The Journal of Agricultural Science

www.cambridge.org/ags

A systems-level framework for climate-resilient maize: integrating genetics, microbiomes, agronomy, and policy

Bushra Quyoom[1], Aijaz Ahmad Wani[1], Ajaz Ahmad Lone[2], Zahoor Ahmad Dar[2] and Latif Ahmad Peer[1]

[1]Department of Botany, University of Kashmir, Srinagar, Jammu and Kashmir, India and [2]Dryland Agriculture Research Station, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir, Jammu and Kashmir, India

Crops and Soils Review

Cite this article: Quyoom B, Wani AA, Lone AA, Dar ZA, and Peer LA (2026). A systems-level framework for climate-resilient maize: integrating genetics, microbiomes, agronomy, and policy. *The Journal of Agricultural Science* **164**(e44), 1–20. https://doi.org/10.1017/S0021859626100835

Received: 4 September 2025 UTC
Revised: 15 July 2026 UTC
Accepted: 7 August 2026 UTC

Keywords:
climate-smart agriculture; food security; maize production systems; microbiome engineering; public–private partnerships

Corresponding author:
Latif Ahmad Peer; Email: peerlatif@gmail.com

Abstract

Maize (*Zea mays* L.), a global staple in food and feed systems, faces intensifying threats from drought, heat, flooding, and shifting pest dynamics under climate change. Building resilient maize systems is essential to sustain yield and secure rural livelihoods. Unlike earlier reviews that address genetics, agronomy, or policy separately, this study presents the first integrative roadmap uniting five domains: genetic innovation, climate-smart agronomy, predictive modelling, microbiome engineering, and enabling policy frameworks. Genetic breakthroughs, including Clustered regularly interspaced short palindromic repeats (CRISPR)-based editing, genomic selection, and doubled haploids, are accelerating stress-tolerant hybrid development. Agronomic practices such as conservation agriculture, intercropping, precision irrigation, and nutrient optimisation enhance soil health, resource efficiency, and yield stability. Digital tools, including remote sensing, AI-enabled forecasting, and decision-support systems, strengthen early warning and adaptive capacity. Microbiome interventions, particularly drought-adaptive rhizobacteria and mycorrhizal fungi, are emerging as frontiers for resilience and nutrient uptake. Socioeconomic enablers, seed system governance, gender-responsive extension, and public–private partnerships, remain decisive for equitable scaling. Case studies from Africa, Asia, and Latin America demonstrate 20–50 % yield gains under stress conditions through integrated approaches. Yet, major gaps persist in multi-stress breeding pipelines, genotype × microbiome × environment studies, and predictive analytics tailored for smallholder systems. By explicitly linking technological, ecological, and institutional innovations, this review advances a systems-level framework for climate-resilient maize. It calls for AI-driven breeding pipelines, carbon-smart agriculture, and inclusive, farmer-centric innovation models to secure maize-dependent livelihoods and future-proof global food systems.

Introduction

Maize (*Zea mays* L.), often regarded as the 'queen of cereals', is a cornerstone of global food security due to its versatility, adaptability, and economic significance. As the leading cereal crop by production volume, maize is projected to become the most widely grown and traded staple in the coming decades (Erenstein *et al.*, 2022). It serves multiple roles, as a staple food in sub-Saharan Africa and Latin America, as a global source of animal feed, and as a raw material for industrial and biofuel applications. This versatility underscores its centrality in both human and livestock food systems, as well as in national economies dependent on agri-food systems (Erenstein *et al.*, 2022; Grote *et al.*, 2021).

In nations like Malawi, maize is not only a dietary staple but also an economic lifeline, intricately linked to food security and rural livelihoods (Nyirenda *et al.*, 2021). However, this dependence makes maize cultivation especially vulnerable to the escalating impacts of climate change. While short-term warming trends may offer yield advantages in certain regions, long-term projections suggest severe threats from rising temperatures, increased drought frequency, and erratic precipitation patterns (Bracho-Mujica *et al.*, 2024). In particular, heat stress during pollination and flowering stages can drastically impair yield, and rainfall variability can disrupt planting cycles and water availability (Liu *et al.*, 2022).

Recent innovations in crop genetics have provided some relief. For instance, drought-resilient hybrids like the AQUAmax series in the U.S. Corn Belt demonstrate yield stability under water-limited conditions (Gaffney *et al.*, 2015). Similarly, advances in nutrient management, such as improving nitrogen and phosphorus use efficiency, are essential for sustainable intensification and closing existing yield gaps (Wang *et al.*, 2023). Beyond conventional breeding, microbial interventions, particularly the use of plant growth-promoting rhizobacteria (PGPR), are being explored to enhance resilience by aiding nutrient solubilisation and improving root architecture (Chattaraj *et al.*, 2025).

© The Author(s), 2026. Published by Cambridge University Press.

While developed regions, such as the U.S. and Corn Belt, focus on advanced genetics to mitigate abiotic stress, developing regions in Africa and Asia face compounding biotic threats, such as fall armyworm, exacerbated by climate variability and limited infrastructure. This divergence in challenges and capacities underscores the need for context-specific strategies.

Despite these advances, several challenges remain to be addressed. Climate variability continues to exacerbate pest outbreaks, such as the fall armyworm invasion in Africa, placing additional pressure on maize production systems (Togola *et al.*, 2025). Furthermore, shifts in global maize trade, biofuel policies, and the diversion of maize from food to non-food uses raise concerns regarding long-term food availability, particularly in import-dependent regions (Wu and Guclu, 2013).

In response to these complex challenges, Climate-Smart Agriculture (CSA) has emerged as a transformative framework. Climate-Smart Agriculture promotes productivity enhancement, climate adaptation, and greenhouse gas mitigation through an integrated suite of practices, including resilient seed systems, precision agriculture, and ecosystem-based approaches (Kabato *et al.*, 2025). It not only improves yield stability but also supports economic viability and sustainability (Bhatnagar *et al.*, 2024).

However, existing reviews often examine these strategies in isolation, focusing either on genetics, agronomy, microbiomes, or policy dimensions separately. However, a unified synthesis that explicitly integrates these domains into a systems-level framework for maize climate resilience is lacking.

This review fills this gap by presenting a novel five-pillar framework (genetic innovations, agronomic practices, microbiome engineering, digital tools, and policy enablers) that collectively charts a roadmap for climate-resilient maize production. Drawing on global case studies, this review identifies synergies across domains, highlights critical knowledge gaps, and proposes interdisciplinary pathways to future-proof maize systems against climate uncertainty (Figure 1). This framework recognises that no single pillar operates in isolation: genetic innovations must be deployed through appropriate agronomic systems, their performance predicted by climate models, their resilience enhanced by beneficial microbiomes, and their adoption enabled by supportive policies to be effective. The arrows in Figure 1 indicate these synergistic interactions and feedback loops. The interconnected nature of these pillars is further elaborated in Table 2, which presents a conceptual matrix of how each domain supports and benefits from the others.

The topic of climate-resilient maize has been addressed in several recent reviews, each focusing on a specific domain. For instance, Li *et al.* (2025) provided a comprehensive overview of genetic diversity and agronomic innovations, whereas Peer *et al.* (2024) focused specifically on the genetic and molecular pathways for drought tolerance. Bhatnagar *et al.* (2024) explored the broader dynamics of Climate-Smart Agriculture practices, and Burlakoti *et al.* (2024) reviewed beneficial plant-microbe interactions for stress tolerance in maize. More recently, Azrai *et al.* (2024) analysed global drought-tolerant maize research with a focus on technological visualisation, and Sahoo *et al.* (2025) examined climate-resilient agriculture from a sustainability and policy perspective in India. Additionally, Peer *et al.* (2025) synthesised advances in drought stress memory mechanisms, covering the transcriptional, epigenetic, and physiological pathways that enable rapid adaptation to recurrent drought events. Recently, Kim *et al.* (2026) synthesised biotechnological strategies, including CRISPR, genomic selection, and AI-driven phenotyping, whereas Sophian (2026) focused specifically on molecular markers and genome-wide association studies for thermotolerance in maize.

Although these contributions are invaluable, they often treat these domains in isolation. The unique contribution of this review is its explicit integrated synthesis of five critical pillars: genetic innovation, climate-smart agronomy, predictive modelling, microbiome engineering, and enabling policy frameworks. The current review goes beyond a simple description of each field to analyse their synergistic interactions, providing a systems-level perspective essential for developing holistic climate resilience. It also critically assesses the translational challenges – from the laboratory to the field to policy – that are often overlooked in domain-specific reviews. This framework identifies not only the latest technological breakthroughs but also the critical socioeconomic and institutional bottlenecks that must be addressed to ensure an equitable and scalable impact, thereby offering a roadmap for future research and action.

Review methodology

To ensure transparency and rigour, the literature for this review was gathered through systematic searches of the following databases: Web of Science, Scopus, Google Scholar, and PubMed. The search strategy employed a combination of keywords related to the five core pillars of the review framework, including: 'climate-resilient maize', 'climate-smart agriculture', 'genomic selection', 'CRISPR maize', 'conservation agriculture', 'microbiome engineering', 'PGPR maize', 'crop modelling', 'AI yield forecasting', 'seed systems', 'climate policy', and 'smallholder adaptation'. The search was confined to articles published between 2015 and 2025, with an emphasis on studies from 2020 onwards to capture the most recent advances. The inclusion criteria prioritised peer-reviewed original research, meta-analyses, and comprehensive reviews that explicitly addressed the intersection of maize production and climate change adaptation. The final selection was guided by the relevance of the findings to the five pillars and their contributions to a system-level understanding of climate resilience.

Climate challenges facing maize production

Maize production is increasingly vulnerable to climate-induced stressors that interact across spatial and temporal scales. These challenges include drought, heat, flooding, and shifts in pest and disease dynamics (Ahmad *et al.*, 2024; Du and Xiong, 2024; Kim and Lee, 2023). While each of these stressors has been studied independently, their combined effects, regional variability, and feedback loops remain inadequately addressed in the current breeding and policy frameworks. This section critically evaluates these dimensions, drawing on recent empirical findings to identify key vulnerabilities, contradictions in current approaches, and underexplored opportunities for building resilience.

Drought and heat stress

The synergistic effects of drought and heat represent the most critical abiotic threats to maize productivity, particularly during the flowering phase (from tassel emergence to silking, VT to R1 stage).

Research has shown that temperatures above 30 °C during flowering reduce grain set by 1.7 % per additional degree, with co-occurring drought capable of causing 30–50 % yield losses in susceptible varieties (Meseka *et al.*, 2018). Physiologically, drought-induced stomatal closure begins early during vegetative

https://doi.org/10.1017/S0021859626100835 Published online by Cambridge University Press

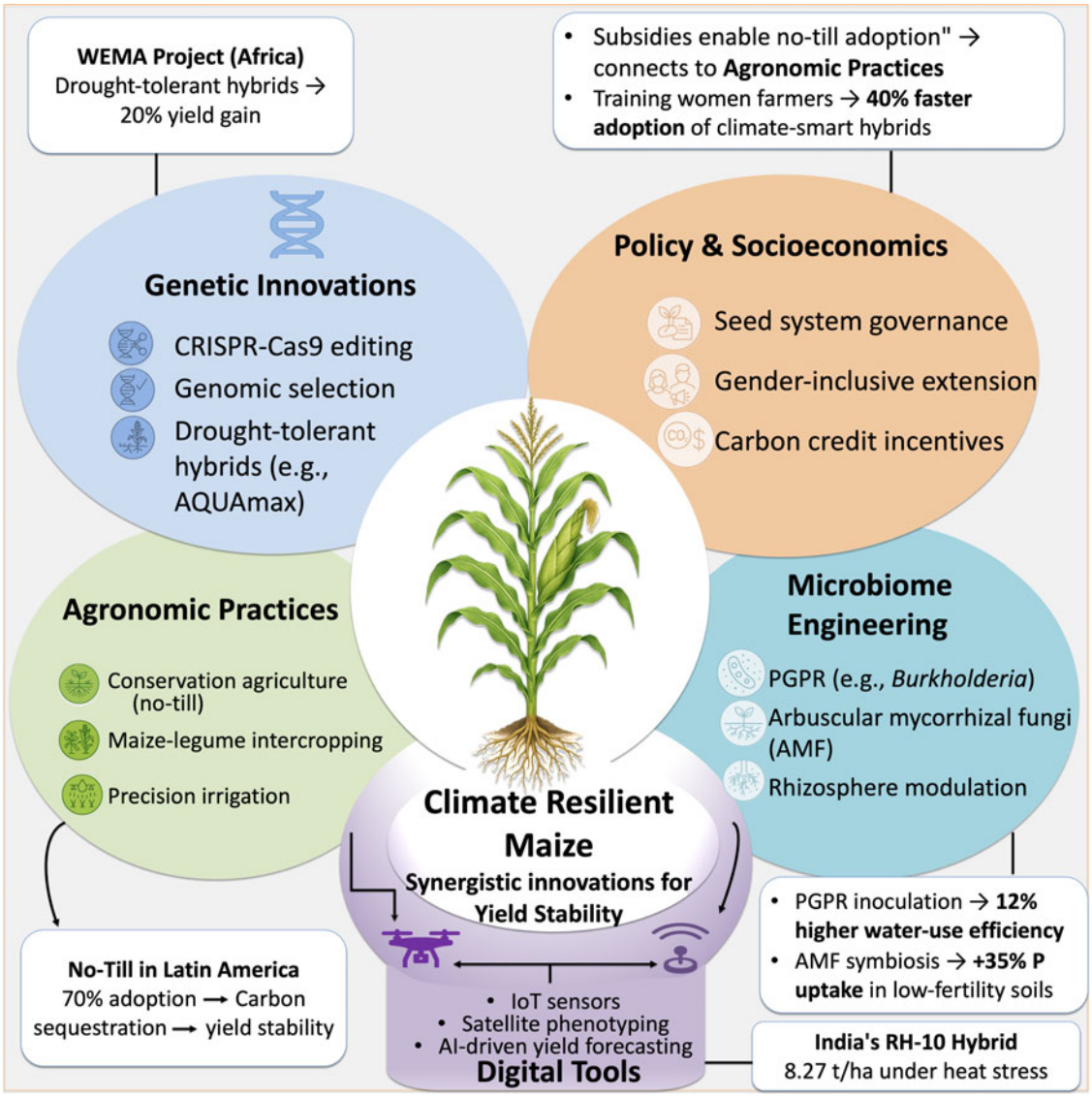


Figure 1. Integrated framework for climate-smart maize systems. This conceptual model illustrates five synergistic pillars of innovation enabling maize resilience under climate change: Genetic Innovations (blue), including CRISPR-Cas9 editing, genomic selection, and drought-tolerant hybrids (for example, AQUAmax), exemplified by the WEMA Project's 20 % yield gain in Africa. Agronomic Practices (green): No-till farming, maize-legume intercropping, and precision irrigation, with Latin American no-till systems achieving 70 % adoption and carbon sequestration. Microbiome Engineering (cyan): PGPR (*Burkholderia* spp.) enhancing water-use efficiency (+12 %) and AMF boosting phosphorus uptake (+35 %) in low-fertility soils. Digital Tools (purple): AI-driven yield forecasting and IoT/satellite phenotyping validated by India's RH-10 hybrid (8.27 t/ha under heat stress). Policy & Socioeconomics (orange): Gender-inclusive extension services and carbon credit incentives. The arrows signify synergistic interactions and feedback loops between these pillars, highlighting that resilience is maximised when these innovations are deployed in concert. AI, artificial intelligence; AMF, arbuscular mycorrhizal fungi; CRISPR-Cas9, clustered regularly interspaced short palindromic repeats–CRISPR-associated protein 9; IoT, Internet of Things; P, phosphorus; PGPR, plant growth-promoting rhizobacteria; WEMA, Water Efficient Maize for Africa.

growth, reducing photosynthesis and biomass accumulation even before visual symptoms appear (Li *et al.*, 2024). When combined with heat stress, the damage compounds, impaired pollen viability, and silk desiccation disrupt fertilisation, while high root zone temperatures further inhibit nutrient uptake (Liu *et al.*, 2023a; Meseka *et al.*, 2018; Peer *et al.*, 2024; Sheoran *et al.*, 2022; Waqas *et al.*, 2021). A comparative analysis across regions reveals disproportionate impacts on rainfed systems, especially in sub-Saharan Africa and South Asia, where irrigation is minimal and cultivars are often not bred for concurrent stress tolerance (Steward *et al.*, 2019; Zaidi *et al.*, 2023). Despite advances in drought and heat stress breeding, most programmes continue to evaluate genotypes under single-stressor conditions, limiting their real-world relevance. Traits such as heat viability, pollen thermotolerance, and canopy temperature depression remain underutilised in varietal selection. There is a pressing need for harmonised, multi-location trials that simulate combined stress conditions, particularly in rain-fed systems. Incorporating dynamic, field-relevant phenotyping platforms, including remote sensing and AI-assisted screening, could greatly enhance the accuracy and efficiency of genotype selection under overlapping climatic stress conditions.

