

Across regions, the literature repeatedly flags that vulnerable groups — smallholders, women farmers, and rain-fed producers in developing countries — face disproportionate climate exposure alongside the weakest

Table 4: The Global Adaptation Finance Gap

Metric	Value	Year / Horizon
Estimated adaptation finance needed (developing countries)	US\$310–365 billion per year	By 2035
International public adaptation finance flows	US\$26 billion	2023 (down from US\$28 billion in 2022)
Finance gap ratio	12–14× current flows	Current
Share of adaptation finance structured as debt	58%	2023
Potential private-sector contribution with supportive policy	~US\$50 billion per year	Projected

Source: UNEP, Adaptation Gap Report 2025: Running on Empty [13].

adaptive capacity, since poor households often spend the majority of their income on food and have limited buffers against shocks. Closing this gap is identified as a distinct research and policy priority rather than a byproduct of general adaptation progress [5].

India: National Innovations in Climate Resilient Agriculture (NICRA)

India offers one of the largest state-led adaptation programmes in the world. Launched in 2011 by the Indian Council of Agricultural Research, NICRA combines strategic research, on-farm technology demonstration, and capacity building across more than 150 climatically vulnerable districts, promoting climate-resilient crop varieties, natural resource management practices, and livestock interventions. A 2026 synthesis review of the programme's empirical literature concludes that NICRA has demonstrated technical feasibility and localized welfare gains at the village level, but that remaining adoption barriers are structural — tied to input supply, land tenure, and market access — rather than a simple lack of farmer awareness. The review calls for stronger linkage between technology demonstration and the financial and institutional systems farmers need to sustain adoption, echoing the barriers identified elsewhere in this review [11].

ECONOMICS AND FINANCING OF AGRICULTURAL ADAPTATION

Even well-designed adaptation strategies and technologies depend on financing to reach scale, and this is where the global response remains most strained. Agriculture, forestry, and other land-use sectors receive support that is inadequate relative to their climate exposure, and the shortfall is especially acute for smallholder and low-income farming systems that lack access to commercial credit or insurance markets [12].

The literature points to several mechanisms for narrowing this gap: blended finance structures that de-risk

private investment, expanded index-based crop insurance, debt-conscious financing that avoids deepening the debt burden of already-vulnerable countries, and stronger integration of adaptation finance into national development and agricultural budgets rather than treating it as a separate climate line-item [12], [13]. Nature-based solutions — agroforestry, soil carbon projects, and watershed restoration — are increasingly proposed as a way to attract both adaptation and mitigation finance simultaneously, since they generate co-benefits that can be financed from multiple funding streams [12].

BARRIERS TO ADOPTION

Across strategies, technologies, and policy instruments, a consistent set of barriers limits the pace of adaptation:

- **Financial constraints:** high upfront costs of precision technology, irrigation infrastructure, and improved seed limit adoption, particularly for smallholders [3], [4].

- **Institutional gaps:** weak extension services and limited access to climate information reduce farmers' ability to act on available knowledge [9].

- **Technological mismatch:** digital tools designed for large, well-capitalized farms do not always transfer effectively to smallholder or resource-constrained contexts [2].

- **Result variability:** the effectiveness of a given practice depends strongly on local soil, climate, and management conditions, undermining one-size-fits-all recommendations [3], [4].

DISCUSSION AND RESEARCH GAPS

The reviewed literature shows growing consensus that adaptation and mitigation are best pursued jointly through climate-smart agriculture, with encouraging quantified benefits across yield, emissions, and soil

health [3], [4]. However, several gaps persist: most quantified performance data comes from a relatively narrow set of well-studied pathways, and comparative evidence across regions with different institutional capacity remains limited [4]. Digital agriculture research in particular is concentrated in higher-income countries, leaving open questions about how these tools perform under the financial and infrastructural constraints typical of smallholder systems [2]. The finance literature adds a further gap: even validated, cost-effective adaptation practices cannot scale without closing the 12–14-fold gap between adaptation finance needs and actual flows, which means technology and policy design cannot be evaluated in isolation from financing feasibility [12], [13]. Finally, the literature increasingly calls for integrated policy frameworks that treat adaptation and mitigation as a single design problem, rather than evaluating agricultural policy instruments in isolation [7], [8].

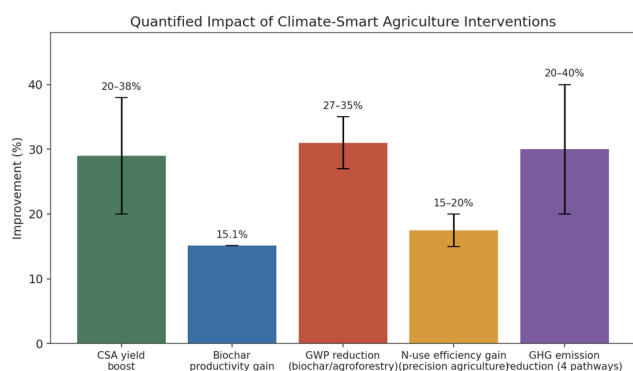


Figure 1: Quantified impact ranges reported for individual climate-smart agriculture interventions.

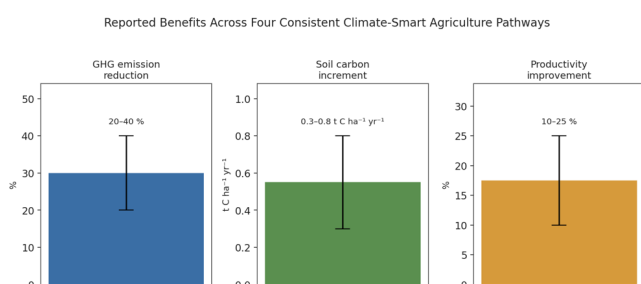


Figure 2: Reported benefit ranges across the four CSA pathways found consistently effective in a 368-study PRISMA review [4].

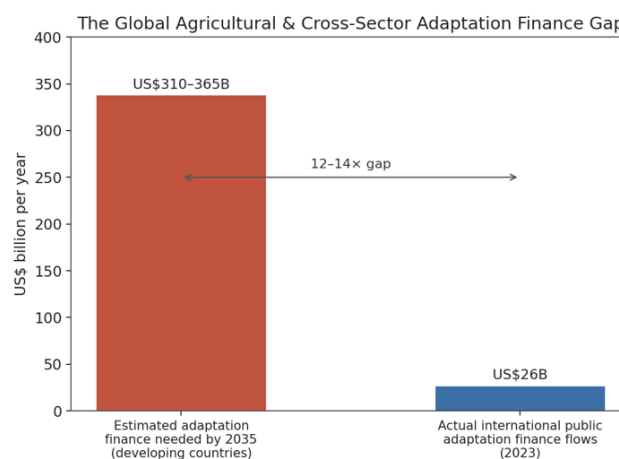


Figure 3: The gap between estimated adaptation finance needs and actual international public adaptation finance flows.

CONCLUSION

Agriculture's adaptation to climate change is advancing along four connected fronts: on-farm agronomic and water-management practices, digital and precision technologies, supportive policy frameworks, and the financing needed to bring all three to scale. The evidence reviewed here shows that climate-smart agriculture interventions can deliver meaningful, quantifiable gains in yield, emissions reduction, and soil health, and that national programmes such as India's NICRA demonstrate these gains can be achieved even in large, resource-constrained farming systems. But realizing these gains broadly depends on financing, institutional support, and locally adapted technology — particularly for the smallholder and vulnerable farming populations who face the greatest climate exposure and the fewest resources to adapt, and who are also furthest from the commercial credit and insurance markets that better-resourced farmers can draw on. Continued regional case-study research, more integrated adaptation-mitigation policy design, and a serious effort to close the global adaptation finance gap will together be essential to closing this implementation gap.

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