Flooding and waterlogging

Flooding and waterlogging, although historically underrepresented in maize stress research, are becoming more frequent because of intensified rainfall patterns (Azrai *et al.*, 2022; Zhi *et al.*, 2024). Within 24–48 h of waterlogging, roots shift from aerobic to

https://doi.org/10.1017/S0021859626100835 Published online by Cambridge University Press

Table 1. Molecular, genetic, and microbial interventions for climate-resilient maize: mechanisms, stress targets, and translational potential. This table synthesises cutting-edge strategies to enhance maize resilience, categorising interventions by domain (genetic, microbial, and molecular), mechanistic action, targeted stresses (e.g. drought and heat), and quantifiable outcomes. Technology readiness levels (TRLs) indicate developmental stages: TRL 3–4: proof-of-concept (greenhouse/controlled trials), TRL 5–6: multi-environment validation, and TRL 7–8: near-commercial deployment. The data provide a roadmap for translating lab-scale innovations into field-ready solutions, with an emphasis on scalability and interdisciplinary integration

Domain	Intervention	Mode of action	Stress targeted	Key outcomes	TRL	References
Genetic (TF regulation)	*ZmNF-YC12* overexpression	ABA pathway activation; antioxidant defence	Drought, heat	↑ RWC, and proline; improved antioxidant defence and recovery	4–5	(Cao *et al.*, 2023)
Genetic (GA pathway)	CRISPR-*ZmGA20ox3*	↓ GA1 → semi-dwarfing; ↑ ABA/JA signalling	Drought	↓ ASI by 2 days; maintains>90% yield	6–7	(Liu *et al.*, 2023b)
Genetic (root traits)	*ZmTIP1*, *ZmPIF3* overexpression	ZmTIP1 → ↑ root hair elongation. ZmPIF3 → ↑ drought-responsive gene expression, water retention	Drought	ZmTIP1: ↑ root density and ↑ water uptake ZmPIF3: ↑ RWC, chlorophyll, membrane stability	5	(Gao *et al.*, 2015; Zhang *et al.*, 2020)
Genetic (ethylene regulation)	*ARGOS8* overexpression (CRISPR)	↓ Ethylene sensitivity → improved flowering	Drought	↑ Grain yield; earlier flowering	7–8	(Shi *et al.*, 2017)
Genetic (ethylene biosynthesis suppression)	Transgenic down-regulation of ACS (ACC synthase)	↓ Ethylene production → ↓ ASI, ↑ kernel number	Drought	↑ Grain yield by 0.58 Mg/ha under flowering stress	7	(Habben *et al.*, 2014)
Genetic (thermotolerance)	*ZmDREB2A* overexpression	Activates LEA genes, detoxification genes	Heat + Drought	↑ Pollen viability, antioxidant expression	4–5	(Qin *et al.*, 2007)
Genetic (cross-species)	*OsMYB55* transgene (rice)	Induces HSPs; reduces oxidative damage	Heat (+ Drought)	↑ Biomass; ↓ leaf damage	3–4	(Casaretto et al., 2016)
Gene editing (metabolic)	Chloroplast-targeted *PGD1/PGD2* fusion	Restores starch biosynthesis under heat	Heat (high night temp)	Maintains kernel starch & yield	4–5	(Ribeiro *et al.*, 2020)
Microbiome (PGPR)	*Burkholderia*, *Mitsuaria*	ACC deaminase → ↓ ethylene; ↑ proline/ROS scavenging	Drought	Improved root traits; ↓ evapotranspiration; ↑ antioxidant activity	5	(Huang et al., 2017)
Microbiome (AMF)	*Glomus* spp., *Rhizophagus irregularis*	↑ P uptake; ↑ WUEi; stabilised redox and osmotic balance	Drought	↑ Shoot water content; ↑ antioxidant activity; modified cell walls	5–6	(Le Pioufle *et al.*, 2019; Wilmowicz *et al.*, 2022)
Microbiome (consortium)	*B. cereus*, *L. amnigena* (mixed PGPR)	P solubilisation, N fixation, IAA production	Drought + Heat	↑ Shoot/root biomass; ↑ leaf water content	5–6	(Notununu *et al.*, 2024)
Microbiome (synergy)	*Piriformospora indica*	↑ Leaf area, antioxidants; ↓ MDA	Drought	↑ Root/shoot biomass; upregulation of drought-responsive genes; Improved physiological resilience	4–5	(Xu *et al.*, 2017)
Molecular priming	*miR397*, *ZmSnRK2.9*	miR397: ↓ lignin, ↑ flavonoids; ZmSnRK2.9: ↑ ABA responsiveness	Drought	Enhanced stress tolerance via metabolic remodelling and ABA signalling	3–4	(Hong *et al.*, 2024; Yan *et al.*, 2024)
Molecular signalling	Ca^{2+}–CDPK7–ROS–sHSP pathway	Heat-triggered Ca^{2+} influx → ZmCDPK7 activation → sHSP17.4 phosphorylation	Heat	↑ HSP expression; ↑ antioxidant activity; ↓ MDA/H_2O_2	3–4	(Zhao *et al.*, 2021)
Molecular signalling	UPR pathway (*IRE1*, *ZmbZIP17*)	ER stress/ABA → ZmbZIP17 activation → ↑ UPR gene expression	Heat	↑ Protein folding capacity; ↑ ABA-responsive gene expression	3	(Yang *et al.*, 2013)

TF, transcription factor; ABA, abscisic acid; RWC, relative water content; GA, gibberellin; CRISPR, clustered regularly interspaced short palindromic repeats; JA, jasmonic acid; ASI, anthesis-silking interval; ACC, 1-aminocyclopropane-1-carboxylic acid; LEA, late embryogenesis abundant; HSP, heat-shock protein; PGPR, plant growth-promoting rhizobacteria; ROS, reactive oxygen species; AMF, arbuscular mycorrhizal fungi; P, phosphorus; WUEi, intrinsic water-use efficiency; N, nitrogen; IAA, indole-3-acetic acid; MDA, malondialdehyde; Ca^{2+}, calcium ion; CDPK, calcium-dependent protein kinase; sHSP, small heat-shock protein; H_2O_2, hydrogen peroxide; UPR, unfolded protein response; IRE1, inositol-requiring enzyme 1; ER, endoplasmic reticulum;.

anaerobic metabolism, resulting in a sharp decline in ATP production and nutrient uptake (Sanclemente, 2023). Secondary effects include nitrogen leaching, potassium loss, and increased vulnerability to root and stalk rot pathogens (Jha and Prajapati, 2024; Mishra *et al.*, 2024). Although traits such as aerenchyma formation and enhanced anaerobic metabolism have been identified as tolerance mechanisms (Gong *et al.*, 2019; Kaur *et al.*, 2021), they remain poorly integrated into breeding objectives.

The severity of waterlogging stress is influenced by the soil type and growth stage. Heavy clay soils exacerbate hypoxia owing to poor drainage, whereas the V3–V6 (vegetative) and reproductive (VT-R2) stages are particularly sensitive owing to their roles in root

https://doi.org/10.1017/S0021859626100835 Published online by Cambridge University Press

Table 2. Conceptual matrix of interconnected pillars for climate-resilient maize systems. This matrix illustrates the synergistic interactions between the five innovation domains. Each row shows a primary pillar, while columns indicate the potential benefits it can provide to or receive from other pillars, fostering cross-domain integration

Innovation pillar (primary)	Supports genetic innovations (GI) by:	Supports agronomic practices (AP) by:	Supports predictive modelling (PM) by:	Supports microbiome engineering (ME) by	Supports policy frameworks (PF) by:
Genetic innovations (GI)	–	Providing stress-tolerant varieties suited to specific management practices (Steward *et al.*, 2019)	Providing genotypic data (GxE interactions) to improve model predictions (Yuan *et al.*, 2018)	Identifying host genes that enhance beneficial microbial colonisation (Patyal *et al.*, 2025)	Providing evidence of effectiveness to justify policy support for breeding programmes (Prasanna, 2023)
Agronomic practices (AP)	Creating environments (e.g., stressed) for robust phenotyping and selection (Bhatnagar et al., 2024)	–	Providing management data (e.g., irrigation, planting dates) for model calibration (Saddique *et al.*, 2020)	Modifying soil conditions to promote beneficial microbial communities (Crystal-Ornelas *et al.*, 2021)	Demonstrating on-farm viability to encourage adoption of supportive policies (Adam and Abdulai, 2023)
Predictive modelling (PM)	Prioritising traits and environments for breeding (GS) (Shahhosseini *et al.*, 2021)	Optimising timing/placement of agronomic inputs via forecasts (Ahmed *et al.*, 2022)	–	Predicting microbial community dynamics under climate scenarios (Beck *et al.*, 2022)	Informing risk assessments and early warning systems for policy planning (Pienaah *et al.*, 2023)
Microbiome engineering (ME)	Unlocking novel stress-tolerance genes from native microbes (Gonzalez-Mendoza *et al.*, 2023)	Enhancing nutrient availability and water uptake, reducing input needs (Bouremani *et al.*, 2023)	Offering biological indicators for monitoring soil health and stress (Burlakoti *et al.*, 2024)	–	Providing bio-based solutions for sustainable intensification, aligning with environmental goals (Kumar *et al.*, 2022)
Policy frameworks (PF)	Funding research and streamlining regulations for breeding (Sahoo *et al.*, 2025)	Subsidising and incentivizing adoption of CSA practices (Holden and Fisher, 2015)	Supporting open data and infrastructure for digital agriculture (Balyan *et al.*, 2024)	Creating regulatory pathways for safe deployment of bioinoculants (Baloch, 2025)	–

GxE, genotype x environment; CSA, Climate-Smart Agriculture.

and ear development (Huang *et al.*, 2022; Zhi et al., 2024). Despite this, global breeding investments remain heavily skewed toward drought tolerance, creating an imbalance in the resilience efforts. Agronomic solutions (e.g. raised beds and ridge planting) dominate waterlogging mitigation strategies, whereas genetic improvement remains marginal. This asymmetry reflects both a gap in funding priorities and limited physiological understanding of flooding tolerance mechanisms.

Despite the growing recognition of its importance, waterlogging remains underprioritized in maize breeding programmes and funding portfolios. The physiological basis for tolerance, such as constitutive aerenchyma formation and metabolic adaptations under hypoxia, is increasingly understood but rarely incorporated into mainstream hybrid development. Moreover, breeding pipelines often lack reliable phenotyping protocols for the early-stage screening of flooding resilience. This gap in genetic preparedness is reflected in the disproportionate emphasis on agronomic interventions. Advancing waterlogging tolerance will require the integration of root architectural traits, hypoxia-inducible pathways, and real-time soil moisture diagnostics into varietal evaluation, particularly for low-lying and flood-prone production systems.

Climate-driven pest and disease shifts

Changing climate regimes are altering the epidemiology of pests and diseases in maize, resulting in complex interactions with abiotic stressors (Nega, 2025). Elevated temperatures accelerate pest reproduction, widen overwintering zones, and increase the frequency of vector-borne diseases (Azrag *et al.*, 2023; Skendžić *et al.*, 2021). For example, the fall armyworm (*Spodoptera frugiperda*) and western corn rootworm (*Diabrotica virgifera*) have expanded into new agroecologies, causing substantial losses in sub-Saharan Africa and Asia (Díaz-Álvarez *et al.*, 2023; Singh *et al.*, 2022). Simultaneously, fungal pathogens, such as *Puccinia polysora* and *Fusarium* species, thrive under drought-heat stress combinations, raising food safety concerns due to mycotoxin accumulation (Cao *et al.*, 2024; Kos *et al.*, 2023).

There is a notable research gap in predictive modelling that integrates climate variables with pest life cycles and pathogen virulence. Most national surveillance systems are reactive and fail to incorporate real-time weather data into risk-assessment frameworks. This is particularly problematic in smallholder systems, where timely responses are critical. Moreover, there are important synergistic effects: drought-stressed plants are more susceptible to stem borers, whereas waterlogged conditions favour soil-borne pathogens (Martínez-Arias *et al.*, 2022; Wamatsembe *et al.*, 2017). The 2016–2017 East African season, in which fall armyworm invasion coincided with drought, exemplifies how overlapping stressors can severely magnify yield losses (Paudel Timilsena *et al.*, 2022).

The acceleration of pest and pathogen shifts due to climate change exposes critical weaknesses in current monitoring and response systems. Despite mounting evidence of stress-induced vulnerability and climate-driven pathogen proliferation, pest forecasting tools remain largely disconnected from climate and crop stress datasets. This disconnect is particularly acute in smallholder-dominated regions, where delayed responses can lead to disproportionate loss. Building climate-resilient maize systems will require predictive frameworks that integrate biotic and abiotic

https://doi.org/10.1017/S0021859626100835 Published online by Cambridge University Press

data layers supported by machine learning and real-time environmental monitoring. Coupling early warning systems with targeted breeding for pest- and disease-resilient genotypes will be key to reducing compounded losses in a changing climate.

Regional vulnerability patterns

Climate risks to maize are unevenly distributed across agro-ecological zones, reflecting differences in the baseline climate, resource access, and institutional preparedness.

Sub-Saharan Africa: With over 90 % of the maize area under rainfed cultivation, yield fluctuations closely mirror rainfall variability (Dirwai *et al.*, 2024). Projections estimate yield declines of up to 24 % by 2090 in West Africa (Alimagham *et al.*, 2024). In East Africa, heterogeneity in rainfall patterns may lead to both gains and losses, depending on the local microclimates (Abera *et al.*, 2018; Msigwa *et al.*, 2024). The Drought Tolerant Maize for Africa (DTMA) programme has improved resilience, but its scaling remains inconsistent (Igbatayo, 2022).

South Asia: Projected temperature increases of 1.4–2.6 °C by 2050 threaten maize yield, especially in rainfed systems (Tesfaye *et al.*, 2017). Without adaptation, the yield could decline by up to 12.2 %. However, South Asia has demonstrated adaptive capacity through altered planting schedules, heat-tolerant hybrids, and improved input use.

Latin America: Contrasting climate risks are emerging: whereas highland regions are increasingly affected by flooding, tropical lowlands face recurrent droughts (Hagen *et al.*, 2022). The 2021 Brazilian drought reduced second-season maize yield by 35 % (Lovino *et al.*, 2025), highlighting the vulnerabilities of even technologically advanced systems. Public–private breeding programmes exist, but their reach to smallholders is limited.

These cases highlight a persistent contradiction: while climate stress is a global phenomenon, its manifestations are deeply localised and mediated by socio-economic and institutional factors. However, many current adaptation strategies continue to apply uniform solutions across diverse contexts, undermining their effectiveness. Building resilient maize systems requires granular, region-specific strategies that reflect agroecological heterogeneity and incorporate local knowledge systems.

These spatial differences in climate exposure and institutional capacity highlight the urgent need for localised, evidence-based adaptation strategies. Future efforts must integrate climate forecasts with breeding, extension, and policy platforms that are responsive to local variability and farmer constraints to ensure food security. Figure 2 synthesises global patterns of climate risks and links them to region-specific interventions such as drought-tolerant hybrids, flood-resilient varieties, and pest-resistant cultivars. By mapping both risk hotspots and areas of successful deployment (for example, DTMA hybrids in East Africa, Bt maize in Latin America, and Sub1 lines in Southeast Asia), this visualisation highlights not only where adaptation is needed but also where innovation is taking root.

Genetic innovations for climate-smart maize

The escalating threats to maize production, as detailed in Section Review methodology, require equally sophisticated genetic solutions. Modern breeding programmes now employ an integrated toolkit that combines cutting-edge genomics, precision gene editing, and accelerated breeding systems to develop varieties capable of withstanding compound climate stress (Li *et al.*, 2025). This section reviews the major innovation streams in the genetic improvement of maize under climate stress. The current review advances these into four interlinked domains: (i) harnessing genetic diversity, (ii) deploying genomic tools and gene editing, (iii) accelerating breeding cycles via doubled haploid systems, and (iv) enabling field deployment through partnerships and regulatory frameworks (Figure 3, Table 1).

Mining genetic diversity for stress resilience

Building on the physiological stress responses outlined in Section Review methodology, researchers have systematically screened germplasm collections for adaptive traits. Landraces and wild relatives are reservoirs of adaptive traits. For instance, landraces such as GH-3505 and GH-4859 from Ghana and TZm-1353 from Tanzania exhibit exceptional drought and heat tolerance capabilities, whereas wild relatives such as *Zea nicaraguensis* contribute alleles for waterlogging adaptation, including aerenchyma formation and adventitious root development (Gong *et al.*, 2019; Nelimor *et al.*, 2019). CIMMYT's studies of tropical maize populations have revealed that landrace polygenic stress tolerance often shows partial dominance, with additive genetic variance playing a greater role than non-additive effects in traits such as waterlogging tolerance (Zaidi *et al.*, 2010). Despite their rich adaptive potential, landraces and wild relatives remain underutilised in elite breeding because of phenotyping bottlenecks and the challenge of linkage drag. Future efforts should combine multi-environment field screening with advanced genomic introgression tools to unlock the potential of stress-resilient breeding under real-world conditions.

Decoding resilience through genomic tools

Marker-assisted selection (MAS) has enabled the introgression of major-effect QTLs, such as qRfg1 and qRfg2 for Gibberella stalk rot resistance (conferring 32–125 % increased resistance) or meta-QTLs for drought tolerance linked to reduced anthesis-silking interval (ASI) (Semagn *et al.*, 2013; Zhang *et al.*, 2012). However, the environmental instability of many QTLs, exemplified by CIMMYT's findings that only six of 15 drought-related meta-QTLs were expressed across multiple environments, has driven the adoption of genomic selection (GS) (Yuan *et al.*, 2018). GS leverages genome-wide single nucleotide polymorphism (SNP) data from high-density arrays (for example, Illumina's 9k SNP chip) to predict breeding values for polygenic traits, proving particularly effective for complex stresses, such as combined heat and drought conditions, where CIMMYT's whole-genome prediction models outperform conventional MAS (Sandhu *et al.*, 2022; Yuan *et al.*, 2018).

Recent advances in functional genomics have accelerated trait discovery and deployment. GWAS panels of >500 diverse lines have identified 78 significant SNPs associated with lipid metabolism under heat stress, while fine mapping has localised critical regions, such as the 300-kb qRfg2 locus on chromosome 1, that modulates auxin signalling during stalk rot resistance (Prasanna *et al.*, 2021; Ye *et al.*, 2019). CRISPR/Cas9 editing now targets these loci, modifying stomatal regulators for drought adaptation or heat-shock proteins, such as *ZmHSP101*, with transgene-free edits bypassing regulatory hurdles (Li *et al.*, 2022; Sami *et al.*, 2021). Parallel transgenic approaches overexpress validated candidates, such as OsMYB5,5, to enhance osmotic adjustment (Casaretto *et al.*, 2016). For polygenic cold tolerance, GWAS of 306 tropical hybrids revealed stable SNPs clustered in

https://doi.org/10.1017/S0021859626100835 Published online by Cambridge University Press

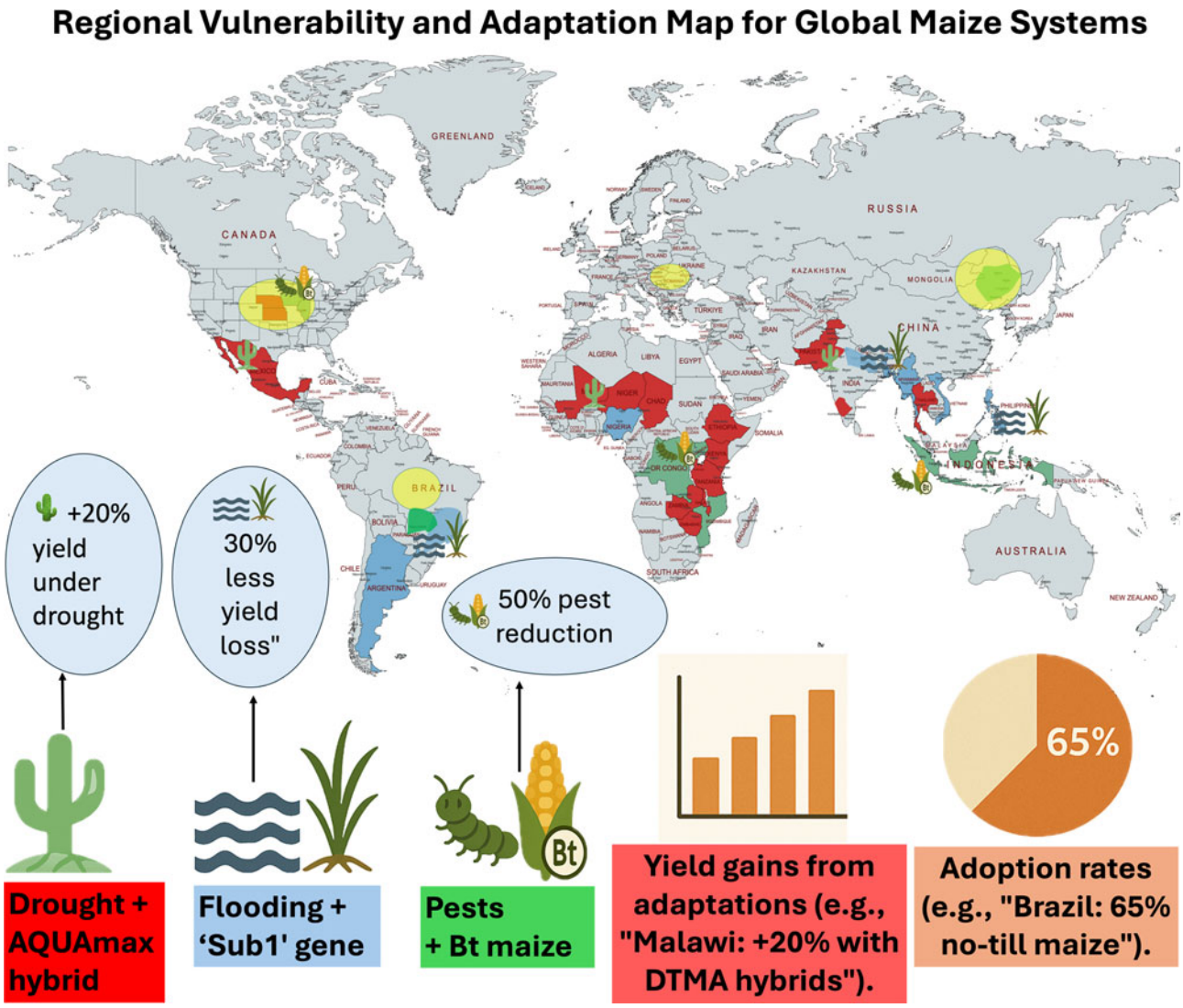


Figure 2. Map illustrating the key maize-growing regions facing climate risks – drought (red), flooding (blue), and pest pressures (green). Icons denote specific interventions: AQUAmax hybrids for drought resilience, 'Sub1' gene varieties for flood tolerance, and Bt maize for pest resistance. The inset graphics summarise the quantitative benefits, including 20 % yield gains in Malawi using DTMA hybrids, 30 % reduction in yield loss from flood-adapted varieties, and 65 % adoption of no-till maize in Brazil. The highlighted regions indicate where these innovations are most urgently needed and effectively deployed. Bt, *Bacillus thuringiensis*; DTMA, Drought Tolerant Maize for Africa.

chromosomal bins 2.08 and 6.01, although their minor effects necessitate GS rather than MAS for breeding applications (Li *et al.*, 2025). The transition from MAS to genomic selection reflects a necessary shift toward handling complex polygenic stress traits; however, predictive accuracy still suffers from poor trait heritability and limited cross-environment stability. Integrating high-throughput phenotyping, stress-responsive transcriptomics, and machine learning into GS models is critical for improving their robustness and accelerating trait deployment.

Speed breeding and doubled haploid technology

Speed breeding protocols are now being combined with doubled haploid (DH) technology to rapidly fix stress-resilient traits, compressing breeding cycles by up to 50 % (Chaikam *et al.*, 2019). CIMMYT's pipelines utilise paternal inducers with high haploid induction rates (HIR > 10 %) to generate homozygous lines in a single generation, particularly for polygenic traits such as waterlogging tolerance (QTLs on chromosomes 1 and 7) and cold tolerance (29 SNPs across growth stages) (Chaikam *et al.*, 2018; Chen *et al.*, 2024). This approach synergises with genomic selection, and early generation DH lines are genotyped using high-density SNP chips (for example, Illumina 9k) and phenotyped under controlled stress conditions, enabling concurrent selection for both major and minor effect loci (Bernardeli *et al.*, 2025; Zeng *et al.*, 2025). Colchicine-free chromosome-doubling methods further streamline this process, addressing a key bottleneck in DH production (Boerman *et al.*, 2020). Field validations in multi-environment trials confirmed that DH-derived hybrids retain resilience traits, such as the 22 heat-tolerance regions identified in Asian testcrosses, while maintaining yield stability (Zaidi *et al.*, 2023). This integrated DH pipeline has reduced breeding cycle times by up to 50 % compared to conventional methods, representing a major advancement in breeding efficiency (Chaikam *et al.*, 2019). Although DH and speed breeding have revolutionised generation turnover, their

https://doi.org/10.1017/S0021859626100835 Published online by Cambridge University Press

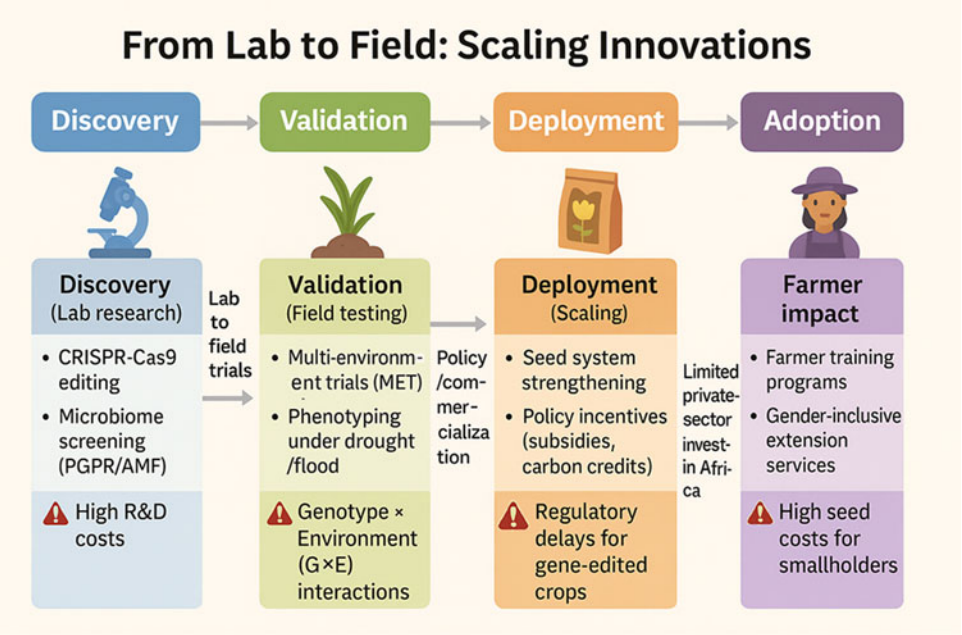


Figure 3. From lab to field – scaling innovations for climate-smart agriculture: this flowchart illustrates the innovation pipeline from laboratory research to farmer adoption in the context of climate-resilient agricultural technologies. The process progresses through four stages: discovery (e.g. CRISPR-Cas9, microbiome screening), validation (e.g. multi-environment trials, phenotyping under stress), deployment (e.g. seed system development, policy incentives), and adoption (e.g. farmer training, inclusive extension). Key barriers, such as high R&D costs, genotype × environment interactions, regulatory delays, and affordability issues, are highlighted, along with enabling actions and success stories to support equitable scaling. AMF, arbuscular mycorrhizal fungi; CRISPR-Cas9, clustered regularly interspaced short palindromic repeats–CRISPR-associated protein 9; G×E, genotype × environment; MET, multi-environment trials; PGPR, plant growth-promoting rhizobacteria; R&D, research and development.

full potential in climate-resilient breeding is constrained by technical costs and genotype × environment variability. Scaling these platforms will require open-access DH technology pipelines, especially in low-resource regions, and the integration of predictive phenotyping to guide early generation selection.

Deployment, field validation, and policy support

The translation of genetic innovations into farmer-accessible varieties requires rigorous multi-location testing and supportive-policy frameworks. Accelerated breeding lines undergo extensive field validation across diverse stress environments, confirming both the stability of GWAS-identified resilience loci (e.g. heat-tolerance regions) and the expression of heterotic advantages (such as 27–30 % reductions in *Fusarium* ear rot incidence) (Hung and Holland, 2012; Yin *et al.*, 2024). Successful deployments, including drought-tolerant hybrids in sub-Saharan Africa, have been facilitated by public–private partnerships and CIMMYT collaborations with NARS partners in South Asia (Prasanna, 2023). However, significant barriers remain, particularly the high costs of genotyping for genomic selection in resource-limited regions and regulatory delays for gene-edited varieties, despite their transgene-free nature (Namata *et al.*, 2025). Effective scaling requires coordinated investments in phenotyping infrastructure, centralised genotyping hubs, and breeding training programmes (Awada *et al.*, 2024). Policy frameworks must evolve to accommodate new breeding technologies while ensuring equitable access to climate-resilient varieties for smallholder farmers globally (Sahoo *et al.*, 2025). Genetic innovation alone cannot deliver climate resilience without synchronised policies, seed systems, and extension infrastructure. Closing the delivery gap will require regulatory streamlining for gene-edited crops, sustained investment in breeder networks, and inclusive strategies to ensure equitable access to climate-resilient varieties among marginalised farming communities.

The overall flow of discovery-to-deployment is summarised in Figure 3, highlighting the key stages of innovation, structural bottlenecks, and enabling conditions required for scaling genetic solutions in climate-vulnerable maize systems to be effective.

Agronomic strategies and climate-smart practices

To mitigate the effects of climate change on maize production, as discussed in Section Review methodology, agronomic strategies aligned with CSA and Conservation Agriculture (CA) are increasingly being adopted. These practices not only boost productivity and efficiency but also contribute to environmental sustainability and farmer resilience (Bhatnagar *et al.*, 2024). However, the effectiveness and scalability of these interventions remain uneven across regions, constrained by resource limitations, institutional support, and adaptation to local conditions. This section reviews the key climate-smart interventions in maize cultivation, including conservation agriculture, intercropping, crop rotation, precision nutrient management, smart irrigation, and the integration of digital technologies.

Conservation agriculture: minimum tillage and residue retention

CA is a cornerstone of climate-smart farming. It emphasises minimum soil disturbance, permanent soil cover, and crop diversification to build resilient farming systems (Mizik, 2021). Minimum Tillage (MT) reduces soil disturbance and promotes water retention, improves structure, and reduces erosion (Busari *et al.*, 2015). In Ghana, MT has led to a 4.3 % increase in maize yield and a 42 % reduction in household food insecurity (Adam and Abdulai, 2023). Long-term adoption enhances soil organic carbon (SOC) and improves biodiversity (Crystal-Ornelas *et al.*, 2021). Residue Retention involves leaving crop residues on the field, which enhances soil fertility, nutrient cycling, and carbon sequestration. It improves aggregate stability, reduces erosion, and increases SOC by up to 26 % when combined with no-tillage practices (Gatkal *et al.*, 2024; Srivastava, 2025). The combined Effects of MT and residue retention improve maize yield by 1.2–1.8 × in sub-Saharan Africa

https://doi.org/10.1017/S0021859626100835 Published online by Cambridge University Press

and reduce labour and CO_2 emissions, making CA an environmentally and economically viable solution (Micheni *et al.*, 2022; Sithole and Olorunfemi, 2024). However, reductions in iron bioavailability and initial investment costs pose challenges to its widespread adoption (Galani *et al.*, 2022). Despite its proven benefits, CA adoption in maize systems is often hindered by short-term trade-offs, such as reduced nutrient availability and delayed yield gains. Future efforts must focus on context-specific CA packages supported by soil health diagnostics, carbon accounting tools, and incentives for long-term ecological services.

Intercropping and crop rotation with legumes

Intercropping, especially maize-legume combinations (e.g. maize-cowpea or maize-pigeonpea), enhances yield, nitrogen fixation, and resilience to climatic stress. This system optimises land use and improves soil moisture retention, pest suppression, and food security (Akchaya *et al.*, 2025; Renwick *et al.*, 2020; Sahoo *et al.*, 2023). Crop rotation with legumes enhances nitrogen availability, stabilises yield and supports carbon sequestration. Studies from Northeast China and South Asia have shown increased NUE and climate resilience when maize is rotated with soybeans or velvet beans (Jiang *et al.*, 2022; Zou *et al.*, 2024). These systems reduce input costs and carbon footprints while increasing long-term productivity, although they may require careful timing and additional labour management (Brankatschk and Finkbeiner, 2015). While intercrops and rotations clearly enhance agroecosystem function, their success depends on labour availability, market incentives, and agroecological tailoring to local conditions. Scaling such systems requires participatory research and flexible policy mechanisms that reward diversity and resilience, rather than monoculture productivity alone.

Smart irrigation and precision nutrient management

Smart Irrigation practices, such as deficit irrigation, have demonstrated water savings of up to 19 % and reduced carbon inputs by 26 % in semi-arid regions (Halli *et al.*, 2024; Teshome *et al.*, 2023). In regions such as China, CSA irrigation methods have reduced carbon footprints by over 40 % while boosting grain yield (Feng *et al.*, 2023). Precision Nutrient Management, especially using Site-Specific Nutrient Management (SSNM) tools such as Nutrient Expert and chlorophyll metres, improves nitrogen efficiency and profitability. SSNM can increase yield by 14.7 % and generate a benefit-to-cost ratio of 2.47 (Panta *et al.*, 2022). The integration of organic inputs further enhances soil health and reduces nitrous oxide emissions (Graham *et al.*, 2017). Despite their potential, high initial costs and knowledge requirements limit their adoption in smallholder settings, necessitating stronger extension support and policy incentives (Chivenge *et al.*, 2022). The promise of smart irrigation and SSNM is often constrained by infrastructure and knowledge asymmetries in smallholder regions. To move beyond pilot success, integration with digital diagnostics, subsidy redesign, and decentralised training platforms is essential to enable a scalable and climate-responsive input management.

Digital tools: remote sensing, IoT, and decision-support systems

Remote Sensing technologies provide cost-effective, noninvasive tools for monitoring plant stress, nutrient status, and disease outbreaks. They enable timely interventions and spatially targeted management in large-scale maize systems (Parra-López *et al.*, 2025). IoT Devices capture real-time data on soil moisture, temperature, and crop conditions, facilitating informed decisions regarding irrigation, fertilisation, and pest control (Islam *et al.*, 2023; Mansoor *et al.*, 2025). In Uganda, IoT-based systems have helped smallholder farmers adapt to climate variability and improve their productivity (Godwin and Johnson, 2025). Decision Support Tools (DSTs), such as DSSAT and the Cornell Climate Smart Farming suite, help farmers optimise planting schedules and input use based on climate forecasts, leading to yield improvements and better risk management (Ahmed *et al.*, 2022; Lambert *et al.*, 2019). The challenges include the digital divide, access to infrastructure, and user training. However, the potential for scalable impact makes digital integration a key priority for future CSA programmes (Rodríguez-Barillas *et al.*, 2024). Although digital tools offer unprecedented precision, their transformative impact hinges on overcoming structural barriers, such as digital literacy, affordability, and network coverage. Public–private partnerships and open-source platforms will be central to democratising access and embedding climate intelligence into everyday farming decisions.

Climate modelling and predictive tools

Climate change introduces considerable uncertainty to maize production systems, making accurate yield forecasting essential for food security, resource management and agricultural planning (Zhang *et al.*, 2022). Integrating process-based crop models such as DSSAT and APSIM with climate simulation, remote sensing, and machine learning technologies provides a robust framework for predicting maize yield under dynamic climatic conditions (Aderele *et al.*, 2025). However, despite technological advances, these tools face barriers related to data quality, calibration complexity and institutional uptake. This section explores the role of integrated modelling frameworks, hybrid approaches, and AI-driven forecasting systems in enhancing climate resilience and adaptive capacity in maize farming.

Integration of crop simulation models

Crop models, such as the Decision Support System for Agrotechnology Transfer (DSSAT) and Agricultural Production Systems Simulator (APSIM), simulate maize growth based on the interactions between genotype, environment, and management practices (Holzworth *et al.*, 2014; Jones *et al.*, 2003). These models have been widely validated across agroecological zones and support decision-making under climate change scenarios (Gobezie *et al.*, 2025). DSSAT and APSIM have demonstrated strong performance in predicting maize growth stages and yield, particularly when they are properly calibrated with local data (Feleke *et al.*, 2021). Although the operational use of remote sensing for real-time crop monitoring is discussed in Section Deployment, field validation, and policy support, its integration with these simulation models enhances predictive accuracy by supplying spatial and temporal data on crop performance and environmental conditions (Omia *et al.*, 2023). Ensemble modelling using multiple crop models helps reduce prediction uncertainty and improve reliability in diverse environments (Dale *et al.*, 2017). Although widely validated, process-based models such as DSSAT for Agrotechnology Transfer and APSIM remain highly sensitive to local calibration data, limiting their scalability in data-poor regions. Future studies should focus on modular model architectures and automatic calibration tools to enhance usability across diverse agroecological contexts.

https://doi.org/10.1017/S0021859626100835 Published online by Cambridge University Press

Coupling with climate models and scenario simulations

Climate projections based on the Coupled Model Intercomparison Project Phase 6 (CMIP6), including Shared Socioeconomic Pathway (SSP) scenarios such as SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5, are increasingly coupled with crop simulation models to assess yield responses under alternative future climate conditions (IPCC, 2021). Studies in China, Ethiopia, and Kenya have shown that scenario-based simulations can help evaluate adaptation strategies such as irrigation scheduling and sowing date optimisation (Ogutu *et al.*, 2018; Saddique *et al.*, 2020). Recent modelling studies have highlighted the importance of long-term scenario planning for the adaptation of dryland maize. For instance, Wang *et al.* (2026) demonstrated that plastic film mulching could increase biomass and seed yield by 22.2 and 21.0 %, respectively, under future 50-year warming scenarios, underscoring the critical role of adaptive agronomic practices in enhancing climate resilience. These systems predict yield loss under extreme weather scenarios and demonstrate gains under mitigation pathways, informing resilient cropping calendars and land-use planning (Wen *et al.*, 2023). Coupling crop and climate models offers powerful insights for long-term planning; however, their accuracy depends on downscaled climate inputs and dynamic adaptation parameters. Further integration with socioeconomic scenarios will be critical for aligning yield forecasts with practical adaptation strategies.

Hybrid approaches with machine learning

Combining crop models with machine learning (ML) enhances predictive accuracy by leveraging both physical process simulations and statistical learning (Shahhosseini *et al.*, 2021). Models such as Random Forest, XGBoost, and Artificial Neural Networks have been integrated with APSIM/DSSAT features to forecast maize yield with improved precision (Han *et al.*, 2024). Hybrid ML-crop models can detect nonlinear relationships and climate thresholds, enabling the early detection of yield risks during critical crop stages (Gyamerah *et al.*, 2024; Shahhosseini et al., 2021). Hybrid ML–crop models bridge process knowledge with data-driven flexibility; however, their effectiveness relies on interpretability and model transparency. Incorporating explainable AI frameworks will help enhance trust and usability in operational settings.

AI and predictive analytics for yield forecasting

AI-driven tools incorporate climate, satellite, and field data to forecast maize yield and support adaptation to climate change. Deep learning models using satellite imagery and IoT sensor data have been used in Africa, Brazil, and the U.S. to predict yield 1–2 months in advance (Baio *et al.*, 2023; Cunha *et al.*, 2018; Pukrongta *et al.*, 2024). AI models have also been employed to assess the impact of CO_2 levels, rainfall variability, and extreme heat on maize phenology and production (Abbas *et al.*, 2023; Elghamrawy, 2023). AI tools offer unmatched scalability and real-time capacity but risk the marginalisation of low-connectivity regions and require robust data governance. Prioritising open-access AI models and farmer-centred data platforms is essential to avoid digital exclusion in climate-adaptation planning.

Seasonal forecasting and early warning systems

Dynamic forecasting systems integrate seasonal weather predictions with crop simulations and geospatial data to generate yield outlooks and alerts. Platforms such as TAMSAT-ALERT, CRAFT, and DSSAT-CFSv2 combine satellite observations with real-time meteorological data to deliver location-specific yield warnings months prior to harvest (Asfaw *et al.*, 2018). In Sub-Saharan Africa and South Asia, these systems have improved early intervention strategies, enhanced farmers' preparedness, and minimised losses due to droughts or erratic rainfall (Pienaah *et al.*, 2023). Early warning platforms are pivotal for anticipatory action; however, their success hinges on farmer access, local credibility, and integration into extension networks. Co-designing alert systems with end-users will increase adoption and ensure actionable outputs.

Limitations and future opportunities

Despite their growing utility, climate-crop modelling systems face several challenges. Model calibration requires site-specific agronomic and soil data, which are often scarce in low-income regions (Beveridge *et al.*, 2018). Uncertainty in climate projections, especially extreme events, can reduce prediction reliability without multi-model ensemble approaches (Dale et al., 2017). Adoption barriers include limited access to computational tools, digital literacy, and institutional support for decision-making. Future advances will depend on integrating multi-source data (e.g. omics, IoT, and drones), expanding the use of probabilistic forecasting, and improving policy alignment to make climate-smart tools more accessible and actionable at the farm level (Balyan *et al.*, 2024). Ultimately, the utility of climate modelling tools will depend not only on their technical sophistication but also on their integration into inclusive, adaptive governance systems that support farmer decision-making at scale.

Role of microbiomes in climate resilience

The role of microbiomes in enhancing the climate resilience of maize, particularly under drought conditions, is emerging as a transformative frontier in plant science. Rhizosphere and endophytic microbiota play pivotal roles in modulating stress responses, improving nutrient dynamics, and enhancing physiological performance under climatic extremes (Burlakoti *et al.*, 2024). However, despite their significant potential, translation to field systems remains limited because of ecological complexity, formulation challenges, and policy gaps. This section explores core microbial mechanisms, the role of indigenous taxa, and advances in microbiome engineering and biofertilizer application, with a focus on their integration into climate-resilient maize systems.

Drought-tolerant endophytes and rhizosphere microbes

Microbial-mediated drought resilience in maize involves synergistic interactions between the plant and soil microbiomes. Plant Growth-Promoting Rhizobacteria (PGPR), including *Mitsuaria* sp. and *Burkholderia* sp., enhance drought tolerance by restructuring root architecture to reduce evapotranspiration and producing ACC deaminase to degrade ethylene precursors, thereby mitigating stress-induced growth inhibition (Bouremani *et al.*, 2023; Huang *et al.*, 2017). These bacteria work in concert with Arbuscular Mycorrhizal Fungi (AMF), which amplify drought resilience through enhanced root colonisation and microbial biomass carbon, improving nutrient-use efficiency while reducing oxidative damage to maintain cellular homeostasis (Sun and Shahrajabian, 2023; Wahab *et al.*, 2023). Drought triggers dynamic shifts in rhizosphere and endosphere microbial communities, favouring taxa specialised in nutrient mobilisation and stress

https://doi.org/10.1017/S0021859626100835 Published online by Cambridge University Press

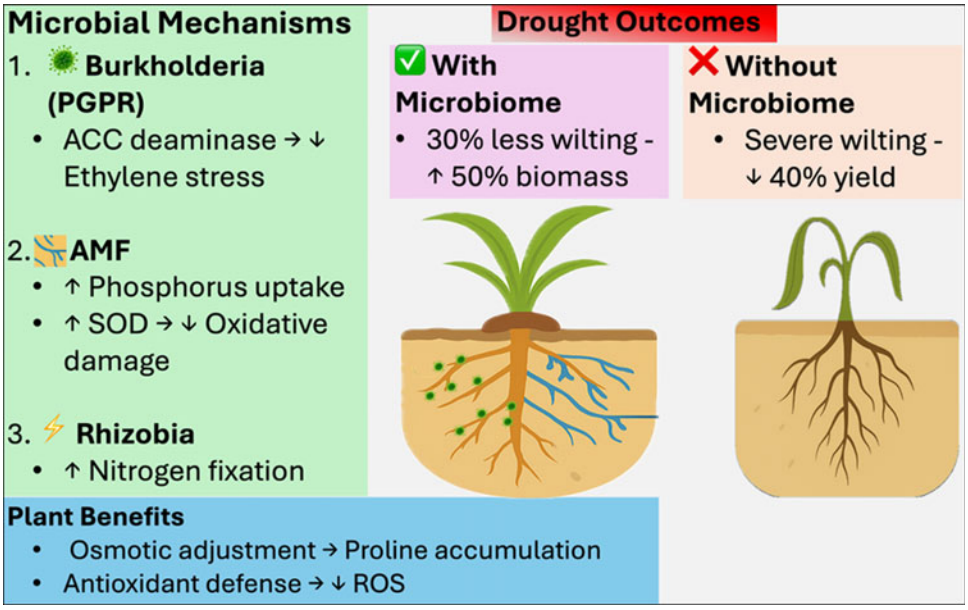


Figure 4. Microbiome-mediated drought resilience mechanisms in maize. This schematic illustrates the role of (🦠) *Burkholderia* in ethylene regulation via ACC deaminase, (🌿) arbuscular mycorrhizal fungi (AMF) in enhancing phosphorus uptake and ROS defence through SOD activation, and (⚡) Rhizobia in nitrogen fixation. Plants with microbiome associations show 30 % less wilting and up to 50 % greater biomass under drought, supporting their integration into stress-resilient maize systems. ACC, 1-aminocyclopropane-1-carboxylic acid; AMF, arbuscular mycorrhizal fungi; PGPR, plant growth-promoting rhizobacteria; ROS, reactive oxygen species; SOD, superoxide dismutase.

mitigation, creating an ecological buffer against water scarcity (Santos-Medellín *et al.*, 2017; Wang *et al.*, 2020). Notably, soils with prior drought exposure develop microbial legacies, adapted communities that transfer resilience traits to subsequent plant generations, enhancing water-use efficiency and photosynthetic performance through conditioned soil-plant feedbacks (Carter *et al.*, 2023). Although the ecological role of drought-adapted microbes is increasingly recognised, their practical deployment remains constrained by variability in colonisation success across soil types and environments. Future strategies should prioritise region-specific microbial screening and long-term field validation to ensure consistent performance under variable climatic regimes.

Mechanisms of microbial-mediated drought tolerance

Microbial-mediated drought tolerance in maize operates through three synergistic mechanisms. First, osmotic adjustment and antioxidant defence are enhanced through microbial induction of osmolyte accumulation (proline and glycine betaine) and activation of antioxidant enzymes, such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), which collectively mitigate oxidative damage during water stress (Mikiciuk *et al.*, 2024). Second, phytohormone modulation occurs as beneficial microbes fine-tune auxin, cytokinin, and abscisic acid levels, stimulating root elongation and priming stress-responsive signalling pathways (Shaffique *et al.*, 2022). Third, microbes directly improve nutrient availability by solubilising phosphorus and nitrogen, critical for energy metabolism and osmotic regulation, thereby sustaining maize growth even under arid, nutrient-depleted conditions (Burlakoti *et al.*, 2024). These mechanisms are summarised in Figure 4, which illustrates how key microbial taxa, such as *Burkholderia*, AMF, and *Rhizobia*, synergistically regulate stress-responsive pathways to enhance drought resilience. Together, these microbial functions form an integrated defence system that enhances drought resilience at the biochemical, physiological, and metabolic levels. These mechanisms underscore the complex multi-layered contributions of microbiota to drought resilience, yet the understanding remains largely derived from controlled experiments. Field-level expression of these microbial traits requires deeper investigation into soil-microbe-plant interactions under dynamic stress gradients and diverse genotypes.

Microbiome engineering and biofertilizers

Microbiome engineering and biofertilizers represent transformative approaches for enhancing maize climate resilience. Advances in synthetic biology now enable the design of tailored microbial consortia through CRISPR-based gene editing, optimising microbe-host interactions to boost drought tolerance, nutrient-use efficiency, and disease resistance (Patyal *et al.*, 2025). In addition to these engineered solutions, commercial biofertilizers harness native beneficial microbes, including PGPR, nitrogen-fixing bacteria, phosphate solubilisers, and mycorrhizal fungi, to sustainably replace chemical inputs while improving soil health and crop stress adaptation (Kumar *et al.*, 2022; Yusuf *et al.*, 2025). Notably, traditional maize systems harbour untapped microbial diversity, with indigenous cultivars hosting stress-adapted endophytes that offer valuable genetic resources for microbiome-assisted breeding programmes (Correa-Galeote *et al.*, 2018; Gonzalez-Mendoza *et al.*, 2023). Together, these strategies bridge cutting-edge biotechnology with ecological wisdom to create synergistic solutions for climate-smart maize production. Although microbiome engineering offers a leap forward in targeted resilience-building, the stringent regulatory landscape and the lack of farmer-ready formulations currently limit its scalability. A pragmatic approach combining low-tech native consortia with high-tech synthetic biology may offer a tiered pathway toward widespread field application.

Challenges and prospects

Microbiome-based interventions for maize face both technical and systemic challenges that must be addressed to realise their full potential in the future. Field-level effectiveness is often compromised by environmental variability, which disrupts microbial colonisation and functions (Anas *et al.*, 2024). Scaling these solutions requires overcoming production hurdles to ensure formulation stability and efficacy at commercial scales, while regulatory frameworks struggle to keep pace with engineered microbial technologies (Baloch, 2025). The inherent complexity

https://doi.org/10.1017/S0021859626100835 Published online by Cambridge University Press

of plant-microbe-environment interactions presents additional scientific challenges in predicting and optimising outcomes (Beck *et al.*, 2022). Future progress will depend on integrating precision agriculture tools with omics-based microbial profiling and AI-driven modelling to develop context-specific solutions. Ultimately, successful incorporation of microbiome strategies into maize breeding programmes and farming systems could become a cornerstone of climate-resilient agriculture, enabling sustainable intensification despite increasing environmental uncertainties. With proper integration into maize breeding and extension systems, microbiome-based strategies could serve as both a buffer and a catalyst, buffering crops against immediate climatic shocks, while catalysing a shift toward more ecologically grounded intensification.

Socioeconomic and policy dimensions

Despite the accelerating technological innovation in climate-smart agriculture, as detailed in Sections Climate challenges facing maize production–Climate modelling and predictive tools, widespread adoption in maize systems remains uneven and constrained. These adoption gaps are rooted not in technical limitations but in structural barriers related to governance, equity, and institutional capacity. The adoption and scalability of climate-smart maize practices are significantly shaped by socioeconomic structures, policy environments, and institutional frameworks. While technological innovations and agronomic strategies are foundational to enhancing maize resilience, their effectiveness is deeply contingent on the broader sociopolitical and economic landscape in which they are embedded (Bhatnagar *et al.*, 2024; Olabanji and Chitakira, 2025). Smallholder farmers, who constitute most maize cultivators in regions such as sub-Saharan Africa and South Asia, face numerous constraints, ranging from limited access to improved seed systems to exclusion from financial safety nets (Asfaw *et al.*, 2024; Erenstein *et al.*, 2022). This section critically examines the interplay of socioeconomic factors, governance mechanisms, seed systems, gendered dynamics, and policy innovations that influence the adoption and success of CSA for maize.

Socioeconomic constraints and adoption barriers

A significant challenge to the widespread implementation of CSA practices in maize cultivation is the socioeconomic vulnerability of smallholder farmers (Wakweya, 2023). Factors such as low-income levels, lack of education, restricted access to climate information, and resource limitations severely hinder the ability of farmers to invest in new technologies or shift to adaptive practices (Autio *et al.*, 2021). Moreover, smallholders often experience higher exposure to climate-related risks, including drought and soil degradation, which exacerbate their production uncertainties and reduce their appetite for technological adoption (Touch *et al.*, 2024). The lack of physical infrastructure, such as storage facilities, irrigation systems, and transportation, further amplifies these vulnerabilities (Harvey *et al.*, 2014). Consequently, CSA adoption remains uneven and context-dependent, often requiring complementary interventions to address socioeconomic disparities (Olabanji and Chitakira, 2025). Mitigating socioeconomic barriers requires more than improved inputs; it demands social protection schemes, education, and tailored extension models that reduce adoption risk. Without systemic interventions, technology-led adaptation will remain skewed toward wealthier or better-networked farmers. In low-resource settings, these barriers are further amplified by limited institutional support, weak market linkages, and insufficient infrastructure. Even when climate-resilient technologies are available, smallholders often cannot afford the upfront costs of improved seeds, biofertilizers, or irrigation equipment, and the absence of effective extension services limits their capacity to adopt and benefit from these innovations. Furthermore, risk-averse behaviour among smallholders, driven by the lack of safety nets, often discourages experimentation with new technologies, perpetuating low adoption cycles (Touch *et al.*, 2024; Wakweya, 2023).

Governance of seed systems and regulatory bottlenecks

Access to climate-resilient maize varieties is contingent on the efficiency and inclusiveness of seed systems (Shilomboleni *et al.*, 2023). However, in many regions, national seed systems remain fragmented, overregulated or underdeveloped (Marechera *et al.*, 2016). Although the formal seed sector is regulated for quality assurance, it often fails to reach marginal farmers due to high costs and limited distribution networks (Mondo *et al.*, 2024). Simultaneously, the informal seed sector, which includes farmer-saved and exchanged seeds, remains the primary source of planting material but lacks mechanisms for climate-resilient trait integration (Westengen *et al.*, 2023). Countries such as Ethiopia, Malawi, and Tanzania have implemented reforms to streamline seed certification and promote the inclusion of smallholder-oriented varieties; however, policy gaps persist (Haug *et al.*, 2023). In contrast, community-based seed banks in Mexico demonstrate the potential of localised seed governance models that preserve genetic diversity and foster participatory breeding (Cuevas and De la Torre Sánchez, 2015). Closing the gap between the formal and informal seed sectors through decentralised certification, community-based seed banks, and participatory breeding can democratise access to climate-resilient germplasm. For smallholder farmers, regulatory bottlenecks manifest as delayed access to improved varieties, high certification costs passed on to end-users, and limited availability of climate-resilient seeds in local markets. Overly stringent regulatory frameworks, while intended to ensure quality, can inadvertently exclude small-scale seed producers and limit the diversity of varieties available to farmers (Haug *et al.*, 2023; Mondo *et al.*, 2024).

Financial incentives, subsidies, and insurance schemes

Financial and institutional incentives play pivotal roles in catalysing climate adaptation in maize farming (Ma and Rahut, 2024). Targeted input subsidies, including seed and fertiliser vouchers, have shown promise in facilitating the adoption of drought-resilient maize varieties (Holden and Fisher, 2015). However, poorly designed subsidy programmes can lead to market distortions and dependency (Peñalosa-Martinell *et al.*, 2025). Crop insurance mechanisms, particularly those bundled with climate-resilient technologies, are emerging as a crucial safety net. These schemes protect farmers from yield losses due to climatic extremes, enabling them to invest in adaptive inputs (Aina *et al.*, 2024). Nonetheless, insurance penetration remains low in many low-income settings due to affordability issues, lack of trust, and administrative inefficiencies. Strengthening rural financial institutions and developing inclusive credit and insurance models are essential for scaling CSA (Ellis, 2016; Nyaaba *et al.*, 2019). Designing bundled, weather-indexed insurance with input support and micro-credit access could dramatically increase farmer uptake of CSA innovations. However, institutional innovation must accompany financial tools to ensure transparency, trust, and scalability. For resource-limited farmers, affordability remains the

https://doi.org/10.1017/S0021859626100835 Published online by Cambridge University Press

single most critical barrier. Even subsidised inputs may be beyond the reach of the poorest households, while insurance products often fail to reach remote areas due to high transaction costs and low financial literacy. Bundling insurance with credit and input packages and leveraging mobile technology for premium collection and payout disbursement could enhance accessibility for smallholders (Aina *et al*., 2024; Nyaaba *et al.,* 2019).

Public–private partnerships (PPPs) and technology deployment

Collaborative models, such as public–private partnerships (PPPs), are increasingly recognised for their role in bridging the gap between research innovation and field-level application (Prajapati *et al*., 2025). Programmes such as Water Efficient Maize for Africa (WEMA), which integrates private seed companies, CGIAR institutions, and national governments, have successfully developed and distributed drought-tolerant maize hybrids (Edge *et al*., 2018). Such initiatives not only facilitate the commercialisation of climate-resilient varieties but also promote regulatory harmonisation, technology transfer, and capacity building across the value chains (Sithole *et al*., 2023). In Nepal, the Maize Crop Model (MCM) pilot, developed in collaboration with CIMMYT, has demonstrated the benefits of integrating predictive analytics and localised policy responses to guide decision-making at the farmer level (Choudhary *et al*., 2023). While PPPs accelerate varietal deployment, their success depends on equitable benefit sharing, transparency in licencing, and safeguards against the private capture of public goods.

Gender and equity in climate-smart maize systems

Gender disparities significantly influence climate vulnerability and the adoption of resilience-building technologies (Adhikari and Ghimire, 2025). Despite comprising a substantial proportion of the agricultural labour force, women farmers often have limited access to land, credit, extension services, and decision-making platforms (Ankrah *et al*., 2020). These structural inequalities hinder their ability to benefit from climate-smart innovations in maize cultivation. Moreover, climate shocks, such as droughts and floods, tend to disproportionately affect women because of their roles in food provision, caregiving, and informal labour (Antriyandarti *et al*., 2024). Promoting gender-responsive CSA requires targeted interventions that address systemic barriers, including tailored extension models, inclusive seed systems, and participatory breeding that reflects women's varietal preferences and production constraints (Bryan *et al*., 2024). Empowering women in maize systems is not only a matter of social equity, but also a catalyst for enhanced household resilience and agricultural productivity (Akter *et al*., 2017). Gender mainstreaming in CSA requires more than quotas; it calls for the inclusive design of technologies, decision-making processes, and market access to ensure that resilience outcomes are truly shared.

Governance challenges and policy recommendations

The governance of climate-smart maize systems must evolve to become more inclusive, adaptive, and decentralised (Fischer, 2021). Top-down policy approaches often fail to accommodate local ecological and sociocultural conditions. Therefore, the integration of local knowledge systems, participatory policy design, and cross-sectoral coordination is imperative (Kiesel *et al*., 2022). Transparent monitoring mechanisms, outcome-based evaluation, and feedback loops can further enhance policy responsiveness (Dinesh *et al*., 2018). Governments should prioritise investments in rural infrastructure, information dissemination, and institutional capacity to support climate-resilient agricultural practices. In parallel, efforts must be made to align national CSA strategies with global frameworks, such as the Sustainable Development Goals (SDGs) and the Paris Climate Agreement, to leverage technical and financial resources (Zewdu *et al*., 2025). Resilient governance in maize systems requires flexible, multiscalar institutions that can respond to localised climate signals while aligning with global adaptation frameworks. The co-production of policy with farmer communities is critical for closing the design–delivery gap. Strengthening extension capacity is particularly urgent in smallholder contexts, where farmer-to-farmer learning, participatory demonstrations, and digital advisory services have shown promise in bridging knowledge gaps. Investments in decentralised, demand-driven extension models that are responsive to local needs and gender sensitivity can significantly enhance adoption rates (Bryan *et al.,* 2024; Zewdu *et al*., 2025).

Case studies: success stories in climate-smart maize

This section presents illustrative case studies to demonstrate how climate-smart maize innovations, both genetic and agronomic, translate into measurable impacts. By analysing context-specific successes, the current review identifies enabling conditions, systemic bottlenecks, and lessons for scaling climate resilience.

CIMMYT's climate-smart maize in Africa

CIMMYT has played a transformative role in enhancing maize resilience across sub-Saharan Africa through the development and deployment of stress-tolerant maize cultivars. These include drought- and heat-tolerant hybrids and early maturing varieties that are now cultivated across more than 60 % of the maize-growing regions in some countries (Prasanna *et al*., 2020). The WEMA project, a pioneering public–private partnership, achieved a 20 % yield advantage under drought conditions, with the widespread dissemination of both transgenic and non-transgenic varieties (Oikeh *et al*., 2014). Technological breakthroughs, such as marker-assisted selection and genomic prediction, have led to enhanced nitrogen-use efficiency (NUE) and drought resilience (Azrai *et al.,* 2024; Ertiro *et al*., 2020).

Beyond genetics, CIMMYT's efforts have extended to integrated climate-smart agricultural practices, including intercropping, precision agriculture, and sustainable land use (Jat *et al*., 2020). Extension services and public–private collaborations have driven high adoption rates, especially in Eastern Africa, improving smallholder incomes, food security, and resilience to environmental shocks (Edge *et al*., 2018). Kenya saw maize yield rise from 0.5 to 3.2 tons per hectare, and over 90 % of the watershed communities in the region achieved food security (Kwena *et al*., 2018). Economic impacts are substantial in Ethiopia and Madagascar, households reported increased incomes, while MLN-resistant hybrids and land rehabilitation initiatives tackled long-standing regional constraints (Geffersa *et al*., 2022; Johnmark *et al*., 2022; Kwena *et al*., 2018; Tesfaye and Amare, 2023).

Success in Eastern Africa was enabled by integrated seed systems, multi-stakeholder coordination, and context-responsive varietal development. However, translating these project-based successes into sustained national-level programmes requires overcoming persistent adoption barriers. High seed costs, limited

https://doi.org/10.1017/S0021859626100835 Published online by Cambridge University Press

availability in remote areas, and insufficient extension support continue to constrain the access of smallholders. To achieve a scalable impact, efforts must shift from project-driven delivery to institutionalised national programmes that integrate seed systems, credit mechanisms, and farmer training as core components of agricultural policy.

India's heat-resilient hybrid trials

Fertility management using a 100 % recommended dose of fertiliser has been shown to significantly enhance grain yield and benefit-cost ratios (Bharti *et al.*, 2023). India's adaptation to rising temperatures is reflected in its robust maize breeding programmes, which focus on heat and drought resilience. Hybrids such as RCRMH-3, UM-12, and RH-10 have demonstrated yield of up to 8.27 t/ha under stress conditions in regions such as Tungabhadra and Prayagraj (Jose *et al.*, 2022; Pandu *et al.*, 2023). These efforts have been bolstered by the integration of CMS to reduce labour and advanced breeding tools, such as genomic selection and doubled haploid technologies, to accelerate varietal development (Chaikam *et al.*, 2019). Fertility management using the recommended fertiliser dose has further enhanced yield and benefit-cost ratios (Bharti *et al.*, 2023). Collaborations with CIMMYT have scaled certified seed production from 70 MT in 2018–19 to over 1000 MT by 2021–22, reaching more than 128 000 farm families (Beshir and Vinayan, 2024; Cimmyt, 2021). Nonetheless, the variability in genotype-environment interactions highlights the ongoing need for adaptive breeding and enabling seed policy reforms.

India's success illustrates the benefits of precision breeding and fertility management; however, uneven adoption across agro-ecologies underscores the need for targeted extension and better genotype × environment mapping.

Latin American maize systems under no-till and climate adaptation

Latin America presents a unique blend of traditional landrace cultivation and conservation agriculture (Guzzon *et al.*, 2021). CIMMYT-supported hybrids, such as CL-04368 and CL-02181, demonstrate superior yield and market performance (Cordova *et al.*, 2007). No-till farming, applied to over 70 % of cultivated land in some countries, has yielded multiple co-benefits, including carbon sequestration, improved soil organic carbon, and reduced GHG emissions (Ogle *et al.*, 2019; Wingeyer *et al.*, 2015).

In Mexico and Southern Brazil, integration of leguminous cover crops and conservation practices enhanced soil fertility and microbial biomass (Alvarado-Lopez *et al.*, 2023; Andrade *et al.*, 2025). Simultaneously, smallholder reliance on resilient landraces continues to support food security and agrobiodiversity conservation (Monroy-Sais *et al.*, 2024). Market collaborations and seed company partnerships further enabled the adoption of hybrid varieties resistant to biotic and abiotic stresses (Prasanna *et al.*, 2021).

Economic analyses from Brazil and Central America have revealed reduced input costs, improved resource-use efficiency, and enhanced profitability. However, challenges include ensuring varietal diversity and overcoming adoption barriers related to risk perception, education, and market dynamics. Agroforestry and community-based conservation approaches are being explored to buffer climatic shocks and sustain productivity (Borges Pequeno *et al.*, 2025; Gonçalves *et al.*, 2024; Guzzon *et al.*, 2021).

Latin American examples show that combining conservation agriculture with hybrid deployment and landrace conservation can yield co-benefits. However, adoption remains constrained by market access, policy continuity, and risk management tools.

Conclusions and perspective

Despite rapid technological advances, current approaches to climate-resilient maize remain fragmented and technocentric, failing to address interconnected environmental, socioeconomic, and institutional dimensions of resilience. This review introduces a novel systems-level framework that unites genetics, agronomy, microbiome engineering, digital tools, and enabling policies, demonstrating that only integrated strategies can deliver transformative benefits. The evidence is clear: incremental and siloed solutions will not prepare maize systems for escalating climate extremes. The current review calls on the research and development community to adopt this integrative paradigm as the foundation for future actions. Breeders, agronomists, and microbiologists must co-design multi-stress breeding pipelines that incorporate genotype × microbiome × environmental insights. Data scientists and farmers must jointly develop interpretable, low-cost digital tools that function in resource-limited contexts. Economists and policy analysts must reimagine seed systems, subsidies, and extension services to guarantee equitable access and gender inclusivity. Priority areas for immediate action include: (i) multi-location trials of bioinoculants and edited germplasm to establish ecological robustness; (ii) bundled climate-smart agriculture packages linking genetics, agronomy, and digital forecasting; (iii) participatory seed governance frameworks to decentralise variety access; and (iv) gender-responsive financial instruments that align resilience with equity. The call is urgent: climate resilience in maize will not emerge from silver-bullet technologies but from equity-centred, integrative, and co-produced solutions. By embracing this framework, the global community can safeguard maize-dependent livelihoods while offering a transferable blueprint for adaptation to agri-food systems worldwide.

Data availability statement. The data supporting the findings of this study are available from the corresponding authors upon reasonable request.

Author contributions. Authors LAP and BQ contributed to the conception of the study, preparation, and design of this review article. The literature survey was done by the authors BQ and LAP, who wrote the manuscript's first draft, and all authors commented on it. All authors read, revised, and approved the final manuscript.

Funding statement. This study was not supported by any funding.

Competing interests. The authors declare no conflicts of interest.

Ethical standards. Not applicable.

References

Abbas G, Ahmed M, Fatima Z, Hussain S, Kheir AMS, Ercişli S and Ahmad S (2023) Modelling the potential impact of climate change on maize-maize cropping system in semi-arid environment and designing of adaptation options. *Agricultural and Forest Meteorology* **341**, 109674.

Abera K, Crespo O, Seid J and Mequanent F (2018) Simulating the impact of climate change on maize production in Ethiopia, East Africa. *Environmental Systems Research* **7**, 4.

Adam B and Abdulai A (2023) Minimum tillage as climate-smart agriculture practice and its impact on food and nutrition security. *PLoS One* **18**, e0287441.

https://doi.org/10.1017/S0021859626100835 Published online by Cambridge University Press

Aderele MO, Srivastava AK, Butterbach-Bahl K and Rahimi J (2025) Integrating machine learning with agroecosystem modelling: Current state and future challenges. *European Journal of Agronomy* **168**, 127610.

Adhikari A and Ghimire S (2025) Gendered dimensions of climate change impacts: Challenges and adaptive strategies. *Turkish Journal of Agriculture-Food Science and Technology* **13**, 1354–1367.

Ahmad U, Hussain M, Ahmad W, Javed J, Arshad Z and Akram Z (2024) Impact of global climate change on maize (Zea mays): Physiological responses and modern breeding techniques. *Trends Biotech Plant Sci* **2**, 62–77.

Ahmed Z, Gui D, Qi Z, Liu Y, Liu Y and Azmat M (2022) Agricultural system modelling: Current achievements, innovations, and future roadmap. *Arabian Journal of Geosciences* **15**, 363.

Aina I, Ayinde O, Thiam D and Miranda M (2024) Crop index insurance as a tool for climate resilience: Lessons from smallholder farmers in Nigeria. *Natural Hazards* **120**, 4811–4828.

Akchaya K, Parasuraman P, Pandian K, Vijayakumar S, Thirukumaran K, Mustaffa MRAF, Rajpoot SK and Choudhary AK (2025) Boosting resource use efficiency, soil fertility, food security, ecosystem services, and climate resilience with legume intercropping: A review. *Frontiers in Sustainable Food Systems* **9**, 1527256.

Akter S, Rutsaert P, Luis J, Htwe NM, San SS, Raharjo B and Pustika A (2017) Women's empowerment and gender equity in agriculture: A different perspective from Southeast Asia. *Food Policy* **69**, 270–279.

Alimagham S, van Loon MP, Ramirez-Villegas J, Adjei-Nsiah S, Baijukya F, Bala A, Chikowo R, Silva JV, Soulé AM, Taulya G, Tenorio FA, Tesfaye K and van Ittersum MK (2024) Climate change impact and adaptation of rainfed cereal crops in sub-Saharan Africa. *European Journal of Agronomy* **155**, 127137.

Alvarado-Lopez C, Santos L, Jiménez-Osornio J and Estrada-Medina H (2023) Growth and mineral composition of legume cover crops for sustainable agriculture in southern Mexico. *Tropical Agriculture* **100**, 182.

Anas M, Khalid A, Saleem MH, Ali Khan K, Ahmed Khattak W and Fahad S (2024) Symbiotic synergy: Unveiling plant-microbe interactions in stress adaptation. *Journal of Crop Health* **77**, 18.

de Andrade HAF, Sagrilo E, de Oliveira Júnior JOL, de Sousa DC, Costa CPdM, Costa PM, de Araújo Neto RB, de Alcantara RMCM, Leite LFC, Furtado MB, Beltrán MJ, Cafaro La Menza N and Souza HA (2025) Cover crops optimize soil fertility and soybean productivity in the Cerrado of MATOPIBA, Brazil. *Agronomy* **15**, 1083.

Ankrah DA, Freeman CY and Afful A (2020) Gendered access to productive resources – Evidence from small holder farmers in Awutu Senya West District of Ghana. *Scientific African* **10**, e00604.

Antriyandarti E, Suprihatin DN, Pangesti AW and Samputra PL (2024) The dual role of women in food security and agriculture in responding to climate change: Empirical evidence from Rural Java. *Environmental Challenges* **14**, 100852.

Asfaw D, Black E, Brown M, Nicklin KJ, Otu-Larbi F, Pinnington E, Challinor A, Maidment R and Quaife T (2018) TAMSAT-ALERT v1: A new framework for agricultural decision support. *Geoscientific Model Development* **11**, 2353–2371.

Asfaw DM, Asnakew YW, Sendkie FB, Abdulkadr AA, Mekonnen BA, Tiruneh HD and Ebad AM (2024) Analysis of constraints and opportunities in maize production and marketing in Ethiopia. *Heliyon* **10**, e39606.

Autio A, Johansson T, Motaroki L, Minoia P and Pellikka P (2021) Constraints for adopting climate-smart agricultural practices among smallholder farmers in Southeast Kenya. *Agricultural Systems* **194**, 103284.

Awada L, Phillips PWB and Bodan AM (2024) The evolution of plant phenomics: Global insights, trends, and collaborations (2000-2021. *Frontiers in Plant Science* **15**, 1410738.

Azrag AGA, Obala F, Tonnang HEZ, Hogg BN, Ndlela S and Mohamed SA (2023) Predicting the impact of climate change on the potential distribution of the invasive tomato pinworm Phthorimaea absoluta (Meyrick) (Lepidoptera: Gelechiidae). *Scientific Reports* **13**, 16477.

Azrai M, Bahrun AH, Efendi R, Andayani NN, Jihad M, Bahtiar Z, Muslimin B and Aqil M (2024) Global drought tolerant maize research and development: Analysis and visualization of cutting-edge scientific technologies. *Journal of Agriculture and Food Research* **18**, 101323.

Azrai M, Efendi R, Muliadi A, Aqil M, Suwarti Z, Syam B, Junaedi A, Syah UT, Dermail A, Marwiyah S and Suwarno WB (2022) Genotype by environment interaction on tropical maize hybrids under normal irrigation and waterlogging conditions. *Frontiers in Sustainable Food Systems* **18**, 101323.

Baio FHR, Santana DC, Teodoro LPR, ICd O, Gava R, de Oliveira JLG, CAd S J, Teodoro PE and Shiratsuchi LS (2023) Maize yield prediction with machine learning spectral variables and irrigation management.. *Remote Sensing* **15**, 79.

Baloch N (2025) Microbial contributions to maize crop production: A comprehensive review of challenges and future perspectives. *Discover Agriculture* **3**, 10.

Balyan S, Jangir H, Tripathi SN, Tripathi A, Jhang T and Pandey P (2024) Seeding a sustainable future: Navigating the digital horizon of smart agriculture. *Sustainability* **16**, 475.

Beck AE, Kleiner M and Garrell A-K (2022) Elucidating plant-microbe-environment interactions through omics-enabled metabolic modelling using synthetic communities. *Frontiers in Plant Science* **13**, 910377.

Bernardeli A, Guilhen JHS, Oliveira ICM, Guimarães LJM, Borém A, Jarquin D and Pastina MM (2025) Genomic selection of maize test-cross hybrids leveraged by marker sampling. *The Plant Genome* **18**, e70030.

Beshir A and Vinayan MT (2024) Seeds to Beat the Heat in Lowland Tropics. CIMMYT.

Beveridge L, Whitfield S and Challinor A (2018) Crop modelling: Towards locally relevant and climate-informed adaptation. *Climatic Change* **147**, 475–489.

Bharti J, Manjhi R, Karmakar S, Singh C, Mahapatra P and Kumar R (2023) Integrated nutrient management practice for maize-wheat cropping system in Chhotanagpur Plateau region. *Indian Journal of Ecology* **50**, 108–113.

Bhatnagar S, Chaudhary R, Sharma S, Janjhua Y, Thakur P, Sharma P and Keprate A (2024) Exploring the dynamics of climate-smart agricultural practices for sustainable resilience in a changing climate. *Environmental and Sustainability Indicators* **24**, 100535.

Boerman NA, Frei UK and Lübberstedt T (2020) Impact of spontaneous haploid genome doubling in maize breeding. *Plants* **9**, 369.

Borges Pequeno JR, Oliveira DPC, dBLCJ E, Gilberto GA and Pérez Marin AM (2025) Ecological-economics of agroecological systems in the Brazilian semiarid region. *Agroecology and Sustainable Food Systems* **49**, 1625–1646.

Bouremani N, Cherif-Silini H, Silini A, Bouket AC, Luptakova L, Alenezi FN, Baranov O and Belbahri L (2023) Plant growth-promoting rhizobacteria (PGPR): A rampart against the adverse effects of drought stress. *Water* **15**, 418.

Bracho-Mujica G, Rötter RP, Haakana M, Palosuo T, Fronzek S, Asseng S, Yi C, Ewert F, Gaiser T, Kassie B, Paff K, Rezaei EE, Rodríguez A, Ruiz-Ramos M, Srivastava AK, Stratonovitch P, Tao F and Semenov MA (2024) Effects of changes in climatic means, variability, and agro-technologies on future wheat and maize yields at 10 sites across the globe. *Agricultural and Forest Meteorology* **346**, 109887.

Brankatschk G and Finkbeiner M (2015) Modelling crop rotation in agricultural LCAs — Challenges and potential solutions. *Agricultural Systems* **138**, 66–76.

Bryan E, Alvi M, Huyer S and Ringler C (2024) Addressing gender inequalities and strengthening women's agency to create more climate-resilient and sustainable food systems. *Global Food Security* **40**, 100731.

Burlakoti S, Devkota AR, Poudyal S and Kaundal A (2024) Beneficial plant–microbe interactions and stress tolerance in maize. *Applied Microbiology* **4**, 1000–1015.

Busari MA, Kukal SS, Kaur A, Bhatt R and Dulazi AA (2015) Conservation tillage impacts on soil, crop and the environment. *International Soil and Water Conservation Research* **3**, 119–129.

Cao L, Ma C, Ye F, Pang Y, Wang G, Fahim AM and Lu X (2023) Genome-wide identification of NF-Y gene family in maize (Zea mays L.) and the positive role of ZmNF-YC12 in drought resistance and recovery ability. *Frontiers in Plant Science* **14**, 1159955.

Cao Y, Cheng Z, Ma J, Yang W, Liu X, Zhang X, Zhang J, Wu X and Duan C (2024) Advances in research on southern corn rust, a devasting fungal disease. *International Journal of Molecular Sciences* **25**, 13644.

Carter KR, Nachtsheim AC, Dickman LT, Moore ER, Negi S, Heneghan JP, Sabella AJ, Steadman CR, Albright MBN, Anderson-Cook CM,

https://doi.org/10.1017/S0021859626100835 Published online by Cambridge University Press

Comas LH, Harris RJ, Heikoop JM, Lubbers N, Marina OC, Musa D, Newman BD, Perkins GB, Twary S, Yeager CM and Sevanto S (2023) Drought conditioning of rhizosphere microbiome influences maize water use traits. *Plant and Soil* **492**, 587–604.

Casaretto JA, El-kereamy A, Zeng B, Stiegelmeyer SM, Chen X, Bi Y-M and Rothstein SJ (2016) Expression of OsMYB55 in maize activates stress-responsive genes and enhances heat and drought tolerance. *BMC Genomics* **17**, 312.

Chaikam V, Molenaar W, Melchinger AE and Boddupalli PM (2019) Doubled haploid technology for line development in maize: Technical advances and prospects. *Theoretical and Applied Genetics* **132**, 3227–3243.

Chaikam V, Nair SK, Martinez L, Lopez LA, Utz HF, Melchinger AE and Boddupalli PM (2018) Marker-assisted breeding of improved maternal haploid inducers in maize for the tropical/subtropical regions. *Frontiers in Plant Science* **9**, 1527.

Chattaraj S, Samantaray A, Ganguly A and Thatoi H (2025) Employing plant growth-promoting rhizobacteria for abiotic stress mitigation in plants: With a focus on drought stress. *Discover Applied Sciences* **7**, 68.

Chen Y-R, Lübberstedt T and Frei UK (2024) Development of doubled haploid inducer lines facilitates selection of superior haploid inducers in maize. *Frontiers in Plant Science* **14**, 1320660.

Chivenge P, Zingore S, Ezui KS, Njoroge S, Bunquin MA, Dobermann A and Saito K (2022) Progress in research on site-specific nutrient management for smallholder farmers in sub-Saharan Africa. *Field Crops Research* **281**, 108503.

Choudhary D, Khanal NP, Pandit NR, K.C. D and Timsina KP (2023) Public private cooperative partnerships for scaling commercial maize production in Nepal: Linking innovations with policy. *Nepal Public Policy Review* **3**, 79–94.

CIMMYT (2021) Stress-resilient hybrids help maize farmers in tropical rainfed conditions in Africa and Asia. CIMMYT Annual Report 2021.

Cordova H, Trifunović S, Ramirez A and Sierra M (2007) CIMMYT maize hybrids for Latin America: Head-to-head analysis and probability of out-performing the best check. *Maydica* **52**, 471–476.

Correa-Galeote D, Bedmar EJ and Arone GJ (2018) Maize endophytic bacterial diversity as affected by soil cultivation history. *Frontiers in Microbiology* **9**, 484.

Crystal-Ornelas R, Thapa R and Tully KL (2021) Soil organic carbon is affected by organic amendments, conservation tillage, and cover cropping in organic farming systems: A meta-analysis. *Agriculture, Ecosystems & Environment* **312**, 107356.

Cuevas FA and De la Torre Sánchez JF (2015) Conservación de las especies subvaloradas como recursos genéticos agrícolas. *Revista Digital Universitaria* **16**(5).

Cunha RLF, Silva B and Netto MAS (2018, A Scalable Machine Learning System for Pre-Season Agriculture Yield Forecast. *In 2018 IEEE 14th International Conference on e-Science (e-Science)*, pp. 423–430.

Dale A, Fant C, Strzepek K, Lickley M and Solomon S (2017) Climate model uncertainty in impact assessments for agriculture: A multi-ensemble case study on maize in sub-Saharan Africa. *Earth's Future* **5**, 337–353.

Díaz-Álvarez EA, Martínez-Zavaleta JP, López-Santiz EE, de la Barrera E, Larsen J and del-Val E (2023) Climate change can trigger fall armyworm outbreaks: A developmental response experiment with two Mexican maize landraces. *International Journal of Pest Management* **69**, 184–192.

Dinesh D, Zougmore RB, Vervoort J, Totin E, Thornton PK, Solomon D, Shirsath PB, Pede VO, Lopez Noriega I, Läderach P, Körner J, Hegger D, Girvetz EH, Friis AE, Driessen PPJ and Campbell BM (2018) Facilitating change for climate-smart agriculture through science-policy engagement. *Sustainability* **10**, 2616.

Dirwai TL, Taguta C, Senzanje A, Nhamo L, Cofie O, Lankford B, Nyambe HN and Mabhaudhi T (2024) Status of agricultural water management practices in Africa: A review for the prioritisation and operationalisation of the Africa Union's irrigation development and agricultural water management (AU-IDAWM) strategy. *Environmental Research Letters* **19**, 103005.

Du S and Xiong W (2024) Weather extremes shock maize production: Current approaches and future research directions in Africa. *Plants* **13**, 1585.

Edge M, Oikeh SO, Kyetere D, Mugo S and Mashingaidze K (2018) Water efficient maize for Africa: A public–private partnership in technology transfer to smallholder farmers in sub-Saharan Africa. In Kalaitzandonakes N, Carayannis EG, Grigoroudis E and Rozakis S (eds.), *From Agriscience to Agribusiness: Theories, Policies and Practices in Technology Transfer and Commercialization*. Cham: Springer International Publishing, pp. 391–412.

Elghamrawy S (2023, An AI-Based Prediction Model for Climate Change Effects on Crop production using IoT. *In 2023 International Telecommunications Conference (ITC-Egypt)*, pp. 497–503.

Ellis E (2016) Farmers willingness to pay for crop insurance: Evidence from Eastern Ghana. PhD thesis, McGill University (Canada).

Erenstein O, Jaleta M, Sonder K, Mottaleb K and Prasanna BM (2022) Global maize production, consumption and trade: Trends and R&D implications. *Food Security* **14**, 1295–1319.

Ertiro BT, Labuschagne M, Olsen M, Das B, Prasanna BM and Gowda M (2020) Genetic dissection of nitrogen use efficiency in tropical maize through genome-wide association and genomic prediction. *Frontiers in Plant Science* **11**, 474.

Feleke HG, Savage MJ and Tesfaye K (2021) Calibration and validation of APSIM–Maize, DSSAT CERES–Maize and AquaCrop models for Ethiopian tropical environments. *South African Journal of Plant and Soil* **38**, 36–51.

Feng X, Sun T, Guo J, Cai H, Qian C, Hao Y, Yu Y, Deng A, Song Z and Zhang W (2023) Climate-smart agriculture practice promotes sustainable maize production in northeastern China: Higher grain yield while less carbon footprint. *Field Crops Research* **302**, 109108.

Fischer HW (2021) Decentralization and the governance of climate adaptation: Situating community-based planning within broader trajectories of political transformation. *World Development* **140**, 105335.

Gaffney J, Schussler J, Löffler C, Cai W, Paszkiewicz S, Messina C, Groeteke J, Keaschall J and Cooper M (2015) Industry-scale evaluation of maize hybrids selected for increased yield in drought-stress conditions of the US corn belt. *Crop Science* **55**, 1608–1618.

Galani YJH, Ligowe IS, Kieffer M, Kamalongo D, Kambwiri AM, Kuwali P, Thierfelder C, Dougill AJ, Gong YY and Orfila C (2022) Conservation agriculture affects grain and nutrient yields of maize (Zea Mays L.) and can impact food and nutrition security in sub-Saharan Africa. *Frontiers in Nutrition* **8**, 804663.

Gao Y, Jiang W, Dai Y, Xiao N, Zhang C, Li H, Lu Y, Wu M, Tao X, Deng D and Chen J (2015) A maize phytochrome-interacting factor 3 improves drought and salt stress tolerance in rice. *Plant Molecular Biology* **87**, 413–428.

Gatkal NR, Nalawade SM, Sahni RK, Walunj AA, Kadam PB, Bhanage GB and Datta R (2024) Present trends, sustainable strategies and energy potentials of crop residue management in India: A review. *Heliyon* **10**, e39815.

Geffersa AG, Agbola FW and Mahmood A (2022) Improved maize adoption and impacts on farm household welfare: Evidence from rural Ethiopia. *Australian Journal of Agricultural and Resource Economics* **66**, 860–886.

Gobezie A, Ademe D and Sharma LK (2025) CERES-maize (DSSAT) model applications for maize nutrient management across agroecological zones: A systematic review. *Plants* **14**, 661.

Godwin N and Johnson DM (2025) A Smart IoT Framework for Climate-Resilient and Sustainable Maize Farming In Uganda. arXiv preprint arXiv:2501.12483.

Gonçalves CdBQ, Schlindwein MM and da Silva MC (2024) Economic viability of an agroforestry system for indigenous communities in Brazil: A differentiated approach to risk reduction. *Agroforestry Systems* **98**, 1523–1539.

Gong F, Takahashi H, Omori F, Wang W, Mano Y and Nakazono M (2019) QTLs for constitutive aerenchyma from Zea nicaraguensis improve tolerance of maize to root-zone oxygen deficiency. *Journal of Experimental Botany* **70**, 6475–6487.

Gonzalez-Mendoza VM, Rocha J and de la Torre M (2023) Plant-growth promoting endophytic bacteria and their role for maize acclimatation to abiotic stressIn Oliveira M and Fernandes Silva AA (eds.), *Abiotic Stress in Plants - Adaptations to Climate Change*. Rijeka: IntechOpen, pp. 1–15.

Graham RF, Wortman SE and Pittelkow CM (2017) Comparison of organic and integrated nutrient management strategies for reducing soil N2O emissions. *Sustainability* **9**, 510.

Grote U, Fasse A, Nguyen TT and Erenstein O (2021) Food security and the dynamics of wheat and maize value chains in Africa and Asia. *Frontiers in Sustainable Food Systems* **4**, 617009.

https://doi.org/10.1017/S0021859626100835 Published online by Cambridge University Press

Guzzon F, Arandia Rios LW, Caviedes Cepeda GM, Céspedes Polo M, Chavez Cabrera A, Muriel Figueroa J, Medina Hoyos AE, Jara Calvo TW, Molnar TL, Narro León LA, Narro León TP, Mejía Kerguelén SL, Ospina Rojas JG, Vázquez G, Preciado-Ortiz RE, Zambrano JL, Palacios Rojas N and Pixley KV (2021) Conservation and use of Latin American maize diversity: Pillar of nutrition security and cultural heritage of humanity. *Agronomy* **11**, 172.

Gyamerah SA, Asare C, Agbi-Kaeser HO and Baffour-Ata F (2024) Assessing the impact of climate variability on maize yields in the different regions of Ghana—A machine learning perspective. *PLoS One* **19**, e0305762.

Habben JE, Bao X, Bate NJ, DeBruin JL, Dolan D, Hasegawa D, Helentjaris TG, Lafitte RH, Lovan N, Mo H, Reimann K and Schussler JR (2014) Transgenic alteration of ethylene biosynthesis increases grain yield in maize under field drought-stress conditions. *Plant Biotechnology Journal* **12**, 685–693.

Hagen I, Huggel C, Ramajo L, Chacón N, Ometto JP, Postigo JC and Castellanos EJ (2022) Climate change-related risks and adaptation potential in Central and South America during the 21st century. *Environmental Research Letters* **17**, 033002.

Halli HM, Govindasamy P, Wasnik VK, Shivakumar BG, Swami S, Choudhary M, Yadav VK, Singh AK, Raghavendra N, Govindasamy V, Chandra A and Reddy KS (2024) Climate-smart deficit irrigation and nutrient management strategies to conserve energy, greenhouse gas emissions, and the profitability of fodder maize seed production. *Journal of Cleaner Production* **442**, 140950.

Han Y, Wang K, Yang F, Pan S, Liu Z, Zhang Q and Zhang Q (2024) Prediction of maize cultivar yield based on machine learning algorithms for precise promotion and planting. *Agricultural and Forest Meteorology* **355**, 110123.

Harvey CA, Rakotobe ZL, Rao NS, Dave R, Razafimahatratra H, Rabarijohn RH, Rajaofara H and Mackinnon JL (2014) Extreme vulnerability of smallholder farmers to agricultural risks and climate change in Madagascar. *Philosophical Transactions of the Royal Society B: Biological Sciences* **369**, 20130089.

Haug R, Hella JP, Mulesa TH, Kakwera MN and Westengen OT (2023) Seed systems development to navigate multiple expectations in Ethiopia, Malawi and Tanzania. *World Development Sustainability* **3**, 100092.

Holden ST and Fisher M (2015) Subsidies promote use of drought tolerant maize varieties despite variable yield performance under smallholder environments in Malawi. *Food Security* **7**, 1225–1238.

Holzworth DP, Huth NI, deVoil PG, Zurcher EJ, Herrmann NI, McLean G, Chenu K, van Oosterom EJ, Snow V, Murphy C, Moore AD, Brown H, Whish JPM, Verrall S, Fainges J, Bell LW, Peake AS, Poulton PL, Hochman Z, Thorburn PJ, Gaydon DS, Dalgliesh NP, Rodriguez D, Cox H, Chapman S, Doherty A, Teixeira E, Sharp J, Cichota R, Vogeler I, Li FY, Wang E, Hammer GL, Robertson MJ, Dimes JP, Whitbread AM, Hunt J, van Rees H, McClelland T, Carberry PS, Hargreaves JNG, MacLeod N, McDonald C, Harsdorf J, Wedgwood S and Keating BA (2014) APSIM – Evolution towards a new generation of agricultural systems simulation. *Environmental Modelling & Software* **62**, 327–350.

Hong Z, Xu H, Shen Y, Liu C, Guo F, Muhammad S, Zhang Y, Niu H, Li S, Zhou W and Wu L (2024) Bioengineering for robust tolerance against cold and drought stresses via co-overexpressing three Cu-miRNAs in major food crops. *Cell Reports* **43**, 114828.

Huang C, Gao Y, Qin A, Liu Z, Zhao B, Ning D, Ma S, Duan A and Liu Z (2022) Effects of waterlogging at different stages and durations on maize growth and grain yields. *Agricultural Water Management* **261**, 107334.

Huang X-F, Zhou D, Lapsansky ER, Reardon KF, Guo J, Andales MJ, Vivanco JM and Manter DK (2017) Mitsuaria sp. and Burkholderia sp. from Arabidopsis rhizosphere enhance drought tolerance in Arabidopsis thaliana and maize (Zea mays L.). *Plant and Soil* **419**, 523–539.

Hung HY and Holland JB (2012) Diallel analysis of resistance to Fusarium ear rot and fumonisin contamination in maize. *Crop Science* **52**, 2173–2181.

Igbatayo SA (2022) Drought tolerant maize in Africa: A novel technology fostering regional food security in sub-saharan Africa. In Leal Filho W, Kovaleva M and Popkova E (eds.), *Sustainable Agriculture and Food Security*. Cham: Springer International Publishing, pp. 215–229.

IPCC (2021) *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. https://doi.org/10.1017/9781009157896.

Islam MR, Oliullah K, Kabir MM, Alom M and Mridha MF (2023) Machine learning enabled IoT system for soil nutrients monitoring and crop recommendation. *Journal of Agriculture and Food Research* **14**, 100880.

Jat ML, Jat HS, Agarwal T, Bijarniya D, Kakraliya SK, Choudhary KM, Kalvaniya KC, Gupta N, Kumar M and Singh LK (2020) A compendium of key climate smart agriculture practices in intensive cereal based systems of South Asia.

Jha S and Prajapati S (2024) Bacterial stalk rot (Dickeya zeae) and its impact on maize: The emerging silent invader. *Journal of Experimental Agriculture International* **46**, 827–837.

Jiang Y, Zhang J, Manuel D-B, Op de Beeck M, Shahbaz M, Chen Y, Deng X, Xu Z, Li J and Liu Z (2022) Rotation cropping and organic fertilizer jointly promote soil health and crop production. *Journal of Environmental Management* **315**, 115190.

Johnmark O, Indieka S, Liu G, Gowda M, Suresh LM, Zhang W and Gao X (2022) Fighting death for living: Recent advances in molecular and genetic mechanisms underlying maize lethal necrosis disease resistance. *Viruses* **14**, 2765.

Jones JW, Hoogenboom G, Porter CH, Boote KJ, Batchelor WD, Hunt LA, Wilkens PW, Singh U, Gijsman AJ and Ritchie JT (2003) The DSSAT cropping system model. *European Journal of Agronomy* **18**, 235–265.

Jose P, Singh V, George SG and Singh A (2022) Determination of maize (Zea mays L.) hybrids under agro-climatic conditions of Prayagraj, Uttar Pradesh, India. *International Journal of Environment and Climate Change* **12**, 696–699.

Kabato W, Getnet GT, Sinore T, Nemeth A and Molnár Z (2025) Towards climate-smart agriculture: Strategies for sustainable agricultural production, food security, and greenhouse gas reduction. *Agronomy* **15**, 565.

Kaur G, Vikal Y, Kaur L, Kalia A, Mittal A, Kaur D and Yadav I (2021) Elucidating the morpho-physiological adaptations and molecular responses under long-term waterlogging stress in maize through gene expression analysis. *Plant Science* **304**, 110823.

Kiesel C, Dannenberg P, Hulke C, Kairu J, Revilla Diez J and Sandhage-Hofmann A (2022) An argument for place-based policies: The importance of local agro-economic, political and environmental conditions for agricultural policies exemplified by the Zambezi region, Namibia. *Environmental Science & Policy* **129**, 137–149.

Kim KH and Lee BM (2023) Effects of climate change and drought tolerance on maize growth. *Plants (Basel)* **12**, 3548.

Kim KH, Park D and Lee BM (2026) Biotechnological strategies to enhance maize resilience under climate change. *Biology (Basel)* **15**, 161.

Kos J, Anić M, Radić B, Zadravec M, Janić Hajnal E and Pleadin J (2023) Climate change-A global threat resulting in increasing mycotoxin occurrence. *Foods* **12**, 2704.

Kumar S, Diksha SSS and Kumar R (2022) Biofertilizers: An ecofriendly technology for nutrient recycling and environmental sustainability. *Current Research in Microbial Sciences* **3**, 100094.

Kwena K, Ademe F, Serge J, Asmerom N, Musana B, Razakamiaramanana R, Ruttoh R, Mogaka H, Dereje A and Woldearegey K (2018) Bringing climate smart agriculture to scale: Experiences from the water productivity project in East and Central Africa. In Rao CS, Shanker AK and Shanker C (eds.), *Climate Resilient Agriculture-Strategies and Perspectives*. IntechOpen, pp. 37–58.

Lambert J, Sekhar NU, Chatrchyan A and DeGaetano A (2019) Agricultural decision support tools: A comparative perspective on these climate services. In Sarkar A, Sensarma SR and vanLoon GW (eds.), *Sustainable Solutions for Food Security : Combating Climate Change by Adaptation*. Cham: Springer International Publishing, pp. 459–478.

Le Pioufle O, Ganoudi M, Calonne-Salmon M, Ben Dhaou F and Declerck S (2019) Rhizophagus irregularis MUCL. 41833 improves phosphorus uptake and water use efficiency in maize plants during recovery from drought stress. *Frontiers in Plant Science* **10**, 897.

https://doi.org/10.1017/S0021859626100835 Published online by Cambridge University Press

Li G, Long H, Zhang R, Xu A and Niu L (2024) Photosynthetic traits, water use and the yield of maize are influenced by soil water stability. *BMC Plant Biology* **24**, 1235.

Li X, Li Y, Sun Y, Li S, Cai Q, Li S, Sun M, Yu T, Meng X and Zhang J (2025) Integrating genetic diversity and agronomic innovations for climate-resilient maize systems. *Plants* **14**, 1552.

Li Y, Huang Y, Sun H, Wang T, Ru W, Pan L, Zhao X, Dong Z, Huang W and Jin W (2022) Heat shock protein 101 contributes to the thermotolerance of male meiosis in maize. *The Plant Cell* **34**, 3702–3717.

Liu M, Dong X, Zhang Y, Gu M, Yu Y, Xie H, Yang H, Yu X and Huang S (2022) Heat stress on maize with contrasting genetic background: Differences in flowering and yield formation. *Agricultural and Forest Meteorology* **319**, 108934.

Liu M, Zhou Y, Sun J, Mao F, Yao Q, Li B, Wang Y, Gao Y, Dong X, Liao S, Wang P and Huang S (2023a) From the floret to the canopy: High temperature tolerance during flowering. *Plant Communications* **4**, 100629.

Liu Y, Chen Z, Zhang C, Guo J, Liu Q, Yin Y, Hu Y, Xia H, Li B, Sun X, Li Y and Liu X (2023b) Gene editing of ZmGA20ox3 improves plant architecture and drought tolerance in maize. *Plant Cell Reports* **43**, 18.

Lovino MA, Pierrestegui MJ, Masaro L, Müller OV, Müller GV and Berbery EH (2025) Agricultural flash droughts and their impact on crop yields in southeastern South America. *Environmental Research Letters* **20**, 054058.

Ma W and Rahut DB (2024) Climate-smart agriculture: Adoption, impacts, and implications for sustainable development. *Mitigation and Adaptation Strategies for Global Change* **29**, 44.

Mansoor S, Iqbal S, Popescu SM, Kim SL, Chung YS and Baek J-H (2025) Integration of smart sensors and IOT in precision agriculture: Trends, challenges and future prospectives. *Frontiers in Plant Science* **16**, 1587869.

Marechera G, Muinga G and Irungu P (2016) Assessment of seed maize systems and potential demand for climate-smart hybrid maize seed in Africa. *Journal of Agricultural Science* **8**, 171–182.

Martínez-Arias C, Witzell J, Solla A, Martin JA and Rodríguez-Calcerrada J (2022) Beneficial and pathogenic plant-microbe interactions during flooding stress. *Plant, Cell & Environment* **45**, 2875–2897.

Meseka S, Menkir A, Bossey B and Mengesha W (2018) Performance assessment of drought tolerant maize hybrids under combined drought and heat stress. *Agronomy* **8**, 274.

Micheni A, Gicheru P and Kitonyo O (2022) Conservation agriculture for climate smart agriculture in smallholder farming systems in Kenya. CABI, 431–442.

Mikiciuk G, Miller T, Kisiel A, Cembrowska-Lech D, Mikiciuk M, Łobodzińska A and Bokszczanin K (2024) Harnessing beneficial microbes for drought tolerance. *A Review of Ecological and Agricultural Innovations. Agriculture* **14**, 2228.

Mishra B, Chaturvedi M, Arya R, Singh RP and Yadav G (2024) Excess soil moisture stress in maize: Physiological mechanisms and adaptive strategies. *International Journal of Advanced Biochemistry Research* **8**, 201–211.

Mizik T (2021) Climate-smart agriculture on small-scale farms: A systematic literature review. *Agronomy* **11**, 1096.

Mondo JM, Ndeko AB, Ayagirwe RB, Matiti HM, Bahati C and Civava RM (2024) Seed delivery system in northeastern Democratic Republic of Congo: Characteristics, stakeholders mapping and challenges towards building a well-functioning seed system under humanitarian and security crises. *International Journal of Agricultural Sustainability* **22**, 2335128.

Monroy-Sais AS, Tobin D, Bellon MR, Astier M, Cibrián-Jaramillo A, Gálvez-Reyes N, Mastretta-Yanes A, Ruiz-Arocho J, Wegier A and Chen YH (2024) Smallholder farmers' diverse values in maize landrace conservation: A case study from Chiapas, Mexico. *Journal of Rural Studies* **110**, 103347.

Msigwa A, Makinde AS, Ramoelo A, Komakech HC and Ufoegbune GC (2024) Spatial–temporal seasonal and annual rainfall trends and variability assessment in the Pangani Basin, East Africa. *Physics and Chemistry of the Earth, Parts A/B/C* **136**, 103762.

Namata MJ, Xu J, Habyarimana E, Palakolanu SR, Wang L and Li J (2025) Genome editing in maize and sorghum: A comprehensive review of CRISPR/Cas9 and emerging technologies. *The Plant Genome* **18**, e70038.

Nega A (2025) Climate change impacts on agriculture: A review of plant diseases and insect pests in Ethiopia and East Africa, with adaptation and mitigation strategies. *Advances in Agriculture* **2025**, 5606701.

Nelimor C, Badu-Apraku B, Tetteh AY and N'guetta ASP (2019) Assessment of genetic diversity for drought, heat and combined drought and heat stress tolerance in early maturing maize landraces. *Plants* **8**, 518.

Notununu I, Moleleki L, Roopnarain A and Adeleke R (2024) Enhancing maize drought and heat tolerance: Single vs combined plant growth promoting rhizobacterial inoculation. *Frontiers in Plant Science* **15**, 1480718.

Nyaaba JA, Nkrumah-Ennin K and Anang BT (2019) Willingness to pay for crop insurance in Tolon District of Ghana: Application of an endogenous treatment effect model. *AIMS Agriculture & Food* **4**, 362–375.

Nyirenda H, Mwangomba W and Nyirenda EM (2021) Delving into possible missing links for attainment of food security in Central Malawi: Farmers' perceptions and long term dynamics in maize (Zea mays L.) production. *Heliyon* **7**, e07130.

Ogle SM, Alsaker C, Baldock J, Bernoux M, Breidt FJ, McConkey B, Regina K and Vazquez-Amabile GG (2019) Climate and soil characteristics determine where no-till management can store carbon in soils and mitigate greenhouse gas emissions. *Scientific Reports* **9**, 11665.

Ogutu GEO, Franssen WHP, Supit I, Omondi P and Hutjes RWA (2018) Probabilistic maize yield prediction over East Africa using dynamic ensemble seasonal climate forecasts. *Agricultural and Forest Meteorology* **250–251**, 243–261.

Oikeh S, Ngonyamo-Majee D, Mugo SIN, Mashingaidze K, Cook V and Stephens M (2014) The water efficient maize for Africa project as an example of a public–private partnership. in Songstad DD, Hatfield JL and Tomes DT (eds.), *Convergence of Food Security, Energy Security and Sustainable Agriculture*. Berlin, Heidelberg, Berlin Heidelberg: Springer, pp. 317–329.

Olabanji MF and Chitakira M (2025) The adoption and scaling of climate-smart agriculture innovation by smallholder farmers in South Africa: A review of institutional mechanisms. *Policy Frameworks and Market Dynamics. World* **6**, 51.

Omia E, Bae H, Park E, Kim MS, Baek I, Kabenge I and Cho B-K (2023) Remote sensing in field crop monitoring: A comprehensive review of sensor systems, data analyses and recent advances. *Remote Sensing* **15**, 354.

Pandu U, Channabasavanna AS and Raddy G (2023) Performance of heat resilient maize hybrids to different levels of fertilizers in Tungabhadra Project command area. *Environment Conservation Journal* **24**, 96–109.

Panta D, Amgaina LP, Paudel A and Guragaina G (2022) Assessment of precision nutrient management practices on crop growth, productivity, and profitability of maize grown during winter in Central Terai, Nepal. *Food and Agri Economics Review* **2**, 57–64.

Parra-López C, Ben Abdallah S, Garcia-Garcia G, Hassoun A, Trollman H, Jagtap S, Gupta S, Aït-Kaddour A, Makmuang S and Carmona-Torres C (2025) Digital technologies for water use and management in agriculture: Recent applications and future outlook. *Agricultural Water Management* **309**, 109347.

Patyal U, Bala R, Kaur M, Faizan M and Alam P (2025) Phyto-microbiome engineering: Designing plant-microbe interactions for improved crop performance. *The Microbe* **6**, 100272.

Paudel Timilsena B, Niassy S, Kimathi E, Abdel-Rahman EM, Seidl-Adams I, Wamalwa M, Tonnang HEZ, Ekesi S, Hughes DP, Rajotte EG and Subramanian S (2022) Potential distribution of fall armyworm in Africa and beyond, considering climate change and irrigation patterns. *Scientific Reports* **12**, 539.

Peer LA, Bhat MY, Lone AA, Dar ZA and Mir BA (2024) Genetic, molecular and physiological crosstalk during drought tolerance in maize (Zea mays): Pathways to resilient agriculture. *Planta* **260**, 81.

Peer LA, Wani AA, Lone AA, Dar ZA and Mir BA (2025) Drought stress memory in maize: Understanding and harnessing the past for future resilience. *Plant Cell Reports* **44**, 101.

Peñalosa-Martinell D, Vergara-Solana FJ and Villarreal Colmenares H (2025) Analysis of the impact of aquaculture subsidies on production, the case of Mexico. *npj Ocean Sustainability* **4**, 20.

Pienaah CKA, Batung E, Saaka SA, Mohammed K and Luginaah I (2023) Early warnings and perceived climate change preparedness among smallholder farmers in the Upper West Region of Ghana. *Land* **12**, 1944.

Prajapati CS, Priya NK, Bishnoi S, Vishwakarma SK, Buvaneswari K, Shastri S, Tripathi S and Jadhav A (2025) The role of participatory approaches in modern agricultural extension: Bridging knowledge gaps for sustainable

https://doi.org/10.1017/S0021859626100835 Published online by Cambridge University Press

farming practices. *Journal of Experimental Agriculture International* **47**, 204–222.

Prasanna B (2023) Breeding and deploying climate resilient maize varieties in the tropics. *Indian Journal of Ecology* **50**, 1895–1899.

Prasanna BM, Cairns JE, Zaidi P, Beyene Y, Makumbi D, Gowda M, Magorokosho C, Zaman-Allah M, Olsen M and Das A (2021) Beat the stress: breeding for climate resilience in maize for the tropical rainfed environments. *Theoretical and Applied Genetics* **134**, 1729–1752.

Prasanna BM, Nair SK, Babu R, Gowda M, Zhang X, Xu Y, Olsen M, Chaikam V, Cairns JE, Zaman-Allah M, Beyene Y, Tarekegne A and Magorokosho C (2020) Increasing genetic gains in maize in stress-prone environments of the tropics. In Kole C (ed.), *Genomic Designing of Climate-Smart Cereal Crops*. Cham: Springer International Publishing, pp. 97–132.

Pukrongta N, Taparugssanagorn A and Sangpradit K (2024) Enhancing crop yield predictions with PEnsemble 4: IoT and ML-driven for precision agriculture. *Applied Sciences* **14**, 3313.

Qin F, Kakimoto M, Sakuma Y, Maruyama K, Osakabe Y, Tran LS, Shinozaki K and Yamaguchi-Shinozaki K (2007) Regulation and functional analysis of ZmDREB2A in response to drought and heat stresses in Zea mays L. *The Plant Journal* **50**, 54–69.

Renwick LL, Kimaro AA, Hafner JM, Rosenstock TS and Gaudin AC (2020) Maize-pigeonpea intercropping outperforms monocultures under drought. *Frontiers in Sustainable Food Systems* **4**, 562663.

Ribeiro C, Hennen-Bierwagen TA, Myers AM, Cline K and Settles AM (2020) Engineering 6-phosphogluconate dehydrogenase improves grain yield in heat-stressed maize. *Proceedings of the National Academy of Sciences of the United States of America* **117**, 33177–33185.

Rodríguez-Barillas M, Klerkx L and Poortvliet PM (2024) What determines the acceptance of climate smart technologies? The influence of farmers' behavioral drivers in connection with the policy environment. *Agricultural Systems* **213**, 103803.

Saddique Q, Cai H, Xu J, Ajaz A, He J, Yu Q, Wang Y, Chen H, Khan MI, Liu DL and He L (2020) Analyzing adaptation strategies for maize production under future climate change in Guanzhong Plain, China. *Mitigation and Adaptation Strategies for Global Change* **25**, 1523–1543.

Sahoo S, Singha C, Govind A and Moghimi A (2025) Review of climate-resilient agriculture for ensuring food security: Sustainability opportunities and challenges of India. *Environmental and Sustainability Indicators* **25**, 100544.

Sahoo U, Maitra S, Dey S, Vishnupriya KK, Sairam M and Sagar L (2023) Unveiling the potential of maize-legume intercropping system for agricultural sustainability: A review. *Farming and Management* **8**, 1–13.

Sami A, Xue Z, Tazein S, Arshad A, He Zhu Z, Ping Chen Y, Hong Y, Tian Zhu X and Jin Zhou K (2021) CRISPR-Cas9-based genetic engineering for crop improvement under drought stress. *Bioengineered* **12**, 5814–5829.

Sanclemente MA (2023) Is hypoxia good or bad? Role of oxygen levels in maize kernel development. *Plant Physiology* **192**, 694–696.

Sandhu KS, Merrick LF, Sankaran S, Zhang Z and Carter AH (2022) Prospectus of genomic selection and phenomics in cereal, legume and oilseed breeding programs. *Frontiers in Genetics* **12**, 829131.

Santos-Medellín C, Edwards J, Liechty Z, Nguyen B and Sundaresan V (2017) Drought stress results in a compartment-specific restructuring of the rice root-associated microbiomes. *mBio* **8**, e00764–17. https://doi.org/10.1128/mbio.00764-17.

Semagn K, Beyene Y, Warburton ML, Tarekegne A, Mugo S, Meisel B, Sehabiague P and Prasanna BM (2013) Meta-analyses of QTL for grain yield and anthesis silking interval in 18 maize populations evaluated under water-stressed and well-watered environments. *BMC Genomics* **14**, 313.

Shaffique S, Khan MA, Imran M, Kang S-M, Park Y-S, Wani SH and Lee I-J (2022) Research progress in the field of microbial mitigation of drought stress in plants. *Frontiers in Plant Science* **13**, 870626.

Shahhosseini M, Hu G, Huber I and Archontoulis SV (2021) Coupling machine learning and crop modelling improves crop yield prediction in the US Corn Belt. *Scientific Reports* **11**, 1606.

Sheoran S, Kaur Y, Kumar S, Shukla S, Rakshit S and Kumar R (2022) Recent advances for drought stress tolerance in maize (Zea mays L.): Present status and future prospects. *Frontiers in Plant Science* **13**, 872566.

Shi J, Gao H, Wang H, Lafitte HR, Archibald RL, Yang M, Hakimi SM, Mo H and Habben JE (2017) ARGOS8 variants generated by CRISPR-Cas9 improve maize grain yield under field drought stress conditions. *Plant Biotechnology Journal* **15**, 207–216.

Shilomboleni H, John R, Maren R and Osumba J (2023) Scaling climate resilient seed systems through SMEs in Eastern and Southern Africa: Challenges and opportunities. *Climate and Development* **15**, 177–187.

Singh GM, Xu J, Schaefer D, Day R, Wang Z and Zhang F (2022) Maize diversity for fall armyworm resistance in a warming world. *Crop Science* **62**, 1–19.

Sithole A and Olorunfemi OD (2024) Sustainable agricultural practices in sub-Saharan Africa: A review of adoption trends, impacts, and challenges among smallholder farmers. *Sustainability* **16**, 9766.

Sithole M, Ng'ombe A, Musafiri CM, Kiboi M, Sales T and Ngetich FK (2023) The role of agricultural projects in building sustainable and resilient maize value chain in Burkina Faso. *Sustainability* **15**, 16684.

Skendžić S, Zovko M, Živković IP, Lešić V and Lemić D (2021) The impact of climate change on agricultural insect pests. *Insects* **12**, 440.

Sophian A (2026) Molecular markers and GWAS for thermotolerance in maize: Integrating gene expression, epigenetic regulation and yield stability under climate change. *Journal of Agronomy and Crop Science* **212**, e70212.

Srivastava RK (2025) Conservation tillage practices on GHG emissions, soil health and overall agricultural sustainability. *Soil Use and Management* **41**, e70096.

Steward PR, Thierfelder C, Dougill AJ and Ligowe I (2019) Conservation agriculture enhances resistance of maize to climate stress in a Malawian medium-term trial. *Agriculture, Ecosystems & Environment* **277**, 95–104.

Sun W and Shahrajabian MH (2023) The application of arbuscular mycorrhizal fungi as microbial biostimulant, sustainable approaches in modern agriculture. *Plants* **12**, 3101.

Tesfaye K, Zaidi PH, Gbegbelegbe S, Boeber C, Rahut DB, Getaneh F, Seetharam K, Erenstein O and Stirling C (2017) Climate change impacts and potential benefits of heat-tolerant maize in South Asia. *Theoretical and Applied Climatology* **130**, 959–970.

Tesfaye M and Amare H (2023) Highland maize technology demonstration: Evidence from three maize growing districts of West and Southwest Ethiopia. *Agriculture, Forestry and Fisheries* **12**, 44–51.

Teshome FT, Bayabil HK, Schaffer B, Ampatzidis Y, Hoogenboom G and Singh A (2023) Exploring deficit irrigation as a water conservation strategy: Insights from field experiments and model simulation. *Agricultural Water Management* **289**, 108490.

Togola A, Beyene Y, Bocco R, Tepa-Yotto G, Gowda M, Too A and Boddupalli P (2025) Fall armyworm (Spodoptera frugiperda) in Africa: Insights into biology, ecology and impact on staple crops, food systems and management approaches. *Frontiers in Agronomy* **7**, 1538198.

Touch V, Tan DKY, Cook BR, Liu DL, Cross R, Tran TA, Utomo A, Yous S, Grunbuhel C and Cowie A (2024) Smallholder farmers' challenges and opportunities: Implications for agricultural production, environment and food security. *Journal of Environmental Management* **370**, 122536.

Wahab A, Muhammad M, Munir A, Abdi G, Zaman W, Ayaz A, Khizar C and Reddy SPP (2023) Role of arbuscular mycorrhizal fungi in regulating growth, enhancing productivity, and potentially influencing ecosystems under abiotic and biotic stresses. *Plants (Basel)* **12**, 3102.

Wakweya RB (2023) Challenges and prospects of adopting climate-smart agricultural practices and technologies: Implications for food security. *Journal of Agriculture and Food Research* **14**, 100698.

Wamatsembe IM, Asea G and Haefele SM (2017) A survey: Potential impact of genetically modified maize tolerant to drought or resistant to stem borers in Uganda. *Agronomy* **7**, 24.

Wang H, Ren H, Han K, He Q, Zhang L, Zhao Y, Liu Y, Zhang J, Zhao B, Ren B and Liu P (2023) Sustainable improvement strategies for summer maize yield, nitrogen use efficiency and greenhouse gas emission intensity in the North China Plain. *European Journal of Agronomy* **143**, 126712.

Wang J, Wang B-Z, Mo F, Chen Y, Ashraf M, Wang Y, Li J-M, Duan H-X, Song Y, Kavagi L, Tao H-Y and Xiong Y-C (2026) Enhancing climate resilience of global dryland maize to cope with future 50-year climate warming. *Global Environmental Change* **96**, 103088.

https://doi.org/10.1017/S0021859626100835 Published online by Cambridge University Press

Wang P, Marsh EL, Kruger G, Lorenz A and Schachtman DP (2020) Belowground microbial communities respond to water deficit and are shaped by decades of maize hybrid breeding. *Environmental Microbiology* **22**, 889–904.

Waqas MA, Wang X, Zafar SA, Noor MA, Hussain HA, Azher Nawaz M and Farooq M (2021) Thermal stresses in maize: Effects and management strategies. *Plants (Basel)* **10**, 293.

Wen X, Liu D, Qiu M, Wang Y, Niu J and Liu Y (2023) Estimation of maize yield incorporating the synergistic effect of climatic and land use change in Jilin, China. *Journal of Geographical Sciences* **33**, 1725–1746.

Westengen OT, Dalle SP and Mulesa TH (2023) Navigating toward resilient and inclusive seed systems. *Proceedings of the National Academy of Sciences of the United States of America* **120**, e2218777120.

Wilmowicz E, Kućko A, Bogati K, Wolska M, Świdziński M, Burkowska-But A and Walczak M (2022) Glomus sp. and Bacillus sp. strains mitigate the adverse effects of drought on maize (Zea mays L.). *Frontiers in Plant Science* **13**, 958004.

Wingeyer AB, Amado TJC, Pérez-Bidegain M, Studdert GA, Varela CHP, Garcia FO and Karlen DL (2015) Soil quality impacts of current South American agricultural practices. *Sustainability* **7**, 2213–2242.

Wu F and Guclu H (2013) Global maize trade and food security: Implications from a social network model. *Risk Analysis* **33**, 2168–2178.

Xu L, Wang A, Wang J, Wei Q and Zhang W (2017) Piriformospora indica confers drought tolerance on Zea mays L. through enhancement of antioxidant activity and expression of drought-related genes. *The Crop Journal* **5**, 251–258.

Yan Z, Zhang F, Mu C, Ma C, Yao G, Sun Y, Hou J, Leng B and Liu X (2024) The ZmbHLH47-ZmSnRK2.9 module promotes drought tolerance in maize. *International Journal of Molecular Sciences* **25**, 4957.

Yang Y-G, Lv W-T, Li M-J, Wang B, Sun D-M and Deng X (2013) Maize membrane-bound transcription factor Zmbzip17 is a key regulator in the cross-talk of ER quality control and ABA signalling. *Plant and Cell Physiology* **54**, 2020–2033.

Ye J, Zhong T, Zhang D, Ma C, Wang L, Yao L, Zhang Q, Zhu M and Xu M (2019) The Auxin-regulated protein ZmAuxRP1 coordinates the balance between root growth and stalk rot disease resistance in maize. *Molecular Plant* **12**, 360–373.

Yin Z, Wei X, Cao Y, Dong Z, Long Y and Wan X (2024) Regulatory balance between ear rot resistance and grain yield and their breeding applications in maize and other crops. *Journal of Advanced Research* **75**, 1–22.

Yuan Y, Cairns JE, Babu R, Gowda M, Makumbi D, Magorokosho C, Zhang A, Liu Y, Wang N, Hao Z, San Vicente F, Olsen MS, Prasanna BM, Lu Y and Zhang X (2018) Genome-wide association mapping and genomic prediction analyses reveal the genetic architecture of grain yield and flowering time under drought and heat stress conditions in maize. *Frontiers in Plant Science* **9**, 1919.

Yusuf A, Li M, Zhang SY, Odedishemi-Ajibade F, Luo RF, Wu YX, Zhang TT, Yunusa Ugya A, Zhang Y and Duan S (2025) Harnessing plant-microbe interactions: Strategies for enhancing resilience and nutrient acquisition for sustainable agriculture. *Frontiers in Plant Science* **16**, 1503730.

Zaidi PH, Maniselvan P, Srivastava A, Yadav P and Singh RP (2010) Genetic analysis of water-logging tolerance in tropical maize (Zea mays L.). *Maydica* **55**, 17–26.

Zaidi PH, Thayil Vinayan M, Nair SK, Kuchanur PH, Kumar R, Bir Singh S, Prasad Tripathi M, Patil A, Ahmed S, Hussain A, Prabhakar Kulkarni A, Wangmo P, Tuinstra MR and Prasanna BM (2023) Heat-tolerant maize for rainfed hot, dry environments in the lowland tropics: From breeding to improved seed delivery. *The Crop Journal* **11**, 986–1000.

Zeng Y, Xu X, Jiang J, Lin S, Fan Z, Meng Y, Maimaiti A, Wu P and Ren J (2025) Genome-wide association analysis and genomic selection for leaf-related traits of maize. *PLoS One* **20**, e0323140.

Zewdu D, Krishnan CM, Raj PPN, Arlikatti S and McAleavy T (2025) Climate-smart innovation practices and sustainable rural livelihoods: A systematic literature review. *Technology in Society* **82**, 102914.

Zhang D, Liu Y, Guo Y, Yang Q, Ye J, Chen S and Xu M (2012) Fine-mapping of qRfg2, a QTL for resistance to Gibberella stalk rot in maize. *Theoretical and Applied Genetics* **124**, 585–596.

Zhang X, Mi Y, Mao H, Liu S, Chen L and Qin F (2020) Genetic variation in ZmTIP1 contributes to root hair elongation and drought tolerance in maize. *Plant Biotechnology Journal* **18**, 1271–1283.

Zhang Z, Wei J, Li J, Jia Y, Wang W, Li J, Lei Z and Gao M (2022) The impact of climate change on maize production: Empirical findings and implications for sustainable agricultural development. *Frontiers in Environmental Science* **10**, 954940.

Zhao Y, Du H, Wang Y, Wang H, Yang S, Li C, Chen N, Yang H, Zhang Y, Zhu Y, Yang L and Hu X (2021) The calcium-dependent protein kinase ZmCDPK7 functions in heat-stress tolerance in maize. *Journal of Integrative Plant Biology* **63**, 510–527.

Zhi F, Zhang J, Bao Y, Bao Y, Dong Z, Tong Z and Liu X (2024) Assessment of waterlogging hazard during maize growth stage in the Songliao plain based on daily scale SPEI and SMAI. *Agricultural Water Management* **304**, 109081.

Zou Y, Liu Z, Chen Y, Wang Y and Feng S (2024) Crop rotation and diversification in China: Enhancing sustainable agriculture and resilience. *Agriculture* **14**, 1465.

https://doi.org/10.1017/S0021859626100835 Published online by Cambridge University Press